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Fire Safe Design of Timber Structures

Methods of Analysis and Supporting Data

Technical Design Guide issued by Forest and Wood Products Australia

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Introduction

Timber is used for many building applications and has numerous advantages over other building products, including its environmental sustainability credentials, light weight compared to most structural materials, speed of construction, and aesthetics.

This has increased interest in the use of structural timber for mid-rise buildings (up to an effective height of 25 metres) and high-rise buildings in Australia in addition to the more established applications for low-rise buildings and single dwellings.

Changes to the National Construction Code (NCC) in 2016[1] and 2019[2] introduced Deemed-to-Satisfy (DTS) pathways for demonstrating compliance for mid-rise timber buildings based on the concept of Fire-protected Timber. Figure 1 shows the NCC height limits that correspond to low, mid and high-rise construction.

Low-rise timber buildings
are buildings of:

- Type B or C construction (1 or 2 storey)

Mid-rise timber buildings
have an effective height of not more than 25 metres.} Typically, they are 3-8 storeys high (the maximum number of storeys depends on the floor-to-floor height)

High-rise timber buildings
have an effective height greater than 25 m.

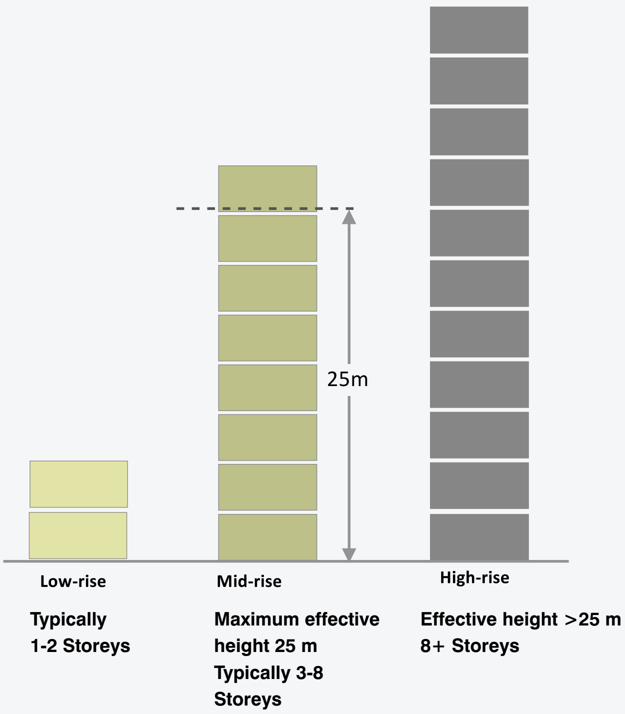


Figure 1: NCC height limits corresponding to low, mid and high-rise timber buildings. Note: The NCC provides a relaxation (dispensation) allowing some 3-storey Class 2 or 3 buildings to be of timber frame construction.

Detailed guidance on the application of NCC[3] DTS Provisions to low-rise and mid-rise timber buildings are provided in the following WoodSolutions Technical Design Guides:

- WoodSolutions Technical Design Guide 1 – Timber-framed Construction for Townhouse Buildings (Class 1a)
- WoodSolutions Technical Design Guide 2 – Timber-framed Construction for Multi-residential Buildings (Low-rise Class 2 & 3) – under revision at the time of preparation of this Guide
- WoodSolutions Technical Design Guide 3 – Timber Framed Construction for Commercial Buildings Classes 5, 6, 9a & 9b – under revision at the time of preparation of the Guide.
- WoodSolutions Technical Design Guide 37R[4] – Mid-rise Multi-residential buildings (Class 2 and 3).
- WoodSolutions Technical Design Guide 37C[5] – Mid-rise Commercial and Education buildings (Class 5, 6, 7, 8 and 9b, including Class 4 parts).
- WoodSolutions Technical Design Guide 37H[6] – Mid-rise Health-care Buildings (Class 9a and Class 9c).
- WoodSolutions Technical Design Guide 42[7] – Timber Aged Care Buildings (Class 9c). Guide 42 describes an alternative DTS pathway to the Fire-protected Timber solution for Class 9c aged care accommodation.

This Technical Design Guide 18 provides information on methods of analysis and supporting data that can be applied to the design of timber structures in Australia if the Performance Solution or DTS pathways are followed. The Guide focuses on methods of analysis and supporting data applicable to timber structures that are of greatest relevance to the Australian building industry and the NCC. It draws on research work undertaken on behalf of the FWPA to support technical changes to the NCC, but other sources are referenced where appropriate.

Document overview

This Guide is part of a series of three design guides that have been rewritten to reflect the significant changes to fire safety regulations and recent research relating to the performance of timber when exposed to fire. This document provides details of methods of analysis and supporting data that may be used as the basis of Assessment Methods/Evidence of Suitability to verify compliance of timber buildings and elements of construction with the NCC.

The other guides in the series are:

- *WoodSolutions Technical Design Guide 17 – Fire Safe Design of Timber Structures – Compliance with the National Construction Code* – introduces fire safe design approaches for timber structures in Australia. The primary focus is compliance with the NCC Volume One, which provides requirements for the technical design and construction for all multi-residential, commercial, industrial and public assembly buildings, and their associated structures (Class 2 to 9 buildings). It explains the need for building designers to consider all relevant legislation and design objectives throughout the building life-cycle in a holistic manner.
- *WoodSolutions Technical Design Guide 19 – Fire Safe Design of Timber Structures – Worked Examples of Performance Solutions* provides worked examples of the analysis and Assessment Methods that can be applied to typical Performance Solutions.

This Guide assumes the reader is familiar with the content of Technical Design Guide 17[8], is appropriately qualified and competent in the fields of fire safety engineering and risk assessment, and has a good understanding of the response of timber to fire. Information relating to the response of timber elements of construction exposed to fire is available in technical literature such as Drysdale[9], Friquin[10] and Bartlett[11].

The worked examples in Technical Design Guide 19 apply the content of Technical Design Guides 17 and 18.

Following is a summary of the content of this Guide (Technical Design Guide 18):

Chapter 1 includes an overview of the fire safety engineering design process to provide a context for the application of the NCC.

Chapter 2 provides information relating to the general properties of wood products with an emphasis on the fire-related properties.

Chapter 3 explains how Design Fires can be characterised so that they are representative of fire scenarios that are being evaluated.

Chapter 4 explores how exposed wood products can influence fire dynamics during an enclosure fire.

Chapter 5 provides a brief introduction to general approaches for the detailed design, specification and Evidence of Suitability of fire safety measures relating to timber construction. More detailed information relating specifically to reaction-to-fire performance is provided in Chapter 6 and in relation to structural fire safety and fire resistance in Chapter 7.

The Appendices include the following supporting information:

Appendix A: Abbreviations and definitions

Appendix B: Summary of natural fire tests relevant to timber structures

Appendix C: Summary of Australian research relating to fire-resistance tests of wood products

Appendix D: Summary of wall and ceiling lining tests relevant to wood products

Appendix E: Examples of Evidence of Suitability for Fire-protected Timber

Appendix F: Description of a simple generic model for conversion of fire-resistant time to scenario time

Appendix G: References

1 Introduction to methods of analysis and supporting data for timber buildings

1.1 Fire safety engineering process

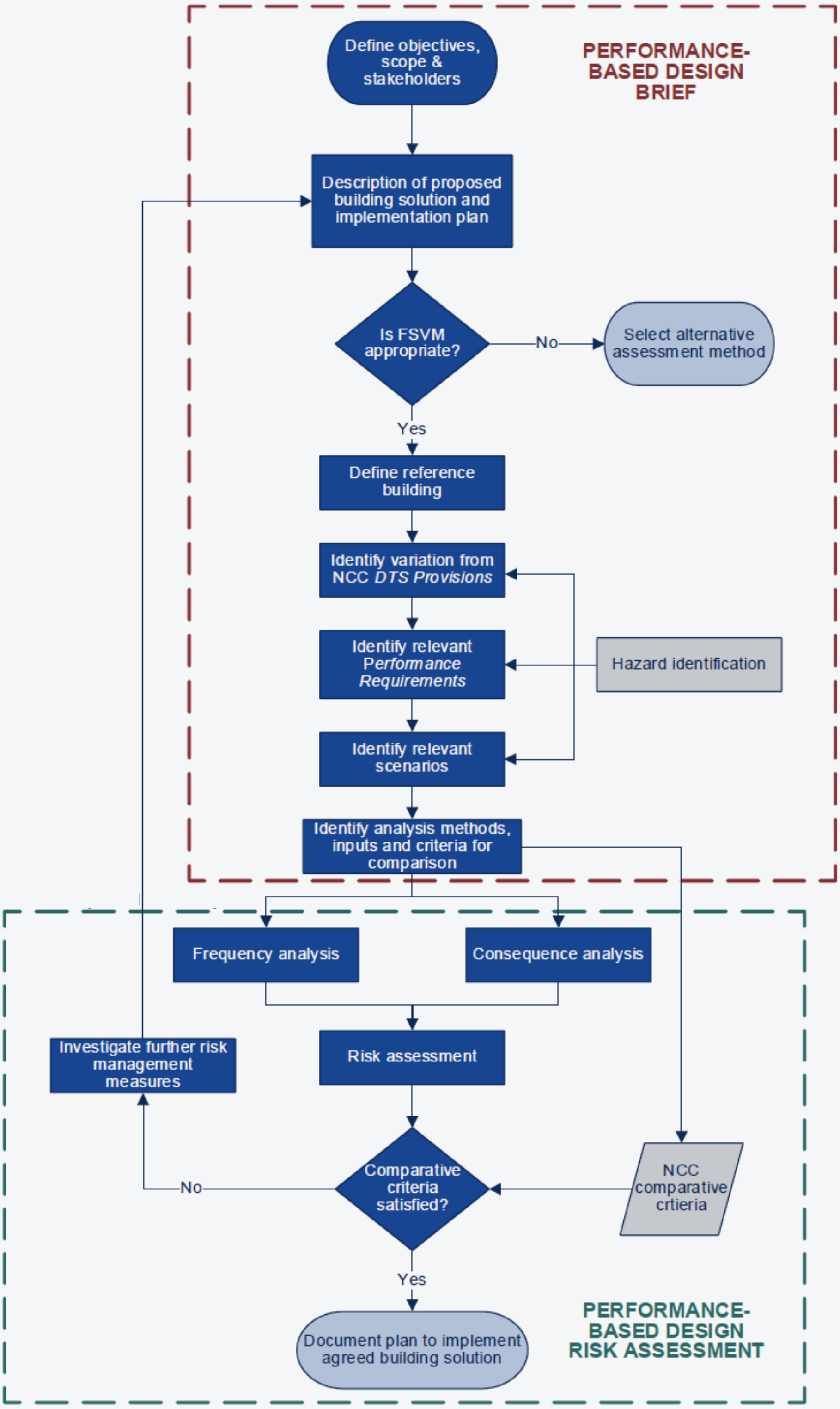


Figure 2: Fire Safety Verification Method flow chart based on FSVM Handbook. (© Commonwealth of Australia and States and Territories 2019, published by the Australian Building Codes Board).

There are numerous guides and standards that outline the fire safety engineering process, but generally the processes that are described are broadly similar. Figure 2 shows a flow chart included in the ABCB Fire Safety Verification Method handbook, which has the greatest relevance to this Guide and the NCC.

The NCC Fire Safety Verification Method (FSVM)[3] adopts a comparative approach. Figure 2 shows the need to consider both the consequence and frequency of occurrence of relevant fire scenarios to obtain a meaningful comparison.

1.2 Design Fire scenarios

Appropriate fire scenarios and related Design Fires need to be selected for analysis when undertaking a fire safety engineering design to demonstrate compliance with the NCC Performance Requirements. There are a large number of possible scenarios and it is not practical or necessary to analyse them all, but simply ignoring scenarios may lead to either overly conservative or unconservative solutions. This can be addressed by selecting scenarios that are representative of clusters of potential fire scenarios and assigning probabilities to their occurrence so that the potential universe of possible fire scenarios is represented.

This process should be undertaken as part of the Performance-based Design Brief (PBDB) to inform the selection of methods of analysis, inputs, and supporting data and associated performance criteria. As the selection of Design Fire scenarios can be critical and some may be specific to timber buildings, information on the selection of design scenarios for timber buildings has been included, where appropriate, within this Guide.

The FSVM nominates specific design scenarios that must be considered to reduce the risk of practitioners overlooking critical scenarios. These are summarised in Table 1 but additional scenarios may be required to investigate the impact of unusual features in a design.

The process of deriving fire scenarios can be demonstrated by considering an example of the design of the structural elements within a small or medium-sized enclosure. A Design Fire scenario representing a fire progressing to the fully developed phase followed by the decay and cooling phases is required to challenge the structural adequacy of the elements. Only a proportion of fires will progress through all these stages.

Typically, once ignition occurs:

- a fire may simply smoulder and self-extinguish or be suppressed by the occupants
- a fire may progress to a small flaming fire but not spread beyond the object first ignited or be suppressed by the occupants
- if an automatic suppression system is provided and operates successfully, the fire may be suppressed
- if the fire growth rate is relatively slow and the fire brigade is notified relatively quickly the fire may be manually suppressed before flashover occurs.

If probabilities are determined for these events, it is possible to derive the probability of a flashover fire occurring by means of a simple event tree similar to that in Figure 3. The event tree can be extended to consider the effectiveness of structural fire protection (or the inherent fire resistance of an element of construction) and fire brigade intervention. When defining the effectiveness of structural fire protection systems, it is important to consider the probability and consequences of gross defects, such as the omission of protection or substitution with materials providing little protection. These types of gross defects are not adequately modelled by a simple assumption of a normal or other common distribution, but can be addressed either by a separate branch in the event tree (scenario cluster) or a two-peak distribution as applied in the analysis supporting the mid-rise DTS Fire-protected Timber building solutions in the NCC (described in more detail in WoodSolutions Technical Design Guide 38[12]).

Table 1: Design scenarios from the fire safety verification method.

Ref	Design Scenario	Design Scenario Description
BE	Fire blocks evacuation route	A fire blocks an evacuation route
UT	Fire in a normally unoccupied room threatens occupants of other rooms	A fire starts in a normally unoccupied room and can potentially endanger a large number of occupants in another room
CS	Fire starts in concealed space	A fire starts in a concealed space that can facilitate fire spread and potentially endanger a number of people in a room
SF	Smouldering fire	A fire is smouldering in close proximity to a sleeping area
IS	Fire spread involving internal finishes	Interior surfaces are exposed to a growing fire that potentially endangers occupants
CF	Challenging fire	Worst credible fire in an occupied space
RC	Robustness check	The objectives of the NCC should be satisfied if failures of critical parts of the fire safety systems occur
SS	Structural stability and other properties	Building does not present risk to other properties in a fire event. Consider risk of structural failure
HS	Horizontal fire spread	A fully developed fire in a building exposes the external walls of a neighbouring building (or potential building) and vice versa
VS	Vertical fire spread involving cladding or arrangement of openings in walls	A fire source exposes a wall and leads to significant vertical fire spread
FI	Fire brigade intervention	Facilitate fire brigade intervention to the degree necessary
UF	Unexpected catastrophic failure	A building must not unexpectedly collapse during a fire event

The probability of fire brigade suppression activities being successful after flashover can be introduced to the event tree (Figure 3). If fire brigade intervention is unsuccessful and the element cannot withstand burnout, structural failure may occur.

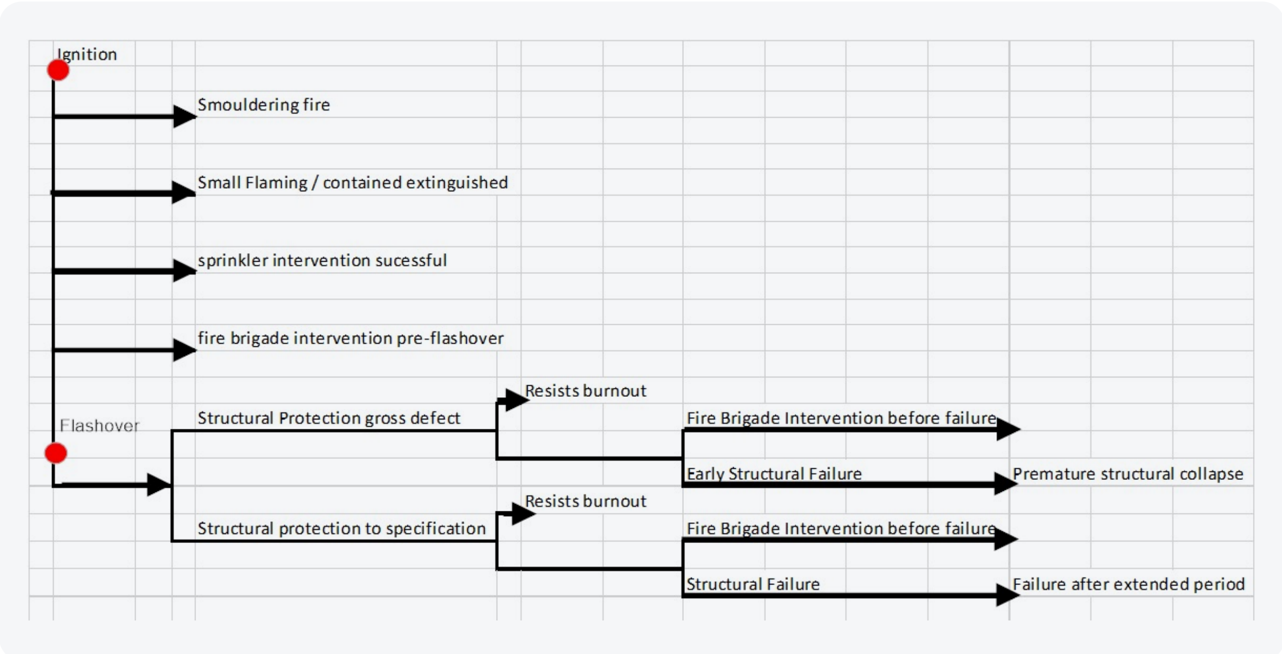


Figure 3: Simple event tree structure for evaluation of structural performance when exposed to fire.

The scenarios involving a gross defect generally have the greatest potential to result in a premature and potentially unexpected failure leading to multiple fatalities and injuries to occupants and firefighters, although the probability of occurrence may be very low.

A risk assessment helps interpret the results objectively by considering both the frequency and outcomes of a representative range of fire scenarios.

Further information relating to the selection of fire scenarios and associated Design Fires can be found in various fire engineering guides and standards including:

- the ABCB Fire Safety Verification Method Handbook[13]
- Fire Safety Verification Method Data Sheets – Handbook Annex[14]
- ISO 17633.1 2015 Fire Safety Engineering-Selection of design fire scenarios and design fires: Part 1 Selection of design fire scenarios[15]
- ISO/TS 16733-2 2021 Fire Safety Engineering-Selection of design fire scenarios and design fires-Part 2: Design Fires[16].

Specific information relating to fire scenarios for timber buildings is included in the relevant chapters of this Guide.

1.3 Overview of design process for the reaction to fire performance of materials and elements of construction

Reaction to fire performance in the context of this Guide is the response of a product or material to a fire source and includes the impact on fire spread, production of products of combustion, contribution to fire severity and release of hazardous debris.

The focus of reaction to fire performance is from fire initiation through the growth phase to flashover, although some criteria such as combustibility also apply to fully developed enclosure fires. Fire spread between buildings and via a building facade can also be addressed to some extent by managing the 'reaction to fire' performance of the external facades of buildings.

The process of the design for reaction to fire performance of building systems and products involves three stages:

- defining Design Fire scenarios including exposure sources
- heat transfer analysis
- measurement of critical parameters that define the performance of a product.

Figure 4 gives a flow chart of the key stages of the process.

The NCC DTS Provisions rely on a framework of reaction to fire tests varying from bench-scale tests to large-scale building facade tests. If a Performance Solution pathway is being adopted, the most practical approach may be to use test methods and criteria prescribed for DTS Solutions, where they are appropriate, to support the fire safety engineering analysis. This approach also simplifies the specification of systems and verification of compliance with Evidence of Suitability in the form of a report from an Accredited Test Laboratory (ATL).

Chapter 2 of this Guide provides information on the properties of wood that relate to the reaction to fire performance and Chapter 6 provides information on the detailed design and specification of the reaction to fire performance of wood products.

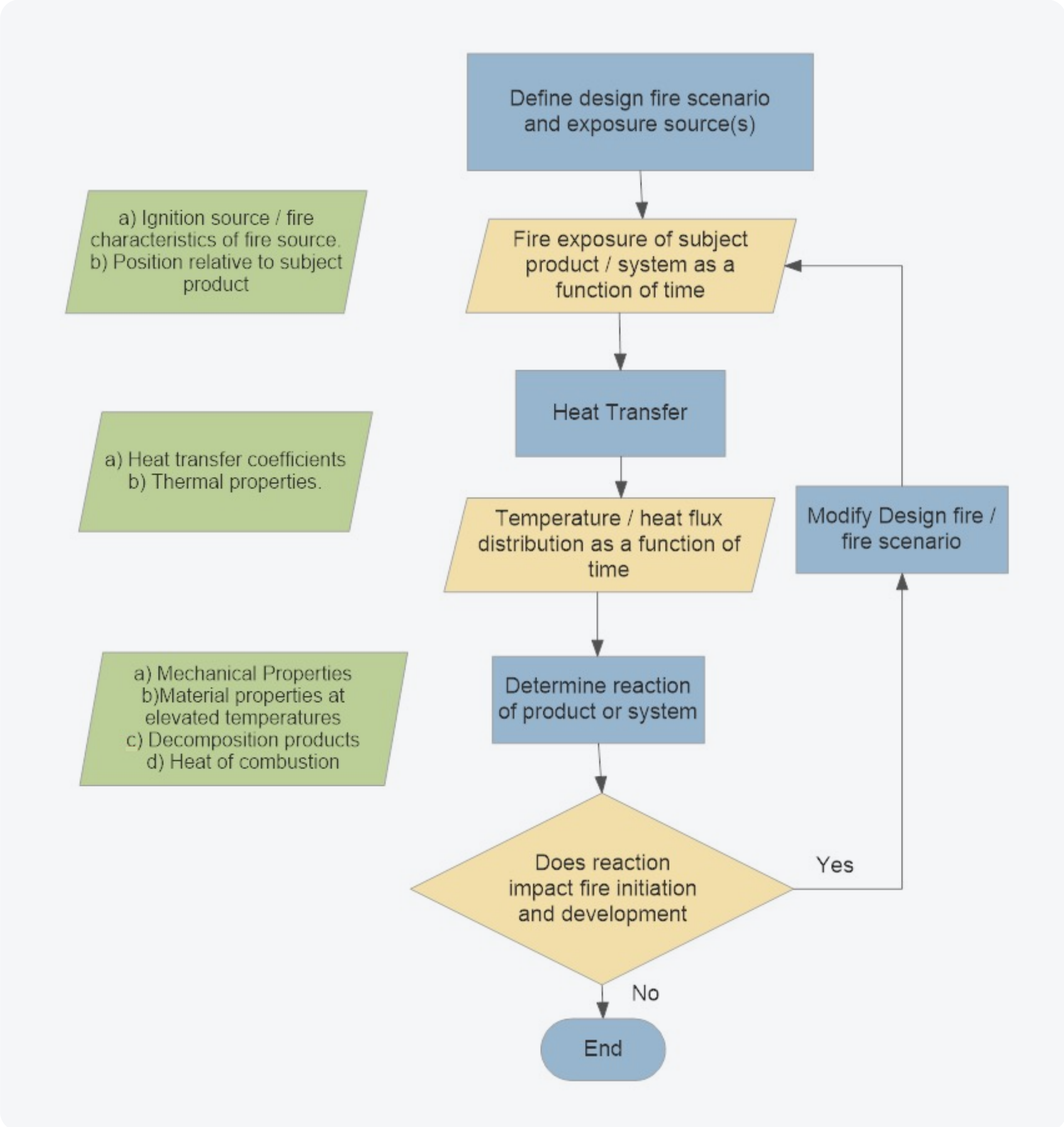


Figure 4: Design process for 'reaction to fire' performance of building systems and materials.

1.4 Overview of design process for the fire resistance of structural elements and barriers

The design of structural elements and barriers to resist exposure to fire involves three stages:

- derivation of fire scenarios and corresponding Design Fires
- heat transfer analysis (including assessment of insulation performance for barrier systems)
- functional/mechanical analysis (including the formation of gaps and openings for assessment of integrity of barriers in addition to structural analysis).

Figure 5 shows the key stages of the process, based on the flow chart from NCC Fire Safety Verification Method (FSVM) Handbook Annex[14], which was derived from a chart originally prepared for structural design by Buchanan[17].

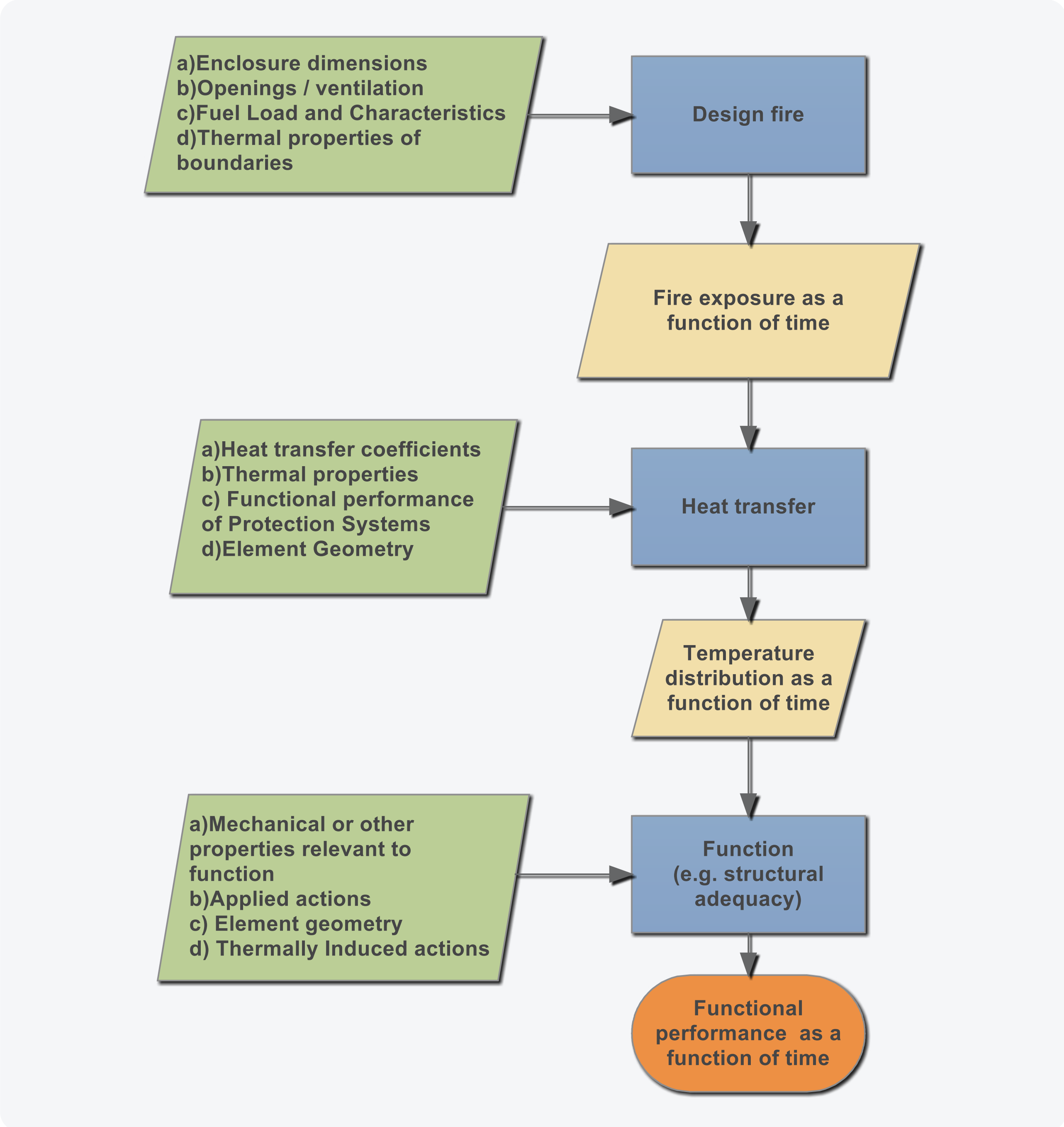


Figure 5: Design process for fire-resistant structural elements and barrier systems.

The three stages can be consolidated, depending on the adopted methods of analysis and selected compliance pathways. For example, the NCC DTS Solutions generally specify a nominal Design Fire based on the standard heating regime of AS 1530.4[18] with the performance of elements of construction expressed in terms of Fire Resistance Levels (FRLs). The required period of exposure to the standard heating regime is varied to address different fire exposure conditions. Heat transfer and functional performance is evaluated by subjecting a representative specimen to a fire-resistance test or other methods permitted by the NCC, such as calculation in accordance with AS 1720.4[19].

The Design Guide: Structural Fire Safety, produced by the Conceil International du Bâtiment (CIB W14)[20], identified three types of heat exposure models (Design Fires) and three types of structural response models based on single elements, sub-assemblies or entire structures. The matrix produced by CIB W14 has been compacted and cross-referenced with NCC performance pathways and required Evidence of Suitability in Table 2.

Table 2: Performance pathways and Evidence of Suitability compared to Design Fire and extent of structural analyses.

Compliance Pathway	Design fire	Extent of structural analysis	Evidence of Suitability
Deemed-to-Satisfy	AS 1530.4 standard heating regime	Generally individual elements Occasionally sub-assemblies	NCC Schedule 5 (test or assessment from an Accredited Testing Laboratory (ATL) or permitted calculations)
Simple Time Equivalence Performance Solution[1]	Equivalence to AS 1530.4 standard heating regime	Generally individual elements Occasionally sub-assemblies	NCC A2.2- demonstration of compliance/ Evidence of Suitability[2] and NCC Schedule 5 (test, assessment from an ATL or permitted calculations)
More Complex Performance Solution	Parametric curve or other theoretical or experimentally derived Design Fire	Varies with application, could be single elements, sub-assemblies, or whole structure	NCC A2.2- demonstration of compliance/ Evidence of Suitability[2] and NCC Schedule 5 (test, assessment from an ATL, permitted calculations or natural fire tests, or alternative heating regime tests)

Notes:

1 Time equivalence is the simplest Performance Solution option and relates the expected real fire exposure to a time of exposure to the standard (AS 1530.4) heating regime. Where timber elements are exposed, or may become exposed, the fire load must be adjusted to take account of the additional contribution from the timber.

2 Evidence of Suitability will also need to include a report from a competent person (e.g. a professional engineer) assessing compliance of the fire safety strategy with the relevant Performance Requirements where the Performance Solution pathway is followed. Additional Evidence of Suitability will also be required to verify the performance of key structural elements/components.

The methods of analysis should be selected based on the compliance pathway adopted. The extent of analysis required for the Design Fire(s), heat transfer and structure (or other required function) must be determined having regard to the requirements of the specific project and be agreed by the relevant stakeholders as part of the Performance-based Design Brief (PBDB) process.

1.5 Heat transfer

This process uses the fire exposure determined during the first stage to derive a temperature distribution with respect to time for individual elements, sub-assemblies or the whole structure, depending on the design approach adopted.

There are a range of methods for determining temperature distributions and critical temperatures, including:

- simple hand calculations
- empirical correlations for lumped thermal mass or char rate calculations
- finite element or finite difference analysis
- application of data from standard fire tests or natural fire experiments.

In some applications, char oxidation, char layer contraction and delamination may need to be considered for timber elements. The methods and validation should be appropriate to the application.

Note: The appendices to this Guide contain test data summaries of natural fire experiments that may be useful for determining temperature distributions within enclosures, the impact of natural fires on elements of construction or for validation of models. The appendices also include summaries of international and Australian data from standard fire tests and similar experiments.

Variations in material properties and quality of installations should be accounted for. In some scenarios this may require consideration of major variations caused by unauthorised substitution of materials or use of inappropriate fixings, for example, to determine the robustness of the overall fire safety strategy. This can be addressed through the consideration of fire scenario clusters.

Further details of heat transfer analysis for timber elements and Fire-protected Timber elements exposed to fully developed fires are provided in subsequent chapters.

1.6 Functional analysis

There are a range of methods that can be used to check the functional performance of individual elements, sub-assemblies or the whole structure. In addition to determination of the time to structural failure for elements providing a separating function, criteria relating to integrity and insulation may also apply.

Analysis options include:

- simple hand calculations using prescribed critical temperatures or char rates and effective residual section for timber elements (e.g. AS 1720.4[21] method)
- finite element modelling or calculations using material properties
- application of data from standard fire tests or natural fire experiments.

Where necessary, the interaction of elements of construction, including thermally induced deflections and stresses, should be evaluated to determine if the structure has adequate robustness. Detailed modelling of the whole or major parts of the structure under a range of fire scenarios may be required for some applications.

In other situations, it may be more appropriate to either directly apply experimental/fire test data where the heating regime and applied loads are representative of the case under consideration, or the impact of variations can be predicted based on fire engineering principles. There are two general approaches to determining the loadbearing capacity of timber elements.

The simplest option is based on determining a residual section of timber that is deemed to be unaffected and determining the loadbearing capacity based on the residual section. This approach is included in AS 1720.4[19] but only applies to the standard heating regime within the field of application defined in the Standard and NCC. The effective depth of charring includes a 7 mm zero-strength layer in addition to the char layer, which is derived based on char rates that apply only to the standard heating regime.

Alternatively, more detailed analyses can be undertaken that account for the material properties of uncharred timber at elevated temperatures below 300°C. Eurocode 5 and other sources provide suggested material property reduction factors that are discussed further in Section 2.10.

1.7 Detailed design, specification and Evidence of Suitability – general approaches

Having developed a fire safety strategy, using either the Performance Solution or Deemed-to-Satisfy pathway, the strategy then needs to be translated into detailed documentation including requirements for Evidence of Suitability and Expert Judgement of the various parts of the holistic fire safety strategy. Figure 6 shows a flow chart for the process for the initial development of this documentation.

Although the development of the detailed documentation follows the derivation of the fire safety strategy, it is critical that the responsible designer focuses on the following matters to avoid unnecessary complications during implementation:

- buildability (including safe design principles)
- in-service performance/maintenance
- how to specify measures and components that form the strategy including:
  - integration with other components of the fire safety system
  - defining Evidence of Suitability and commissioning procedures
  - availability of appropriate products/systems and Evidence of Suitability.

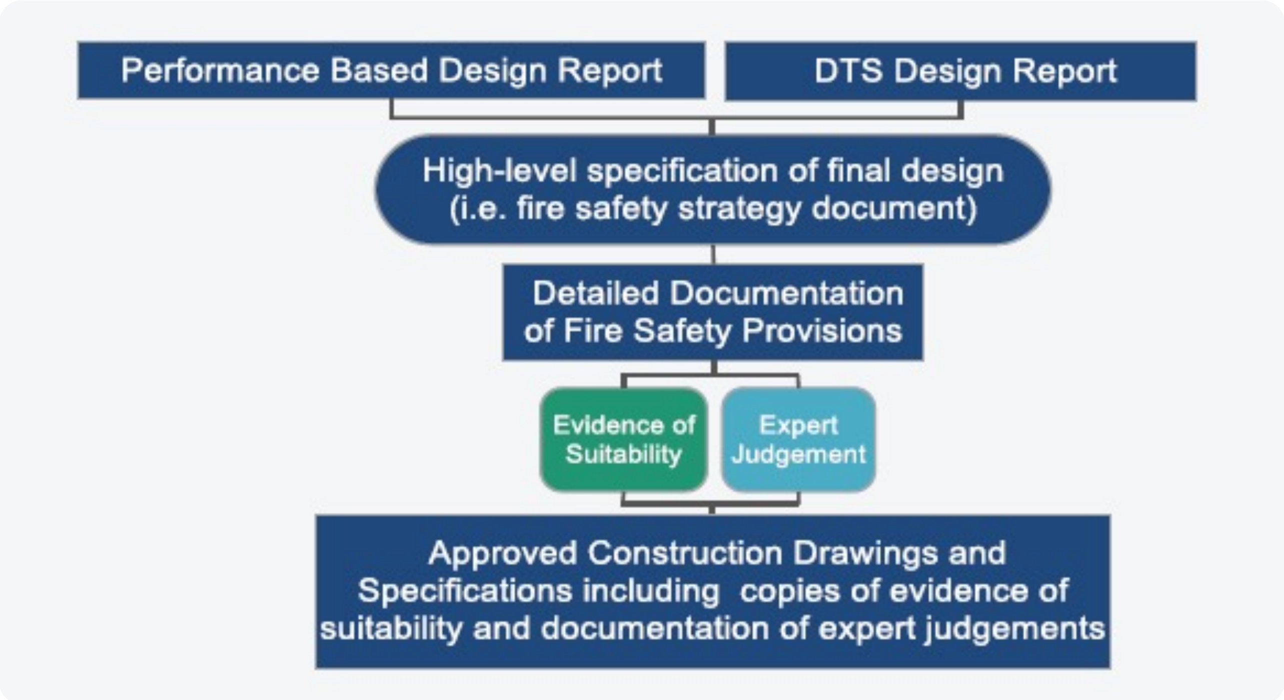


Figure 6: Design documentation process.

Many of the above issues can be easier to manage if the DTS Pathway is followed because the NCC DTS Provisions draw heavily on Australian and International Standards where appropriate for the detailed design and specification of the component parts of a fire strategy and are supported by various industry guides and training resources. For example, the WoodSolutions site (www.woodsolutions.com.au) provides extensive resources relating to wood products.

The NCC DTS Provisions provide detailed minimum requirements for Evidence of Suitability for many fire safety measures, including specific requirements for elements required to achieve Fire Resistance Levels. These provisions are supported by additional resources and educational materials on the Australian Building Codes Board site (www.abcb.gov.au).

When adopting a Performance Solution pathway, the scope and methods of analysis will depend on the solution being evaluated but the designer needs to keep in mind that it is also necessary to specify products and systems that are available to the Australian market and facilitates compliance; by specifying requirements for Evidence of Suitability that can be easily verified. The specifications need to be provided in a manner that is easily understood by product suppliers and installers.

A practical means of achieving this is to apply appropriate existing Australian and International Standards where practicable and use the approaches to Evidence of Suitability that are applied in the NCC for DTS Solutions. Where elements within a Performance Solution cannot be specified using this approach, the specification may need to be more detailed and may need to place more emphasis on industry codes. In some cases, project-specific testing and inspection procedures (including acceptance criteria) may need to be included or referenced in the specification.

Chapters 5 and 6 provide information relating to design and specification relating to wood products that may form part of a fire safety strategy. The content is generic and avoids reference to proprietary systems, as far as practical, and so this Guide should not be used as the sole Evidence of Suitability and should be supplemented by additional documentation relating to specific products.

The NCC DTS Provisions provide substantial flexibility in relation to design choices that may affect the fire severity if a fully developed fire occurs. For example:

- combustible wall and ceiling linings are permitted for many applications subject to compliance with the fire hazard properties prescribed in the NCC
- fire loads are generally not limited, although automatic fire sprinklers may be prescribed for potential high-risk uses such as high-rack storage
- the thermal inertia of bounding construction is not prescribed (other than indirectly to satisfy thermal efficiency and acoustic requirements
- there are few limits on the window openings and other ventilation openings.

If developing a Performance Solution, critical design decisions that need to be made early in the process include determining the need for:

- detailed specifications to place additional control on matters, such as the combustibility of wall and ceiling linings, control of moveable fire loads, thermal properties of bounding construction and window opening sizes and construction, etc, or
- conservative assumptions to be made to allow flexibility.

These decisions will have an impact on the selection of a Design Fire, future flexibility during occupancy and building costs.

Similar considerations apply to the emergency management within a building, including training and emergency procedures. This will need to be specified with sufficient detail to ensure the design objectives can be achieved.

2 General and fire properties of wood

2.1 Typical chemical composition of wood

Timber is made up of three major organic polymers - cellulose, hemicellulose and lignin - with organic extractives and inorganic minerals making up the remainder (4-10%). Timber used within buildings includes 8-12% water at equilibrium with typical temperatures and relative humidity conditions.

Softwoods tend to have higher proportions of lignin (25-35% of the dry weight) compared to hardwoods (18-25% of the dry weight)[22]. As lignin tends to decompose at higher temperatures than cellulose and produce more char protecting the core, the proportion of lignin can affect the 'reaction to fire' properties and fire-resistance properties of timber.

The proportions of cellulose, hemicellulose and lignin vary between species but also within a species due to factors such as climate, land conditions and age at which a tree is felled. The composition also varies across the cross-section, with potentially significant variations between sapwood and heartwood.

Table 3: Proportions of cellulose and lignin for typical Australian timbers. (Derived from Ximenes et al[23])

Species	Cross-section			Heartwood			Sapwood		
	Cellulose	Hemi-cellulose	Lignin	Cellulose	Hemi-cellulose	Lignin	Cellulose	Hemi-cellulose	Lignin
Blackbutt	56.3	12.9	19.2	57.3	12.6	17.1	60.1	9.9	24.3
Messmate	63.9	9	16.1	56.9	8.2	23	57	9.9	17.9
Spotted Gum	58.5	11.1	17.2	57	9.9	17.9	63.7	11.9	16.5
Radiata Pine	52	18.5	25.4	40.6	14.7	27.2	52.3	17.9	26.3
Cypress Pine[1]	40.3	16.6	35.6	37.9	14.9	36.3	44.3	18	34.4

[1] Now referred to as White Cypress

The majority of pyrolysis occurs within the following temperature ranges (Janssens and Douglas[22]):

- hemicellulose 200–260°C
- cellulose 240–350°C
- lignin 280–500°C.

In addition, after lignin has undergone pyrolysis approximately 50% of the mass remains as char, which is considerably more than the residual char from pyrolysis of hemicellulose and cellulose. Because softwoods have higher proportions of lignin, the surface temperature at ignition tends to be higher than for hardwoods and char yields tend to be higher for softwoods.

Since the rate of temperature rise of timber under fire conditions is relatively quick, a common simplification is to assume that charring occurs instantaneously at approximately 300°C.

For Fire-protected Timber applications in Australia, a char temperature of 300°C is assumed for Massive Timber elements but 250°C is assumed for lightweight timber-frame construction and general timber construction when applying the Resistance to Incipient Spread of Fire criterion.

More detailed reviews of the composition of timber and influence on fire properties are provided throughout this Guide. The reader should also reference standard texts and papers, including Drysdale[9], Janssens[22], Friquin[10] and Bartlett[11] for further information.

2.2 Pyrolysis and ignition of wood

When exposed to sufficient heat, wood will decompose and its structural properties will be modified. The speed of decomposition is relatively low at temperatures below 100°C; although even at these temperatures there may be significant reductions in a wood product's strength and stiffness. When the wood's surface temperature exceeds 100°C any remaining moisture is vaporised, leaving dry wood. If surface temperatures continue to rise, decomposition (pyrolysis) increases, breaking down the polymers into smaller molecules, a large proportion of which are released as volatiles. Once the concentration of combustible volatiles is sufficient, ignition may occur. Sustained flaming can be maintained if the external heat source and contribution from the burning volatiles are sufficient to maintain the required pyrolysis rate for flaming combustion.

For most fire engineering applications, flaming ignition is assumed to occur when the pyrolysis rate substantially increases as the surface temperatures approach the critical surface temperature for ignition, typically between 300°C and 400°C, although there is substantial variability, depending on factors such as orientation, the nature of the ignition source and rate of heating. Some typical values for species available in Australia are provided in Table 4.

Bartlett[11] noted that there is reasonable agreement that the critical heat fluxes for flaming ignition are in the range of 10-13 kW/m^2 for piloted ignition and 25-33 kW/m^2 for unpiloted ignition. The critical heat flux for piloted ignition is defined as the minimum external heat flux required to achieve piloted ignition of an exposed material. Theoretically, no time limit is specified for ignition but in practice most tests are terminated after a notional period, typically of the order of 30-60 min, although shorter test durations are sometimes adopted. For example, cone calorimeter tests can be terminated after 10 min if there is no sign of combustion.

The above heat fluxes are assumed to apply to heat sources perpendicular to the grain. If heat fluxes are applied parallel to the grain, flaming ignition may occur at incident heat fluxes below 10 kW/m^2. Spearpoint and Quintiere[24] suggest the lower values could be due to localised glowing ignition presenting an additional heat source. Bartlett also noted that sustained glowing/smouldering ignition had been found to occur at surface temperatures around 200°C and heat fluxes of 5-10 kW/m^2 although lengthy exposure periods are required. These processes may contribute to the failure of elements of construction close to joints and connections substantially after visible flaming combustion has ceased unless attention is paid to design detailing.

The rate of heating of the timber prior to ignition is dependent on various parameters, including:

- the imposed heat flux regime
- thermal inertia of the timber (kρc) (surface temperatures rise quicker for materials with a low thermal inertia)
- moisture content
- size/thickness of the timber element
- protective treatments applied to the timber
- orientation of element.

The potential for ignition and continued flaming combustions is dependent on parameters such as:

- presence of and size/type of ignition source
- oxygen content in the local environment
- air flows
- surface finish and grain orientation of timber
- species/chemical composition and impurities of timber
- protective treatments applied to the timber.

The following data relates to some species commonly used in Australia:

Richardson and England[25] investigated the piloted ignition of timber exposed to radiant heat. While a general non-species specific weak correlation linked to density was identified, it was recommended that species-specific correlations (e.g. Janssens correlation[26]) should be adopted if accurate predictions are required for specific materials. Grey Ironbark data from cone calorimeter testing in the horizontal orientation was used to demonstrate Janssens method[25], yielding the following relationship with a correlation coefficient for the fitted line of 0.995:

$t_{ig} = (0.0028\dot{q}_e'' - 0.0289)^{-1/0.55}$

t_{ig} is the time to ignition – s

and $\dot{q}_e''$ is the imposed heat flux – kW/m^2

The results are plotted in Figure 7 and compared to the results for Radiata Pine after oven drying and with a moisture content of 15% based on results published by Babrauskas[27]. The impact of increased moisture contents and timber densities can be seen in Figure 7. The mean density of the Grey Ironbark samples was approximately 1,095 kg/m^3, one of the higher-density Australian Eucalypts. The density of the oven-dry Radiata Pine was approximately 430 kg/m^3 and at a 15% moisture content the density was approximately 496 kg/m^3.

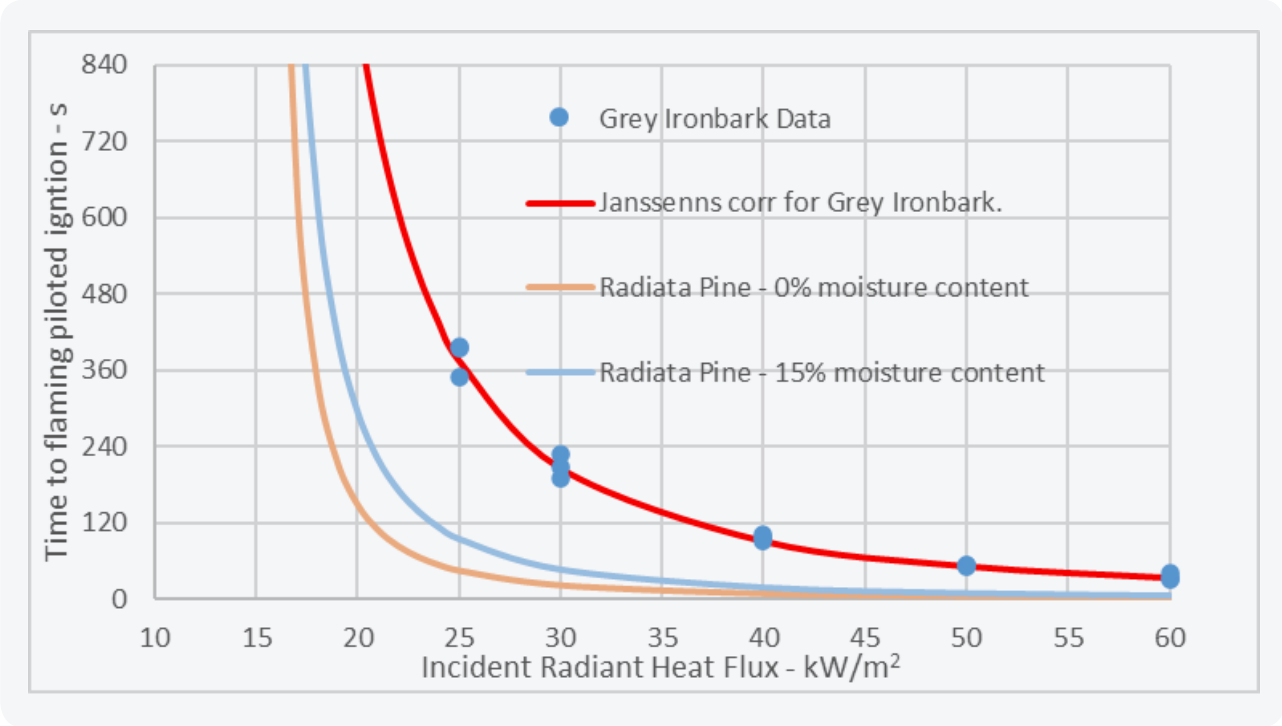


Figure 7: Time of flaming piloted ignition of Grey Ironbark and Radiata Pine under differing moisture contents based on England[25] and Babrauskas[27].

Janssens[28] investigated a series of timber species, some of which are readily available in Australia, and applied an updated correlation method assuming the following relationship:

$\dot{q}_e'' = \dot{q}_{cr}''\ [1 + A(k\rho c / h_{ig}^{\ 2}\ t_{ig})^a]$

where:

$\dot{q}_{cr}''$ is the incident heat flux (kW/m^2)

A = constant

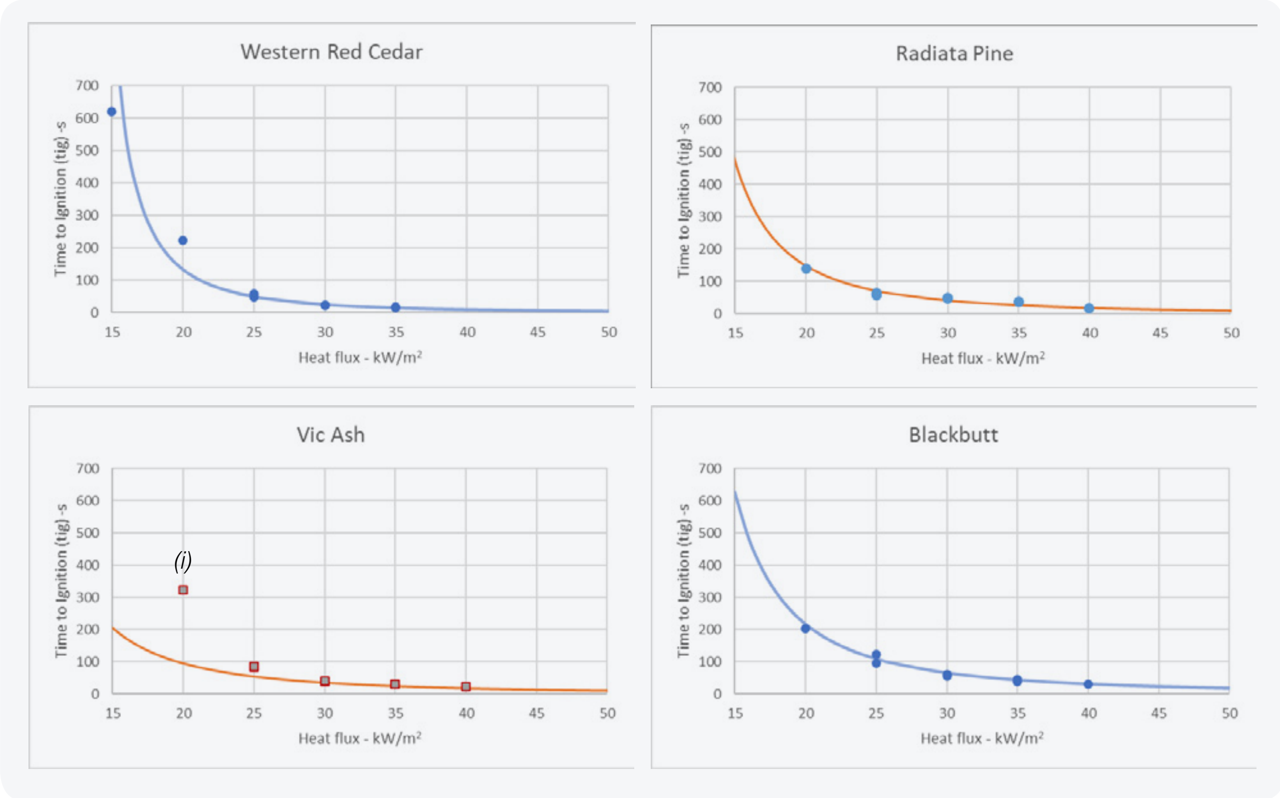
a = constant

$k\rho c$ is the thermal inertia (kW^2·s/m^4·K^2)

h_{ig} is surface heat transfer coefficient at ignition (kW/m^2·K)

Further details are provided in Janssens[28].

The samples were nominally 17 mm thick and were tested after oven drying in a vertical orientation with piloted ignition in a cone calorimeter. The results of the four species readily available in Australia are plotted in Figure 8 with additional results from the analysis included in Table 4.



Note: (i) Janssens omitted the 20 kW/m² data point from his analysis as it was outside the 95th percentile confidence limit.

Figure 8: Time to ignition for four commonly available species in Australia.

Testing oven-dry timber will reduce the time to ignition compared to timbers at typically equilibrium moisture contents (8-12%) but testing in the vertical orientation will tend to increase the time to ignition compared to cone calorimeter tests in the horizontal orientation.

Table 4: Additional data derived from cone calorimeter testing after oven drying of four commonly available species in Australia. (Derived from Janssens[28])

Species	Density, ρ (kg/m³)	T_{ig} (°C)	Measured T_{ig} (°C)	q'_{cr} (kW/m²)	Apparent kρc (kW².s/m⁴.K²)	kρc literature (kW².s/m⁴.K²)
Western Red Cedar	330	399	338-358	12.0	0.075	0.101
Radiata Pine	460	349	349	8.6	0.220	0.162
Victorian Ash	640	336	337-346	7.8	0.293	0.288
Blackbutt	810	334	314-352	7.7	0.409	0.444

Note: T_{ig} is the surface temperature at ignition, q'_{cr} is the estimated critical heat flux for ignition, and kρc is the thermal inertia.

The variation between the measured or derived values and general literature values highlights the need to apply apparent or effective values within the field of application for which they have been validated.

Spearpoint and Quintiere[24] indicated that integral models for the time to ignition give good agreement with experimental data at incident heat fluxes above 20 kW/m². For some applications, such as managing the spread of fire between buildings, the time to ignition at heat fluxes below 20 kW/m² may be critical and verification using bench-scale tests, such as the cone calorimeter at the specific heat fluxes of interest, can provide more confidence, provided acceptable repeatability of test results can be attained.

The SFPE Engineering Guide – Piloted Ignition of Solid Materials Under Radiant Exposure[29] includes relevant data on a large range of materials, including wood products, and describes and compares models for predicting ignition, including methods developed by:

- Mikkola and Wichman
- Tewarson
- Quintiere and Harkleroad
- Janssens
- Silcock and Shields.

The time to ignition of 20 mm thick Radiata Pine exposed to a heat flux of 20 kW/m^2 was predicted using each of the models and ignoring the Tewarson method, which significantly over-predicted the time to ignition due to the method requiring a linear regression to pass through the origin. The other predictions were in good agreement, varying from 111 s to 150 s.

Shortly after ignition, a substantial peak in the rate of pyrolysis is common as the exposed surface of dried wood burns. The pyrolysis rate then reduces as the char layer develops, forming a protective layer over the pyrolysis zone. A common simplification is to assume pyrolysis occurs at a fixed temperature, typically between 250°C and 300°C, and the char provides no contribution to strength or stiffness. The transition from char to unaffected timber can be defined as the heat-affected zone where the mechanical properties of the timber vary with temperature.

A simple schematic of the response of a timber element exposed to fire is shown in Figure 9.

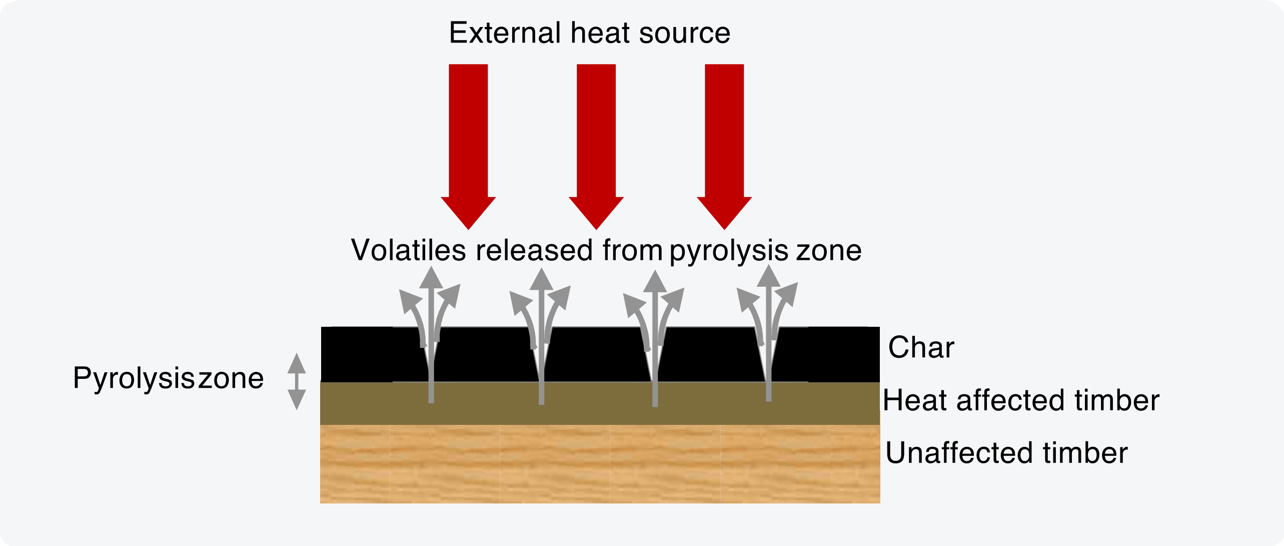


Figure 9: Schematic showing a section through a burning section of timber.

The rate of pyrolysis depends on factors such as:

- the imposed heat flux regime (including thermal feedback from other elements in the enclosure and from combustion of the released volatiles)
- ability of the timber char to remain in place and insulate the uncharred timber, which is influenced by element orientation, timber adhesives, etc
- species/chemical composition including impurities
- moisture content
- size/thickness of the timber element
- treatments applied to the timber
- oxygen content in the local environment, which influences char oxidation and hence char layer contraction as well as generating heat.

The variability of the pyrolysis rate with time can be clearly demonstrated from cone calorimeter data. For example, Figure 10 shows the pyrolysis rate for a 50 mm thick White Cypress specimen exposed to a constant heat flux of 25 kW/m^2 in a horizontal orientation with piloted ignition. The control (blue plot) was an untreated specimen and shows minor mass loss until ignition occurs after approximately 2.5 min followed by a high peak mass loss rate that reduces as the char layer develops, approximating to quasi steady state conditions approximately 6 min after ignition. A second sample was pre-charred prior to test. There was no peak because the insulating char was already in place and protected the uncharred timber. The pyrolysis rate progressively increased for the first 4 min before plateauing at a similar mass loss rate to the quasi-steady state conditions achieved by the control. Coatings can be applied to the surface of timber to retard burning, achieving similar effects, but are specifically excluded under the NCC DTS Provisions in Australia. Therefore, in most applications the Performance pathway needs to be adopted if fire-retardant coatings are to be used. The NCC DTS Provisions do allow other fire-retardant treatments, such as impregnation with fire-retardant chemicals.

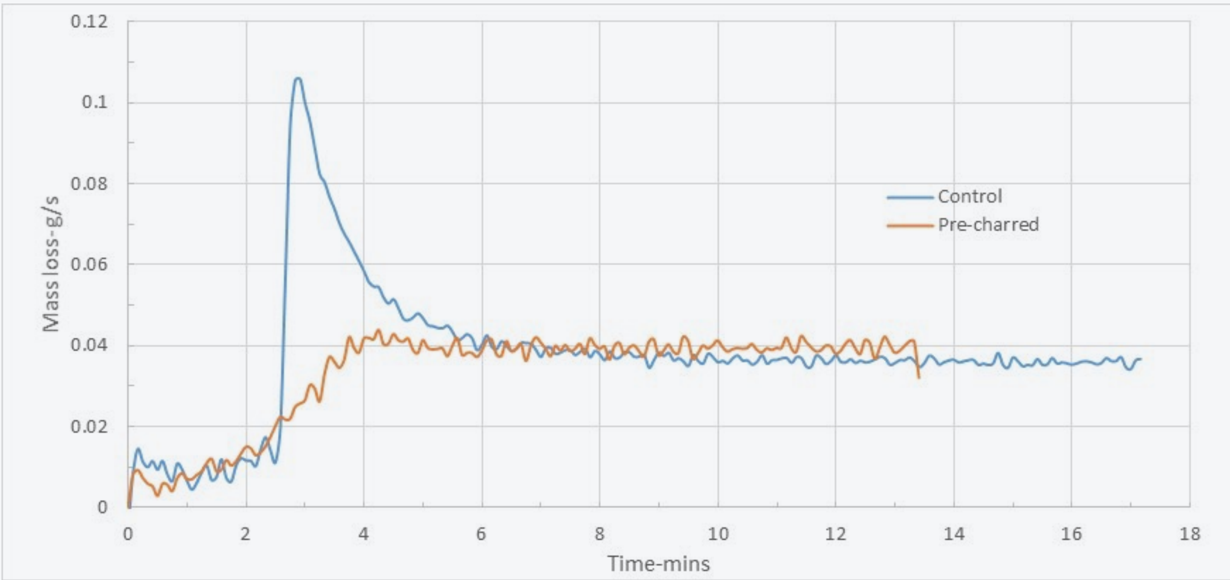


Figure 10: Mass loss rate v time plot from cone calorimeter test of White Cypress 50 mm thick with irradiance of 25 kW/m² compared to a pre-charred sample.

Notwithstanding the complexity, for engineering design purposes simplifying assumptions can be applied but users should be aware of these assumptions. For example, it is commonly assumed that the onset of charring occurs at approximately 300°C (ignoring minor degradation [pyrolysis] of the timber that will occur below this temperature). For most applications, such as the response of timber elements to fully developed fires, this assumption is reasonable. Pyrolysis and char development are discussed futher in subsequent chapters.

2.3 Self-extinguishment

The combustion of a timber element is not sustainable without an external heat source. This may be another burning timber surface or even a non-combustible surface at a high temperature that is radiating heat. This has been demonstrated in large-scale tests and smaller-scale experiments where the number and area of timber surfaces, incident heat flux and duration of exposure has been varied.

It is important to clearly define the term 'self-extinguishment' and what the intent of self-extinguishment is if used as the basis of a fire engineering design.

ISO 13943 Fire Safety Vocabulary[30] defines:

- self-extinguish as to cease combustion without being affected by any external agent
- combustion as an exothermic reaction of a substance with an oxidising agent.

These definitions have been adopted throughout this Guide.

Terms such as 'flame extinguishment', 'self-extinguishment of flaming combustion' and 'self-extinguishment without any qualification' are commonly used in technical literature to describe the transition from flaming to smouldering combustion. To avoid any confusion, this Guide uses the term 'transition from flaming to smouldering combustion' and terms such as 'self-extinguish' refer to the termination of all combustion (smouldering and flaming).

This is a critical clarification because ongoing smouldering combustion can initiate a structural failure after flaming combustion has ceased if there is no fire brigade intervention. Crielaard et al[31] identified that extinguishment of a fire could be achieved in combination with active measures such as automatic sprinklers and fire brigade intervention but also indicated that, for tall buildings, the fire safety design and structure should withstand the burnout of all combustible materials present (i.e. any exposed timber structure should self-extinguish). The paper does not provide a definition of tall buildings but the NCC threshold for high-rise buildings as having an effective height greater than 25 m is consistent with the common interpretation.

Applying the above principles, a potential fire safety strategy for timber buildings with an effective height greater than 25 m would include encapsulation of the timber structure such that the timber elements will not ignite, except for specific defined areas of exposed timber that would be designed to self-extinguish after burnout of the contents for scenarios where active suppression measures fail to operate effectively.

Critical values for self-extinguishment (of smouldering combustion) suggested by Crielaard et al were heat fluxes below 5-6 kW/m² if air flow is below 0.5 m/s.

Terrei[32] examined surface temperatures and modes of ignition of spruce using the cone calorimeter in the vertical orientation. Smouldering combustion without flame was observed at heat fluxes between 15 kW/m^2 and 35kW/m^2. Smouldering combustion was estimated to begin at a surface temperature of approximately 380-390°C after 15-20 min to an irradiance of 15 kW/m^2 without transition to flaming combustion. Once smouldering combustion began, the surface temperature progressively increased to approximately 590°C after 25 min and remained constant until the test was terminated after 60 min. If an emissivity of 0.9 is assumed, the radiant heat released from the surface of the specimen would be approximately 10 kW/m^2 when smouldering combustion commenced increasing to a maximum steady state condition of approximately 29 kW/m^2. These results suggest a source radiation from the surface of smouldering spruce in the vertical orientation of the order of 30 kW/m^2 when exposed to an incident heat flux of 15 kW/m^2 with a plentiful supply of oxygen.

Bartlett[33] investigated the transition from flaming to smouldering combustion and found that at ambient oxygen concentrations the mass loss rate at which flaming combustion ceased was 3.48 +/- 0.31 g/m^2/s, which was estimated to correlate with an incident heat flux of 30 kW/m^2 using the Fire Propagation Apparatus. The Fire Propagation Apparatus applies similar principles to the cone calorimeter except that infrared heating lamps are used as the heat source.

These estimates were derived from CLT specimens constructed with spruce and pine lamella and the following constraints applied:

- fuel burnout time is less than the penetration time for the first lamella and less than the time to structural collapse
- no encapsulation failures of protected elements
- number and orientation of exposed surfaces provides sufficiently low levels of re-radiation
- no delamination occurs.

The study acknowledged that different test methods and specimen orientations could also affect results significantly.

This is highlighted by the results of cone calorimeter tests performed in accordance with AS 3837[34] at an irradiance of 25 kW/m^2 in the horizontal orientation. For example, a test on White Cypress continued to flame throughout a 60 min test exposure period but flaming terminated within 10 s after the test was terminated and the specimen removed from the heat-source.

2.4 Heat of combustion

2.4.1 Gross heat of combustion

The gross heat of combustion is the heat of combustion of a material when any produced water is in liquid form. It is generally determined from bomb calorimeter tests in which a small amount of the fuel is burned in pure oxygen inside a sealed vessel (EN ISO 1716:2018[36]).

Bartlett[11] suggested that typical gross heats of combustion for wood are: 19.5 MJ/kg +/- 2.5 MJ/kg.

However, the gross heats of combustion vary depending on the state of the timber, with lower rates from combustion of volatiles and higher rates from wood char. The following values are quoted by Drysdale[37] for European beech:

- wood: 19.5 MJ/kg
- wood volatiles: 16.6 MJ/kg
- wood char: 34.3 MJ/kg (predominantly smouldering or glowing combustion).

The gross heat of combustion also varies based on the lignin and extractive content. Cellulose and hemicellulose have a gross heat of combustion of the order of 18.5 MJ/kg and lignin has a gross heat of combustion of the order of 24.8 MJ/kg. Softwoods with a higher lignin content will tend to have a higher gross heat of combustion. The type and proportion of extractives varies from species to species and may also influence the gross heat of combustion. Correlations based on experiments on four softwoods and four hardwoods were derived by White[38].

2.4.2 Net heat of combustion

The net heat of combustion means the heat of combustion when any water produced is in the gaseous state. It is always smaller than the gross heat of combustion because the heat released by condensing the water vapour is not included. Net heat of combustion is often defined as the gross heat of combustion minus the latent heat of water evaporation produced from the combustion and therefore will depend on the moisture content of the timber, among other things.

The net heat of combustion of wood will typically be in the range of 17.5 +/- 2.5 MJ/kg.

Eurocode 1: Actions on structures —Part 1-2: General actions — Actions on structures exposed to fire[39] specifies a net heat of combustion for timber of 17.5 MJ/ kg.

2.4.3 Effective heat of combustion

The effective heat of combustion (HOC_{eff}) is the heat released from a burning material divided by the mass loss over a given time interval. It will be equal to the net heat of combustion if the material is fully oxidised but, in most cases, combustion will not be 100% efficient and the HOC_{eff} will be less than the net heat of combustion.

HOC_{eff} is sensitive to environmental conditions in a fire or fire test scenario, such as oxygen content, applied heat flux, air flows as well as the material properties of the subject material. Therefore, the HOC_{eff} determined under test conditions will strictly only apply to the specific test conditions.

Eurocode 1: Actions on structures - Part 1-2: General actions specifies a combustion factor of 0.8 for a ventilation-controlled fire to allow for combustion efficiency yielding an HOC_{eff} of 17.5 x 0.8 = 14 MJ/ kg.

Estimates of HOC_{eff} can be derived directly from tests performed using the cone calorimeter or similar techniques where both the heat release rate and pyrolysis rate are measured but results will be affected by scale, orientation and environmental conditions. Under normal test conditions (horizontal specimen with an unmodified laboratory atmosphere) the specimen can be regarded as burning freely in a normal environment with oxygen concentrations similar to a fuel-controlled burning regime.

The effective heat of combustion tends to increase as the incident heat flux increases and is greater for samples tested in the horizontal compared to the vertical orientation (Moghtaderi and Fletcher[40]). It decreases as the timber density increases (Janssens[41]). The difference in the HOC_{eff} between the vertical and horizontal orientation may be accounted for to some extent by the higher net incident heat flux (imposed and contributed by flaming from the timber specimen) in the horizontal compared to the vertical orientation.

Janssens also compared the Heat Release Rate (HRR) and effective heat of combustion against time for White Pine at an incident heat flux of 60 kW/m^2 in the horizontal orientation[41]. Ignition and the first HRR peak occurred within approximately 10 s with the HOC_{eff} subsequently peaking at approximately 17 MJ/kg. A char layer developed, reducing the HRR. The effective heat of combustion during this stage was approximately 12.5-13 MJ/kg between 2 min and 7 min before the HRR commenced, climbing to a second peak. The effective HOC_{eff} then progressively increased to approximately 32 MJ/kg as flaming combustion reduced, and char oxidation became the dominant mode of combustion as the remaining fuel comprised mainly char (carbon).

While an assumed average HOC_{eff} of 14 MJ/kg may be appropriate for some applications, other values may be required for detailed analysis. For example, when considering the potential for self-extinguishment after transition from flaming to char oxidation as the mode of combustion, a HOC_{eff} of 32 MJ/kg may be more appropriate.

2.4.4 Ventilation-controlled burning regimes/heat of combustion of air

Heat release rates can also be determined based on the mass of oxygen (or air consumed) because the heat released per unit mass of air consumed is reasonably constant for combustion of common materials. This observation is used in calorimetry when applying oxygen consumption methods for calculating heat release rates and the following general value is recommended when undertaking cone calorimeter tests (AS 3837[34]):

Heat of Combustion (O_2) = 13.1 MJ/kg (equivalent to a Heat of Combustion (Air) of 3.04 MJ/kg)

Drysdale[37] provided the following stoichiometric equation using an empirical formula to represent the complete combustion of timber in air indicating that the stoichiometric air requirement is 5.38 g of air per gram of dry timber:

$CH_{1.5}O_{0.75} + O_2 + 3.76N_2 = CO_2 + 0.75H_2O + 3.76N_2$

Using the above air requirement for complete combustion, a typical net heat of combustion for timber would be 16.4 MJ/kg.

2.5 Thermal properties of wood – thermal inertia

The thermal properties of wood can be combined and expressed as the thermal inertia for many applications. The thermal inertia of a material is commonly expressed as either the product of the material density, thermal conductivity and heat capacity ($k\rho c$) or the square root of the product of the material density, thermal conductivity and heat capacity [$\sqrt{(k\rho c)}$]. The thermal inertia can have a significant influence on the ignition and fire spread across a surface of timber as well as influencing heat losses through the boundaries of an enclosure and hence the severity of a fully developed fire.

The thermal properties of timber vary with the fire exposure and change significantly as moisture evaporates/vaporises at approximately 100°C. Pyrolysis occurs over a range of temperatures, typically from 200°C to 500°C. With respect to the thermal inertia of wood products, changes to thermal conductivity, heat capacity and density tend to compensate for each other over a broad range of temperatures.

The difficulties in measuring thermal properties at elevated temperatures while combustion is occurring are often addressed by deriving effective empirical properties. These should only be used within the field of application for which they have been validated.

A typical example of such an approach is the derivation of values for thermal inertia and other properties to estimate the time to ignition of different timber species exposed to radiant heat fluxes in a cone calorimeter.

Annex B of Eurocode 5 provides suggested thermal and mechanical properties for advanced calculation methods. Many of the values are empirically derived effective values from fire-resistance tests and, as noted above, should only be used within their field of application. Eurocode 5[42] was in the process of being revised when this Guide was prepared and readers should refer to subsequent editions of the code.

2.6 Mass, volume and density variations

A large range of timber species is available for building applications in Australia, varying from low-density timbers such as Western Red Cedar with a nominal density of 350 kg/m^3 to Grey Ironbark with a nominal density of 1100 kg/m^3. These densities assume a 12% moisture content.

Details of most readily available timbers in Australia are provided at www.woodsolutions.com.au/wood-species.

The density of timber elements under normal service conditions will vary with the timber's moisture content, which is a function of the preceding ambient conditions. It is useful to quote density ratios for timbers at elevated temperatures relative to the dry density and the ratios below 100°C can then be adjusted to account for the expected moisture content as appropriate.

Both mass and volume of timber vary with temperature and will influence the density at elevated temperatures.

When exposed to elevated temperatures, the mass of timber is reduced initially due to the evaporation of moisture within the timber as the temperature exceeds 100°C and due to pyrolysis, which will commence between 200°C and 300°C. Most of the pyrolysis will be completed below 600°C, so the residual mass at 600°C is a reasonable basis for predicting the density of wood char for many applications.

The linear dimensions of timber and hence volume will tend to reduce due to drying of the timber as the temperature approaches 100°C. This will be partially offset by thermal expansion of the timber. Once pyrolysis commences and the wood decomposes, forming a char, the volume will tend to reduce due to char contraction. The volume reduction and mass loss will also be influenced by char oxidation, which is a function of the oxygen content and air flows the timber is exposed to in addition to the imposed heat flux. A further complication is that the dimensional changes vary with direction relative to the grain direction.

Table 5 shows the variation of the density ratio, with temperature nominated for softwoods in Eurocode 5 assuming an initial moisture content of 12%. This highlights the increased reductions in density within the temperature ranges most affected by evaporation of the moisture and subsequent pyrolysis of the timber.

Table 5: Variation of density ratio with temperature for softwoods with assumed moisture content of 12%. (Derived from values provided in Eurocode 5[42])

Temperature (°C)	Density ratio
20	1.12
99	1.12
120	1.0
200	1.0
250	0.93
300	0.76
350	0.52
400	0.38
600	0.28
800	0.26

Janssens and Douglas[22] identified the following relationships relating to mass loss for both hardwoods and softwoods:

Softwoods: $Z_{600} = 0.12 + 0.41Y_l$

Hardwoods: $Z_{600} = 0.02 + Y_l$

where:

Y_l is the Klason Lignin content kg/kg

Z_x is the ratio of the wood mass at temperature x °C to the oven-dry mass (0% moisture content)

and hence:

Z_{20} = 1 plus the moisture content at ambient conditions

$Z_{200} \approx 1$ due to evaporation of moisture before pyrolysis commences

$Z_{600} \approx$ ratio of mass at 600°C divided by the oven-dry mass.

Typical predicted values compared to measured values based on data from White and Beall presented by Janssens and Douglas[22] are summarised in Table 6 together with calculated values for typical Australian species.

If it is necessary to derive a mass loss curve as a function of temperature, Janssens and Douglas developed the correlations shown in Table 7 for softwoods and hardwoods where:

$\Delta Z \equiv 0.3 - Z_{600}$

For many applications it may be sufficient to adopt an approximate effective density by, for example, assuming any changes in volume due to elevated temperatures are negligible. If more accurate estimates are required and variations in the wood volume are to be accounted for, the mass loss ratios will require adjustment to determine changes in density. Janssens and Douglas[22] describe procedures and provide supporting data to account for dimensional changes associated with drying of wood, thermal expansion and char contraction. Since many of these variables are sensitive to the fire exposure history, there may be little advantage in deriving more precise estimates of changes in density; effective values based on mass variation alone may suffice. Under these circumstances it is important that model outputs are validated against representative experimental data.

Table 6: Predicted residual mass proportion of char at 600°C compared to measured values.

Species	Klasson Lignin content (kg/kg)	Predicted Z_{600} (kg/kg)	Measured Z_{600} (kg/kg)
White Oak	0.27	0.29	0.31
Hard Maple	0.23	0.25	0.25
Southern Pine	0.29	0.24	0.25
Douglas Fir	0.27	0.23	0.24
Basswood	0.21	0.23	0.22
Redwood	0.37	0.27	0.29
Engelmann Spruce	0.29	0.24	0.24
Western Red Cedar	0.37	0.27	0.26
Southern Pine	0.29	0.24	0.24
Redwood	0.37	0.27	0.28
Hard Maple	0.23	0.25	0.25
Yellow Poplar	0.2	0.22	0.23
Red Oak	0.25	0.27	0.26
Basswood	0.21	0.23	0.22
Blackbutt	0.19	0.21	-
Messmate	0.16	0.18	-
Spotted Gum	0.17	0.19	-
Radiata Pine	0.25	0.22	-
Cypress Pine	0.36	0.27	-

Table 7: Generic mass loss ratios for softwoods and hardwoods and results for example species.

Temperature °C	Z softwoods	Z hardwoods	Z Radiata Pine	Z Spotted Gum
200	1	1	1	1
250	0.95–0.5 ΔZ	0.79–0.5 ΔZ	0.91	0.71
300	0.78– ΔZ	0.48– ΔZ	0.70	0.37
350	0.54– ΔZ	0.42– ΔZ	0.46	0.31
400	0.40– ΔZ	0.38– ΔZ	0.32	0.21
600	0.30– ΔZ	0.30– ΔZ	0.22	0.11
>800	0.28– ΔZ	0.28– ΔZ	0.20	0.09

The mass loss percentages in Figure 11 were derived from thermogravimetric analysis of CLT samples from two manufacturers undertaken in ambient and nitrogen environments, as reported by Brandon et al[43]. Differences between the CLT from different manufacturers were not significant. The data was consolidated to provide average values for all environments up to 450°C. Above 450°C there was divergence between the results in different environments that can be explained by char oxidation, which is expected to occur in oxygen-rich environments but not in environments with oxygen concentrations below 10%.

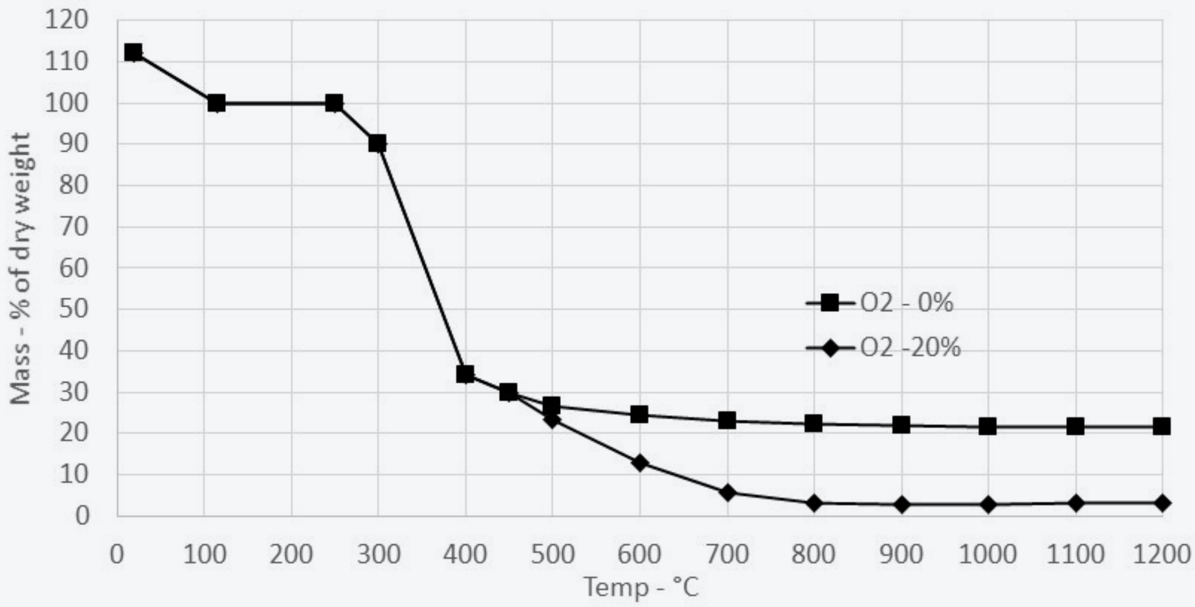


Figure 11: Approximate mass as percentage of dry weight based on thermogravimetric analysis results of CLT samples in ambient and nitrogen environments. Heating rate of 20°C/min. (Derived from Brandon et al[43])

2.7 Specific heat

Eurocode 5[42] provides tabulated values for the effective specific heat capacity of wood products that inherently addresses the heat of evaporation (vaporisation) of the moisture by specifying an elevated specific heat capacity between 99°C and 120°C of approximately 13.6 kJ/kg/K as shown in Table 8.

Table 8: Effective specific heat values for wood from Eurocode 5.

Temperature (°C)	Specific heat capacity (kJ/kg/K)
20	1.53
99	1.77
99	13.60
120	13.50
120	2.12
200	2.00
250	1.62
300	0.71
350	0.85
400	1.00
600	1.40
800	1.65
1200	1.65

However, the magnitude of this effective specific heat will vary with the moisture content.

Janssens and Douglas[22] provided correlations for the specific heat of dry wood and moist wood, summarised below, that can be used to assemble an effective specific heat capacity relationship as a function of temperature.

Specific heat of dry wood (c_0):

$c_0 = 1159+3.86\ T$

Specific heat of wood at u moisture content (c_u):

$c_u = [(c_0 + 4187u) /(1+u)] + c_{corr}$

where:

$c_{corr} = (23.55T – 1326u + 2417)$

u = moisture content expressed as a ratio of the oven dry weight

T = temperature (°C)

The following correlation for the specific heat of char (c_c) was also provided that is similar to the specific heat of carbon:

$c_c = 714 + 2.3T – 8T^2 \times 10^{-4} – 3.7T^3 \times 10^{-7}$

Wade[44] indicated that the temperature-dependent specific heat could be adjusted for the heat of vaporisation and release of the bound water (water molecules within the timber cell walls) over a notional temperature range between 100°C and 120°C in a similar manner to Eurocode 5[42].

This approach has been adopted to derive a relationship for the specific heat of wood and char as a function of temperature for various moisture contents as detailed in the following example for wood with a moisture content of 10% (u=0.1).

Step 1 Calculate the specific heat of moist wood assuming $c_{corr} = 0$ since a separate adjustment for bound water will be made and substituting for c_0 yielding:

$c_u = (1159+3.86\ T + 4187u) /(1+u)$

if u=0.1

$c_u = 1472 + 3.5\ T$

This is a linear relationship varying from 1542 J/kg/K at 20°C to 1819 J/kg/K at 99°C.

Step 2 Adopting the Eurocode 5 approach, calculate the energy required to release and vaporise the moisture between 99°C and 120°C.

The energy required for these processes can be estimated using the following relationships from Janssens and Douglas

The integral heat of wetting: $\Delta hw = 92.1/(0.07 + u)$ kJ/kg of water

The heat of vaporisation: $\Delta hv = 2552 – 2.93\ T$ kJ/kg of water

Assuming water is vaporised at T =100°C $\Delta hv = 2552 – 293 = 2259$ kJ/ kg of water

Thus, total energy to remove water from wood is $2259 + 92.1/(0.07 + u)$ kJ/kg of water

i.e. $[2259 + 92.1/(0.07 + u)]\ (u/1+u)$ KJ/kg moist timber

If u =0.1

Contribution to specific heat to vaporise and release moisture is:

255 kJ/kg

Assuming this is distributed over a temperature range of 20°C this equates to 12.8 kJ/kg/K.

This increase in the specific heat will be added to the specific heat between 100°C and 120°C.

Step 3 Calculate the specific heat for dry timber between 120°C and 250°C (i.e. before commencement of significant pyrolysis) using:

$c_0 = 1159+3.86\ T$

Refer to Table 9 for typical values. Specific heat values for dry wood should be applied only before significant pyrolysis occurs. Specific heat at temperatures above 250°C should only be applied for short-term exposures such as prediction of ignition times under relatively high heat fluxes. For most applications the specific heat of char should be used above 300°C.

Table 9: Specific heat for dry wood based on correlations provided by Janssens and Douglas.

Temperature (°C)	Specific heat capacity (kJ/kg/K)
120	1.62
200	1.93
250	2.12
300	2.32
400	2.70

Step 4 Calculate the specific heat for char using:

$c_c = 714 + 2.3T - 8T^2 \times 10^{-4} - 3.7T^3 \times 10^{-7}$

The results are provided in Table 10. Values below the typical pyrolysis range have been included. These values could have some relevance to the decay and cooling phase if it is necessary to calculate heat loses from enclosures to investigate the potential for general or localised smouldering combustion.

Table 10: Specific heat of char based on correlations provided by Janssens and Douglas.

Temperature (°C)	Specific heat capacity (kJ/kg/K)
100	0.94
200	1.14
250	1.23
300	1.32
350	1.41
400	1.48
600	1.73
800	1.85
1,000	1.84
1,200	1.68

Step 5 Construct the specific heat profile for the specific application under consideration. In this case, the application is for exposed timber walls involved in an enclosure fire, including the fully developed phase. Values between 200°C and 600°C have been arbitrarily estimated by linear interpolation for the range where pyrolysis is most active, but the timber will not have been fully converted to char. The heat of pyrolysis has been ignored (Δhp = 0 kJ/ kg) because estimates vary substantially from endothermic to exothermic reactions.

Table 11: Estimated specific heat for wood at an initial moisture content of 10%.

Temperature (°C)	Specific heat capacity (kJ/kg/K)	Description
20	1.54	Properties for moist wood from step 1
99	1.82	
100	14.62	Increased over 20°C band to account for release of bound water and heat of vaporisation from step 2
120	14.42	
121	1.62	Dry timber properties prior to pyrolysis from step 3
200	1.93	
250	1.9	Interpolated values assumed to approximate to partial pyrolysis step 5
300	1.88	
350	1.85	
400	1.83	
600	1.73	Char properties when pyrolysis is substantially complete from step 4
800	1.85	
1000	1.84	
1200	1.68	

The estimated specific heat distribution for wood with a moisture content of 10% derived as described above is compared with the Eurocode distribution in Figure 12.

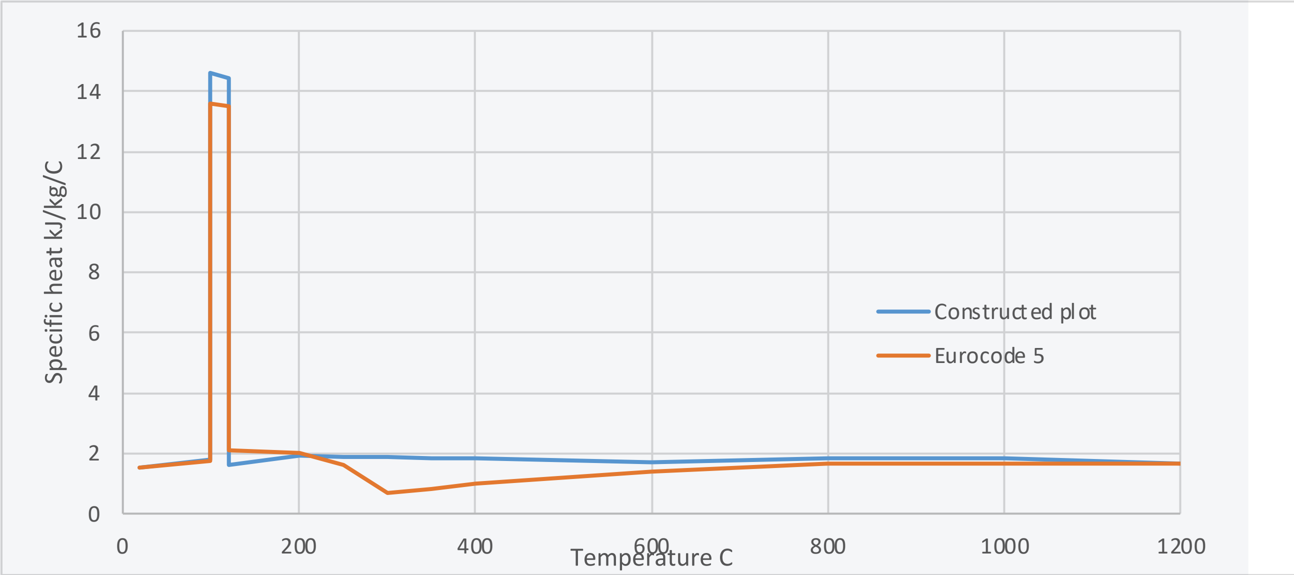


Figure 12: Specific heat for wood/char based on correlations provided by Janssens and Douglas[22] compared to Eurocode 5[42].

The plots are broadly similar except between 250°C and 600°C. This is the temperature range that applies to the pyrolysis zone where the char has not fully formed. The material properties could vary significantly, measurements are difficult and arbitrary decisions have been made in relation to interpolation methods. Care should be taken when applying these values and validations against relevant experimental data, supported by sensitivity analyses as appropriate to the application should be undertaken.

2.8 Thermal conductivity

Eurocode 5[42] nominates the values for the thermal conductivity of timber and char (summarised in Table 12). Konig[45] identified considerable variations in thermal conductivity values in literature with some values being derived from direct measurements while others are effective values that have been calibrated with specific models and the corresponding assumptions. For example, thermal conductivity values may be increased to indirectly address mass transfer due to moisture movement prior to char formation. Konig identified that quoted values that did not make this adjustment were reasonably consistent below 300°C. Higher effective thermal conductivities for char, such as those in Eurocode 5, at higher temperatures were associated with modifications to account for the formation of fissures and char contraction.

Table 12: Thermal conductivity values from Eurocode 5[46].

Temperature (°C)	Thermal conductivity (kW/m/K)
20	0.12
200	0.15
350	0.07
500	0.09
800	0.35
1200	1.50

Note: Thermal conductivities are stated to be apparent (effective values as defined in this Guide) to take account of increased heat transfer due to shrinkage cracks above 500°C and consumption of the char layer at about 1000°C. They are intended to be used with the standard heating regime of ISO834[47] and AS 1530.4[18] in conjunction with the effective specific heat values and densities in Eurocode 5[46]. The corresponding effective density at 1200°C in Eurocode 5 is zero, which yields an unrealistic value for thermal inertia of zero at the same time as the effective thermal conductivity increases substantially. At these temperatures, there may be some char contraction but for solid timber an underlying char would remain. Caution is needed in applying these thermal conductivity values above 800°C.

Generally, furnace fire tests provide fire exposures with low oxygen content similar to the oxygen content during fully developed ventilation-controlled enclosure fires. Fully developed enclosure fire temperatures and heating rates may also vary from the standard heating regimes and therefore, as for other thermal properties, the effective thermal conductivity values require validation for the relevant application and may require some adjustments.

2.9 Charring of wood

2.9.1 Introduction

During the charring process timber will decompose, releasing volatiles but also forming a char layer that provides a degree of protection to the underlying timber; so timber elements having a large cross-section can achieve high inherent Fire Resistance Levels. There will be a heat-affected zone between the char and unaffected timber where some pyrolysis may occur and the mechanical properties of the timber will be modified. The process is depicted in the simplified Figure 13 schematic.

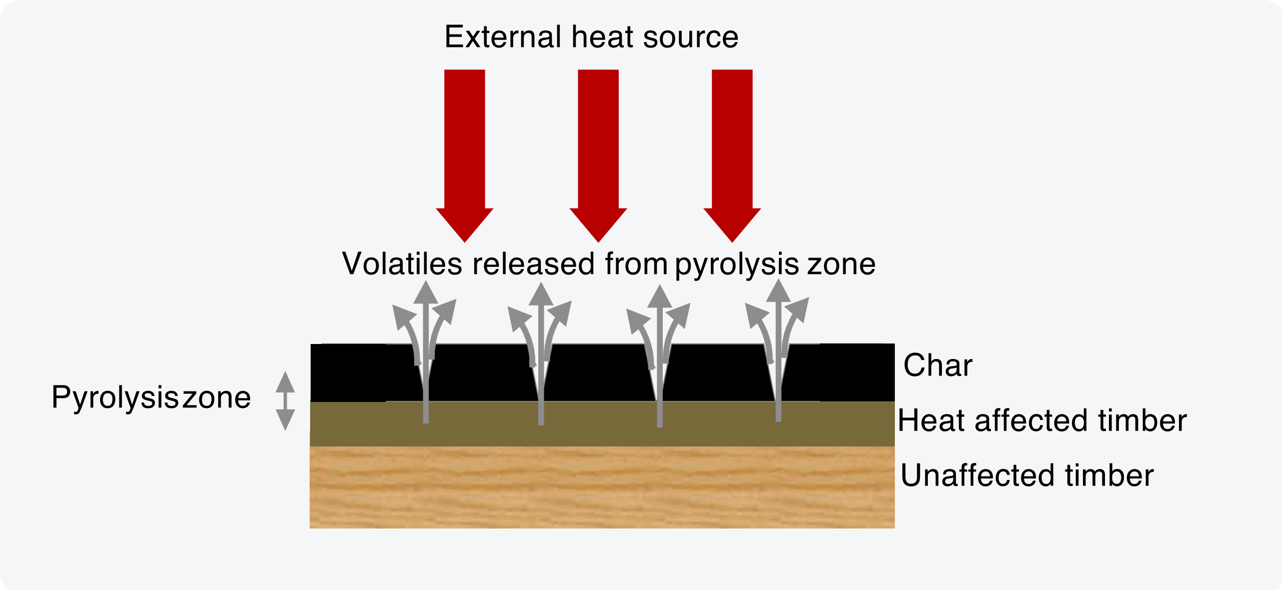


Figure 13: Schematic showing a section through a burning section of timber.

The charring behaviour of timber is more complex and there are variations between species due to, for example, variations in the proportions of hemicellulose, cellulose and lignin. Softwoods tend to provide higher char yields due to higher concentrations of lignin compared to hardwoods. Even within the same timber species charring behaviour varies with material properties and external environmental conditions. Some typical factors are summarised below:

Environment conditions	Material properties
• heating conditions • oxygen content in the local environment • air flows	• density • moisture content • orientation of the timber grain • type of adhesives for products such as CLT • dimensions of the timber element • chemical composition and impurities • protective treatments

For engineering design purposes, simplifying assumptions can be applied but users should be aware of the significance of these assumptions. For example, it is commonly assumed that the onset of charring coincides with the onset of rapid pyrolysis (approximately 300°C) although some minor degradation (pyrolysis) of the timber will occur below this temperature; particularly if the timber is exposed to temperatures above 200°C for a lengthy period. However, for many applications the heating will be relatively rapid and the 300°C onset of charring may provide a reasonable approximation.

A detailed discussion of the charring behaviour of timber when exposed to fire and underlying chemistry is outside the scope of this Guide. Refer to appropriate literature such as Drysdale[9], Friquin[10] and Bartlett[11] for more detailed information.

The following sub-sections provide an overview of the potential impact of the above factors on the rate of charring.

2.9.2 Sensitivity of charring rate to heating conditions

Mikkola[48] derived the following simple (approximate) model to demonstrate how different factors impact the char rate by considering the energy balance:

$\beta = q_n / \rho \, [c\,(T_p - T_o) + L_v]$

where:

β is the char rate

q_n is the net heat flux

ρ is the density of wood including moisture

c is the specific heat capacity of wood

T_p is the average pyrolysis temperature of wood

T_o is the initial temperature of the wood

L_v is the heat of gasification of wood

and

$q_n = q_e - q_l - q_c$

where:

q_e is the imposed heat flux

q_l is the heat loss from the char surface

q_c is the heat absorbed by the char layer

As the imposed heat flux increases the net heat flux will increase and hence the char rate will increase.

This is supported by experimental work using heat release rate calorimeters. Typical results for a range of species are shown in Figure 14. While lines of best fit were derived assuming a linear relationship, at the higher heat fluxes some departure from a linear relationship has been observed.

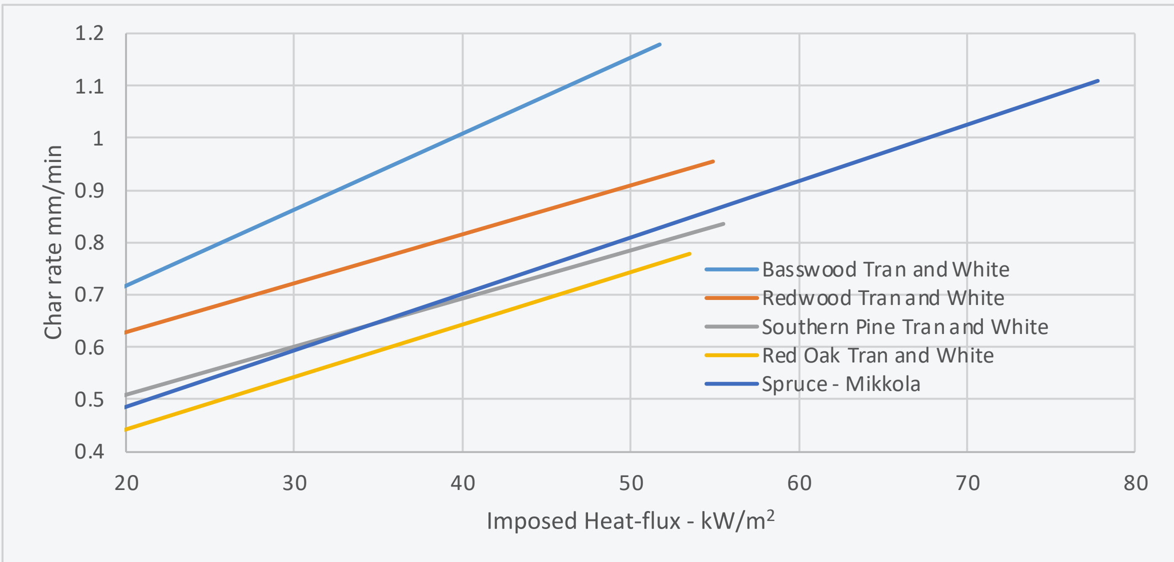


Figure 14: Char rate v imposed heat flux from HRR calorimeter tests from Tran and White[49] and Mikkola[48].

The Figure 14 data was obtained in a standard environment (approximately 21% oxygen), which is more appropriate for applications where a fire is fuel controlled (e.g. the growth phase and decay phases if the air supply is not constrained), rather than an environment with low oxygen content, which typically occurs during the fully developed phase of ventilation-controlled fires; especially where timber structural elements are exposed.

Modifications can be made to cone calorimeters to evaluate the performance of wood products in a reduced oxygen environment but a large body of char rate data at high heat fluxes/temperatures with oxygen concentrations typically between 4% and 10% is available from furnace tests using the standard heating regime of AS 1530.4 and similar fire-resistance test standards.

Further discussion relating to the impact of oxygen concentrations on charring rates is provided in Section 2.9.3.

Char rate data has been used to define notional char rates for wood products exposed to the standard fire-resistance test heating regimes. For example, the char rate when exposed to the standard heating regime of AS 1530.4[45] can be calculated using the following equation from AS/NZS 1720.4[19] for Radiata Pine:

$c = 0.4 + (280/\rho)^2$

where:

c is the notional charring rate (mm/min)

ρ = timber density at a 12% moisture content (kg/m^2)

AS 1720.1[49] quotes a density of 550 kg/m^2 for seasoned Radiata Pine, yielding a notional char rate of 0.66 mm/min.

Eurocode 5[42] adopts a simpler approach than AS 1720.4 by assuming a notional char rate of 0.65 mm/min for one dimensional charring of solid softwoods with a characteristic density greater than 290 kg/m^3. The Eurocode 5 approach will therefore underpredict char rates for low densities compared to the AS 1720.4.

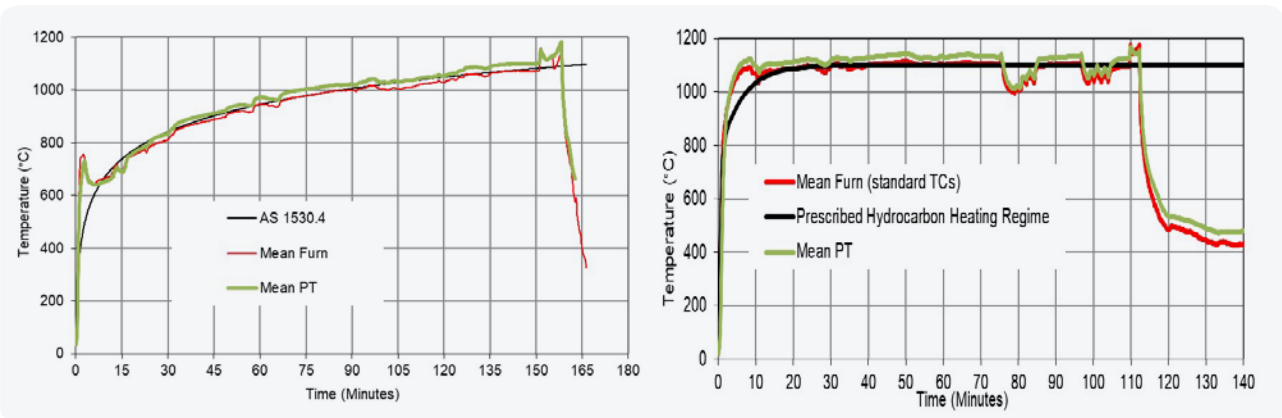
A study was undertaken for FWPA (England[50]), which is summarised below with further details in Appendix C9 to investigate the sensitivity of char rates to differences in heating regimes. Comparative tests were undertaken using the standard and more severe hydrocarbon regime defined by AS 1530.4 on CLT panels in the horizontal orientation at Warringtonfire Melbourne Laboratories.

The tests were performed on CLT panels with a rebated joint of overall dimensions approximately 1.76 m x 1.76 m x 225 mm in thickness with five 45 mm deep Radiata Pine lamella bonded together with Purbond HS Polyurethane adhesive. Only the faces of the lamella were bonded not the sides. The density of the Radiata Pine was approximately 500 kg/m^3 and the moisture content 8.4%. An area 1.2 m x 1.2 m of each element was exposed to the furnace heating regime from the underside. Figure 15 shows the specimen undersides before testing.

Specimen H1 AS 1530.4 standard exposure *Specimen H7 AS 1530.4 hydrocarbon exposure*

Figure 15: Fire-exposed face of CLT panels before testing.

The furnace temperatures in each test were measured by four mineral insulated metal sheathed Type K thermocouples complying with AS 1530.4 requirements with additional furnace temperature measurements being taken by two plate thermometers. These are plotted against time in Figure 16.



Standard Heating Regime *Hydrocarbon Heating Regime*

Figure 16: Test 1 plate thermometer and AS 1530.4 thermocouple furnace temperatures – unprotected CLT tests.

Heat flux measurements level with the initial soffit of the specimen were taken in both tests using a Medtherm Heat Flux Gauge. These are plotted against time in Figure 17.

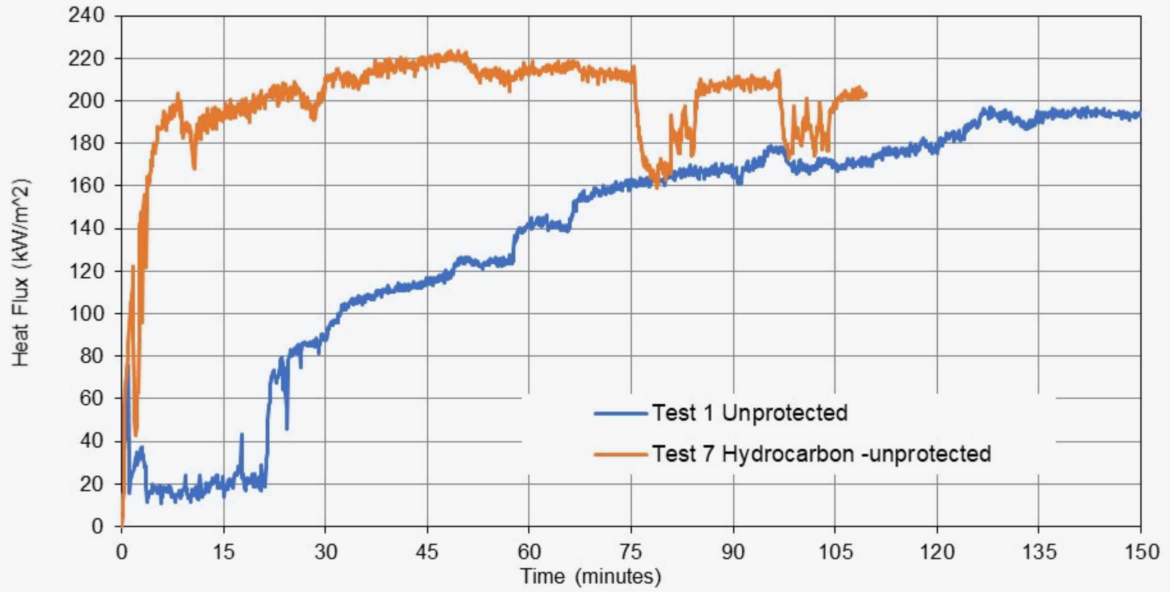


Figure 17: Comparison of heat flux at specimen soffit with CLT panels exposed to the standard and hydrocarbon heating regimes in Tests 1 and 7 respectively.

An additional heat flux measurement was taken in the hydrocarbon test, 100 mm below the soffit but the results are not reported in this comparison.

Internal panel temperatures were measured at various depths with the thermocouples running perpendicular to the expected isotherms, which would tend to reduce the measured temperatures due to heat losses along the thermocouple wires. The effects would be similar in both tests and due to rapid increases in temperature as 300°C is approached any errors would be expected to be small. The derivation of the char rates based on internal thermocouples are provided in Figure 18 for test 1 (standard heating regime) and test 7 (hydrocarbon heating regime). Linear regression performed on the data indicates an average char rate of 1.45 for the hydrocarbon regime and 1.11 mm/min for the standard regime, however, a large zero offset for the standard heating regime is predicted. This may be due to the low heat fluxes measured at the soffit during the first 20 min of the standard fire test shown in Figure 17. The reasons for these low heat fluxes require further investigation but during the early stages of a fire test there is a greater reliance on convective heat transfer, with the proportion of radiant heat increasing considerably as the furnace wall temperatures increase. Both convective and radiant heat transfer may be reduced by the interaction with steam and volatiles released from the surface.

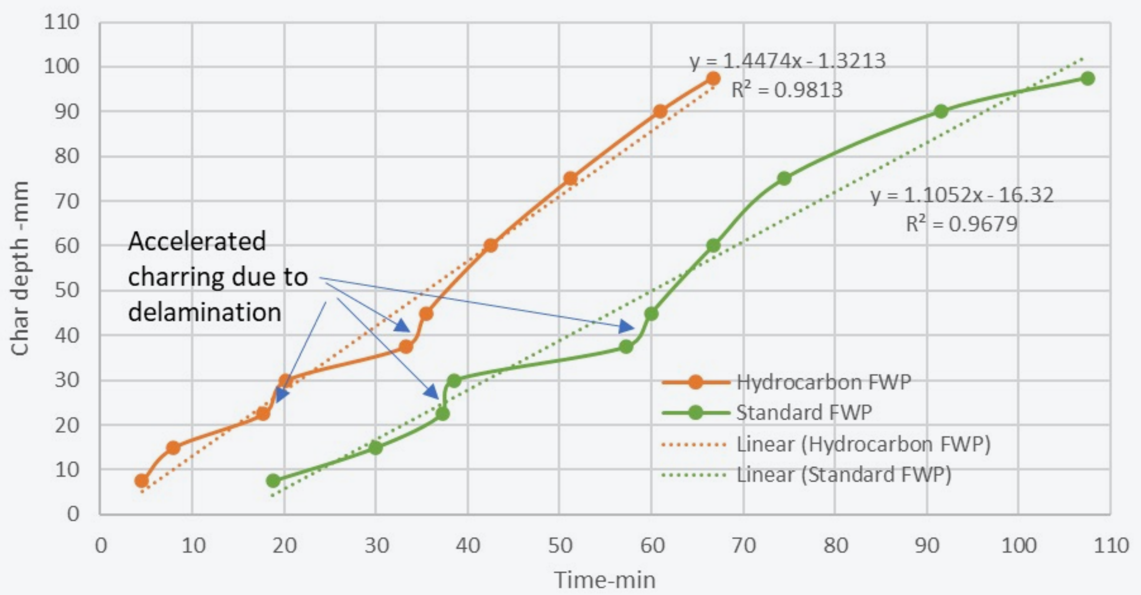


Figure 18: Exposure time v char depth for unprotected CLT panel exposed to AS 1530.4 standard heating regime (Test H1) and hydrocarbon heating regime (Test H7).

Comparative char rate data in Table 13 is calculated in accordance with AS/NZS 1720.4:2019 Appendix A[19], i.e. the depth of the 300°C isobar divided by the heating duration. This provides a more meaningful comparison of the char rates under the alternate heating regime because the zero offset is avoided.

Table 13: Calculated char rates for exposed CLT subjected to standard and hydrocarbon heating regimes – FWPA data tests H1 and H7.

Char depth range (mm)	Standard regime		Hydrocarbon Regime		Hydrocarbon/ standard char rate ratio
	Time (min)	Char rate (mm/min)	Time (min)	Char rate (mm/ min)	
0-22.5	37.5	0.6	17.5	1.29	2.2
0-37.5	57.25	0.66	33.25	1.13	1.7
0-45	60	0.75	35.5	1.27	1.7
0-90	91.5	1.02	61	1.49	1.5
0-97.5	107.5	0.91	66.75	1.46	1.6

The oxygen concentration was estimated to be approximately 6-7% based on measured values from similar tests in the series.

Substantially higher char rates occurred within the 2nd and 3rd lamella due to substantial delamination.

The char rates obtained under the standard heating regime were similar to the notional char rates from Eurocode 5 and AS 1530.4 (0.66 mm/min) until delamination occurred after the char depth had reached 37.5 mm. Subsequently, char rates increased significantly for both heating regimes, demonstrating the importance of adhesive performance.

2.9.3 Oxygen content and airflows

Char oxidation will reduce the mass and thickness of char as the char is consumed (commonly referred to as char contraction). This has the effect of increasing heat transfer to the underlying timber and hence the rate of charring.

In ventilation-controlled fully developed fires, oxygen content is very low and commonly approaches zero. But, as the fuel is consumed and the fire begins to decay, it will eventually transition to a fuel-controlled burning regime and the oxygen content will increase (see Section 3.6 and Schmid[51] for further details).

Low-oxygen atmospheres are commonly maintained throughout fire-resistance tests. Babrauskas[52] noted that oxygen concentrations generally range from about 4% up to 8–10% in fire-resistance furnaces.

Schmid reported test data showing the oxygen content measured during fire-resistance tests on non-combustible construction was approximately 4-8% in the general furnace enclosure but when testing combustible elements could drop to below 4% if the oxygen content is measured close to a combustible specimen. During test series H (summarised in Appendix C9) the oxygen content measured approximately 290 mm below the specimen was typically 7% for the combustible and non-combustible specimens.

The 2012 amendment to ISO 834[47] included the following requirements, which are consistent with the lower oxygen limit noted by Babrauskas:

"The fuel/air ratio to the burners and the introduction of any secondary air shall be set to give a minimum oxygen content of furnace atmosphere of 4% when testing specimens with no combustible content such as described in ISO/TR 834-2. This fuel /air ratio setting of burners including secondary air shall not be changed after the last verification of the furnace performance."

It follows that the furnace oxygen content at the interface with combustible specimens will be substantially below 10% and be representative of values that are likely to occur during fully developed fires.

A limited number of investigations into the sensitivity of char rates to variations in oxygen content at high temperatures have been undertaken. Friquin[10] identified the following relevant data in 2011:

"The mean charring rates were found by Hadvig to decrease little as the oxygen concentration decreased from 10 to 0%. Mikkola, based on a review of literature estimated a 20% reduction in char rate if the oxygen content is reduced from 20 to 10%."

Cedering[53] found that, at 12% moisture content, an increase in the oxygen content from 4% to 10% increased the char rate of Norwegian Spruce (dry density 321-454 kg/m^3 corresponding to 360-508 kg/m^3 at 12% moisture content) from 0.65 to 0.7 mm/min (a less than 8% increase in the char rate) when exposed to the standard ISO 834 (similar to AS 1530.4) heating regime for 60 min.

Schmid[54] undertook a series of 14 tests to evaluate the impact of variations in temperature, oxygen content and air velocity. Variations in temperature between 550°C and 850°C were found to increase the char rate between 0.09 mm/min and 0.12 mm/min. The char rate at approximately 850°C varied between 0.64 mm/min and 0.73 mm/min.

Char oxidation/contraction was noted for oxygen contents of 15% but not at oxygen contents of 5% and 10% when exposed to temperatures of approximately 750°C, indicative of a limit for significant glowing combustion between 10% and 15% oxygen content. At 15% oxygen content, the char oxidation or contraction became more significant as the velocity was increased from 3 m/s to 10 m/s.

2.9.4 Density and timber species

Reviews by Friquin[10] and Bartlett[11] found that the charring rate tended to decrease as the density increases, although some researchers did not identify this relationship. Bartlett also observed that most of the data was derived from standard fire-resistance tests. AS 1720.4[21] recognises that char rates will tend to reduce as the density increases and takes this into account using the following correlation for determining char rates for timber exposed to the standard heating regime of AS 1530.4[18]:

$c = 0.4 + (280/\rho)^2$

where:

c is the notional charring rate (mm/min)

ρ = timber density at a moisture content of 12% (kg/m^2)

In 1991, Gardner and Syme[55] studied the charring of glued-laminated beams, 270 mm x 150 mm, manufactured from Australian-grown species commonly used for structural purposes covering a range of mean densities varying from 526 kg/m^3 to 968 kg/m^3.

The results from the Gardner and Syme series are compared to the AS 1720.4 char correlation in Figure 19. The first group of eight specimens in the Gardner and Syme study were tested for 60 min but it was observed that the furnace thermocouples were not placed in accordance with the Standard, which exposed the element to more severe heating conditions. The second group of eight specimens was tested with the furnace thermocouples adjusted to comply with the test standard. Generally, the upper data point of each pair relates to the more severe heating conditions and the lower point is more representative of the standard heating regime.

Notwithstanding this observation, the Radiata Pine data from series 2 is also higher than expected. The char rate derived from testing of CLT panels constructed from Radiata Pine prior to delamination derived in Appendix C9 of this Guide is also included in Figure 19 and is consistent with the AS 1720.4 char correlation. The broken line in Figure 19 defines the envelope of char rates from technical literature identified by Bartlett[11].

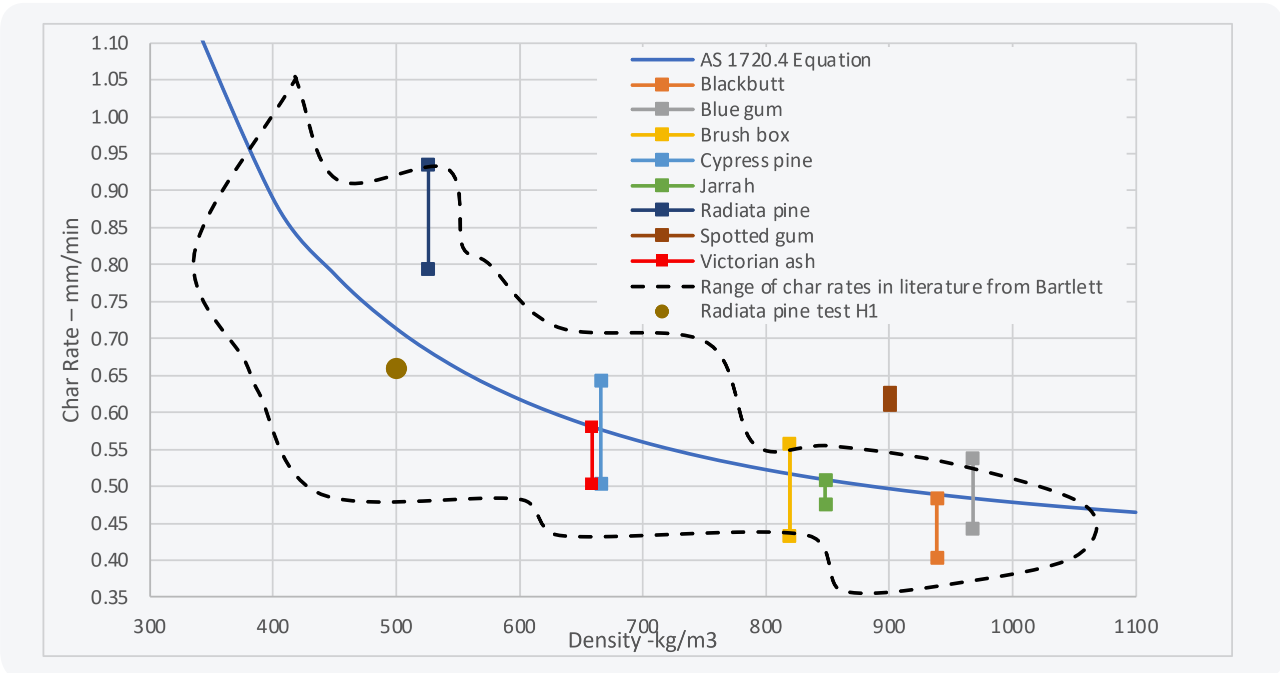


Figure 19: Density/char rate results for Australian-grown timber species subjected to a test following the procedures of AS 1530.4 1985 compared to the AS/NZS 1720.4 char rate equation.

2.9.5 Moisture content

Increasing the moisture content in wood is expected to delay ignition and commencement of charring because the additional mass of water has to be heated and then vapourised before the wood attains temperatures above 300°C. This absorbs energy, thus retarding the char rate. Mikkola[48] derived the following relationship by taking into account the impact of moisture content on typical thermal properties of softwood:

$\beta = 1/(1+2.5\ w)$

where β is the char rate (mm/min) of species and w is the moisture content expressed as a proportion of the dry wood density for timbers such as pine and spruce when exposed to a radiant heat source of 50 kW/m^2 in a horizontal orientation.

The results from tests on a range of wood species and products were reported by Mikkola (summarised in Table 14) and confirmed reduced charring rates at higher moisture contents.

Table 14: Charring rate at different moisture contents with an external heat flux of 50 kW/m^2.

Wood species or product	Charring rate (mm/min) at nominated moisture content			
	0 %	8%	10 %	20 %
Pine	1.11		0.80	
Spruce	1.06		0.80	0.60
LVL	1.05		0.82	0.68
Plywood	1.44	1.14		
Particleboard	1.10	0.97		
Fibreboard	2.40	1.80		

Collier[56] reported char rate data based on exposure to the standard heating of AS 1530.4 over test periods of nominally 30 min and 60 min, including wood samples with moisture contents varying from 0 to 23%, which indicated a reduction in char rate with increasing moisture content. Included in the report is a comparison with predicted char rates derived from AS 1720.4[21] that showed the AS 1720.4 predictions were conservative (overestimated char rates) for specimens that were air dried or at higher moisture contents but underestimated char rates for the oven-dry samples (0% moisture content).

Bartlett[11] provides further experimental data showing the same trend of reducing char rates as the moisture content increases.

For most building applications the moisture content is impractical to modify/control and tends towards equilibrium with the environment. Generally, fire tests are undertaken on timber specimens with a moisture content in the 8% to 12% range, depending on the pre-test conditioning and this provides representative results for most applications.

One application where modification of moisture content of timber may be practical and provide benefits is in external timbers during a bushfire where pre-wetting timbers ahead of the fire front can reduce the risk of ignition and subsequent char/heat release rates.

2.9.6 Adhesives

Adhesives and other fixings can significantly influence the response of engineered timber elements to elevated temperatures. For example, some types of adhesive can cause premature loss of the protective char layer, which accelerates the effective char rate. Figure 18 gives a typical example of the acceleration of charring resulting from delamination between lamella in a CLT panel.

This risk is recognised in AS/NZS 1720.4[19], which prescribes the following specific types of structural adhesives for the manufacture of glue-laminated timber, plywood and laminated veneer lumber fabricated in accordance with the relevant Australian Standards, on the basis that these thermosetting adhesives are less sensitive to high temperatures and the effect on charring rates can be ignored:

- phenol
- resorcinol
- phenol-resorcinol
- poly-phenolic.

AS/NZS 1720.4 allows the notional char rates for solid timber members to be applied to glue-laminated timber, plywood and laminated veneer lumber manufactured using these adhesives.

For structural wood products manufactured with other adhesives and other types of wood products such as cross-laminated timber (CLT) and nailed laminated timber (NLT) AS/NZS 1720.4 requires that the strength, durability and integrity of the bond be maintained, and the performance be verified by fire-resistance testing for the required period.

There is a demand for the use of adhesives other than the nominated thermosetting adhesives to improve manufacturing efficiency and reduce environmental impacts. Many early natural and standard fire tests on CLT products used adhesives that were more temperature sensitive than thermosetting adhesives, and delamination of lamella was observed. Such delamination will result in loss of the protective char associated with the delaminated wood and exposure of uncharred wood, thereby accelerating pyrolysis and potentially prolonging or reinitiating flaming combustion within an enclosure. In some cases, secondary flashover may occur. Many of the earlier natural fire tests (e.g.[57-59]) listed in the appendices demonstrated this type of behaviour.

Figure 20 shows delamination on the the underside of a CLT panel after exposure to the hydrocarbon heating regime for 109 min in an intermediate-scale fire test undertaken by Warringtonfire for FWPA.

Figure 20: Underside of CLT panel after exposure to hydrocarbon heating regime, showing delamination and flaming from interface between lamellae.

New generations of non-thermosetting adhesives that have greater high temperature resistance have been developed and are less prone to delamination. For example, the US CLT product standard was modified to call up a 4-hour large-scale test to determine if delamination is unlikely to occur. The test method and tests are described by Janssens[60] and the performance of products that comply with the revised product standard were demonstrated in the natural fire tests reported by Brandon[43].

The current Australian approach of requiring full-scale standard fire-resistance testing provides data on the structural performance of elements of construction when exposed to elevated temperatures, but additional measurements/observations are necessary to determine char rates, the extent of delamination and potential for transition from flaming to smouldering combustion and subsequently self-extinguishment.

2.9.7 Orientation of timber grain

Permeability and thermal conductivity along the grain is greater than that across the grain, which would be expected to allow an increased flow of volatiles and conduction of heat from the surface accelerating pyrolysis when exposed to an external heat source.

Notwithstanding these expectations, Bartlett[11] found no significant difference in char rate based on grain orientation when reviewing technical literature relating to char rate where the grain orientation was identified.

For most elements of construction, the grain is normally perpendicular to the heat source and therefore char rates parallel to the grain are not critical. The exception to this could be certain types of joint where there may be heat transfer between opposing faces with at least one face with exposed end grain. This may be addressed through careful detailing and/or validation by test, depending on the uncertainty and availability of existing Evidence of Suitability.

2.9.8 Timber cross-section

Although the thermal conductivity, and hence heat flow, through wood products is relatively low, the char rate can still be sensitive to the size of timber members. For example, if the thermal penetration depth exceeds the element’s depth, char rates can be accelerated, depending on the boundary conditions.

These effects are recognised in AS/NZS 1720.4, which restricts the use of the residual cross-section/notional charring rate method for predicting the structural performance to elements of construction with minimum dimensions no less than 75 mm.

2.10 Mechanical properties of timber at elevated temperatures

Eurocode 5 provides reduction factors for the strength and modulus of elasticity of softwoods at elevated temperatures (summarised in Table 15). Linear interpolation between the nominated values is permitted. Strength and modulus of elasticity is assumed to be zero once the char layer is reached with an assumed interface temperature of 300°C.

Table 15: Eurocode 5[42] reduction factors for strength and modulus of elasticity for wood at elevated temperatures.

Temp (°C)	Strength			Modulus of Elasticity	
	Compression	Tension	Shear	Compression	Tension
20	1	1	1	1	1
100	0.25	0.65	0.4	0.35	0.5
300	0	0	0	0	0

Young[61] undertook a number of bench-scale measurements of the modulus of elasticity in compression of Radiata Pine at elevated temperatures as part of a thesis investigating the structural modelling of lightweight timber stud partitions clad with plasterboard. The modulus of elasticity in compression was found to be critical as the mode of failure was buckling of the studs. Measurements of oven dry timber (0% moisture content) were undertaken at a range of temperatures up to 250°C and on timber with a moisture content of 11% at 70°C. The results are plotted in Figure 21. There is a substantial difference in the reduction factor between dry and timber at 11% moisture content.

The reduction would be expected to be high at 100°C for moist timber but the timber would then be expected to dry and potentially recover to some extent. This can have significant implications for applications where a thermal wave travels across a structural element.

The mechanical properties are also sensitive to heating rates, among other things, and have been largely derived for elements of construction exposed to the standard heating regime of AS 1530.4. Results should therefore be validated against test/experimental data having similar fire exposure conditions.

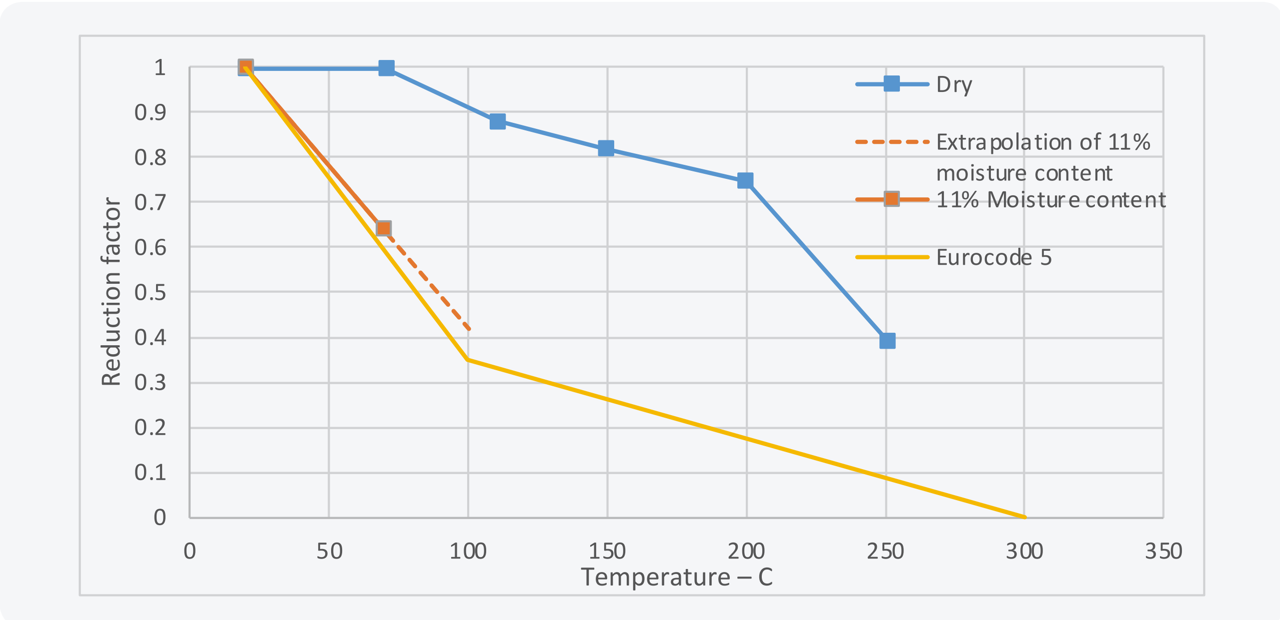


Figure 21: Reduction factor for modulus of elasticity at elevated temperatures measured by Young[61] compared to Eurocode 5[46] factors.

2.11 Emissivity

The following values of emissivity for wood products prior to charring/blackening have been provided by Lautenberger[62]:

- Wood Beech 0.91 (70°C)
- Oak, planed 0.91 (40°C)
- Sawdust 0.75 (40°C)
- Spruce, sanded 0.82 (100°C).

Lautenberger also presented integrated surface absorptivity values from Wesson for various species exposed to flame radiation prior to charring with typical values of 0.76.

Janssens[22] recommended using:

- a value for the emissivity of timber of 0.88 prior to ignition, based on the average of 0.76 (the average of Wesson's absorptivity results) and a black body emissivity of 1
- an emissivity of 1 during flaming combustion and for charred timber.

Eurocode 5[46] recommends a value for emissivity of 0.8 for timber and plasterboard at all temperatures.

Due to the variability of the data when selecting emissivity values, the application should be considered. If there is uncertainty with the emissivity values selected, sensitivity analyses should be considered to provide additional confidence in the outcomes.

3 Characterisation of fires for design purposes

3.1 Overview

Once a fire scenario has been identified for analysis it is necessary to define the corresponding Design Fire. This chapter provides a general review of Design Fires. Subsequent chapters consider application to timber buildings or elements of construction.

It is common to subdivide an enclosure fire into the following four stages for fire engineering analyses:

- incipient/initiation
- growth
- fully developed
- decay.

In some applications, it may be necessary to extend the analysis and consider a cooling phase if the behaviour of elements of construction after extinction of the contents (moveable fire load) and combustible elements is to be considered. Typically, this may be necessary where degradation of elements of construction occurs after extinction of the contents due to thermal inertia, degradation on cooling (Dimia et al[63]) and/or localised smouldering combustion of elements of construction (McGregor[58]).

A schematic example of an enclosure fire is shown as the solid red line in Figure 22.

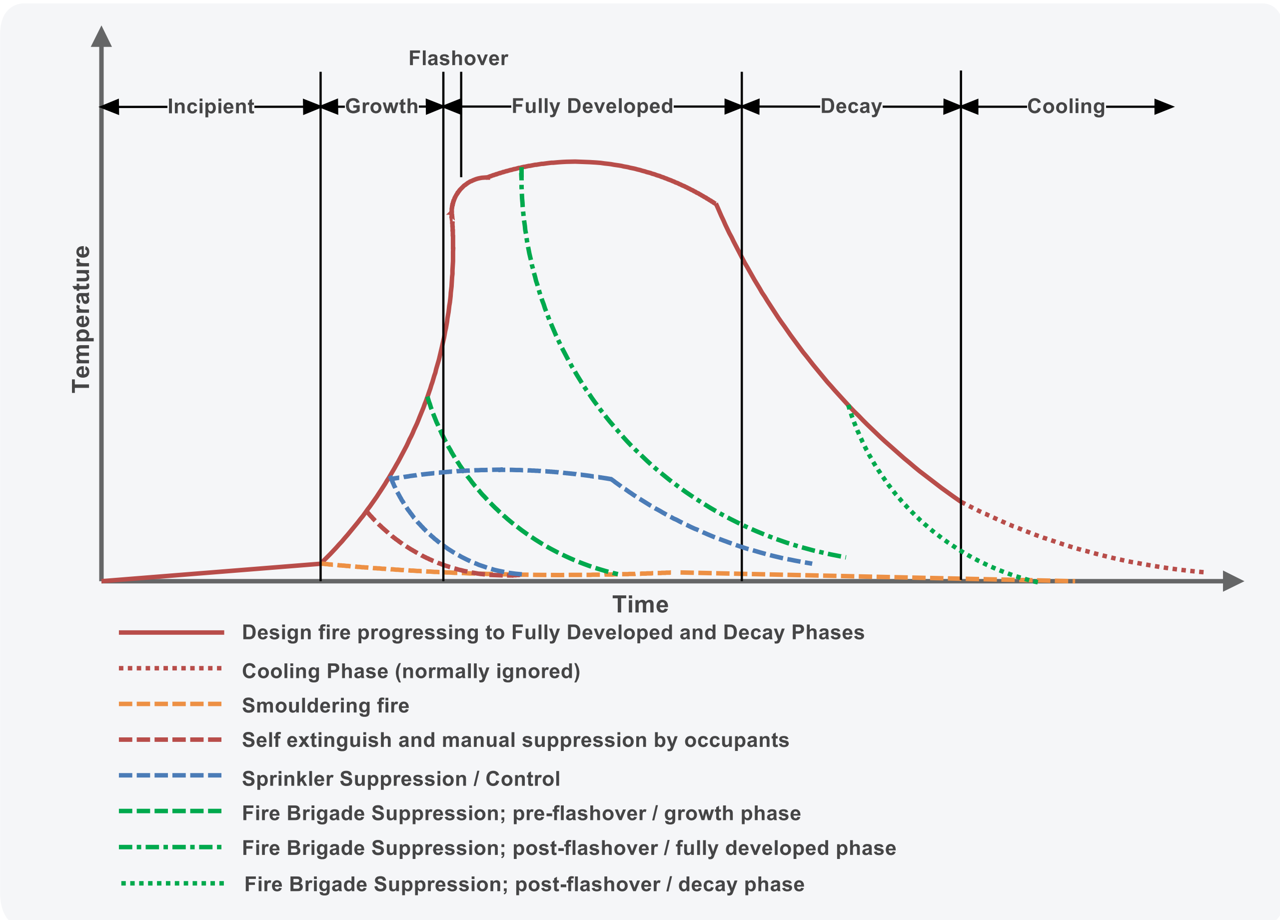


Figure 22: Design fire stages and interventions.

3.2 Definition of fire exposure

When discussing the application of test data to fire safety engineering analyses there has been much discussion in technical literature about the relevance of exposure conditions including issues such as oxygen content with a particular emphasis on fire-resistance tests. However, most of the issues raised apply equally to other standard and ad hoc test procedures.

Schmid[64, 65] suggested the introduction of the term 'fire exposure', which accounts for both thermal and environmental exposures. The term has been adopted using the following definition that can be applied to a broad range of Design Fire scenarios and test methods.

Fire exposure: The exposure of an element of construction, material, object or person to thermal and other environmental or fire-related actions, including variations to oxygen concentrations and other species concentrations, air flows and pressure differentials, as appropriate to the application.

3.3 Incipient phase

The incipient phase is commonly applied for evaluation of small flaming fires and smouldering fires, e.g. the Smouldering Fire (SF) scenarios in sleeping areas in the NCC Fire Safety Verification Method (FSVM[13]). The thermal exposure of elements of construction during the incipient phase is expected to be minor in most scenarios.

When undertaking an analysis, the following scenarios/events may be relevant:

- smouldering/small flaming fires in concealed spaces affecting structural elements
- the timing of detection and alarm during the incipient phase
- the risk to occupants if they do not respond or are slow to respond to fire cues.

3.4 Growth phase

After the incipient stage, a fire may transition to a flaming fire corresponding to the fire growth stage. The characteristics of the Design Fire during this stage can be determined using one or more of the following sources if a Performance pathway is followed:

- full-scale enclosure fire tests /experiments
- furniture calorimeter tests
- cone calorimeter tests
- statistical data/fire incidents
- calculation/fire modelling.

Depending on the methods of analysis and design fires adopted, it may be necessary to quantify the exposure of an element (and its response) to a growing fire, although in many calculation methods or fire models the growth phase may be incorporated into the design fire for the fully developed phase when considering the performance of structural elements and fire-resistant barriers.

Figure 22 shows the potential impact of typical interventions by occupants, fire brigade and automatic suppression/control systems (e.g. sprinklers) that can modify the fire exposure of the element of construction.

If the growth phase is considered separately, it is common for it be characterised as a t-squared fire or a series of t-squared fires to address a range of credible Design Fires within an enclosure.

A t-squared fire is defined by the following equation:

$Q=\alpha t^2$

Where Q is the Heat Release Rate (HRR) (kW)

t is the time (s)

α is the proportionality constant (fire growth parameter) (kW/s^2)

A characteristic growth time (t_g – s), which is the time taken for the Design Fire to reach a reference heat release rate Q_g of 1,055 kW, is also used to define t-squared fires in a way that can be more readily related to a fire scenario and can be converted to the proportionality constant using the following equation.

$\alpha = Q_g/t_g^2$

While the proportionality constant can be derived for a specific application, it is common to categorise a t-squared fire using the growth categories shown in Table 16.

Table 16: Typical t-squared fire categories.

Growth Category	Proportionality constant (α – kW/s^2)	Growth time (t_g – s)
Slow	0.00293	600
Medium	0.0117	300
Fast	0.0470	150
Ultra-fast	0.188	75

Data Sheet B2 in the Annex to the NCC FSVM handbook[14] provides distributions of characteristic t-squared fires for NCC Building Classes together with details of the derivation. These values may be selected if more accurate information is unavailable and the use of the characteristic values is agreed to during the PBDB process. The proposed distributions in Data Sheet 2 assume that the wall and ceiling linings and flooring materials comply with the NCC Clause C1.10 DTS fire hazard property requirements.

More detailed discussion relating to the behaviour of exposed timber building elements during the fire growth phase and the 'reaction to fire' properties of timber elements is provided in Chapter 5.

3.5 Localised fires

A significant proportion of fires do not progress to the fully developed phase either because the fire remains confined to a single or limited number of objects without interventions or because there is a sucessful automatic or manual intervention. Design Fires for these localised fires are often modelled by applying a maximum limit to the HRR during the growth phase appropriate to the fire scenario. The fire may then be assumed to maintain a constant heat release rate before decaying or simply decay if manual or automatic suppression is incorporated in the scenario. Fire exposures of elements and adjacent materials can be determined by hand calculations and/or models.

3.6 Fully developed phase

3.6.1 Overview of fully developed fires and travelling fires

Flashover is the transition from a localised to a fully developed fire, simultaneously involving all exposed combustible surfaces within a fire enclosure. In most applications, the majority of fires will not flashover and progress to the fully developed phase. The ABCB FSVM handbook Annex Data Sheet B2[14] provides typical proportions of flashover fires for various NCC Building Classes.

Flashover leading to simultaneous involvement of all exposed combustibles within the enclosure may not occur for some large enclosures and enclosure geometries. Instead, localised areas within an enclosure can burn with a similar intensity to a fully developed fire and progressively spread around the enclosure as the fuel is consumed and/or ventilation conditions change so that the fire burns over a limited area at any one time. These fires are commonly termed travelling fires[66].

There are a number of simple analysis approaches that typically pre-define the travelling fire size and rate of spread and assess the impact on the structure but, because of the practical difficulties and costs of undertaking full-scale experiments, validation of these models is limited.

To address these limitations, the following practical approach for design of the fire resistance of structures in large enclosures or less common geometries should be considered during the PBDB process if specific data is not available.

- Assume a fully developed fire can occur and design the structure to resist exposure to fully developed fires based on the potential range of fire loads, ventilation conditions and enclosures. Fires contained within part of a large enclosure by elements that are not defined as fire resistant within the fire safety strategy but have an inherent fire resistance should be considered as appropriate.
- Undertake sensitivity studies simulating travelling fires of various sizes and travel speeds that are considered viable for the enclosure.
- If the simulated travelling fires highlight vulnerabilities with the base design, make enhancements to address the potential travelling fire scenarios and fully developed fire scenarios.

The remainder of this section focuses on fully developed fires simultaneously involving all exposed combustible surfaces within a fire enclosure. This is addressed in greater detail than the preceding phases of a fire because the fully developed phase generally poses the greatest risk to structural elements and also can make the structure more vulnerable during the decay and cooling phases.

3.6.2 Common empirical relationships and simplifying assumptions for defining fully developed design fires

There are numerous standard texts that address the fire dynamics of fully developed fires in small to medium-sized enclosures, including Drysdale[9], Karlsson and Quintiere[67] and Beyler[9]. These references provide information relating to the derivation of parametric curves and other correlations based on equating the energy balance and mass balance within an enclosure and correlating the results with experimental data.

Typically, the following relationship is assumed, based on consideration of the energy balance (Figure 23):

$$\dot{q}_C = \dot{q}_L + \dot{q}_W + \dot{q}_R + \dot{q}_B$$

where:

$\dot{q}_C$ is the rate of heat release due to combustion

$\dot{q}_L$ is the rate of heat loss due to the escape of hot gases

$\dot{q}_W$ is the rate of heat loss through the solid enclosure boundaries

$\dot{q}_R$ is the rate of heat loss through openings by radiation

$\dot{q}_B$ is the rate of heat storage in gas volume (usually ignored)

The mass balance of the gases within the enclosure is given by:

$$m_F = m_a + m_b$$

where:

m_F is the mass rate of out flow of gases from the enclosure

m_a is the mass rate of inflow of air

m_b is the fuel pyrolysis from the moveable fire load and exposed combustible elements of construction.

This relationship is often simplified by ignoring the gases released by pyrolysis of the moveable fire load and combustible elements of construction (fixed fire load) on the assumption that the impact is relatively small compared to the mass of air entering the enclosure yielding:

$$m_F \approx m_a$$

This is not necessarily valid, particularly if significant areas of the bounding surfaces are combustible (e.g. exposed Massive Timber elements or timber wall and ceiling linings). The impact of the assumption that the mass flow from pyrolysis products can be ignored is discussed in the following sub-section.

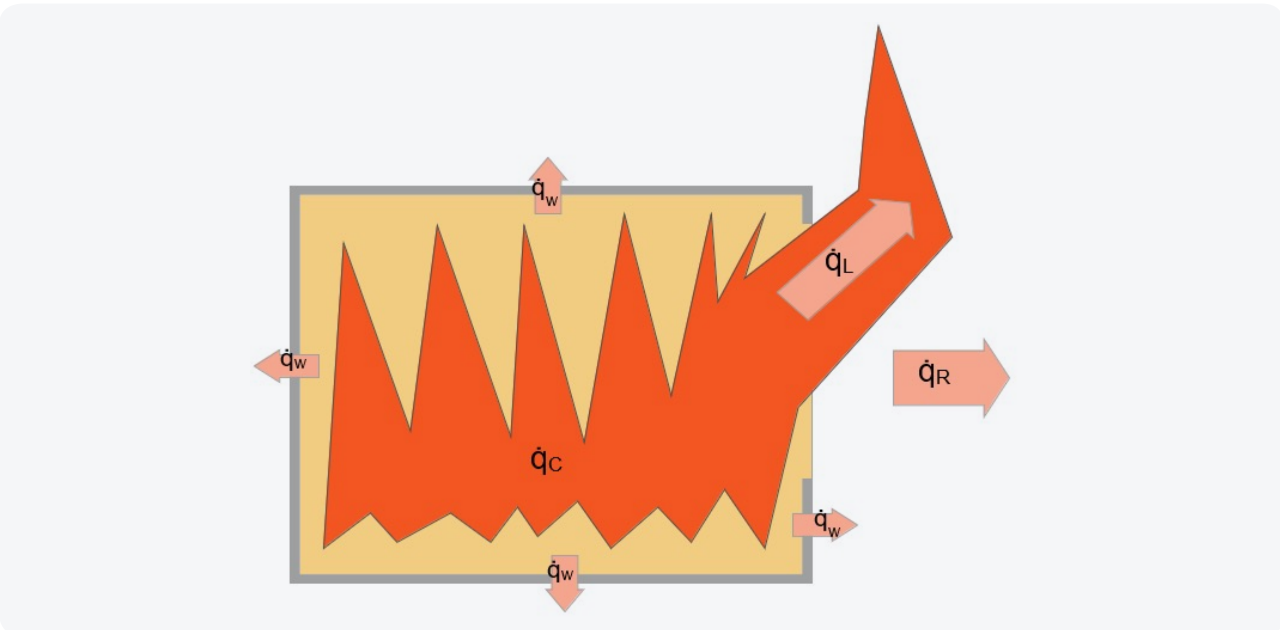


Figure 23: Schematic of energy balance for a fully developed enclosure fire.

Estimates of the rate of heat release and heat losses from the enclosure can be obtained if the following assumptions are made in addition to ignoring the mass flow of pyrolysis products as indicated in the equations below:

- Combustion is complete and takes place within the fire enclosure
- The temperature is uniform within the compartment at all times
- A single surface heat transfer coefficient applies to the entire inner surface of the compartment
- The heat flow through the compartment boundaries is unidimensional

This yields:

$\dot{q}_C = 0.09A_w H^{1/2} \Delta h_c$

(This relationship can be derived theoretically with gross simplifying assumptions but is also based on a mass burning rate empirical formula derived from compartment experiments generally with non-combustible linings and wood crib fuel with various opening sizes. Refer Drysdale (Chapter 10)[9] for further details).

$\dot{q}L = \dot{m}_F C_p (T_g - T_o)$

$\dot{q}_W \approx h_k A_T (T_g - T_o)$

$\dot{q}_R = A_w \varepsilon\sigma(T_g^4 - T_o^4)$

$\dot{q}_B \approx 0$

where:

A_W is the area of the opening (m^2)

H is the height of the opening (m)

Δh_c is the heat of combustion of the fuel (MJ/kg).

ε is the emissivity of the gases within the compartment

σ is the Stefan Boltzmann constant = 5.67×10^{-8} (W/m^2K^4)

m_F is the mass of gases exiting the enclosure unit time period (kg)

C_p is the specific heat of the gas exiting the enclosure (kJ/kg K)

h_k is the effective heat transfer coefficient to the surrounding construction (kJ/m^2 K)

A_T is the surface area of the boundary to the enclosure (m^2)

T is the absolute temperature (K)

Solving the above equations to derive values for T_g is not straightforward but numerical solutions deriving time/temperature regimes for post-flashover compartments with fire load, ventilation and thermal properties of boundaries representing the primary inputs have been derived. Many of these have been reviewed by Hurley[69] and include:

- design charts (e.g. Magnusson and Thelandersson[70])
- parametric relationships (e.g. Eurocode 1 Part 1.2 Annex A[39])
- zone models (e.g. Babrauskas[71] – the Babrauskas model has been implemented and developed within the B-Risk Software package[72]).

Some zone models or computational fluid dynamics (CFD) models can take account of combustion occurring outside the fire enclosure and may yield more realistic results for configurations that are heavily ventilation controlled.

3.6.3 Example of the application of Eurocode 1 Part 1.2 Annex A Parametric Curves and comparison to natural fire experiments

Background

Natural fire experiments/fire tests can be used directly as Evidence of Suitability if they are directly applicable to a particular application, although they are more generally undertaken to provide data for validation of methods of analysis. A good example of direct use of test data, without the additional complication of exposed timber wall and ceiling linings, was a series of two natural fire experiments undertaken to determine if there was any appreciable contribution to the fire severity from protected timber framing and combustible insulation. These tests were undertaken in Melbourne, Australia, in 2011 to address issues raised regarding the potential contribution from timber structural framing elements when protected by common Australian fire-protective grade plasterboard walls used for bounding construction of sole occupancy units (SOUs) in residential buildings.

The tests were undertaken as part of a project seeking the extension of a concession within the NCC (BCA at the time) allowing the use of timber-framed construction in low-rise Class 2 (apartment buildings) to Class 3 buildings, which includes buildings used for accommodation of the aged and other vulnerable occupant groups. As a result of a submission supported by the experimental results the concession was extended to Class 3. The opportunity was also taken to investigate the effect of a horizontal projection on the fire plume from the opening during a fire.

Details of the tests and additional background information are available in the following Forest & Wood Products Australia reports:

- Extension of the Concession which Allows Timber Framed Construction in Class 2 Buildings to Include Class 3 Buildings: England and Eyre[73]
- Fire Safety Engineering Design of Combustible Façades: England and Eyre[74].

Information relating to the technical studies undertaken to support the original concession for low-rise Class 2 timber frame buildings was reported by Beck[75, 76].

Test configuration

A control test was performed on a specimen with lightweight steel framing and non-combustible insulation, protected by fire-protective grade plasterboard and a second test was performed with timber framing and combustible insulation protected by fire-protective grade plasterboard with all other variables within the enclosure the same. The results indicated that there was no appreciable contribution to the fire load from the timber framing.

An instrumented facade was fitted above the opening and a corridor protected by a fire door was provided at the rear of the compartment. A 600 mm horizontal projection was mounted above the opening of the timber framed specimen to demonstrate the reduction in heat transfer to the wall above.

The test enclosures were 4 m x 4 m x 2.4 m constructed with either timber frame or steel frame walls protected by 2 x 13 mm thick fire-grade plasterboard on each face and a ceiling system comprising two layers of 16 mm fire-grade plasterboard fixed to steel furring channels.

The total surface area of enclosure (including openings) (A_t) was 70.4 m^2.

The opening to the enclosure was:

- 2 m wide x 1.2 m high with the sill 500 mm above floor level
- Opening Area 2.4 m^2
- Opening factor – $A_v(h_{eq})^{1/2}/A_t = 0.037m^{1/2}$.

The moveable fire load was simulated using 16 Radiata Pine cribs providing a total fire load of 656 kg (41 kg/m^2) – approximately 718 MJ/m^2 (assuming Δ_H =17.5 MJ/kg). The cribs were constructed from 40 mm x 40 mm x 440 mm sticks with a 1:1 spacing ratio. The test configuration is shown in Figure 24.

Figure 24: Typical configuration of a natural fire experiment – FWPA project PNA217-1011[73, 74].

Enclosure temperatures

The parametric time/temperature curve derived based on enclosure dimensions and fire load in accordance with the method described in EN1991-1-2 Annex A[39] is shown in Figure 25 and compared to the standard and hydrocarbon heating regimes from AS 1530.4[18] and the two natural fire experiments.

The commencement times for the standard, hydrocarbon and parametric time/temperature curves plotted in Figure 25 were offset by 4 min so that the increase in growth rate leading to flashover occurred at a similar time to the two experiments.

Throughout the whole heating period, the time/temperature regimes for the two experiments were closely aligned, indicating excellent repeatability and confirming that there was no appreciable increase in fire severity from the timber framing.

The parametric curve (blue line) starts to decay just prior to 60 min with a peak temperature above 1100°C and generally is bounded by the AS 1530.4 standard and hydrocarbon curves (yellow and brown) except for a 12 min period from 44 min where the parametric curve slightly exceeded the hydrocarbon curve.

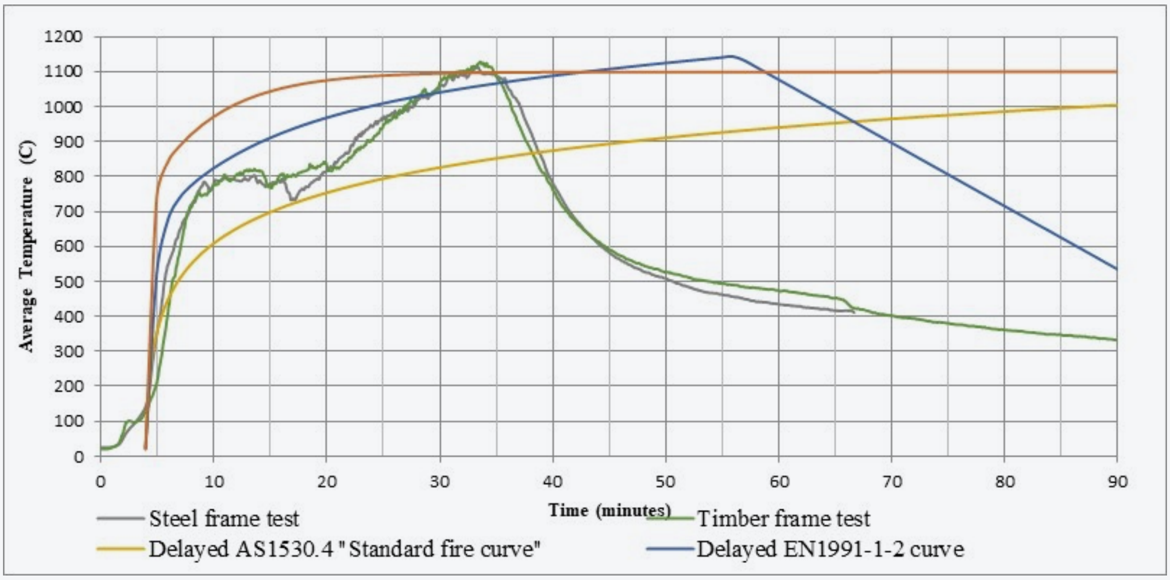


Figure 25: Natural fire enclosure temperatures compared to AS 1530.4 Standard, hydrocarbon heating regimes and a parametric curve calculated in accordance with EN1991-1-2 Annex A from England and Eyre[73].

The natural fire average enclosure temperatures were below the parametric curve for the first 30 min of the test, slightly exceeded the parametric curve between 30 min and 37 min before commencing to decay, however the peak temperatures were similar to the peak temperature of the parametric curve.

The lower temperatures measured in the enclosures during the experiments between 10 min and 25 min can be explained by the large volumes of unburnt volatiles ejected from the apartment, which would lower the neutral axis in the opening, reducing the air flow into the enclosure, and hence the heat release rate within the enclosure, while at the same time additional energy is consumed heating the excess volatiles; which are then vented from the enclosure. This loss of volatiles (fuel) also explains the shorter fully developed fire duration in the natural fire test compared to the parametric curve, which assumes the fuel burns wholly inside the fire compartment under stoichiometric conditions. Due to these simplifying assumptions in Annex A of EN 1991-1-2, parametric curves would generally be expected to yield conservative heating regimes within the fire enclosure. This was confirmed by the natural fire tests. The parametric design curves would also be expected to overestimate the temperatures within the fire enclosure during the fully developed phase if there is significant excess fuel (strongly ventilation-controlled conditions) although the risk of external fire spread to openings above may be increased as the excess volatiles burn outside the enclosure.

If the performance of structural elements is to be determined by fire-resistance testing, the thermal exposure of the natural fires would lie between the standard heating regime and the hydrocarbon heating regime. This is commonly addressed by extending the required heating period (FRL period) for materials and systems.

To demonstrate that an element of construction is not unduly sensitive to more severe heating rates and maximum temperatures and/or provide data to validate calculation methods, specimens can be exposed to alternate heating regimes using fire-resistance test furnaces. While alternate heating regimes can be derived from parametric curves or natural fires for specific purposes, there are advantages in adopting standardised curves, e.g. to facilitate evaluation of products and systems in a repeatable manner for verification purposes.

Beyler[68] identified this need in a study of fire-resistance testing for performance-based fire design of buildings and recommended a heating curve with very rapid growth to 1200˚C that was to be maintained throughout the remaining heating period. The intention was to provide an upper bound to a database of experimental fires. In some cases, this may result in a very conservative heating regime.

A more common approach is to adopt a 'standard' hydrocarbon heating regime if it is considered necessary to evaluate the sensitivity of an element of construction to conditions more severe than the standard heating regime. A hydrocarbon curve has been included in Appendix B of AS 1530.4 that can be used for this purpose and is plotted in Figure 25 (brown line).

Pressure differentials and predictions of air flows

During the two fire tests described previously, the pressures differentials between the fire enclosure and the corridor at the rear of the enclosure, were measured at heights of 2.1 m and 0.3 m above floor level at the rear of the fire compartment. The lower probe in the steel frame test malfunctioned and the upper probe in the steel frame test indicated similar pressures to the upper probe in the timber frame test. Only the pressure differentials measured during the first 45 min of the timber frame test is analysed and plotted against time in Figure 26 together with 30 s moving averages to reduce the impact of transient variations in pressure readings.

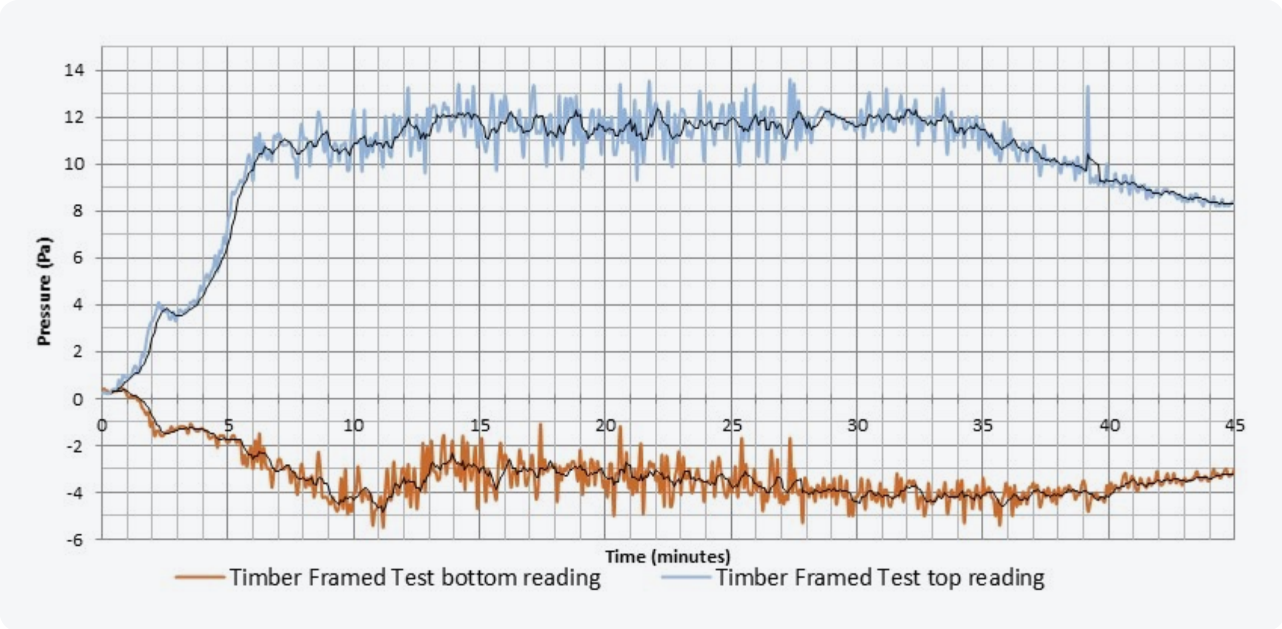


Figure 26: Pressure differential measurements during timber frame test FWPA project PNA217-1011[73, 74].

The approximate pressure differentials were estimated after approximately 15 min of the test when the fire was strongly ventilation controlled and after 33 min when the fire behaviour was close to stoichiometric. From this information pressure gradients and the positions of the neutral axis were calculated and are summarised in Table 17.

Table 17: Pressure calculations based on test measurements.

Parameter	Strong ventilation-controlled regime	Close to stoichiometric regime
Pressure measured at 2.1 m above floor (Pa)	11.7	11.9
Calculated pressure at sill – 0.5 m above floor (Pa)	-1.4	-2.2
Pressure measured at 0.3 m above floor	-3	-4
Pressure difference between probes 1.8 m apart	14.7	15.9
Pressure gradient (Pa/m)	8.2	8.8
Calculated neutral axis height (m above floor level)	0.67	0.75

The air supply to a naturally vented fire enclosure is generated by the pressure differential across openings due to buoyancy effects if no other airflows and pressure differentials are applied. The pressure gradient generated by a fully developed fire can be obtained based on the buoyancy of hot gases using the following equation from Klote and Milke[77].

$\Delta p/h = 3460(1/T_0 - 1/T_f)$ where:

Δp is the pressure difference from the fire compartment to surroundings (Pa)

h is the height above the neutral axis (m)

T_0 is the absolute temperature of outside air (K)

T_f is the absolute temperature within the fire compartment (K).

Pressure gradients calculated using the above relationship are summarised in Table 18 and correlate reasonably well with the experimental values.

Table 18: Pressure gradient calculations based on test measurements.

Test Condition	Temp (°C)	Pressure gradient (Pa/m)		
		Calculated	Test measurement	Difference
	1,200	9.5		
Stoichiometric	1,100	9.3	8.8	0.5
	1,000	9.1		
	900	8.9		
Ventillation Controlled	800	8.6	8.2	0.4

The table shows that the magnitude of the pressure gradient does not vary to a large extent with temperature for the range of temperatures associated with the fully developed phase (i.e. a variation from 8.6 Pa/m to 9.5 Pa/m occurs for a temperature variation between 800°C and 1200°C).

The differences between the calculated and measured values may be due to the air flow resistance in the corridor relative to the general laboratory atmosphere compared to the opening position at the front of the enclosure. A view of the enclosure opening when the fire was strongly ventilation controlled compared to when the conditions were close to a stoichiometric behaviour is shown in Figure 27, which highlights the increase in flame projections under heavily ventilation-controlled regimes and a reduction in the height of the neutral axis.

Ventilation Controlled conditions *Approximately Stoichiometric conditions*

Figure 27: Flame projections from openings under differing ventilation conditions.

Quantifying impact of mass released by pyrolysis in fire enclosure

It is common to ignore the mass released due to pyrolysis of solid fuels or vaporisation of liquid fuels when considering enclosure fires, assuming the impact is minimal. This assumption may not be valid, particularly in the case of strongly ventilation-controlled fires involving predominately solid fuels.

Karlsson and Quintiere[67] derived simple expressions for the mass of inward airflow and the height of the neutral axis taking into account the mass of volatiles produced within the room that are compared below to commonly used relationships that ignore the mass of volatiles produced within the enclosure:

$\dot{m}_a = 0.5Aw\,H^{1/2}$

$h_n = H/[1+(\rho_0/\rho_F)^{1/3}]$

where:

$\dot{m}_a$ is the mass inward flow of air (kg/s)

A_w is the area of the opening (m^2)

H is the height of the opening (m)

h_n is the height of the neutral axis above sill level (m)

ρ_0 is the density of air at ambient temperature (kg/m^3)

ρ_F is the density of the gases within the enclosure (kg/m^3)

Approximate expressions for inward gas flow and height of the neutral axis taking account of volatiles produced within the enclosure:

$$\dot{m}_a = 2.1A_w H^{1/2}/[1+1.6(1+\dot{m}_b/\dot{m}_a)^{2/3}]^{3/2}$$

$$h_n = H/(1+[(1+\dot{m}_b/\dot{m}_a)/(\rho_F/\rho_0)^{1/2}]^{2/3})$$

where:

$\dot{m}_b$ is the rate of mass of volatiles produced in the enclosure (kg/s)

The mass loss from the enclosure due to venting hot gases is:

$$\dot{m}_F = \dot{m}_a + \dot{m}_b$$

Returning to the natural fire test described earlier in this section:

Following flashover there was a strongly ventilation-controlled burning regime with an average enclosure temperature of approximately 800°C. The burning rate of the cribs during this phase was estimated to be approximately 0.6 kg/s. Using the expressions that take account of the volatiles produced within the enclosure; the rate of inward airflow was calculated by iteration to be approximately 0.96 kg/s which, assuming a heat of combustion for air of 3 MJ/kg, would generate a Heat Release Rate (HRR) of 2.9 MW and the neutral axis would be approximately 0.38 m above sill level.

As the cribs were consumed, the burning rate reduced and the regime progressively transitioned to stoichiometric conditions. If the effects of the mass of volatiles generated on air flows into the enclosure are ignored the simplified equations can be used yielding an inward mass flow of air of 1.31 kg/s, equating to a HRR of 3.9 MW and a neutral axis approximately 0.45 m above sill level with an enclosure temperature of 1100°C.

If the mass burning rate of the timber cribs corresponding to stoichiometric conditions (approximately 0.23 kg/s) is applied, the inward mass flow of air is reduced to 1.18 kg/s which equates to a HRR of 3.5 MW and a neutral axis approximately 0.42 m above sill level.

The above results may have significance for enclosures with large areas of exposed Massive Timber where the mass released by pyrolysis of the timber within the enclosure can be high. In these circumstances enclosure temperatures may be significantly reduced but the mass of volatiles venting from the enclosure and burning externally will be increased presenting an increased risk of fire spread to adjacent buildings and the levels above the floor of fire origin.

This type of behaviour was demonstrated in a series of tests performed by Hakkarainen[57] that included tests with exposed timber used for all internal walls and the ceiling, and with the walls and ceilings protected with plasterboard. The enclosure temperatures were substantially lower for the exposed timber case. A simple energy balance analysis using methods similar to those described above indicated that the increased production of volatiles with exposed timber constrained the inward flow of air reducing the heat release rate within the enclosure.

3.6.4 Oxygen concentration and airflows

The oxygen concentration within enclosures during fully developed fires depends on the burning regimes. For ventilation-controlled fires and fires with close to stoichiometric conditions, the oxygen content is unlikely to exceed a few percentage points. Where a fire is fuel controlled (e.g. a large enclosure with low fire load) and during the decay and cooling phases, higher oxygen concentrations may occur.

Oxygen concentrations were not measured in the example natural fire test described in this section but the 'TF 2000' test series performed in the UK and reported by Lennon[78] provides a representative example. Throughout a natural fully developed fire experiment, oxygen concentrations were measured 200 mm below the ceiling level in the living area of a timber-frame residential building with plasterboard protection applied to timber elements. A schematic graph showing the variation between oxygen content and enclosure temperature with time from this test are shown in Figure 28.

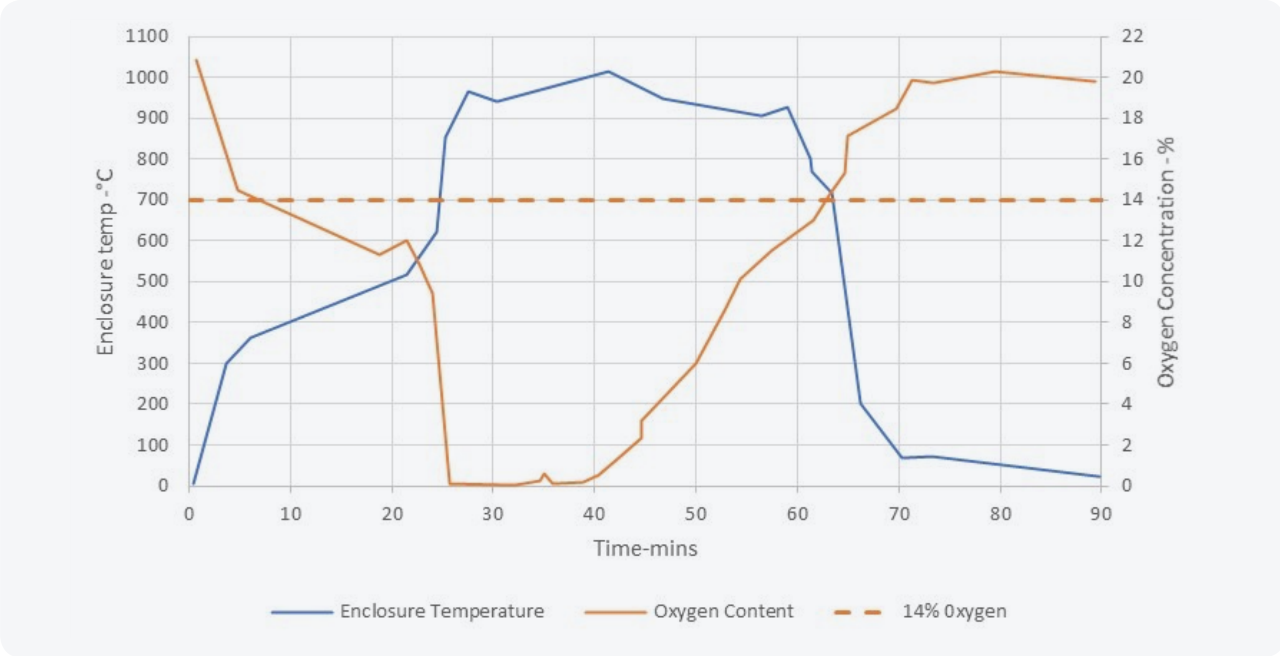


Figure 28: Schematic graph showing living room temperature and oxygen content from TF 2000 test. Modified from Lennon et al. (2000) – refer to Lennon et al for detailed plots.

The impact of oxygen concentrations and air flows has been investigated by Schmid[54] who concluded, among other things, that glowing combustion influences the char layer (char oxidation or contraction) for oxygen contents above about 15%. This is consistent with another study of calorimetric experiments by Jervis[79] where the critical oxygen limit for char oxidation was found to be approximately 14%.

The oxygen content measurements from the TF 2000 test (Figure 28) indicate that during the fully developed phase the oxygen level was below 14%, confirming that conditions that facilitate char oxidation are unlikely to occur while the burning regime is ventilation controlled.

Typically, the oxygen content within fire-resistance test furnaces is of the order of 4-8% although some furnaces with secondary air supplies may have a capability to vary oxygen concentrations. Some fire-resistance test standards nominate a minimum value for a furnace calibrated against a non-combustible specimen. For example, ISO 834 Part 1 Amendment 1 issued in 2012[47] requires a minimum oxygen content in the furnace atmosphere of 4% when testing specimens with no combustible content.

With exposed combustible materials, the oxygen concentration would be expected to decrease and fire exposure conditions within a fire-resistance furnace with respect to oxygen concentrations would be consistent with those occurring during a fully developed fire phase of a ventilation-controlled fire provided secondary air is not supplied.

During the decay and cooling phases, enclosure fires would be expected to transition to a fuel-controlled burning regime and oxygen concentrations within the enclosure would increase as demonstrated in Figure 28, which could facilitate flaming and/or smouldering combustion of exposed timber elements.

For further information relating to the applicability of fire-resistance tests to timber products, refer to:

- Technical note – Thermal exposure of wood in standard fire-resistance tests (Schmid[80])
- The use of furnace tests to describe real fires of timber structures (Schmid[51])
- Chapters 4 and 6 of this Guide.

3.6.5 Fire exposure from plumes venting through external openings

Introduction and reference materials

During the fully developed phase of a fire there is potential for volatiles to be vented through openings and burn outside the enclosure, potentially increasing the risk of fire spread between buildings and to the upper levels of multi-storey buildings as shown in Figure 29.

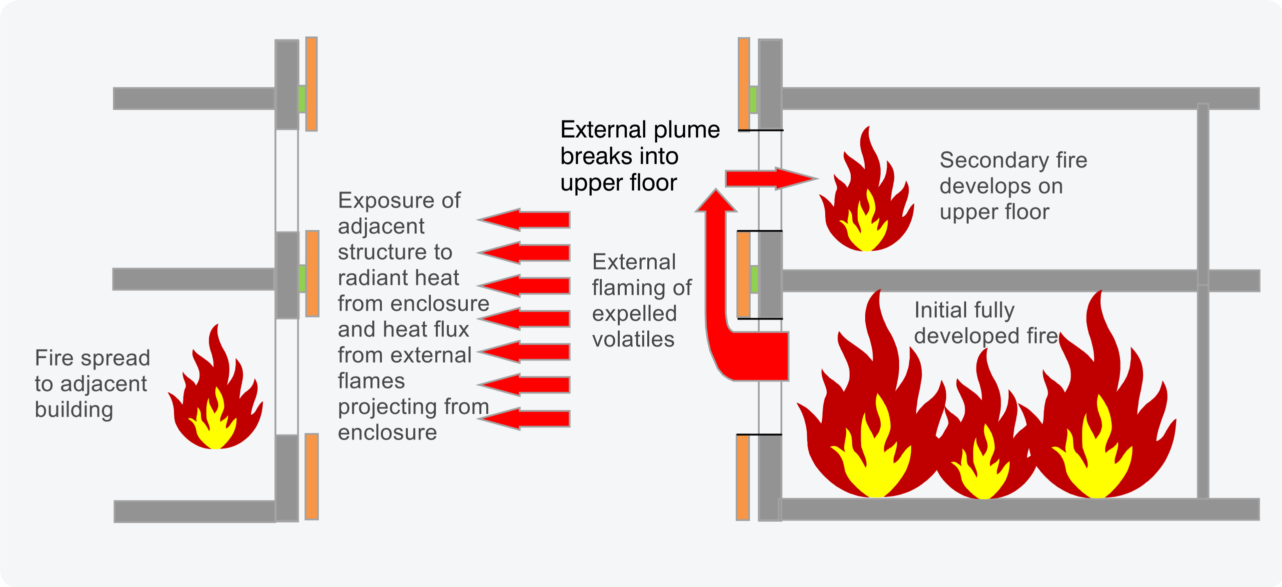


Figure 29: External fire spread involving vented volatiles from a fully developed fire.

These modes of external fire spread are managed by a number of NCC DTS measures including, specification of non-combustible construction or Fire-protected Timber construction for external walls, the prescription of minimum separation distances between buildings and prescription of automatic sprinklers or horizontal projections or vertical separations between openings.

Similar mitigation methods can be adopted for Performance Solutions but, depending on the scope of the Performance Solution and methods of analysis, it may be necessary to characterise the size, projection and temperature/heat flux from vented hot gases and flames in addition to the fire exposure within the fire compartment, taking into account any additional contribution from the facade if it is combustible.

Since the severity of external flaming is dependent on the amount of excess fuel expelled from the enclosure, the area of exposed timber in addition to the type and configuration of other combustible materials within the enclosure can have a significant effect. The potential for flame spread will also depend on the size and configuration of external openings and the proximity of openings on the floor above, among other things.

Various empirical correlations have been developed for determining the exposure of elements of construction to external plumes including:

- Law[81] and further codified in Annex B of Eurocode 1 Part 1-2[39]
- Quintiere and Cleary[82]
- Delichatsios[83].

Various zone and computational fluid dynamics models have capabilities to model fire plumes venting from openings. The extent of validation of the methods varies and should be considered when selecting the method. A useful summary of available correlations, models and comparison with experimental data is provided in BRANZ Study Report SR360[84].

In many instances it is useful to either use appropriate experimental data if available and/or validate model outputs, as far as practical, against experimental data before applying the results. Some of the natural fire experiments summarised in Appendix B included measurements to determine the facade exposure and further relevant information is provided in the following example and Section 4.4 of this Guide.

Test configurations, for example natural fire test

The burning regime in the FWPA test series[74] varied from strongly ventilation controlled through stoichiometric conditions to a fuel-controlled burning regime during the decay phase and provides comparative data of facade exposures under these regimes. The tests also demonstrated the potential impact of a 600 mm horizontal projection located 500 mm above an opening compared to a vertical facade.

Two tests were performed with test configurations similar to that required by ISO 13785-2 with the enclosures lined with fire-protective grade plasterboard protecting either timber studs or steel studs. The plasterboard facings remained intact and protected the framing. No appreciable differences in the performance of the walls and ceilings were noted during the test period.

The opening was 2 m wide x 1.2 m high and a plasterboard-faced facade was located above the opening with a return wall detail. One specimen had a straight facade (identified as the control) and the other a horizontal projection (identified as the balcony configuration). Further details of the test arrangement have been described previously in this section with further details provided in England and Eyre[74].

Observations from the two tests are provided in Table 19 supplemented by images from the test. The corresponding temperature measurements and heat fluxes are summarised in Table 20. Facade incident heat fluxes are plotted in Figure 30 and facade temperature exposures are plotted in the graphs in Table 21.

The results confirmed that during a strongly ventilation-controlled, fully developed burning regime, the flame extension and corresponding exposure of the facade above is substantially greater than a fire burning close to stoichiometric conditions, or a fuel-controlled regime, but maximum fire enclosure temperatures occurred when the burning conditions where close to stoichiometric. The results quantified the exposures and indicated that under the specific test conditions a vertical separation of 1 m to openings above would be unlikely to prevent fire spread to upper levels unless openings had some form of additional protection, e.g. one or a combination of horizontal projections, windows capable of resisting the fire exposure, or automatic sprinkler systems.

Table 19: Test observations of burning behaviour.

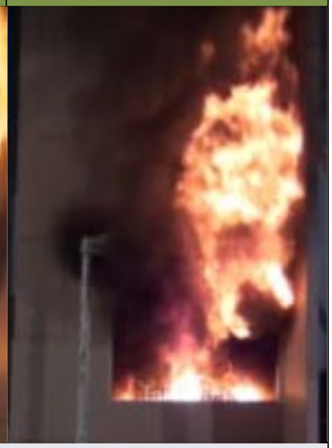
Control	Balcony	Control	Balcony
			
t = 2 min – Growth Phase		t = 10 min – Flashover transition to fully developed phase	
			
t = 15 min – Strongly ventilation-controlled regime		t = 35 min – approximate stoichiometric regime	
			
t=40 min decay phase – balcony removed ≈ 39 min		t=50 min decay phase – balcony removed	

Table 20: Temperatures and heat fluxes corresponding to observations of burning regimes from England and Eyre[74].

Test reference	*Test time (minutes)*	*Burning regime*	*Enclosure Temp (°C)*	*Heat flux 1.5 m above opening (kW/m²)*	*Heat flux 3 m above opening (kW/m²)*	*Temp 1.5 m above opening (°C)*	*Temp 3.0 m above opening (°C)*
Control	2	Growth (fuel controlled)	50	2	1	46	39
Balcony			67	1	1	53	24
Control	20	Strong vent controlled	813	104	43	1000	741
Balcony			831	67	15	639	461
Control	28	Vent controlled	1018	65	29	777	433
Balcony			1029	41	11	467	386
Control	35	Stoichiometric (approximate)	1090	30	18	636	417
Balcony			1088	13	5	312	313
Control	40	Decay phase (fuel controlled)	785	20	12	467	303
Balcony (removed)			763	17	5	420	262

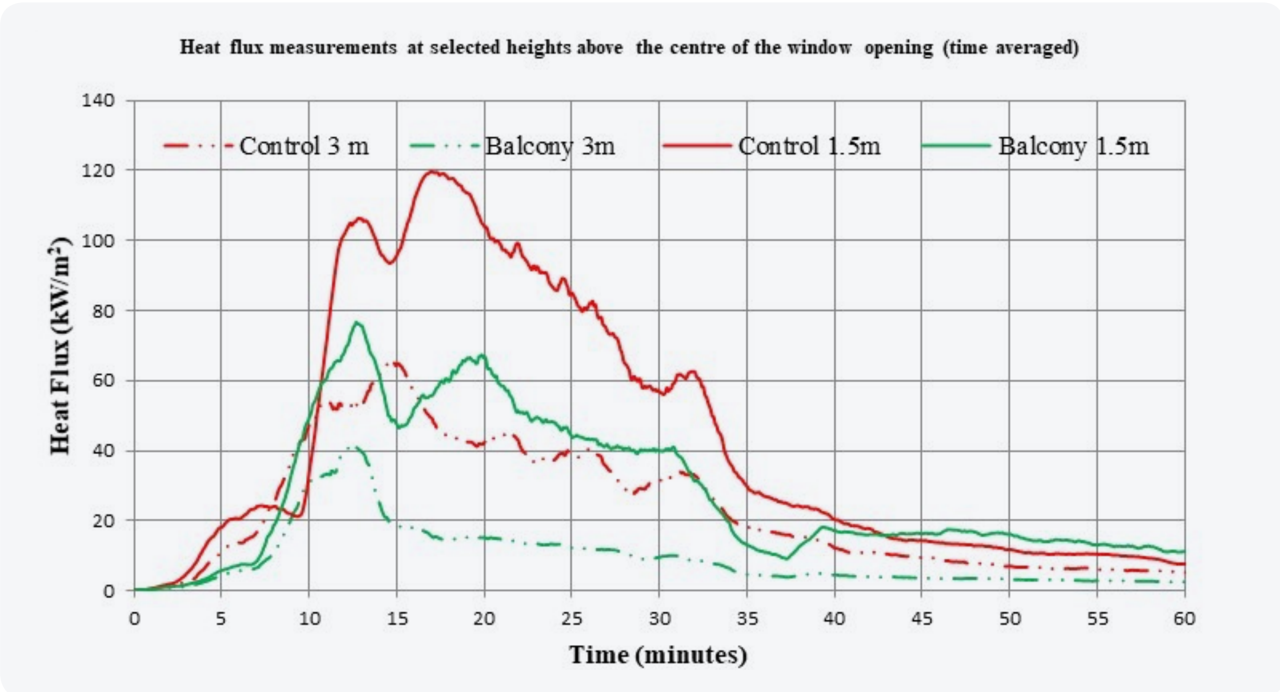


Figure 30: Facade incident heat flux at various heights above openings.

Table 21: Facade air temperatures at various heights above openings.

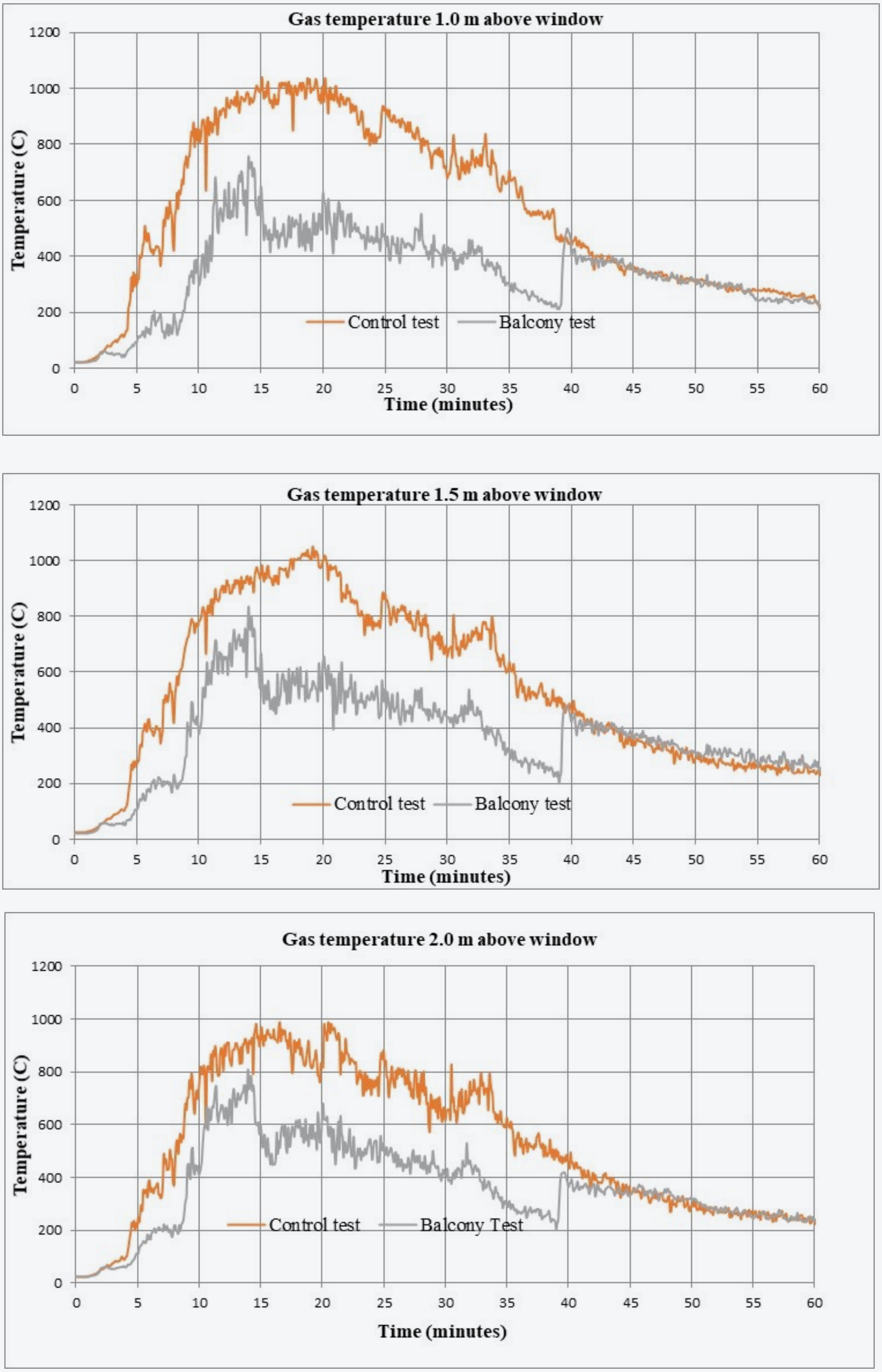
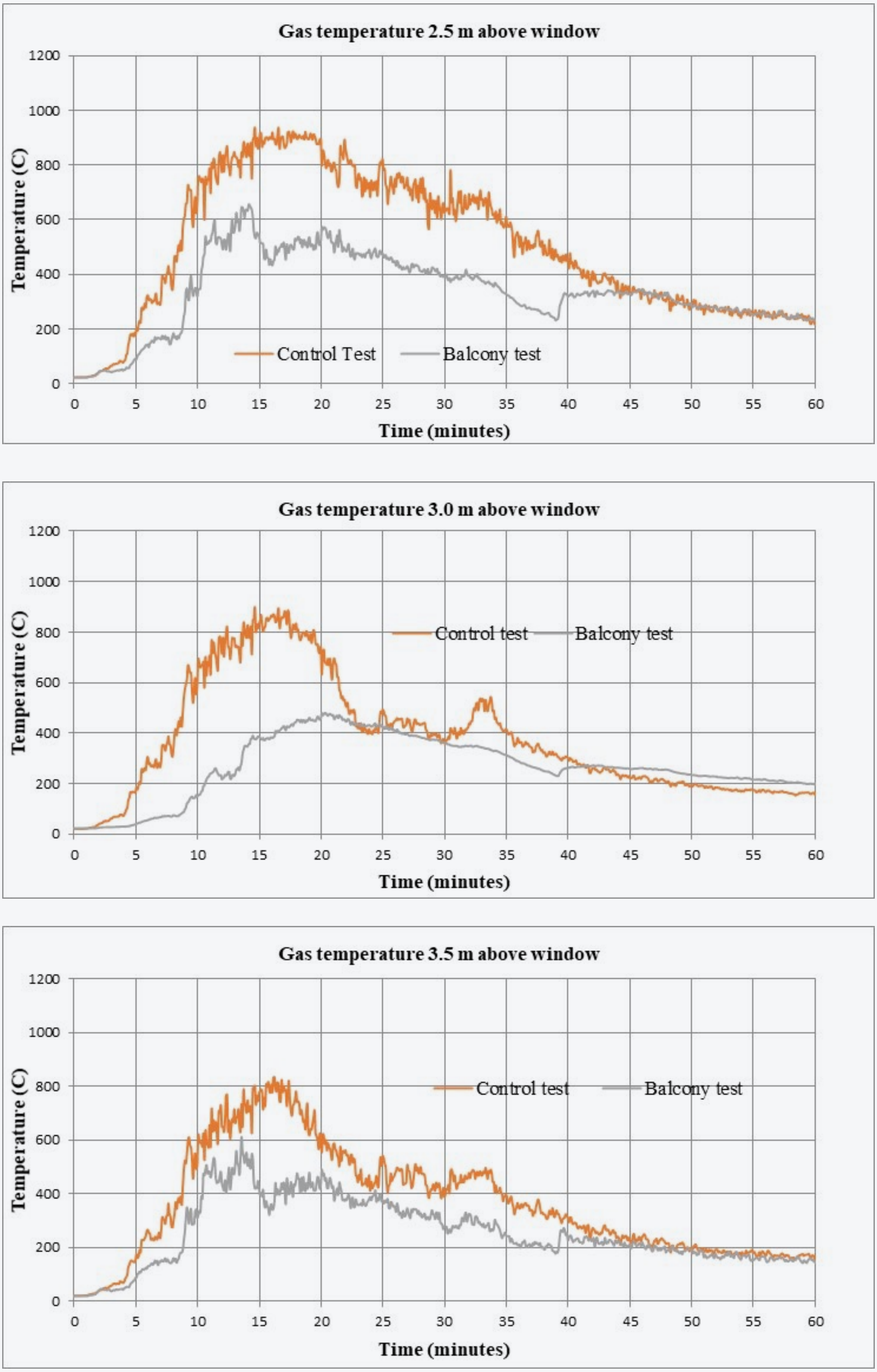


Table 21: Facade air temperatures at various heights above openings (continued).



3.7 Decay phase

Once the majority of the fire load is consumed the burning rate will reduce significantly leading to reduced enclosure temperatures. Often, arbitrary cooling rates are assumed but if timber elements are exposed more detailed consideration of the decay stage may be required to determine if exposed timber elements continue to burn and the likelihood of successful fire brigade intervention prior to further fire spread or structural collapse.

Care is needed if experimental data is being used as the basis for deriving the decay phase of a Design Fire; particularly if the moveable fire load has been simulated using liquid or gas fuels where the reduction in the Heat Release Rate (HRR) is unrealistically fast compared to typical contents in an occupied building. If timber cribs are constructed from sticks of the same cross-section, the HRR may also decay at an unrealistically fast rate.

Representative moveable fuel loads will include a mix of timber, plastics and natural fabrics with a range of densities and surface area to mass ratios. For example, a solid timber bookcase filled with books may continue burning after the rest of the moveable fire load has been consumed. In some instances, this may significantly prolong the flaming or smouldering combustion of timber elements of construction within the enclosure.

3.8 Cooling phase

Once the moveable load has been fully consumed and flaming combustion ceases, there may still be potential for the thermal wave to spread through an element due to its thermal inertia and/or for smouldering combustion of timber structural elements to continue. Under some circumstances a thermal wave can subsequently lead to structural collapse of common structural materials, such as timber, concrete and steel. The risks of smouldering combustion during the incipient phase is specific to char forming combustible materials and can also eventually lead to structural collapse or reignition of flaming combustion.

3.9 Automatic suppression systems

In Australia, the most likely automatic sprinkler system in timber buildings is a wet pipe automatic fire sprinkler system; although dry pipe systems may be used in the few areas where temperatures below freezing regularly occur (e.g. alpine areas/ski resorts).

Data Sheet C2 in the Annex to the NCC FSVM handbook[14] provides general estimates for the effectiveness of wet pipe sprinkler systems designed, installed, commissioned and maintained in accordance with the following standards as appropriate:

- AS 2118.1 Automatic fire sprinkler systems — General systems[85]
- AS 2118.4 Automatic fire sprinkler systems — Sprinkler protection for accommodation buildings not exceeding four storeys in height[86]
- AS 2118.6 Automatic fire sprinkler systems — Combined sprinkler and hydrant systems in multistorey buildings[87]
- AS 1851 – 2012 Routine service of fire protection systems and equipment. 2012, SAI Global: Sydney[88].

The estimates include typical values varying from 83% to 92% depending on the NCC Building Classes as well as low and high estimates. Data Sheet C2 provides further details on the values and basis of the derivation.

If a sprinkler system operates effectively, it is common to assume that flashover will be prevented even if a fire is controlled rather than automatically suppressed and that the exposure of fire-resistant elements of construction would not be sufficient to cause failure. The provision of an automatic sprinkler system will substantially reduce the frequency of severe fires and the occurrence of fully developed fires, greatly enhancing fire safety; but like all fire safety systems, the reliability and efficacy of automatic fire sprinkler systems are not 100%. It will also be necessary to evaluate the outcomes from scenarios where the sprinkler system fails, and greater reliance is placed on other precautions, such as fire-resistant construction in combination with fire brigade intervention and occupant response and evacuation as part of a risk assessment to develop a robust fire safety strategy.

The normal operational performance of automatic sprinkler systems with exposed timber elements has been successfully demonstrated in natural fire test programs with fires being controlled or suppressed during the early stages of the growth stages. Most of these tests have been undertaken with residential/hotel type contents. Some tests demonstrated the late application of water from sprinkler systems simulating scenarios where the water supply was initially isolated/unavailable, but the situation was subsequently rectified. Typical examples include Zelinka[89] (Appendix B.21) and Hox[90-92] (Appendix B.15).

3.10 Fire brigade intervention

In addition to undertaking search and rescue activities, the proportion of fully developed fires and the duration and severity of fires can also be reduced by fire brigade intervention; particularly if the fire brigade is alerted early, adequate fire brigade and equipment access is provided, and adequate water supplies and resources are available to safely fight the fire.

The AFAC Fire Brigade Intervention Model (FBIM)[93, 94] can be used to estimate time/probability distributions for fire suppression activities. It is important for estimates of fire brigade intervention to be developed in conjunction with the relevant fire authorities if a Performance Solution is being developed to enable local conditions and fire brigade capabilities to be addressed as well as building-specific details, such as building height and fire compartment size.

The risk of continuing flaming or smouldering combustion potentially leading to collapse is specific to timber structural elements and will need to be considered as part of a Performance Solution when timber is ignited during a fire scenario. Based on the work of Crielaard[31, 95] imposed heat fluxes above 5 to 6kW/m^2 are required to support smouldering combustion.

The AFAC Fire Brigade Intervention Model Manual[15, 93] states Fire Brigade personnel with full PPE and BA would be able to withstand an incident heat flux of 3 kW/m^2 for 10 min and 4-4.5 kW/m^2 for approximately 1 min.

For high-rise buildings where external fire attack and rescue may be impractical, a design objective for scenarios where both early fire brigade suppression and automatic suppression do not occur would be for the fire to enter the decay phase and general enclosure heat fluxes to be maintained below 5 kW/m^2 while the structure and fire-resistant barriers continue to perform their design functions.

For small enclosures, suppression activities could commence from outside the enclosure and the timing may be less sensitive to the heat flux within the enclosure if successful fire brigade intervention can be shown to be likely prior to structural failure or failure of fire barriers.

Indicative response times for Australian fire brigades are summarised in Table 22. Response times are the time from call receipt to attendance at the site. Further time will be required for set-up before firefighting and search and rescue activities can be undertaken, which can be estimated using the AFAC Fire Brigade Intervention Model[93, 94]. The number of fires in Australia to which the fire brigade does not respond is very small but notwithstanding this, fire brigade coverage and the likely response times should be confirmed with the relevant fire brigade during the PBDB process.

Table 22: Australian fire brigade response times from Report on Government Services 2021[96].

Percentile	Year	Response time (min)							
		NSW	Vic	Qld	WA	SA	Tas	ACT	NT
50	2019-20	7.8	6.9	8.1	9.3	8.0	9.1	7.5	8.4
	2018-19	7.6	6.6	8.1	9.7	8.0	8.5	7.1	8.0
90	2019-20	14.5	10.8	12.5	16.4	17.0	17.7	10.9	19.8
	2018-19	14.0	10.4	12.6	17.1	16.0	17.2	10.5	17.5

4 Exposed wood products and enclosure fire dynamics

4.1 Established uses of wood products within Australian buildings

4.1.1 Furniture and general building contents

The NCC and previous Australian State and Territory regulations placed few restrictions on the contents/furnishings of buildings except for a few specific applications; such as fixed seating in the audience area or an auditorium in Class 9b buildings used as a theatre, public hall or the like, which require a Spread-of-Flame Index of 0 and a Smoke-Developed Index not greater than 5 when tested in accordance with AS 1530.3.

Evidence of Suitability in the form of tests evaluating the flammability and smoke production rates of furniture is therefore not generally required under the NCC DTS Provisions. Application of performance criteria for furniture when following the Performance Solution pathway is difficult due, in part, to the limited availability of furniture that has been developed and tested for the intended applications.

There are few controls for materials, such as plastics and composites, that may present significant hazards due to their greater flammability and smoke production rates compared to materials such as timber.

Therefore, unless specific additional controls are prescribed and implemented as part of a Performance Solution, it is necessary to assume that the moveable fire loads within buildings are unregulated and the nature and magnitude of moveable fire loads within various occupancies will need to be based on surveys and statistical analysis to define appropriate distributions. Refer Section 4.4 for further information regarding moveable fire loads.

4.1.2 Wall linings, ceiling linings and floor coverings

The NCC DTS Solutions contain extensive provisions for wall and ceiling linings and floor coverings that are applied broadly throughout most buildings. The current framework for these applications in Australia was based on detailed research and led to the adoption of a first principles approach in the NCC based on the work of the Fire Code Reform Centre[97] (described in more detail in Section 4.4).

Wood products are suitable for many of these applications and are used extensively but where higher performance levels are required, fire-retardant treatments may be required.

The use of wood products for internal linings and coverings has been long established and permitted under the NCC DTS Provisions for many applications. For these applications it is reasonable to conclude, unless there is contrary evidence, that the NCC DTS Provisions account for the potential fire growth rates and impacts on the fire load of permitted combustible materials, including wood products used as lining materials. Reference should be made to the following Fire Code Reform Centre (FCRC) reports for further information and the discussion in the subsequent chapters of this Guide.

- FCRC – PR 98-02 Fire Performance of Wall and Ceiling Lining Materials Final Report – With Supplement, in FCRC Project 2 – Stage A Fire Performance of Materials. 1998, FCRC: Sydney[97].
- FCRC Project 2 B-1 Fire Performance of Floors and Floor Coverings, in FCRC Project 2 – Stage B Fire Performance of Materials. 1999, FCRC: Sydney[98].
- FCRC-PR 96-03 Fire Resistance and Non-Combustibility – Objectives & Performance Levels for Fire Resistance[99]
- FCRC-PR 01-02 Evaluation of Fire Resistance Levels: Techniques, Data Project Report and Results[100].

4.1.3 Attachments to wall and ceiling linings

Attachments to wall and ceiling linings are generally required by the NCC DTS Provisions to comply with Clause 7 of Specification C1.10, which requires other materials (including attachments) to achieve a Spread-of-Flame Index of 9 and Smoke-Developed Index of not more than 8 if the Spread-of-Flame Index is more than 5 when tested in accordance with AS 1530.3[101]. Many wood products satisfy these criteria.

AS 1530.3 was originally developed for evaluation of wall and ceiling linings but was broadly applied to other applications. When the recommendations of the FCRC for the adoption of the Group number method for wall and ceiling linings in the NCC were implemented, the use of AS 1530.3 for other applications was retained, notwithstanding the limited validity for these applications.

Therefore, the use of wood products for internal attachments is generally permitted under the NCC DTS Provisions but there are some limitations under the provisions, such as the prohibition of combustible attachments to the internal face if they form an integral part of an external wall, in addition to the external face, of external walls. Further advice is provided in relation to interpreting the requirements for external walls in ABCB Advisory Note 2020.2.3[102].

4.1.4 Fire resistant, structural and other elements required to be non-combustible.

For Type A and B construction (typically mid and high-rise construction), the NCC DTS Provisions place severe restrictions on the use of combustible materials for fire resistant elements and structural elements.

Concessions apply to mid-rise Fire-protected Timber and low-rise timber construction that permit the use of timber construction for these elements under the NCC DTS Provisions. Refer to the Introduction of this Guide for further information relating to these applications.

Where concessions are not available, for applications such as high-rise buildings, the Performance Solution pathway can be adopted if it is shown that the performance requirements have been satisfied.

When developing a Performance Solution, the moveable and fixed fire loads will need to be accounted for based on statistical analysis of survey results or comparison with NCC DTS provisions unless specific additional precautions are taken to limit these fire loads, in addition to the impact of any combustible structural and fire-resistant timber elements of construction.

4.2 Frequency of ignition

Based on the preceding discussion, there is unlikely to be significant variations to the moveable fire load and wall and ceiling linings that are permitted if the NCC DTS Provisions are applied. Therefore, within the occupied spaces it is unlikely that there would be an appreciable increase in the frequency of ignitions if wood products are used in a manner consistent with the NCC DTS Provisions.

In lightweight timber frame construction, the internal structure of walls/floors may include timber surfaces within concealed spaces/cavities. This configuration may increase the probability of the ignition of fires within cavities in addition to facilitating fire spread through concealed spaces unless adequate precautions are taken.

When undertaking the analysis to support the Fire-protected Timber concession for midrise buildings within the NCC, it was assumed that 0.8% of fires initiated in cavities based on a review of fire incident data from fires in single dwellings[12]. This was considered to be a conservative estimate and is an order of magnitude greater than the estimate of approximately 0.07% of fire starts from a detailed investigation of cavity fires undertaken as part of the TF 2000 project in the UK by Lavender[103].

Guidance is provided in the WoodSolutions Technical Design Guide series[4-6], for practical design measures to reduce the probability of ignition within cavities including selection of building services and materials, location of service runs, treatment of service penetrations in addition to building in use issues such as managing hot works.

4.3 Fire scenarios within concealed spaces

There are two main fire scenario clusters to consider for fires in concealed spaces:

- Fires initiating within the cavities that ignite combustible materials and spread through the cavity, potentially bypassing fire compartment boundaries.
- Flashover fires with sufficient intensity to penetrate the fire-protective linings and ignite the substrate. Once a timber element is ignited, fire can spread through the cavity, potentially bypassing fire compartment boundaries.

The TF 2000 analysis indicated that where the cavity construction material is the material first ignited or primarily responsible for fire growth and spread, the ignition mechanism is commonly attributable to the misuse of devices such as blow torches, paint strippers or other equipment generating similar levels of heat output or sparks. In most of these scenarios, it is likely that the fire will be seen at or close to the time of ignition. Although much less likely, another ignition risk is from electrical faults and overheating, which could develop without the knowledge of the occupants.

The other scenario cluster relates to fire spread occurring when the wall and ceiling system coverings are breached, which can be due to thermal penetration of the coverings at the position of unprotected service penetrations, joints and other unprotected openings.

Typical fire dynamics associated with cavity fires were demonstrated during the TF 2000 testing series on a mid-rise multi-storey timber-frame residential building when fire spread to a wall cavity and continued to develop and spread after a fully developed enclosure fire had been extinguished. Detailed observations and analysis from the test are provided by Lennon[104]. The following is a summary of the building configuration and key test observations:

- Steam was released from the hot structure after suppression of the apartment fire but, after approximately 2.5 hours, hot smoke was released from around the living room window and the fire brigade was called.

- Approximately 5.5 hours later, the fire was declared to be extinguished. The long period for suppression to occur can be explained by the difficulties identifying the seat of the fire and gaining access to apply water. Subsequently, deficiencies were identified with the installations of cavity barriers.
- The cavity fire occurred in an external wall, which comprised a timber frame with two layers of plasterboard lining the internal face; OSB sheathing and a breather membrane was attached to the opposite face of the frame. There was a cavity separating the timber frame from the external brick veneer of the wall. This arrangement presents an increased risk of fire spread because of the prescence of the combustible OSB sheathing within the cavity. OSB sheathing is only required if walls require bracing and OSB sheathing is the selected bracing method. At the base of the gable wall, where most of the vertical fire spread took place, the base of the cavity was open over a length of 4.8 m due to a previous structural test, which may have had a significant influence on vertical flame spread due to the additional ventilation.

The key events on the timeline are summarised below based on a review of Lennon[78,104,166] and Lavender[104]. These vary slightly from some reported times, due to difficulties cross-referencing different time scales.

t=0 min: Initial fire in apartment ignited.

t=64 min: Fire suppression in living area.

t=150 min: Temperature rise in cavity close to living room window.

t=221 min: Fire brigade called – temperature data indicates rapid fire growth within cavity of the flat above. Flaming observed from a timber window frame at approximately this stage.

t=261 min: Cavity temperature in the apartment above the apartment of fire origin peaks above 700°C. Temperature within the apartment above the apartment of fire origin peaks at less than 45°C.

t=262 min: Fire brigade withdraws from building because cracking of brick veneer observed.

t=266 min: The protection at the eaves is removed to access cavity – suppression activity occurs.

t=275 min: Additional window frames removed to provide access.

t=549 min: Fire brigade confirm fire under control.

The investigations concluded that the fire had spread from the wall-ceiling interface in the corner of the living area through timber studs and that the horizontal cavity barriers had not been installed effectively, allowing the fire to spread.

The fire spread from the fire floor through the floor above, effectively removing the loadbearing capacity of the external walls at these locations. After this severe incident, with spread occurring without effective intervention for several hours, the temperature rise within the flat above was of the order of 20°C and damage was restricted to the cavity, so the impact on life safety would be expected to be minimal, provided there was no disproportionate collapse.

The level of damage was considered representative of severe scenarios where: ignition occurs within a cavity; the fire grows without being constrained by lack of oxygen, non-combustible insulation or fire sprinklers within the cavity; and the cavity barriers fail, allowing spread to an adjoining element.

The NCC performance requirement BP1.1 requires a structure “to be designed to sustain local damage, with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage”, among other things. Refer to WoodSolutions Technical Design Guide 39 Robustness in Structures[105] for further information on structural design to meet these requirements.

4.4 Enclosure fires scenarios

This section focuses on the fire dynamics associated with enclosure fires where a fire progresses through all the fire phases, highlighting variations between enclosures with non-combustible bounding construction and structural elements and enclosures where some or all of the bounding construction and structure includes timber or combustible elements of construction that may become involved in a fire.

4.4.1 Incipient and growth phases

During the incipient spread and early part of the growth phase, if the fire is not close to combustible walls (i.e. involving the moveable fire load only) the fire dynamics will be similar for enclosures with combustible and non-combustible bounding construction (including internal linings).

If the fire is close to combustible wall linings there may be an interaction potentially accelerating transition from the incipient to growth phase and subsequently accelerating the rate of growth.

As the growth continues the potential for involvement of combustible ceiling linings also increases.

An accelerated growth rate may decrease the time to untenable conditions and the time to flashover, if it occurs. The probability of flashover may also increase where the combustible linings contribute to the heat release rate during the growth phase. These outcomes may increase the fire hazard.

The potential impact of combustible linings with varying fire hazard properties can be demonstrated by reviewing the NCC classification criteria for wall and ceiling linings. The primary basis for classification is the time to flashover in a test performed in accordance with ISO 9705[106] and the technical basis underpinning the selection of the method and criteria is provided in Fire Code Reform Centre – Fire Performance of Wall and Ceiling Lining Materials Final Report – With Supplement, FCRC Project 2 – Stage A Fire Performance of Materials[97].

Note: Cone calorimeter tests may be used in lieu of the determination of the time to flashover in an AS 9705 test where adequate correlations are available (refer AS 5637[107] for further details).

To determine a time to flashover and the smoke growth rate, using the ISO 9705 test method, the lining material/system is fitted to the walls and ceiling of a test room 2.4 m high x 2.4 m wide x 3.6 m long and a heat source is a gas burner located in the corner of the room. Wall and ceiling linings are assigned a Group number based on the time to flashover as follows, with additional smoke criteria being applied if buildings are not protected by a nominated fire sprinkler system:

- Group 1: Materials do not reach flashover when exposed to 100 kW for 600s followed by exposure to 300 kW for 600 s.
- Group 2: Materials reach flashover following exposure to 300 kW within 600s after not reaching flashover when exposed to 100 kW for 600s.
- Group 3: Materials reach flashover in more than 120 s but within 600 s when exposed to 100 kW.
- Group 4: Materials reach flashover within 120 s when exposed to 100 kW.

Many common wood products achieve Group 3 performance with either a Smoke Growth Rate Index ($SMORGA_{RC}$) less than 100 or an Average Specific Extinction Area (ASEA) less than 250 m^2/kg although a Group Number of 2 can be attained with appropriate fire-retardant treatments. Refer to the WoodSolutions website (www.woodsolutions.com.au/articles/fire-test-reports) for further information including Evidence of Suitability.

The FCRC report[97] indicates that the 100 kW burner output simulates a burning wastepaper basket and the 300 kW output is the equivalent to an upholstered chair.

The FCRC report also compared the results of ISO 9705 tests with fire experiments undertaken in larger rooms from the EUREFIC projects[108, 109] to determine whether there were scaling effects that could limit the usefulness of data obtained in the ISO Room Fire Tests and included the comparative data summarised in Table 23.

Table 23: Comparative data of time to flashover derived from FCRC report[97].

Property	ISO 9705 room	Large room
Room dimensions W x L x H	2.4 m x 3.6 m x 2.4 m	6.7 m x 9.0 m x 4.9 m
Door opening dimensions	0.8 m x 2.0 m	2.0 m x 2.0 m
Gas burner output – increments at 10 min intervals	100/300 kW	100/300/900 kW
Lining materials applied to walls and ceiling	Time to Flashover (seconds)	
Combustible-faced mineral wool	96	1300
Ordinary birch plywood	146	1170
PVC wall carpet on gypsum board	612	N
Textile wall covering on gypsum board	630	N
Fire-retardant treated particleboard type	934	N

The report concluded that the experiments in the larger room produced less severe exposure than the standard ISO 9705 Room Fire Test with only those materials that went to flashover at 100 kW in the ISO room went to flashover in the larger room, and then only when the gas burner had been raised to 300 kW or 900 kW. It was therefore determined that:

- in the presence of minimal contents, represented by the gas burner, flashover due to wall and ceiling linings is less likely in large rooms
- the ISO 9705 test, which is conducted in a small room, gives a conservative assessment of the hazard of wall and ceiling linings.

The NCC DTS Provisions specify the required Group, depending on the location within a building, class of building and presence of a nominated sprinkler system (summarised in Table 24). Group 4 wall and ceiling linings are not permitted under the DTS Provisions. A review of the requirements in Table 24 for buildings not protected by automatic sprinklers, highlights the DTS Solution emphasis on limiting fire spread through fire-isolated passageways (Group 1 specified) and public corridors (Group 1 required for health-care buildings, accommodation for vulnerable occupants and class 9b buildings other than schools and Group 1 or 2 for other occupancies). Except for some nominated specific areas Group 3 materials can be used throughout other areas (i.e. the use of many wood products without fire retardant treatments is permitted for wall and ceiling linings for some applications in buildings that are not protected by automatic fire sprinklers).

The NCC DTS requirements in Table 24 for sprinkler-protected buildings demonstrate the application of the holistic approach to fire safety adopted by the NCC with the use of Group 3 lining materials being extended to all the nominated specific areas and public corridors in all classes except for health-care buildings, accommodation for vulnerable occupants, and class 9b buildings other than schools.

Table 24: NCC DTS requirements from wall and ceiling linings (derived from NCC Specification C1.10 Table 4).

Class of building	Fire-isolated exits and fire control rooms	Public corridors	Specific areas	Other areas
Buildings protected by a sprinkler system (other than a FPAA101D and FPAA 101H system) complying with Specification E1.5				
Class 2 or 3, Excluding accommodation for the aged, people with disabilities, and children	Walls: 1 Ceilings: 1	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 5, 6, 7, 8 or 9b schools	Walls: 1 Ceilings: 1	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 3 or 9a, Accommodation for the aged, people with a disability, children, and health-care buildings	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 9b other than schools	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 9c	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Unsprinklered buildings (and buildings provided with a FPAA101D and FPAA 101H sprinkler systems) Note: For this group of buildings the following smoke production criteria apply in addition to the Group Number: (i) a smoke growth rate index not more than 100; or (ii) an average specific extinction area less than 250 m2/ kg.				
Class 2 or 3, Excluding accommodation for the aged, people with disabilities, and children	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 5, 6, 7, 8 or 9b schools	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 3 or 9a, Accommodation for the aged, people with a disability, children, and health-care buildings	Walls: 1 Ceilings: 1	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3
Class 9b other than schools	Walls: 1 Ceilings: 1	Walls: 1 Ceilings: 1	Walls: 1, 2 Ceilings: 1, 2	Walls: 1, 2, 3 Ceilings: 1, 2, 3
'Specific areas' means within the following areas: Class 2 and 3 buildings, a sole-occupancy unit Class 5 buildings, open plan offices with a minimum floor dimension/floor to ceiling height ratio >5 Class 6 buildings, shops or other building with a minimum floor dimension/floor to ceiling height ratio >5 Class 9a health-care buildings, patient care areas Class 9b theatres and halls, etc, an auditorium Class 9b schools, a classroom Class 9c buildings, resident use area.				

4.4.2 Characteristics of moveable fire loads

Many fire experiments evaluating the fully developed phase have been performed with the following simulated fire sources:

- gas burners
- pool fires
- timber crib fires.

A key feature of these fuel sources is that the pyrolysis/gas supply rates can be predicted with some confidence and the simulated fuel load is often distributed uniformly within the enclosure. When the fuel is consumed, or fuel supply turned off, the decay rate may be unrealistically fast.

Typical moveable fire loads comprise a mix of materials, of varying thicknesses and orientations, which will cause pyrolysis rates to vary through the enclosure. Materials such as some plastics with a low heat of gasification will be quickly consumed while the pyrolysis rate of materials such as timber will be slower. As a fire enters the decay phase the remaining fire load is unlikely to burn uniformly and there will be areas within the enclosure where localised fuel concentrations remain high while there is minimal contribution from the moveable load in other areas. Burning debris may be unevenly distributed over the floor as the moveable load components collapse, further contributing to uneven heating of the walls and ceiling.

This behaviour may have a significant influence on the decay phase and the potential for fixed fire loads to transition to smouldering combustion and subsequently self-extinguish or for regrowth to occur. For example, if isolated fuel packages continue to burn close to combustible structural elements, the net heat flux at the surface of the structural element may be sufficient to maintain localised combustion of the element initiating regrowth of the fire.

A number of the test programs listed in Appendix B included non-combustible or fully encapsulated plasterboard-lined enclosures with typical furnishings as the moveable fire load. Enclosure temperatures from these tests have been plotted in Figure 31.

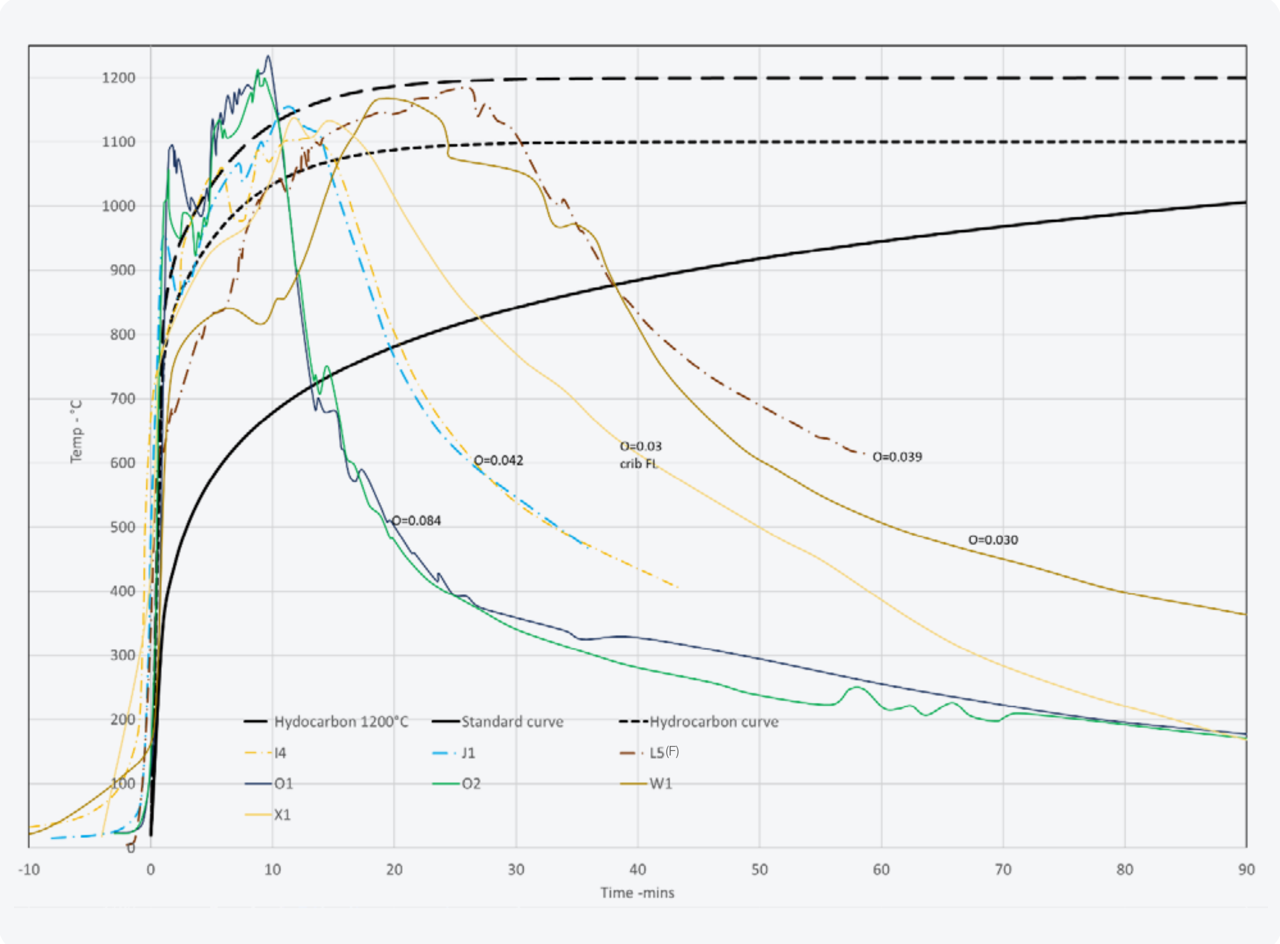


Figure 31: Typical fire test enclosure temperatures from natural fire tests with no contribution from the enclosure perimeter walls and ceiling.

Tests O1 and O2 were similar enclosure configurations with the same opening factors (0.084 $m^{1/2}$) and similar fire loads (570-601 MJ/m^2) comprising furnishings with similar distributions.

Tests I4 and J1 were similar enclosure configurations with the same opening factors (0.042 $m^{1/2}$) and similar fire loads (553-614 MJ/m^2) comprising furnishings with similar distributions.

In both comparisons good repeatability was demonstrated.

Test L5(F) had an opening factor of 0.039 $m^{1/2}$, slightly lower than Tests I4 and J1 and a significantly higher fire load due to the inclusion of combustible flooring of 976 MJ/m^2, which may explain the longer duration of the fully developed phase.

Two cases were provided for comparison with opening factors of 0.030 $m^{1/2}$ with the same magnitude of fire load (550 MJ/m^2) but a timber crib was used in Test X1 and furnishings, combustible flooring and plasterboard paper made up the fire load in test W1. The enclosure temperatures and profiles varied considerably between the test with a timber crib and furnishings, with the furnishing fire load exhibiting a longer burning duration than the timber crib test. The duration of burning and rate of heat release rate from timber cribs is influenced by the stick sizes and crib configuration. For test X1 the stick sizes were 38 mm x 89 mm.

This highlights the importance of considering the burning behaviour and distribution of fire loads as well as simply the total energy content, especially when directly applying tests.

The above tests were performed with the bounding construction predominately having a relatively low thermal inertia. High thermal inertia boundaries (e.g. normal weight concrete) will tend to store more heat, some of which will tend to be released back to the fire enclosure potentially extending the duration of the decay and cooling phases.

4.4.3 Fire exposure during fully developed phase

Fire duration and maximum enclosure temperature

Many fully developed fire models assume a ventilation-controlled fire burning under stoichiometric conditions which in effect means that all fuel is consumed within the enclosure. This can lead to substantial over prediction of the burning time for the moveable fire load within enclosures. This is a well-known limitation but since this approach yields conservative results, within the fire enclosure, it use remains appropriate for many applications.

The potential magnitude of the over-prediction for a fire that was initially strongly ventilation controlled has been demonstrated in numerous natural fire test including the tests performed for the FWPA to support the Fire-protected Timber NCC DTS Solutions where natural fire test enclosure temperatures were compared with Eurocode 1 Part 1-2 Annex 1 method (see Figure 32). The fire load comprised timber cribs only, simulating the moveable fire load with no significant contribution from the structure or linings.

Assuming the fully developed stage of the fire commences when the enclosure temperature exceeds 600°C, and the transition to the decay phase commences at approximately 800°C, then the experimental fully developed fire duration can be estimated to be approximately 32 min while the calculated duration using the Eurocode method was approximately 64 min.

Figure 32 indicates that similar peak temperatures occurred in the natural fire tests (approximately 1130°C), compared to the peak temperature predicted by the Eurocode method (approximately 1140°C), but, prior to the peak temperature, the experimental test enclosure temperatures were significantly below the temperatures predicted by the Eurocode parametric curve for approximately 15 min. This can be explained by considering the efficiency of combustion, which peaks at conditions close to stoichiometric. Excess volatiles were produced in the natural fire tests, lowering the neutral axis and reducing air inflow at the same time as substantial combustion of excess volatiles occurred outside the enclosure, explaining the lower enclosure temperatures compared to the Eurocode parametric curve. As the natural fire experiments progressed and fuel was consumed the pyrolysis rate reduced until the enclosure environment approximated to stoichiometric conditions between 30 min and 35 min of the test, yielding a peak temperature as shown in Figure 32 before progressing to the decay phase.

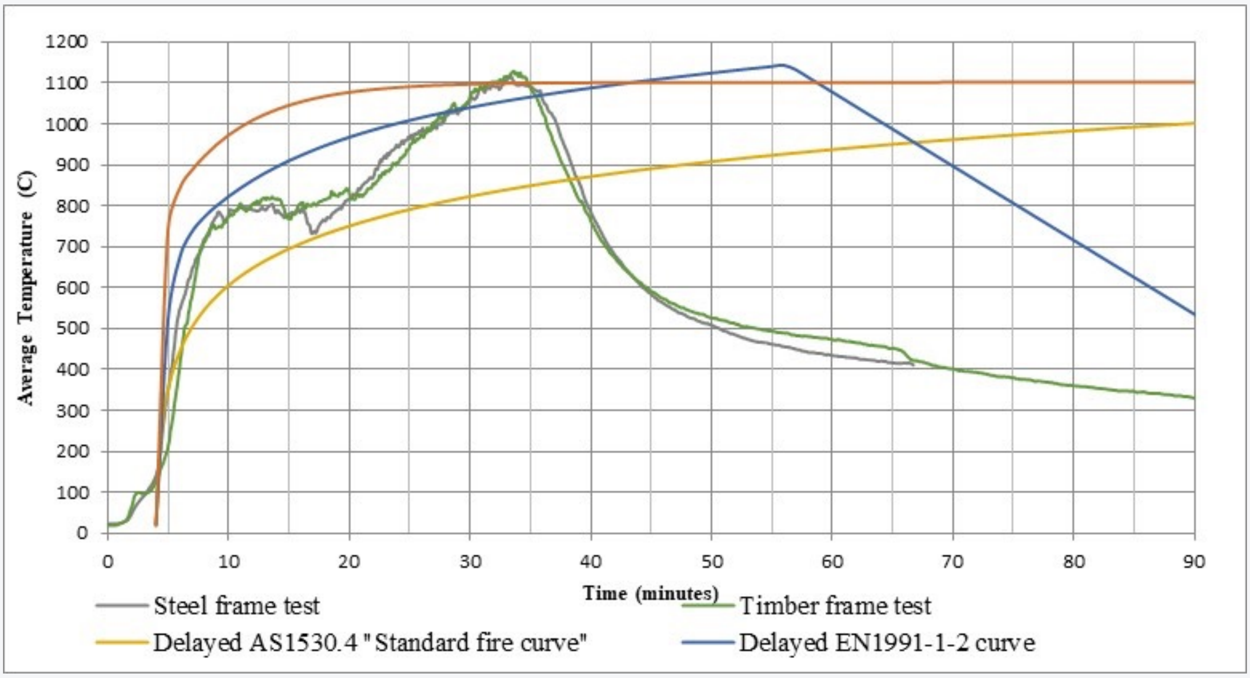


Figure 32: Natural fire enclosure temperatures compared to AS 1530.4 standard, hydrocarbon heating regimes and a parametric curve calculated in accordance with EN1991-1-2 Annex A from England and Eyre[73].

These results highlight a limitation of comparing fire severity only on the basis of the maximum enclosure temperatures or fire duration. The impact of the time/temperature (or heat flux) history needs to be considered when comparing fire severities.

In applications where timber structure and/or lining materials contribute to the fire severity, the potential for strongly ventilation-controlled fires will be increased. The net impact of this will usually be to increase the duration of the fully developed phase of the fire and the decay phase. The impact on enclosure temperatures will depend on the enclosure ventilation conditions because the additional fuel may increase or decrease the energy released within the enclosure depending on the extent of excess fuel produced, which will impact on the combustion efficiency.

Since the pyrolysis rate is a function of the surface area of combustible materials and the imposed heat flux, if the surface area of exposed wood elements of construction is substantial, the pyrolysis rate may be sufficient to maintain the fully developed phase after the moveable fire load has been consumed. But, where the exposed area of timber is limited to, for example, a single wall or ceiling and the geometry is favourable (minimising heat interchange between surfaces) the fire may progress to the decay phase and flaming combustion may transition to smouldering combustion, facilitating safe fire brigade intervention.

Ventilation conditions

The impact of ventilation on the fire severity of an enclosure fire with large areas of exposed timber was demonstrated in the fire safe implementation of visible mass timber test series reported by Brandon[43]. A series of five tests with exposed CLT ceilings, with different configurations of exposed CLT walls, was undertaken with representative residential contents and furnishings making up a moveable fire load of 560 MJ/m^2 for each test. Four tests were undertaken with an opening factor of 0.062 m$^{1/2}$ with areas of exposed CLT varying from 53.8 m^2 to 97.2 m^2. The fifth test configuration had an opening factor of 0.25 m$^{1/2}$ and 77.9 m^2 of exposed CLT surfaces (the difference in exposed area compared to the other tests in the series with more than 90 m^2 exposed area was due to the larger area of external walls with openings).

The enclosure temperatures with time offsets to align the fully developed phases are plotted against time in Figure 33 for a total period of more than 160 min in which the plasterboard coverings effectively prevented contributions from protected areas.

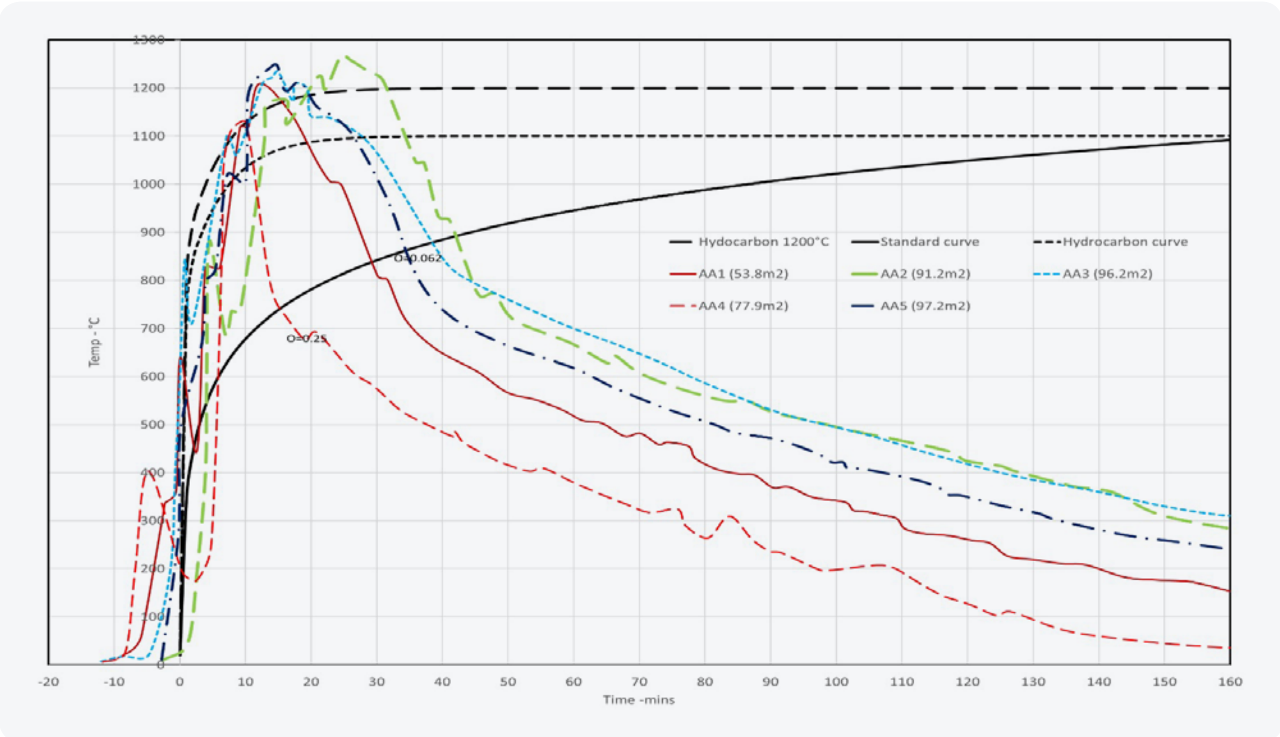


Figure 33: Enclosure temperatures from the fire safe implementation of visible mass timber test series derived from results reported by Brandon[40].

Figure 33 shows that the fully developed fire phase for a configuration with large opening area (AA4) was approximately 5 min compared to the range of 22-31 min with the smaller opening area tests. Enclosure temperatures also reduced faster during the decay/cooling phases.

This demonstrates the critical impact ventilation and the assumed ventilation openings can have on outcomes.
The probability and timing of breakage of glass in glazed openings could significantly impact the fire severity and requires detailed consideration. Where data on the performance of glazing systems is limited, a practical option may be to undertaken a sensitivity analysis covering the range of potential opening sizes that could occur.

Influence of thermal properties bounding construction

The thermal properties of the boundaries to a fire compartment can have a significant impact on the temperatures generated in the fully developed phase of a fire. The potential variations resulting only from variations in the thermal inertia of the boundaries (kρc) and thickness of multilayer systems has been demonstrated using the parametric temperature time curves of Annex A Eurocode 1 Part 1-2[39]. Table 25 summarises typical input values for various common materials used in the comparison and the results for an enclosure with an opening factor of 0.062 $m^{1/2}$ and assumed fire load density of 560 MJ/m^2 of floor area are plotted in Figure 34. This analysis only considers the energy released from the nominated fire load density and does not consider any additional contributions from exposed timber elements.

Table 25: Materials properties used for comparative analysis of impact of bounding construction using parametric time/temperature curves from Annex A Eurocode 1 Part 1-2.

Material	Thermal Conductivity (k) (W/mK)	Density (ρ) (kg/m^3)	Specific Heat (c) (J/kgK)	b=√(kρc) ($J/m^2s^{1/2}$ K)	Source/comment
Normal weight concrete	1.8	2,300	940	1,973	England et al[110.] (Similar to Buchanan and Abu[17] value of b = 1900)
Autoclaved aerated concrete	0.16	450	1,505	329	Kirby[111]
Plasterboard	0.24	900	1,250	520	Kirby[111]
Wood	0.14	470	1,700	334	Hakkarainen[57]

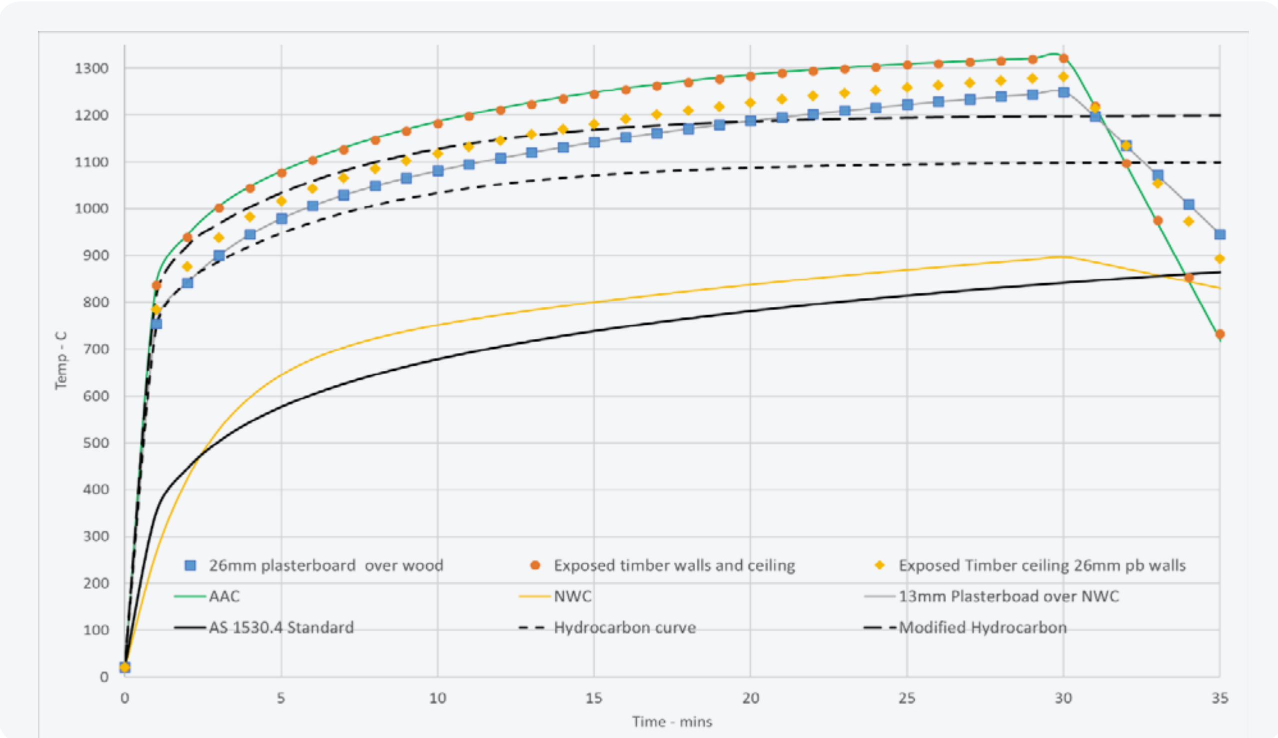


Figure 34: Comparative analysis of impact of the thermal properties of bounding construction using parametric time/temperature curves from Annex A Eurocode 1 Part 1-2.

Since the thermal inertia of wood and autoclaved aerated concrete are similar, the generated time-temperature curves are comparable, as expected, and, since the thermal inertias are low, heat losses through the boundaries will be low and the highest enclosure temperatures result.

The thermal inertia of normal weight concrete is many times greater than AAC, wood and plasterboard and therefore, with exposed normal weight concrete, substantially lower enclosures are predicted that are comparable to the standard heating regime. However, if both timber and normal weight concrete walls are faced with plasterboard, comparable results are achieved that are much closer to the exposed AAC and wood results than those obtained with normal weight concrete.

A common CLT configuration is to expose a CLT ceiling as an architectural feature and apply plasterboard to the walls. This combination yields a time/temperature curve between AAC and plasterboard-lined enclosures and, like many modern enclosure boundaries, provides a low thermal inertia.

From Figure 34, a fully developed fire in an enclosure with bounding construction having a low thermal inertia is likely to generate enclosure temperatures more closely aligned to the modified hydrocarbon heating regime peaking at 1200°C than the standard AS 1530.4 heating regime for the typical conditions analysed. Conversely, the duration of the decay and cooling phases are likely to be reduced in enclosures having low thermal inertia boundaries compared to high thermal inertia boundaries. Ventilation conditions, fire load characteristics and combustion efficiency can further influence the enclosure time/temperature curves.

Exposure of facades and adjacent buildings from enclosure fires

The additional volatiles produced by exposed wood elements in an enclosure fire will potentially increase the mass of unburnt fuel expelled through ventilation openings, especially for enclosure configurations that produce a ventilation-controlled burning regime with a contribution from the moveable fire load if the fixed fire load is ignored. The volatiles in the fire plume expelled from the compartment will burn as air is entrained into the plume potentially exposing the external facade to significant heat fluxes with potential to initiate spread between floors.

Generally, the NCC DTS Provisions (Clause C2.6 Vertical separation of openings in external walls) manage this risk through the provision of automatic fire sprinkler systems which primarily reduce the probability of fully developed fires occurring, or if sprinkler systems are not provided, the use of horizontal projections or spandrels separating openings in external walls.

If separation of external openings is the selected mitigation measure to manage the risk of fire spread between levels of the building, as the mass of volatiles expelled from an enclosure fire increases the flame is likely to increase in length and intensity, which increases the risk of fire spread. The minimum transom height of 0.9 m prescribed in the NCC is generally less effective than the 1.1 m horizontal projection option.

Some of the natural fire test series summarised in Appendix B incorporated instrumented facades to quantify the potential exposure. An example is Series AA Fire Safe Implementation of Visible Mass Timber in Tall Buildings. Enclosure temperatures from this series are plotted against time in Figure 33 and details of the facade component of the test were reported by Sjöström et al[112] from which the external facade plate thermometer temperatures and thermocouple temperatures shown in Figure 35 and Figure 36 have been extracted. The key test parameters are summarised in Table 26. Corresponding measurements were included by Sjöström from tests that adopted the BS 8414 test method crib and vent opening dimension.

The AS 1530.4 standard heating regime has also been plotted on the graphs in Figures 35 and 36.

Some relevant observations are:

- There was a large difference between temperatures measured by the plate thermometer and standard thermocouples, which could be attributed, at least in part, to the radiative heat component in the plume.
- The temperatures measured 1.0 m or more above the opening exceeded the standard AS 1530.4 heating regime for between 10 min and 25 min for the residential configurations tested depending on ventilation conditions and temperature measurement method. There would, therefore, be a high probability that non-fire resistant glazing/wall systems would fail under these exposures.
- The BS8414 fire exposure is broadly comparable to the exposures measured for the residential configurations with exposed timber in the fire enclosure. This is significant since verification method CV3 in the NCC, which applies to Performance Solutions for combustible external facades, requires external wall systems to achieve the classification EW in accordance with AS 5113, which adopts the use of BS 8414 exposure conditions to determine, among other things, compliance with the EW classification.
- Tests 2, 3 and 5 had the largest surface area of exposed wood structural elements, attained the highest heat release over the fully developed phase and imposed higher heat fluxes on the facade than tests 1 and 4.
- Test 1 with a lower exposed timber surface area achieved slightly lower peak temperatures/heat fluxes compared to Tests 2, 3 and 5 and the duration of exposure was reduced.
- Test 4 with substantially higher ventilation briefly achieved an initial peak with the exposure reducing rapidly over 10 min, presenting a substantially reduced risk of fire spread to the upper level.

Table 26: Summary of fire-safe implementation of visible mass timber in tall buildings test parameters.

Component	Test 1	Test 2	Test 3	Test 4	Test 5
Vent area (m^2)	8.0	8.0	8.0	31.2	8.0
Opening factor ($m^{1/2}$)	0.062	0.062	0.062	0.25	0.062
Exposed CLT Area (m^2)	53.8	91.2	96.2	77.9	97.2 m^2
Full developed phase duration (min)	22	28	31	5	30
Total heat release from structure and floor (GJ) during flashover phase	29 ± 5	47 ± 5	44 ± 5	26 ± 5	44 ± 5

Note: Representative residential contents and furnishings were used with a moveable fire load density of 560 MJ/m^2.

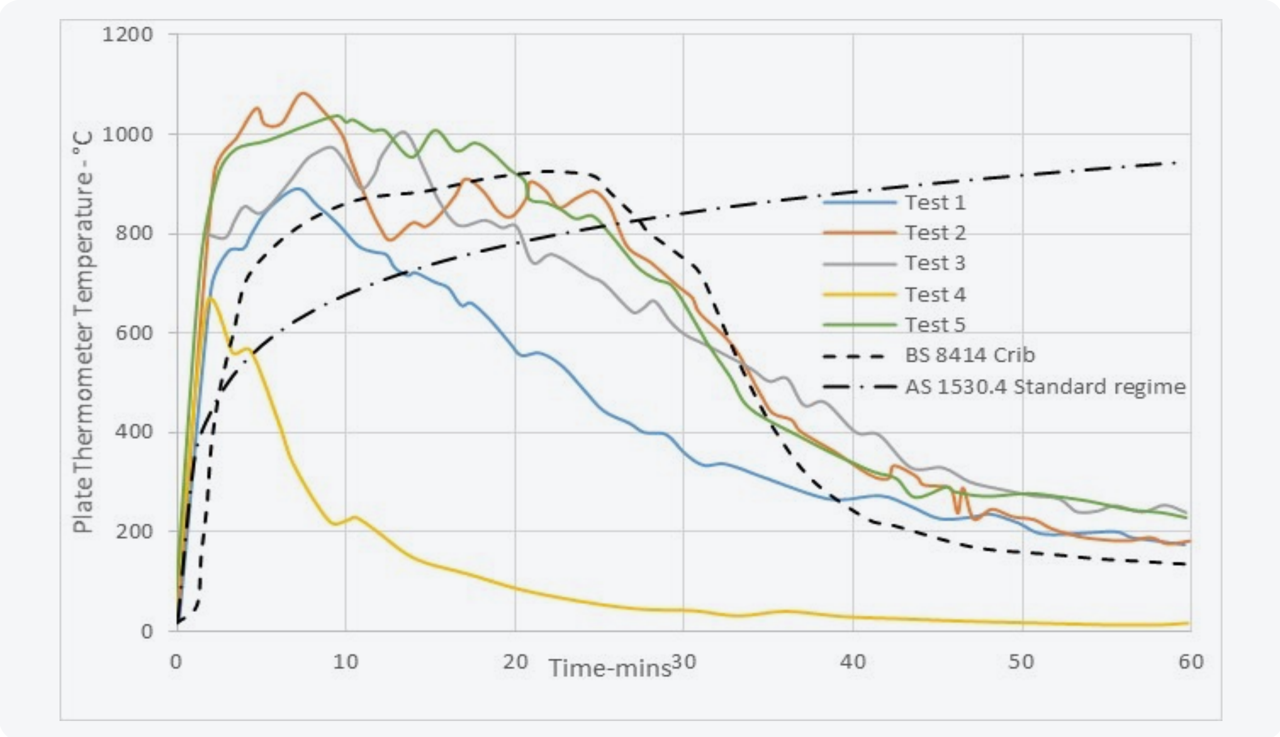


Figure 35: Facade plate thermometer temperatures measured 1.25 m above the opening compared to temperatures measured 1 m above the opening in a BS 8414 crib/opening configuration. Derived from Sjöström et al [112].

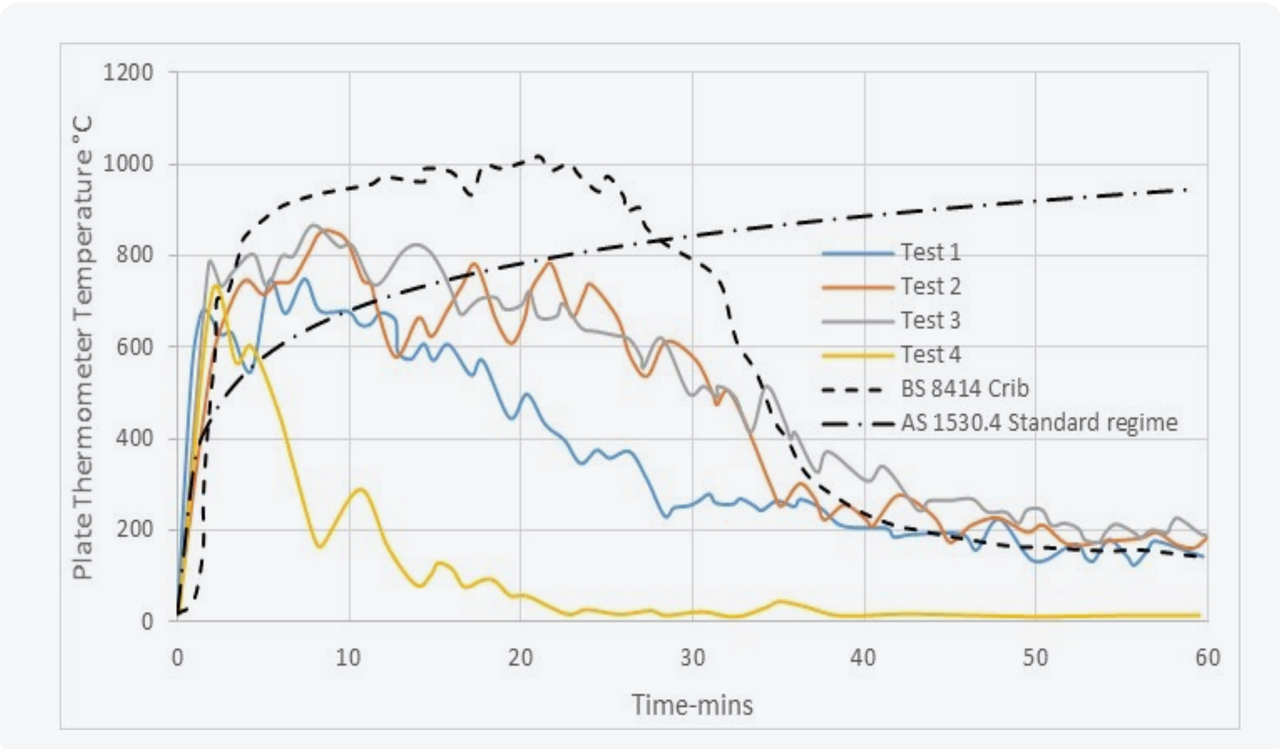


Figure 36: Facade thermocouple temperatures measured 1 m above the opening compared to temperatures measured 1 m above the opening in a BS 8414 crib/opening configuration. (Derived from Sjöström et al [93]).

Refer to Section 3.6 for further information and general correlations relating to the exposure of building facades from fire plumes venting through openings.

Adjacent structures may be exposed directly to a fire plume venting through an opening or to radiant heat from a combination of the plume and through openings to the fire enclosure, depending on the separation distance between structures.

The NCC provides verification methods CV1 and CV2 to assess the risk of spread of fire between buildings.

4.4.4 Decay and cooling phases

Transition from fully developed to decay phase

The transition to the decay phase is not a clearly defined event and for convenience may be taken as the time at which 80% of the available fire load has been consumed or at an arbitrary enclosure temperature, which may be defined as a proportion of the sustained peak temperature (e.g. 70%). If timber structural members contribute to the fire load it is more useful to adopt a temperature benchmark.

In most applications the transition to the decay phase will occur when most of the moveable fuel load has been substantially consumed with only the residual parts of larger and/or slower burning elements continuing to contribute to the fire. A Heat Release Rate (HRR) plot for typical residential enclosure and fire load (fire enclosure single-storey height with floor area approximately 30 m^2 and typical domestic furnishings) is shown as the green line in the idealised HRR plot in Figure 37.

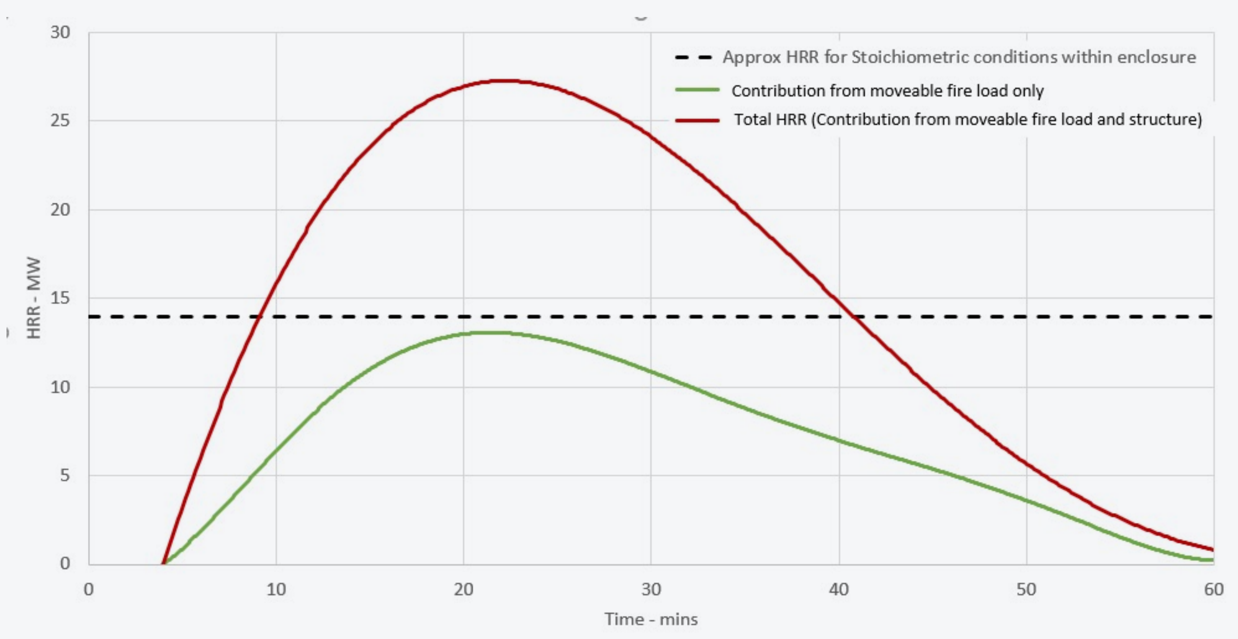


Figure 37: Idealised HRR v time graph for a residential enclosure with exposed timber structural elements self-extinguishing. Note: HRR values include external combustion of volatiles vented from the enclosure. The maximum HRR within the enclosure will be limited to nominally 14 MW by the available ventilation.

In this idealised example of a design scenario, the surfaces of some timber structural elements are exposed but the exposed area is restricted so that after the moveable fire load is consumed, flaming combustion of the exposed timber will transition to smouldering combustion and eventually the elements will self-extinguish as the fire enters the cooling phase. This scenario is shown in Figure 37 where the red-line is a plot of the combined contribution from the moveable fire load and structure. If the design achieves its goal of self-extinguishment the red line will return to a zero heat release rate. Other decay/cooling scenarios that may need evaluating to check the robustness of the design particularly in relation to low probability high consequence events include:

- Additional areas of timber structural members being exposed.
- Delamination of exposed timber panels leading to regrowth of the fire.
- Premature failure of protection systems applied to timber elements increasing the surface area of exposed timber.
- Failure of the timber to self-extinguish leading to eventual failure of structural elements if fire brigade intervention is not successful. Causes can include changes in air flow and detailing of connections and joints with opposing surfaces and exposed end grain that promote continuing combustion.
- The impact of a thermal wave during the cooling phase initiating structural failure.
- The first four dot points may prevent self-extinguishment potentially facilitating regrowth and secondary flashover increasing the probability of collapse of the structure.

Enclosure temperatures for different fire scenarios obtained from natural fire experiments are shown in Figure 38. For experiments B1 to B3 intervention was required to suppress the fires. Further details of these experiments are provided in Appendix B.

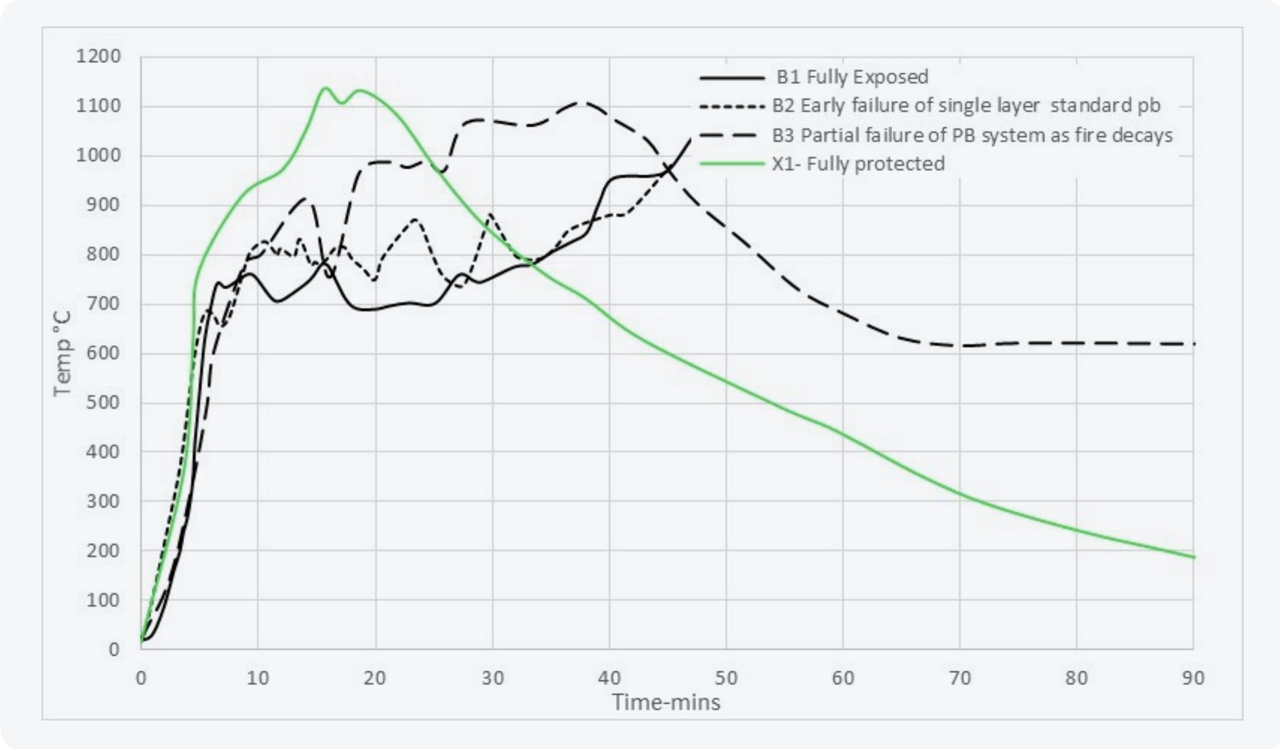


Figure 38: Enclosure temperatures from natural fire tests reported by Hakkarainen[57] and Su[113].

5 Detailed design and specification – reaction to fire

If an innovative Performance Solution for the 'reaction to fire' performance of a material or system is proposed, the focus of the analysis may be on ignition and/or the incipient and growth phases through to flashover. The need to expand the analysis to other fire phases and the extent of analysis of other features forming the fire-safety strategy will depend on the nature of the Performance Solution and outcomes of the PBDB.

5.1 Combustibility

Under the NCC DTS Provisions the combustibility of elements of construction may be controlled to limit fire spread during the growth phase of a fire and/or to limit the contribution of building elements to the fire severity of a fully developed fire. The NCC defines non-combustible as:

- applied to a material – not deemed combustible as determined by AS 1530.1 – Combustibility Tests for Materials
- applied to construction or part of a building – constructed wholly of materials that are not deemed combustible.

The NCC DTS Provisions prescribe non-combustible materials based on the test method and classification criteria of AS 1530.1[114] and this criteria can be appropriate for Performance Solutions where the intention is to minimise the direct involvement of an element or material in a fire. The test method requires a specimen (45 mm diam x 50 mm high), to be inserted into a specimen holder that is then placed within a pre-heated furnace at an initial temperature of approximately 750°C.

Temperatures are measured by furnace and specimen thermocouples and recorded until the test is terminated in accordance with the standard. Mass loss is also measured and sustained flaming from the specimen is observed.

A material is classified as combustible if any of the following occur:

- The mean duration of sustained flaming (for periods longer than 5 s) is other than zero. (i.e. if sustained flaming for longer than 5 s occurs).
- The mean furnace thermocouple temperature rise exceeds 50°C.
- The mean specimen surface thermocouple temperature rise exceeds 50°C.

If tested to AS 1530.1[114], wood products would be classified as a combustible material in accordance with the NCC/AS 1530.1 definitions. The test procedures within AS 1530.1 are similar to those of ISO 1182:2020[115] but the ISO test standard does not include classification criteria and therefore simple specification of compliance with ISO 1182 alone will not adequately specify a material.

The NCC DTS Provisions apply stringent controls to the use of combustible materials but some concessions permitting timber construction within the DTS framework have been justified, as described in Technical Design Guides 17, 37R, 37C and 37H.

If these DTS concessions are not appropriate for a specific application, the Performance Solution pathway will have to be adopted and the combustibility of timber will need to be specifically addressed.

Options to manage the combustibility of wood include deriving Performance Solutions:

- to address increases in fire load. The increase in fire load can be estimated using the heat of combustion from Section 2.4 and enhanced fire protection methods selected to address the increased hazards such as:
  - encapsulation of the exposed wood products
  - provision of automatic sprinkler systems
  - increasing the Fire Resistance Levels of critical elements
- to address the risk of ignition and/or fire spread – refer to sections 5.2 and 5.3.

The NCC also deems some materials or combinations of materials to be non-combustible even though they may not satisfy the criteria for combustibility defined in AS 1530.1. An example is plasterboard where the paper facing of the plasterboard is considered not to present a significant hazard.

5.2 Ignition of timber

There are requirements to manage the risk of ignition in verification methods CV1, CV2 and CV3 and GV5. Bushfire applications are not the focus of this document and therefore no further specific consideration of GV5 will be provided.

Verification methods CV1 and CV2 require a building to withstand the heat fluxes nominated in Table 27 without ignition based on the prescribed distances. No exposure time periods are nominated in the NCC. If the incident heat flux is below the critical heat flux for piloted ignition (typically 10-13 kW/m^2) the period of exposure may be less critical.

Table 27: Distances and limiting heat fluxes from NCC CV1 and CV2.

Distance from boundary	Distance between buildings on the same allotment	Heat flux (kW/m^2)
0 m	0 m	80
1 m	2 m	40
3 m	6 m	20
6 m	12m	10

If the incident heat flux is greater than the critical heat flux for piloted ignition, it will be necessary to estimate the likely time of exposure (fire duration) and compare it to the time of ignition when exposed to the incident heat flux. Figure 7 and Figure 8 in Section 2.2 show that some timbers with high densities may be capable of withstanding heat fluxes of 10-20 kW/m^2 for extended times.

For further information relating to methods and data for the prediction of the time to ignition of timber, refer to Section 2.2.

Note 1: In addition to CV1 and CV2, if a building is provided with an exposed timber facade, the facade will be classified as combustible and a performance assessment to address fire spread over the external wall will be required. Verification CV3 provides a practical option.

Note 2: The Guide to the NCC indicates that an incident heat flux of 20 kW/m^2 in the presence of a spark is typically required for ignition. While this applies to higher-density timbers and limited exposure periods it is recommended that the probability of ignition and/or time to ignition is estimated where lower-density timbers are exposed to heat fluxes of more than 10 kW/m^2.

Further information on the application of CV1, CV2 and CV3 is provided in WoodSolutions Technical Design Guide 17[8].

As part of a holistic Performance Solution other options that may be considered to reduce the risk of ignition include:

- limiting the risk of exposure of wood products by encapsulation
- reducing the probability of ignition or rapid spread by selection of lower risk timber species, use of fire-retardant treatments, or pre-charring timber
- providing automatic sprinkler systems.

There are a number of test methods for determining the time to ignition and methods for the interpolation of times to ignition that can be used as documentary evidence supporting time to ignition for wood products, many of which are discussed in more detail in Section 2.2.

Care is needed when reviewing data because the time to ignition is sensitive to many variables, including the test methods and criteria adopted. For example, cone calorimeter tests performed to AS 3837[34] or ISO 5660.1[116] and similar methods are commonly referenced but the following is a selection of variations that can significantly influence the time to ignition.

Variation	Likely impact
Ignition source piloted v unpiloted ignition	Piloted ignition reduces the time to ignition
Orientation of specimen – horizontal v vertical	Horizonal orientation reduces time to ignition compared to vertical orientation
Moisture content – standard conditioning requirements may be changed	Oven dry/low moisture content wood products will ignite prior to wood products within the range of 8-12%
Grain direction – heat source parallel or perpendicular to grain	If end grain is exposed to heat source, earlier ignition can occur
Material thickness and backing materials	Thin wood products with standard mounting conditions (insulated back face) tend to reduce the time to ignition

5.3.1 DTS classification system and growth times for t-squared fires

The NCC DTS Provisions adopt AS 5637.1[107] for the classification of wall and ceiling linings using the following test methods:

- AS ISO 9705 – 2003[106] Fire tests—Full-scale room test for surface products
- AS /NZS 3837[34] Method of test for heat and smoke release rates for materials and products using an oxygen consumption calorimeter or ISO 5660-1[116] Reaction-to-fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement).

The primary basis for classification is the time to flashover and the Smoke Growth Rate Index determined in an AS /ISO 9705 test that applies a standardised heat source to the corner of a 3.6 m x 2.4 m x 2.4 m high room with the material that is to be classified applied to the wall and ceiling in a representative manner.

Wall and ceiling linings are assigned a Group number based on the time to flashover in a room test, as follows, with additional smoke criteria being applied if buildings are not protected by a nominated fire sprinkler system.

- Group 1 materials do not reach flashover when exposed to 100 kW for 600 s followed by exposure to 300 kW for 600 s.
- Group 2 materials reach flashover following exposure to 300 kW within 600 s after not reaching flashover when exposed to 100 kW for 600 s.
- Group 3 materials reach flashover in more than 120 s but within 600 s when exposed to 100 kW.
- Group 4 materials reach flashover within 120 s when exposed to 100 kW.

Most common wood products achieve Group 3 performance with either a Smoke Growth Rate Index less than 100 or an average specific extinction area less than 250 m^2/kg although the Group number can be reduced to 1 or 2 (reducing the rate of fire growth and spread) with appropriate treatments.

The NCC DTS Provisions specify the required Group, depending on the location within a building, class of building and presence of a nominated sprinkler system. Refer to Section 4.4 and WoodSolutions website (www.woodsolutions.com.au/articles/fire-test-reports) for further information regarding the application of the DTS Provisions and Evidence of Suitability.

Note: The Evidence of Suitability for a DTS Solution should be in the form of a report providing a classification to AS 5637.1.

An alternative DTS pathway that is applicable to most wood products and other suitable materials uses bench-scale cone calorimeter tests and correlations derived by Kokkala[117]. It is used extensively due to the lower testing costs. Detailed guidance on its application is provided in AS 5637.1[107].

While the Kokkala method is an effective tool for determining compliance with the DTS classification of wall and ceiling linings, its application to fire-engineering analysis as part of a Performance Solution is constrained because it only provides indices to determine the Group number and does not provide an estimate of the time to flashover other than to the extent that the material lies within the Group number's applicable range.

For example, a material will be classified as Group 3 if flashover in the ISO 9705 enclosure occurs anywhere between 2 min and 10 min after the test begins, which covers a broad range of fire growth rates and can have a substantial impact on the available safe egress time (ASET). However, conveniently, the selected criterion for flashover in the ISO 9705 test in Australia is the time to attain a HRR of 1 MW and since the ISO 9705 room is a relatively small enclosure, the same growth time (time to reach a HRR of approximately 1.05 MW) can be conservatively assumed for larger enclosures where there would be less thermal feedback. On this basis, a simple approximation for the growth time for a t-squared fire involving lining materials can be taken as the time to flashover from an ISO 9705 test with an initial 100 kW fire source representing a scenario with a flaming fire typical of a waste bin fire in the corner of the room.

Table 28 indicates that slow, medium and fast t-squared fires all have growth times within the time to flashover applicable to Group 3 linings.

Table 28: Growth times and proportionality constant for standard t-squared fires.

Growth Category	Proportionality constant α (kW/s^2)	Growth time t_g (s)
Slow	0.00293	600
Medium	0.0117	300
Fast	0.0470	150
Ultra-fast	0.188	75

While the limited resolution in the Group number approach may not be critical for DTS Solutions, for some Performance Solutions it may be important to estimate time to flashover/growth time in an ISO 9705 test to be able to define the fire growth rate more precisely for a scenario involving fire spread over wall and/or ceiling linings prior to flashover.

Although not prescribed for use under the DTS Provisions of the NCC, there are alternative correlations to Kokkala's using cone calorimeter data to predict time to flashover in an ISO 9705 test. The method selected by Östman and Tsantaridis[118] as the best from seven candidate correlations applies the following equation with the various constants derived by linear regression. A high correlation coefficient of 0.97 was obtained from an analysis of 28 tests including numerous wood products.

$$t_{fo} = 0.07 \frac{t_{ig}^{0.25} \rho^{1.7}}{THR_{300}^{1.3}} + 60$$

Where:

t_{fo} is time to flashover in room fire test (s)

t_{ig} is time to ignition in cone calorimeter at 50 kW/m^2 (s)

THR_{300} is total heat release during 300s after ignition at 50 kW/m^2 (MJ/m^2)

ρ is mean density (kg/m^3)

The coefficients obtained by regression are rounded in the above equation providing slightly conservative results. The equation is less reliable for low times to flashover. The application of this correlation is demonstrated in the following sub-section where it is applied to pre-charred timber.

For general Performance Solutions the specification of lining materials using the AS 5637.1[107] classification system is normally adequate. For applications where a more precise estimate of the time to flashover is required, it may be prudent to obtain cone calorimeter data or a full-scale ISO 9705 test data during the design phase and specify the wood product based on fire-retardent treatment levels (if used) and species. The required performance level (time to flashover in ISO 9705 room) should then be specified in the fire engineering report and supporting Evidence of Suitability referenced.

5.3.2 Pre-charred timber (PCT)

Background

Pre-charred timber (PCT) has been used for centuries in Japan to enhance the durability of timber and is commonly referred to as Yakisugi or Shou Sugi Ban. In recent decades it has become popular predominantly as an architectural feature globally with multiple suppliers in Australia.

The treatment involves exposing the timber to heat in a controlled manner to create a surface char layer that, in addition to producing a popular visual effect and potentially enhancing durability, can also improve the 'reaction to fire' performance without the use of chemical treatments.

This section provides an overview and presents preliminary results from a feasibility study undertaken by the author of this Guide for the FWPA to evaluate the ability of the pre-char treatment to enhance the 'reaction to fire' performance of wood products. The cone calorimeter tests undertaken as part of the preliminary study were carried out by Warringtonfire Melbourne laboratories.

The applications considered included internal wall and ceiling linings and extension of the range of timbers that can be used as Bushfire-resisting Timbers for external applications in Bushfire Prone Areas in accordance with AS 3959[119] without chemical treatments.

White Cypress was selected for the study because it has a high natural resistance to termite attack and is commonly used in external applications in Australia. Also, Yakisugi/Shou Sugi Ban treatments have been successfully applied to the timber for aesthetic purposes.

An earlier study by Akizuki[120] reported ISO 5660 cone calorimeter tests undertaken on pre-charred treated cedar boards used for external wall finishes in Japan and compared results with uncharred boards. The study included 27 mm thick samples exposed to a 50 kW/m^2 source. The initial peak heat release rate for the timber charred on one side was of the order of 70.8 kW/m^2 compared to approximately 160 kW/m^2 for the uncharred specimens. Replicants and details of the pre-char treatment were not provided. Akizuki made the following observation:

"Since the sharp peak heat release just after the ignition is the principal driving force of concurrent flame spread of wood-based materials, the suppression of the peak is believed to reduce fire spread on this material. The charred layer is also believed to function as a form of thermal insulation for the virgin wood beneath the char layer at the beginning of the surface burning. Effectiveness of this treatment naturally becomes insignificant with time."

The treatment becomes insignificant with time once the char layer develops further, and quasi-steady state conditions are established after a few minutes' exposure to heat. These attributes were investigated further in the preliminary study described below.

White Cypress Preliminary Study – Pre Char Timber (PCT)

The cone calorimeter was used to undertake the pre-char treatment in a controlled, quantifiable, and repeatable manner using the following procedures:

a) No temperature or HRR measurements were required during pre-charring but exposure to 50 kW/m^2 must be maintained for the required pre-char period.

b) Pre-weigh and measure dimensions of samples and moisture content and clearly identify each sample.

c) Expose to 50 kW/m^2 and apply the standard piloted ignition source (note the time of ignition).

d) Remove from cone after prescribed exposure time. Typical exposure times are:

- low – 30 s exposure after ignition
- medium – 60 s exposure after ignition
- high – 90 s exposure after ignition
- very high – 120 s exposure after ignition.

e) Drop a non-combustible cover over specimen to quickly suppress burning – no water application and allow to cool.

f) When specimen cooled weigh and record and calculate mass loss.

This pre-char procedure was found to provide a practical approach for pre-charring samples in a repeatable manner. Figure 39 gives typical samples after pre-charring.

With 120 s exposure the char layer was significantly more fragile and therefore a 90s pre-char exposure was the preferred maximum pre-char level. The extent of char can also be expressed in terms of mass loss in addition to the time of exposure (Table 29).

Table 29: Pre-char treatment summary.

Pre-char period (s)	Average Mass Loss (kg/m^2)
30	0.59
60	1.06
90	1.44
120	1.74

30s – Pre-char	60s – Pre-char	120s – Pre-char

Figure 39: Pre-charred samples.

As the program was a preliminary study, indicative results from a limited number of samples were obtained. These are reported in WarringtonFire Report RTF20078 R1.2[35]. The HRR results from a single sample at each pre-char level and a control are shown in Figure 40 when exposed it an irradiance of 50kW/m^2 and in Figure 41 when exposed it an irradiance of 25kW/m^2. As can be seen the pre-char reduces the magnitude of the initial peak HRR significantly and with a pre-char treatment period of 120s the first peak is minimal.

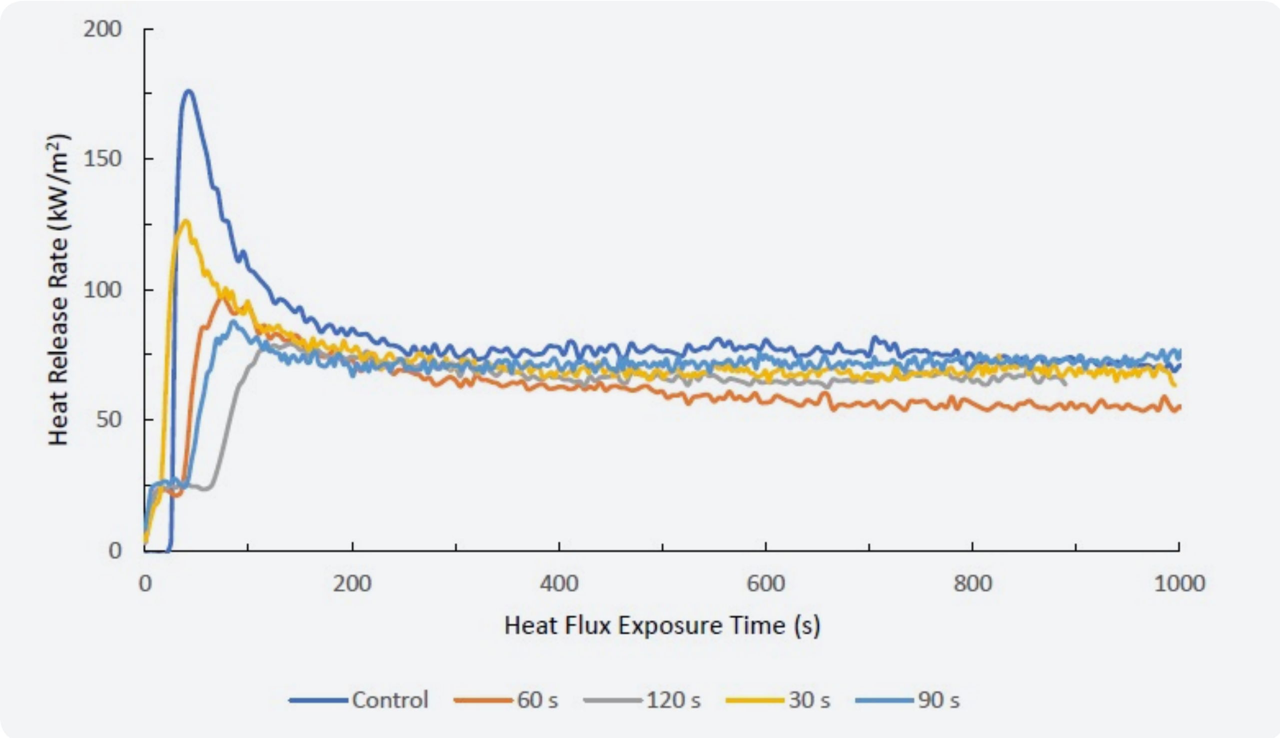


Figure 40: Indicative HRR plot for 50 mm thick White Cypress exposed to 50 kW/m^2.

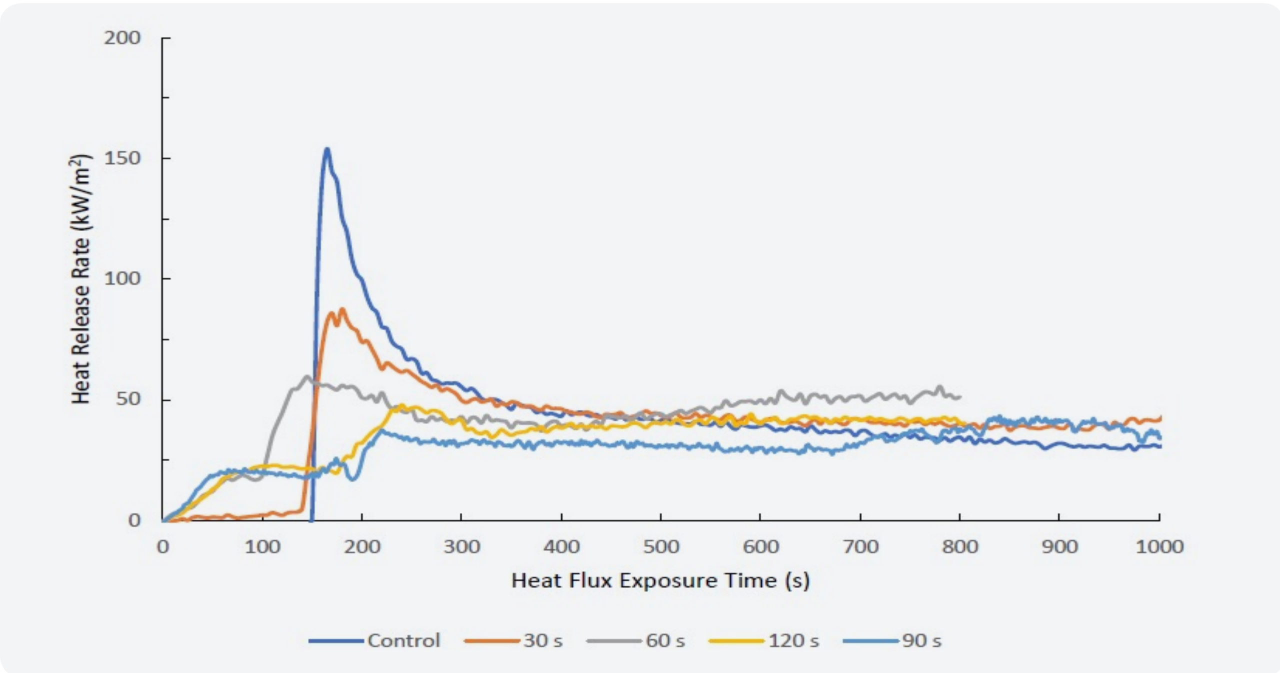


Figure 41: Indicative HRR plot for 50 mm thick White Cypress exposed to 25 kW/m^2.

At the 50 kW/m^2 exposure level the HRR for the untreated control converged with the HRRs for the pre-charred samples after approximately 200 s and at the 25 kW/m^2 exposure level a similar convergence occurred after 400 s.

The indicative estimates in Table 30 have been derived by applying the correlation recommended by Östman and Tsantaridis[118] to the preliminary White Cypress data taken from WarringtonFire Report RTF20078 R1.2[35].

Table 30: Indicative estimates of time to flashover during an ISO 9705[106] test for 50 mm thick White Cypress wall linings based on preliminary cone calorimeter data.

Pre-char (s)	Control (0)	30	60	90	120
Density (kg/m^3)	696	736	696	670	718
Ignition time (s)	33	22	44	51	76
THR for first 300s after ignition (MJ/m^2)	28.89	25.29	22.56	21.87	21.48
Estimated ISO 9705 time to flashover (s)	204	230	273	276	335

The indicative estimates indicated that the time to flashover without pre-char treatment would be approximately 200 s but with a pre-char treatment of approximately 120 s the time to flashover could be extended to more than 300 s. This indicates that the pre-char treatment may be able to significantly reduce the fire growth rate, potentially extending the available safe egress time (ASET) from the enclosure of fire origin, even though the classification determined in accordance with AS 5637.1[107] will remain Group 3.

Although design of buildings to resist bushfires is not a primary focus of this Guide, pre-charred timber has significant potential for external applications in Bushfire Prone Areas such as its use as a bushfire-resisting timber as defined in AS 3959 was examined in the preliminary study. A brief overview of the preliminary results relating to this application is provided below.

AS 3959:2018[119] requires bushfire-resisting timbers to satisfy the following requirements when tested in accordance with AS/NZS 3837[34]:

- the maximum heat release rate shall not be greater than 100 kW/m^2
- the average heat release rate for 10 min following ignition shall not be greater than 60 kW/m^2 when the material is exposed to an irradiance level of 25 kW/m^2.

The preliminary bushfire-resisting timber investigations were performed on 50 mm thick White Cypress timber samples at an irradiance of 25 kW/m^2. One test run for each char level plus an uncharred control sample was undertaken for indicative purposes (at least three samples are required for a formal assessment against AS 3959 requirements). The key results are summarised in Table 31.

Table 31: Results for 50 mm White Cypress cone calorimeter tests at an irradiance of 25 kW/m^2.

Parameter	Control	30 s	60 s	120 s
Mass loss due to pre-char (g/m^2)	-			
Test duration (s)	1035	3585	800	805
Time to Ignition (s)	162	148	112	195
Maximum peak heat release rate	154.0	87.5	59.5	47.8
Average HRR for 10 min after ignition	51.7	48.9	46.3	40.4
Preliminary results	Fail	Pass	Pass	Pass

The preliminary results demonstrate the potential for pre-charring techniques to upgrade the performance of timbers to bushfire-resisting timber as defined in AS 3959.

A formal bushfire-resisting timber report has been issued for White Cypress 20 mm thick with 90 s pre-char, WarringtonFire report RTF200247 R2.0[121].

5.3.3 Fire-retardant treatments

Fire-retardant treatments can be used to enhance the ‘reaction to fire’ performance of wood products, and can be assigned to the following categories:

- Impregnation, whereby fire-retardant chemicals are introduced to a wood product during manufacture or are introduced under an applied pressure. They usually act by interfering with the combustion process and in some cases may enhance char formation providing additional protection. The uptake of chemicals can be significantly impacted by the constitution of the wood products. For solid timber, the proportions of sapwood and heartwood will impact retention rates with the sapwood retaining much larger amounts of the fire retardants than the heartwood.
- Surface coatings, whereby coatings are applied to the surface of a wood product. The coatings may modify the combustion process, preventing or reducing the initial heat release rate peak after the wood product surface is ignited and/or form a barrier protecting the surface (e.g. intumescent coatings). Once the coating has been consumed, the ‘reaction to fire’ performance will rely on a protective char layer in a similar manner to the pre-charred timber described in the previous section.

These systems can be evaluated and classified using the same test methods that apply to general lining materials but under NCC DTS Clause C1.10 (b) the use of fire-retardant coatings is currently not permitted as a DTS Solution:

C1.10 Fire hazard properties

(b) Paint or fire-retardant coatings must not be used to achieve compliance with the required fire hazard properties.

The reasons for this prohibition are not provided in the NCC but the following statement is provided in the guide to the National Construction Code[122] published by the ABCB as an explanation for Clause C1,10 (b):

"Some paints have been designed to reduce flame spread on combustible materials. These paints, usually referred to as 'fire retardant paint', cannot be used to achieve any of the required fire hazard properties. This material is unable to be used because of its susceptibility to damage. C1.10(b) does not prohibit the use of suitable impregnated materials that achieve the relevant fire hazard properties."

A consultation draft prepared by the ABCB in 2007[123] indicated that:

"BCA Deemed-to-Satisfy Provisions currently prohibit the use of fire-retardant coatings to achieve required fire hazard properties. Historic reasons for this prohibition revolve around their perceived susceptibility to damage and the undefined longevity of their performance, particularly when exposed to an external environment.

"The validity of this prohibition was investigated through the Fire Code Reform Centre, the primary outcome of which is captured in the BRANZ statement;" There appears to be no compelling reason why fire-retardant coatings should not be used to enhance the reaction to fire properties of building materials, provided suitable steps are taken to ensure the quality of application and the efficacy of the coating over the expected life of the material."

"As a result of comprehensive research conducted through the Fire Code Reform Centre and subsequent research conducted by BRANZ, the ABCB is positioned to remove the prohibition on the use of fire-retardant coatings to achieve required fire hazard properties".

Despite this recommendation and subsequent submissions, the prohibition has not been removed. One potential outstanding issue was the lack of a Code of Practice. This has been addressed by means of WoodSolutions Technical Design Guide 45 Code of Practice Fire Retardant Coatings applied to Wood Products[124].

A worked example of a Performance Solution for a fire-retardant coating used to modify the fire hazard properties is included in WoodSolutions Technical Design Guide 19.

Notwithstanding the Clause C1.10(b) restriction, methods such as impregnation can be used under the DTS requirements and surface coatings can be used in accordance with AS 3939 for external protection of buildings in Bushfire Prone Areas.

5.3.4 Combinations of lining materials

The NCC DTS Provisions for wall and ceiling linings adopt a simplified approach whereby a Group number is applied to a particular material or composite taking account of profiles and fixing methods where necessary. Some minor additions to linings are allowed to be made in accordance with NCC clause C1.10(c), which is reproduced in the following text box.

C1.10 (c) The requirements of (a) do not apply to a material or assembly if it is—

(i) plaster, cement render, concrete, terrazzo, ceramic tile or the like; or
(ii) a fire-protective covering; or
(iii) a timber-framed window; or
(iv) a solid timber handrail or skirting; or
(v) a timber-faced door; or
(vi) an electrical switch, socket-outlet, cover plate or the like; or
(vii) a material used for—
  (A) a roof insulating material applied in continuous contact with a substrate; or
  (B) an adhesive; or
  (C) a damp-proof course, flashing, caulking, sealing, ground moisture barrier, or the like; or
(viii) a paint, varnish, lacquer or similar finish, other than nitro-cellulose lacquer; or
(ix) a clear or translucent roof light of glass fibre-reinforced polyester if—
  (A) the roof in which it is installed forms part of a single storey building required to be Type C construction; and
  (B) the material is used as part of the roof covering; and
  (C) it is not closer than 1.5 m from another roof light of the same type; and
  (D) each roof light is not more than 14 m^2 in area; and
  (E) the area of the roof lights per 70 m^2 of roof surface is not more than 14 m^2; or
(x) a face plate or neck adaptor of supply and return air outlets of an air handling system; or
(xi) a face plate or diffuser plate of light fitting and emergency exit signs and associated electrical wiring and electrical components; or
(xii) a joinery unit, cupboard, shelving, or the like; or
(xiii) an attached non-building fixture and fitting such as—
  (A) a curtain, blind, or similar decor, other than a proscenium curtain required by Specification H1.3; and
  (B) a whiteboard, window treatment or the like; or
(xiv) timber treads, risers, landings and associated supporting framework installed in accordance with D2.25 where the Spread-of-Flame Index and the Smoke-Developed Index of the timber does not exceed 9 and 8 respectively; or
(xv) any other material that does not significantly increase the hazards of fire.

C1.10 (c) The requirements of (a) do not apply to a material or assembly if it is—

(xvi) plaster, cement render, concrete, terrazzo, ceramic tile or the like; or
(xvii) a fire-protective covering; or
(xviii) a timber-framed window; or
(xix) a solid timber handrail or skirting; or
(xx) a timber-faced door; or
(xxi) an electrical switch, socket-outlet, cover plate or the like; or
(xxii) a material used for—
  (D) a roof insulating material applied in continuous contact with a substrate; or
  (E) an adhesive; or
  (F) a damp-proof course, flashing, caulking, sealing, ground moisture barrier, or the like; or
(xxiii) a paint, varnish, lacquer or similar finish, other than nitro-cellulose lacquer; or
(xxiv) a clear or translucent roof light of glass fibre-reinforced polyester if—
  (F) the roof in which it is installed forms part of a single storey building required to be Type C construction; and
  (G) the material is used as part of the roof covering; and
  (H) it is not closer than 1.5 m from another roof light of the same type; and
  (I) each roof light is not more than 14 m^2 in area; and
  (J) the area of the roof lights per 70 m^2 of roof surface is not more than 14 m^2; or
(xxv) a face plate or neck adaptor of supply and return air outlets of an air handling system; or
(xxvi) a face plate or diffuser plate of light fitting and emergency exit signs and associated electrical wiring and electrical components; or
(xxvii) a joinery unit, cupboard, shelving, or the like; or
(xxviii) an attached non-building fixture and fitting such as—
  (C) a curtain, blind, or similar decor, other than a proscenium curtain required by Specification H1.3; and
  (D) a whiteboard, window treatment or the like; or
(xxix) timber treads, risers, landings and associated supporting framework installed in accordance with D2.25 where the Spread-of-Flame Index and the Smoke-Developed Index of the timber does not exceed 9 and 8 respectively; or
(xxx) any other material that does not significantly increase the hazards of fire.

Notes:

1 State variations are not identified in the above extract from the NCC. Practitioners should check for State/Territory variations.

2 DTS Provisions including requirements relating to Fire-protected Timber require some wall and ceiling linings to be non-combustible.

A review of this concession indicates that the following wood product additions are permitted to be used unless additional State or Territory variations apply, demonstrating the concept of the use of mixed materials without significantly compromising the reaction-to-fire performance of wall and ceiling linings:

- solid timber handrails and skirtings
- timber window frames
- timber-faced doors
- a joinery unit, cupboard, shelving, or the like
- timber treads, risers, landings and associated supporting framework installed in accordance with D2.25 where the spread-of-flame index and the smoke-developed index of the timber does not exceed 9 and 8 respectively.

Sub-clause (xv) also allows any other material that does not significantly increase the hazards of fire. It is not clearly stated what form of Evidence of Suitability should be adopted to demonstrate compliance if this clause is adopted and therefore it is prudent to apply the Performance Solution pathway approach, particularly when considering large areas such as dado linings applied to the lower parts of walls, single walls with exposed timber and exposed timber structural elements such as beams or columns.

There has been a substantial volume of work relating the use of wood products for wall and ceiling linings, including in combination with materials such as plasterboard, that can be used as supporting evidence for Performance Solutions. Some of the more relevant studies are reviewed in Appendix D.

5.4 Floor coverings

AS ISO 9239.1[65] is prescribed by the NCC for control of floor coverings if the DTS pathway is adopted. It also provides a practical method to specify flooring materials for a Performance Solution. It is an intermediate-scale test simulating the thermal radiation levels likely to impinge on the floor of a corridor from the hot layer from a fire in an adjacent room or compartment. The test specimen is placed horizontally below a gas-fired radiant panel inclined at 30°. A pilot flame is applied to the hotter end of the specimen. Results are expressed in terms of the critical heat flux at extinguishment and smoke density versus time.

Critical Heat Fluxes of not less than 1.2, 2.2 or 4.5 kW/m^2 are prescribed depending on the application.

Smoke developed index of 750%-minutes applies in buildings not protected by nominated types of sprinkler system.

Most common wood products do not exceed the Smoke Developed Index limit of 750%-minutes and achieve Critical Heat Fluxes greater than 2.2 kW/m^2 with a minimum thickness of 12 mm when mounted on an appropriate substrate or 17 mm with an airgap behind the boards. Some timber species achieve Critical Heat Fluxes greater than 4.5 kW/m^2 or greater than 2.2 kW/m^2 with thicknesses less than the above thickness limits. Refer to the WoodSolutions website for further information and Evidence of Suitability. (www.woodsolutions.com.au/articles/fire-test-reports).

6 Detailed design and specification – structural fire safety and fire resistance

6.1 Introduction

The functional performance of fire barriers and structural elements is commonly expressed as the elements' fire resistance. This chapter provides information relating to design and specification for wood and related products that may form part of a fire safety strategy with a focus on fire-resistant elements of construction (e.g. elements that may need to fulfill a structural or fire-separating function or remain operational for a required period when exposed to fire or throughout a fire emergency).

Fire-resistant systems are expected to have a high probability of achieving, as a minimum, their design function from ignition through the growth phase and all or part of the fully developed phase, depending on the fire safety strategy. The design function may also be required to have a high probability of being maintained throughout the fully developed fire and subsequent decay and cooling phases (e.g. primary structural elements in high-rise buildings).

This chapter is broken down into sub-sections covering selected applications, but it is not intended to restrict the use of wood products for other applications or to prevent the use of innovative methods of analysis. The information included focuses on more common applications and technology transfer from research undertaken predominately to support code changes in the NCC.

The content is generic and avoids, as far as practicable, reference to proprietary products. In many instances, additional documentation relating to specific products and applications will be required as Evidence of Suitability. The WoodSolutions site provides copies of test reports and assessments of variations from tested prototypes for some common applications and timber species which can be accessed using the link: www.woodsolutions.com.au/articles/fire-test-reports.

Enclosure fire dynamics have been discussed in Chapter 3 in relation to characterising Design Fires and in Chapter 4 in relation to the influence of exposed wood products. This chapter brings this information together to define the fire exposure of products and systems such that the elements or combinations of elements can be designed and specified in a manner that enables product suppliers to provide Evidence of Suitability for general application rather than having to undertake extensive test programs to generate project-specific Evidence of Suitability on a case-by-case basis.

Some supporting fire test data is provided in Appendix B that may provide additional confidence in the selection of inputs such as Design Fires and methods of analysis, and assist with the verification of models and analyses.

6.2 Design actions applied to a structural element's fire limit state

6.2.1 Structural loads and the load duration factors

The structural loading of elements of construction under fire conditions is prescribed in AS 1170.0[125], which requires the design actions (loads) for the fire limit state to be determined based on the following actions:

$G + \psi_l Q$ + (thermal actions arising from the fire)

Where:

G is the permanent action (dead load including self-weight)

Q is the imposed action (live load)

ψ_l is the long-term factor (0.4 for residential, offices, parking, and retail and 0.6 for storage and other occupancies).

AS 1720.1 requires that the design capacity for a member should be greater than the design action. When determining the design capacity of timber elements (R_d) in accordance with AS 1720.1, capacity factors (Φ) modifications factors (k_{mod}) are applied to the characteristic capacity ($f'_o X$) as indicated in the following equation:

$$R_d = \Phi \, k_{mod} \, f'_o \, X$$

The load duration factor k_1 varies between load cases with a value of 0.94 being applied to the fire limit state. Load combinations and load duration factors for common load cases and fire are provided in Table 32.

Table 32: Typical load duration factors (k_1) and load combinations for timber structural elements.

Load Case Description	Load combination	k_1
Permanent action (dead load)	1.35 G	0.57
Permanent and short term-imposed actions	1.2 G +1.5 Q	0.8 – 0.97
Permanent and long-term imposed action	$1.2\ G + 1.5\ \psi_l Q$	0.57
Fire	$G + \psi_l Q$	0.94

ψ_l = 0.4, from Table 4.1 of AS /NZS 1170.0:2002 for residential, offices and retail buildings and 0.6 for other building uses.

6.2.2 Fire test load conditions

It is common practice for test sponsors to nominate test loading for specimens when undertaking fire-resistance tests on loadbearing elements. In many cases the test loads are calculated using relevant structural design codes and characteristic material properties but the basis of the derivation of the test load is often not clearly stated in test reports other than to note the applied load was nominated by the test sponsor.

In situations where significant additional loads are derived from thermal actions arising from the fire a detailed project-specific analysis may be required.

It is useful to express a fire test load (or design load capacity under fire conditions determined by calculation) in terms of the ratio of the fire test load to the design capacity of the member under ‘normal use (ambient) conditions’. This load ratio can be used to compare loading levels, simplifying the process of interpreting test results (Evidence of Suitability) for relevant structural design codes and the National Construction Code.

Design Codes for other structural materials such as AS 4100[126] use the ratio of design action on the member under design load for fire to the design capacity of the member at room temperature to determine load levels for testing and or analysis.

A similar approach can be adopted for timber elements but in addition it is necessary to address the load duration factor (k_1) with varies with the load case.

The derivation of default fire test load conditions that are likely to impose the maximum fire test load on a timber element is provided in the WoodSolutions Technical Design Guide 17, pp 39-42[8], which determined for general application of fire test data:

Loadbearing elements should be fire tested at a load ratio (LR_{fb}) of not less than 0.5 where:

LR_{fb} is the ratio of design action or fire test load applied to the element to the ambient benchmark design capacity (R_b), and

R_b is the ambient benchmark design capacity calculated in accordance with AS 1720.1 at ambient conditions assuming $k_1 = 1$

6.3 The standard fire test (AS 1530.4)

6.3.1 Standard fire test exposure

The performance of elements of construction exposed to fully developed fires is traditionally specified by applying or adapting the NCC DTS pathway that expresses the required performance in terms of fire resistance. The fire resistance of an element is determined by exposing it to a standard heating regime prescribed in AS 1530.4[18], shown in Figure 42, and measuring its functional performance against prescribed criteria. It is similar to the standard regime specified in ISO 834[47] and other international and national fire resistance heating regimes.

The standard heating regime specified in AS 1530.4 has changed little since the first publication of a fire-resistance test in Australian Standard A30–1935, which was an adoption without amendment of British Standard 476-1932.

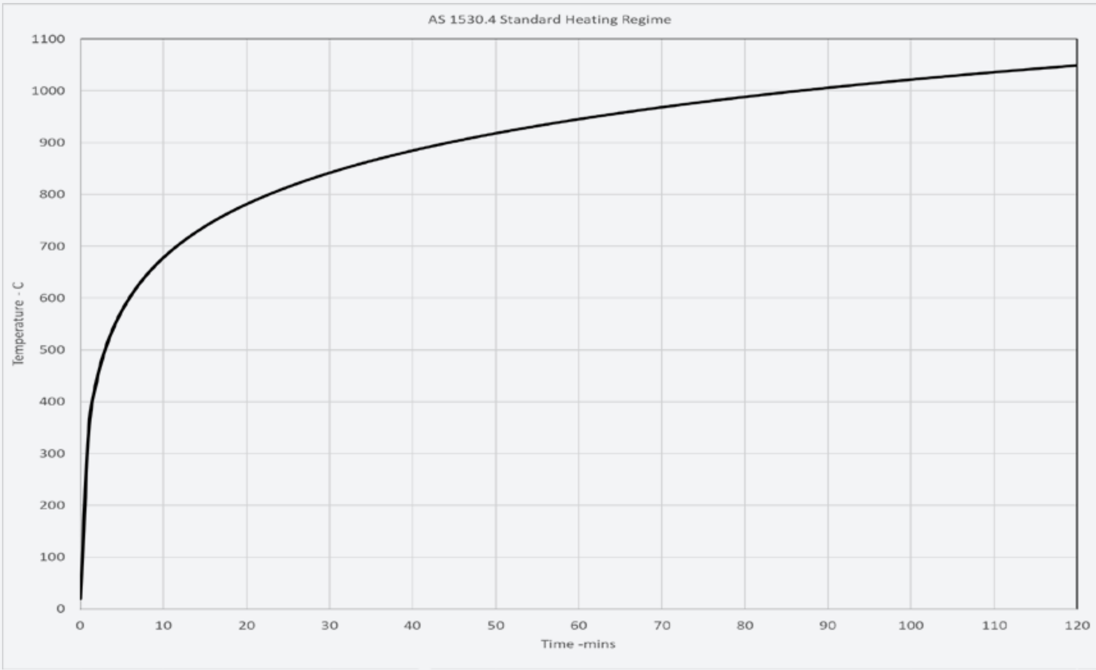


Figure 42: Standard heating regime of AS 1530.4.

There is a substantial distribution of possible fully developed fire scenarios, depending on the enclosure fire dynamics.

Some fire scenarios will expose elements of construction to heating conditions more severe than the standard heating regime of AS 1530.4. Typical examples are shown in Figure 50 and Figure 52 of Section 6.5, which present natural enclosure fire temperatures compared to the standard heating regime of AS 1530.4. An alternative more severe 'hydrocarbon' heating regime that peaks at 1100°C, defined in Appendix B of AS 1530.4, and a modified hydrocarbon regime that peaks at 1200°C are also plotted. These more severe regimes are more representative of the maximum temperatures that may be attained in modern enclosures with increased use of plastics and low thermal inertia bounding elements.

For materials with well-known thermal and mechanical properties at elevated temperatures, it is possible to estimate modified failure times to account for the differing fire exposures, but increased heating rates could also initiate different modes of failure that also need to be checked. Typical examples of these modes of failure include:

- Materials/elements susceptible to thermal shock.
- Materials that undergo significant changes in properties above temperature thresholds that lie between the standard fire-resistance test time/temperature regime and the Design Fire (natural fire) time-temperature regime.
- Elements, sub-assemblies and structures that are constructed from materials with relatively high coefficients of thermal expansion, which may increase thermally induced stresses or differential movement between elements.

The oxygen concentration within an enclosure or fire-resistance furnace may influence the performance of combustible elements of construction or combustible fire protection coatings/coverings. For ventilation-controlled fires the oxygen concentration during the fully developed phase of a fire is expected to be low (below 10%), which is consistent with the oxygen concentrations in modern gas-fired fire-resistance furnaces.

AS 1530.4-2014 requires that the furnace over pressure is adjusted such that the neutral axis occurs 500 mm above sill level for vertical separating elements and the pressure differential 100 mm below the soffit of a horizontal specimen is approximately 20 Pa. These values are broadly consistent with the expectations for natural fires performed in essentially windless conditions with enclosure heights typically 3 m.

Under natural fire conditions the precise position of the neutral axis will vary through the duration of a fire depending on the burning regime and will tend to occur at a lower height if the fire is strongly ventilation controlled and move slightly upwards as the fire progresses through stoichiometric conditions. This behaviour was demonstrated during the natural fire test described in the Pressure differentials and predictions of air flows sub-section of Section 3.6.3 where the estimated position of the neutral axis during the fully developed phase varied from approximately 0.67 m to 0.75 m above floor level as the burning regime progresses to stoichiometric conditions from being strongly ventilation controlled. Some older fire-resistant test methods did not require a positive differential to be established during the test, substantially reducing the stringency of the test for fire-separating elements. Other pressures may be superimposed due to external forces such as wind and airflows/pressure differentials induced within a building.

The standard heating regime specified in AS 1530.4 does not include decay and cooling phases despite the potential for further degradation of elements of construction during these phases. It is generally considered that the impact of the decay and cooling phases is inherently addressed in the NCC DTS Provisions by the package of measures that makes up a DTS Solution, which may include the following:

- prescribed FRLs
- specifications for fire-protected timber
- active fire protection measures such as sprinklers.

However, if the Performance Solution pathway is adopted, specific consideration of the decay and cooling phases will be required. Factors that may require consideration include:

- the impact of a thermal wave and moisture movement through an element (i.e. peak temperatures and load capacity reductions may occur after the fully developed phase)
- induced stresses on cooling of the structure
- continuing degradation due to chemical reactions including continued combustion.

Higher oxygen concentrations are likely during the decay and cooling phases when the burning regime will become fuel controlled. This can have an impact on timber construction by promoting smouldering combustion/char oxidation and regrowth of the fire over exposed timber surfaces.

The above limitations to the applicability of the standard heating regime are well known and provided these limitations are addressed (e.g. by the package of measures forming a DTS Solution) the standard fire-resistance test can facilitate the specification and verification of the performance of fire-resistant elements of construction in a consistent manner.

The standard fire-resistance test can also be used to specify the required performance of structural elements and barriers forming part of a performance solution but the impact of variations from the standard heating regime and exposure to the decay and cooling phases should be taken into account when deriving the required FRL.

For example, if the thermal and mechanical properties at elevated temperatures of the materials are known and have been validated under a range of heating conditions, a modified expected failure time can be calculated for a specific fire scenario. Alternatively, data from supplementary testing under alternative heating regimes or natural fire experiments can provide the necessary information to determine the time to failure under natural fire design conditions with reasonable confidence.

For further details, refer to:

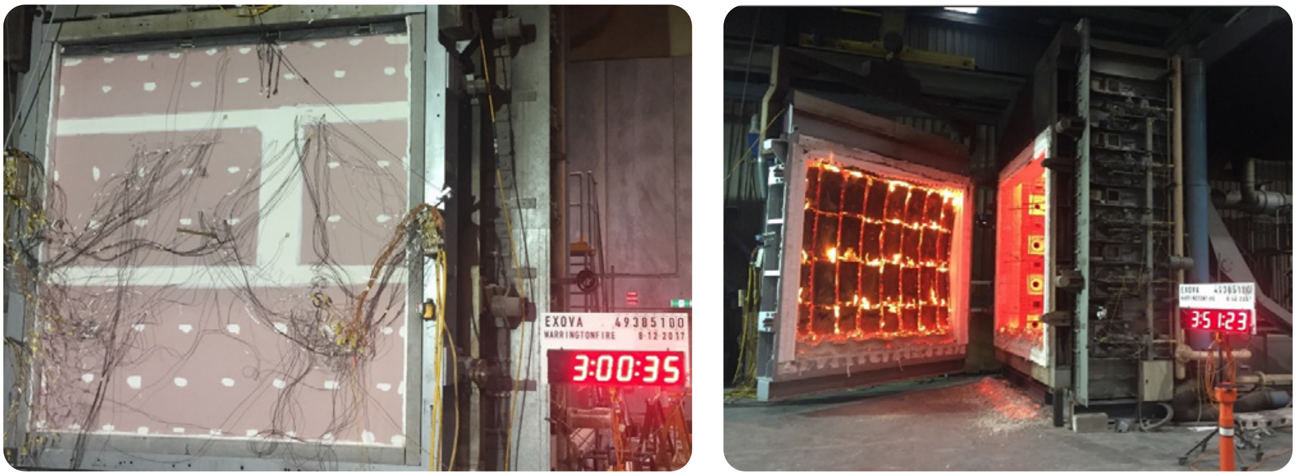
- Section 3.6
- AS 1530.4 Appendix B Alternative and Additional Test procedures for elements of construction[18]
- Fire Resistance Testing For Performance-based Fire Design of Buildings: final report (Beyler[68])
- Technical note – Thermal exposure of wood in standard fire-resistance tests (Schmid[80]).

6.3.2 AS 1530.4 Performance criteria (functional performance) and specification of FRLs

Typically, vertical specimens 3 m x 3 m and horizontal specimens 4 m x 3 m are exposed to the standard heating regime, unless the use of smaller specimens is permitted. Refer to Figure 43 and Figure 44 for typical examples of a loadbearing timber floor and wall tests.

Non-fire side after 90 min of test. *Fire-exposed face after removal from the furnace.*

Figure 43: Loadbearing lightweight timber-frame floor FRL of 90/90/90 RISF>60 min at end of test.



Non-fire side after 180 min with full test load applied.

Fire-exposed face 4 min after removal from furnace. (Test was continued to 227 min under reduced load.)

Figure 44: Loadbearing timber stud wall with cavities filled with high-performance mineral fibre FRL 180/180/180 RISF>120 min.

The application of the standard fire test (AS 1530.4) is not limited to structural elements. It is applicable to a broad range of elements of construction via direct reference in the NCC or as a secondary reference from documents such as AS 1905.1 (fire doors) and AS 4072.1 (service penetrations and fire dampers).

AS 1530.4 identifies the following applications:

- walls
- floors, roofs and ceilings
- columns
- beams, girders and trusses
- doorsets and shutter assemblies
- service penetrations and control joints
- fire damper and air transfer grille assemblies
- uninsulated glazing
- critical services.

While some of these elements may not contain wood products, they may form part of the strategy and/or be incorporated in timber elements of construction.

Observations are made on the performance of the specimen while it is subjected to thermal and, where applicable, physical loading and the elapsed times at which failures occur under various criteria are recorded.

The Fire Resistance level (FRL) is defined in the NCC as the grading periods in minutes determined in accordance with Schedule 5 of the NCC, for the following primary functional performance criteria:

- Structural adequacy – The ability of a loadbearing element of construction to support a load.
- Integrity – The ability of an element of construction to resist the passage of flames and hot gases from one space to another.
- Insulation – The ability of an element of construction to maintain a temperature on the surface that is not exposed to the furnace, below the limits specified in order to prevent the spread of fire.

It is expressed in the following format in terms of the time in minutes for which the criteria was satisfied: structural adequacy/integrity/insulation.

A dash means that there is no requirement for that criterion. For example, 90/–/– means there is no requirement under the performance criteria for integrity and insulation and structural adequacy has to be satisfied for at least 90 min.

–/–/– means there is no requirement for an FRL.

Other criteria, such as radiant heat flux and Resistance to the Incipient Spread of Fire (RISF) may be applied to specific circumstances.

Of direct relevance to wood products is the RISF criterion. The NCC definition is provided in the following text box.

***Resistance to the incipient Spread of fire**, in relation to a ceiling membrane, means the ability of the membrane to insulate the space between the ceiling and roof, or ceiling and floor above, so as to limit the temperature rise of materials in this space to a level which will not permit the rapid and general spread of fire throughout the space.*

RISF is determined by subjecting a ceiling system to a standard fire-resistance test (AS 1530.4). Temperatures are monitored on the upper surface of the ceiling at prescribed positions and, if the measured temperatures are maintained below the maximum permitted temperature (250°C), an RISF can be assigned that is the time in minutes for which temperatures were maintained below the prescribed temperature or the end of the test, whichever is less.

Specification C1.13a extends the application of the RISF criteria to Fire-protected Timber members. The performance criteria and Evidence of Suitability for Fire-protected Timber are described in Appendix E.

6.3.3 Role of fire resistance within the holistic fire safety framework

There has been discussion in technical literature relating to what can be termed the ‘fire resistance framework’ and, in particular, matters such as the objective of the specification of Fire Resistance Levels relating to structural performance, the validity of fire-resistance tests generally and more specifically in relation to combustible methods of construction.

Law[127] provides an overview of the provisions from a UK perspective including the origins of the following terms, applicability to combustible construction and how their meaning has been varied and interpreted since 1903:

- temporary protection
- partial protection
- full protection.

Australia initially adopted the early developments of the fire resistance framework and the first publication of a fire-resistance test standard in Australia was Australian Standard A30–1935[128], which adopted British Standard 476-1932 ‘Definitions for Fire-resistance, Incombustibility and Non-inflammability of building materials and structures’, without amendment. The next revision was A30-1958[129], which was based on BS476-1953 but the divergence from UK requirements had commenced as explained in the following extract from the A30 foreword:

> *“The fire-resistance test of structures (Section Four) corresponds in many respects to the British test, but includes provision for a hose stream test, where required, and there are some other differences in detail.”*

A30 was broken down into separate standards with the fire resistance test method being published as AS 1530.4 in 1975[130] based on A30 content before a significant revision in 1985[131] which included further development of the principles of earlier versions and content relevant to Australian construction practices and also took account of the developments of ISO 834.

Changes included:

- removal of a hose stream test from the method
- significant content relating to fire testing of timber elements
- inclusion of resistance to the incipient spread of flame performance criteria which was stated to ”relate to the ability to insulate the space between the ceiling and roof or ceiling and floor above, so as to limit the temperature rise of combustibles in this space during the course of the test.

This highlights that the application of the standard to combustible/timber construction was envisaged, including the concept of encapsulation using the resistance to the incipient spread of fire criteria. Subsequent revisions have continued to address Australian requirements and take account of developments internationally, in particular, the work of the International Organization for Standardization (ISO).

The fire safety framework also includes the technical provisions within Building Regulations or prescribed by the Regulations. Prior to the general adoption of the Building Code of Australia (BCA) 1990[132], the technical provisions for buildings were contained within State and Territory regulations and there were significant variations in approach. This discussion will relate to the national fire safety framework as expressed in the NCC/Building Code of Australia following its introduction in 1990. Further information on the History of the NCC is provided in Appendix D of the Fire Safety Verification Method Handbook[13].

Following the introduction of the BCA (now known as the NCC) the need was identified for a fully performance-based document. This required a clearly defined fire safety framework that defined fire safety objectives and how the elements of a fire safety strategy interact. The developments drew on the earlier work of Beck[75, 133], the Building Regulation Review Task Force, Warren Centre Studies and the Fire Code Reform Centre projects. This resulted in the release of the first performance-based version of the BCA in 1996[134]; which included a clearly defined holistic approach to fire safety that considered the interaction of all the components that make up a fire safety strategy and not elements such as fire-resistant construction in isolation.

This is best illustrated by considering Performance Requirements, CP1 and CP2, that relate to fire resistant construction. CP1 addresses structural stability during a fire and CP2 the spread of fire.

The fire safety Performance Requirements in NCC Volume One generally state what is to be achieved and provide a list of parameters that must be considered when determining compliance (Figure 45). There are differences between CP1 and CP2 with respect to what is to be achieved but the parameters that have to be considered (within the dashed box) are similar.

Terms such as 'to the degree necessary' are used in a number of the NCC Performance Requirements, including CP1 and CP2, to provide flexibility when applying holistic approaches. For example, timber structural elements can be used in some applications where non-combustible elements are commonly used as part of a DTS Solution, if other design features such as the use of Fire-protected Timber and/or automatic sprinkler systems are adopted to maintain structural stability appropriate to the listed parameters in CP1. These include parameters for consideration such as fire brigade intervention and any active fire safety systems installed in the building.

CP1 Structural stability during a fire

A building must have elements which will, to the degree necessary, maintain structural stability during a fire appropriate to—

(a)the function or use of the building; and

(b)the *fire load*; and

(c)the potential *fire intensity*; and

(d)the *fire hazard*; and

(e)the height of the building; and

(f)its proximity to *other property*; and

(g)any active *fire safety systems* installed in the building; and

(h)the size of any *fire compartment*; and

(i)*fire brigade* intervention; and

(j)other elements they support; and

(k)the *evacuation time*.

CP2 Spread of fire

(a)A building must have elements which will, to the degree necessary, avoid the spread of fire—

(i)to *exits*; and

(ii)to *sole-occupancy units* and *public corridors*; and

Application:
CP2(a)(ii) only applies to a Class 2 or 3 building or Class 4 part of a building.

(iii)between buildings; and

(iv)in a building.

(b)Avoidance of the spread of fire referred to in (a) must be appropriate to—

(i)the function or use of the building; and

(ii)the *fire load*; and

(iii)the potential *fire intensity*; and

(iv)the *fire hazard*; and

(v)the number of *storeys* in the building; and

(vi)its proximity to *other property*; and

(vii)any active *fire safety systems* installed in the building; and

(viii)the size of any *fire compartment*; and

(ix)*fire brigade* intervention; and

(x)other elements they support; and

(xi)the *evacuation time*.

Figure 45: Comparison of performance requirements CP1 and CP2.

Figure 45 is a derivative of the performance requirements CP1 and CP2 of the NCC provided by the Australian Building Codes Board © 2020. (ncc.abcb.gov.au/).

The parameters for consideration can be assigned to the following categories but some parameters may cover more than one category:

- fire hazards
  - fire load
  - fire intensity
  - fire hazard
- mitigation measures
  - any active fire safety systems installed (e.g. automatic sprinkler systems, detection and alarm systems. etc)
  - evacuation time
- risk exposure (people and property), e.g.
  - number of occupants and vulnerability (function and use of the building)
  - other property at risk.

Under the NCC performance-based code, terms such as partial protection, full protection or capable of withstanding burnout require further quantification because it is the residual risk after considering the performance of all fire safety systems (mitigation measures) in combination with the fire hazards and risk exposures that needs to be considered.

For example, the term 'withstanding burnout without qualification' implies that in the event of any fire the structure of a building will remain intact and continue to perform its design function. However, common approaches included consideration of average or 80 percentile fire loads, and as a consequence there is a residual risk of failure if no other interventions occur that will be further increased when material variations and the probability of gross failures are considered.

It is necessary and required by the Performance Requirements for fire resistance to be treated as part of a holistic fire safety framework under the NCC and that the required FRLs (or other means of specifying fire-resistant construction) are determined to limit the risk of collapse to the required level after taking account all the parameters listed for consideration in the relevant performance requirements.

6.3.4 Specification/Evidence of Suitability for fire resistance of building elements

Clause A5.4 of the NCC Governing Requirements nominates specific requirements that apply to the determination of Fire Resistance Levels (FRLs) if the DTS pathway is adopted. These are provided in Schedule 5 of the NCC. If FRLs are to be specified as part of a Performance Solution it is also appropriate in most circumstances, as a minimum, to reference A5.4 for specification purposes.

Options for determining the FRL of an element are summarised in Clause 2 of Schedule 5 which is reproduced in the following text box:

2. Rating

A building element meets the requirements of this Schedule if—

(a) it is listed in, and complies with Table 1 of this Schedule; or

(b) it is identical with a prototype that has been submitted to the *Standard Fire Test*, or an equivalent or more severe test, and the FRL achieved by the prototype without the assistance of an active fire suppression system is confirmed in a report from an *Accredited Testing Laboratory* which—

(i) describes the method and conditions of the test and the form of construction of the tested prototype in full; and

(ii) certifies that the application of restraint to the prototype complied with the *Standard Fire Test*; or

(c) it differs in only a minor degree from a prototype tested under (b) and the FRL attributed to the building element is confirmed in a report from an *Accredited Testing Laboratory* which—

(i) certifies that the building element is capable of achieving the FRL despite the minor departures from the tested prototype; and

(ii) describes the materials, construction and conditions of restraint which are necessary to achieve the FRL; or

(d) it is designed to achieve the FRL in accordance with—

(i) AS/NZS 2327, AS 4100 and AS/NZS 4600 if it is a steel or composite structure; or

(ii) AS 3600 if it is a concrete structure; or

(iii) AS 1720.4 if it is a timber element other than *fire-protected timber,*; or

(iv) AS 3700 if it is a masonry structure; or

(e) the FRL is determined by calculation based on the performance of a prototype in the *Standard Fire Test* and confirmed in a report in accordance with Clause 3; or

(f) for *fire-protected timber,* it complies with Specification C1.13a where applicable.

A more detailed review of Evidence of Suitability is provided in Chapter 6 of WoodSolutions Technical Design Guide 17[8]. The following is a brief overview of the options:

Because no timber elements are listed in Table 1 of Schedule 5, the following are the options for such elements.

- A report of a Standard Fire Test prepared by an Accredited Testing Laboratory (ATL) and where appropriate a report from an ATL that certifies that a building element is capable of achieving an FRL despite minor variations from a tested prototype are commonly used as Evidence of Suitability and are required for DTS Fire-protected Timber Solutions for mid-rise construction.
- Determination of the FRL by calculation based on the performance of a prototype as described in Clause 3 of Schedule 5 is restricted to minor variations. It is common for product suppliers to request that these minor variations are included in a general (field of application) assessment prepared by an ATL using data from one or more fire-resistance tests. This approach enables test programs to be designed to generate the necessary information in a cost-effective manner.

- Design in accordance with AS 1720.4 is commonly used for applications where its use is appropriate. Note: Use of AS 1720.4 is not permitted to determine the FRLs of Fire-protected Timber elements used as a DTS Solution and AS 1720.4 excludes the use of the Standard for certain types of elements and adhesives. An overview of AS 1720.4 is provided in Section 6.4.

The NCC DTS Provisions include enhanced requirements for Fire-protected Timber elements of construction in addition to the prescribed FRL to compensate for the relaxation of the requirements for elements of construction to be non-combustible or of masonry or concrete construction. The requirements for Fire-protected Timber are provided in Specification C1.13a of the NCC and include requirements for:

- non-combustible coverings to be used
- extended application of the Resistance to the Incipient Spread of Fire (RISF) criteria to walls as well as ceilings.
- modified RISF criteria for application to Massive Timber construction
- use of cavity barriers within some elements of construction
- where cavities are present any insulation within the cavities must be non-combustible.

Generally, the requirements for Evidence of Suitability for Fire-protected Timber are consistent with those for fire-resistant building elements except that:

- calculation of the FRL in accordance with methods such as AS 1720.4 is not permitted. (i.e., FRL performance has to be determined on the basis of AS 1530.4 fire tests)
- Evidence of Suitability verifying coverings and insulation are non-combustible is required
- Evidence of Suitability that the Resistance to Incipient Spread of Fire or modified criteria have been satisfied (for walls and ceilings) is required
- Evidence of Suitability for internal cavity barriers if they are required for the form of timber elements selected.

6.4 AS 1720.4 fire resistance of timber elements – calculation method

AS 1720.4:2006[21] and AS /NZS 1720.4:2019[19] apply a reduced cross-section method for calculating the fire resistance performance under the criteria for structural adequacy for the following wood products as an alternative to a fire test in accordance with AS 1530.4.

- sawn timber
- timber poles
- plywood
- laminated veneer lumber (LVL)
- glued-laminated timber elements.

The 2019 edition of the NCC references the AS 1720.4:2006 edition but both versions of AS 1720.4 apply similar methods and are described below. The NCC reference to the 2006 edition is expected to be updated by reference to later editions.

The following structural adhesives are permitted to be used by AS 1720.4; if other adhesives are used, evaluation through testing to AS 1530.4 is required:

- phenol
- resorcinol
- phenol – resorcinol
- poly-phenolic.

AS 1720.4:2006 limits the application of the method to structural adequacy and the standard heating regime. AS 1720.4:2019 additionally allows an estimate of insulation performance to be made but the integrity performance of barriers requires determination by testing to AS 1530.4. In such cases, the insulation performance can be verified by test at the same time.

The reduced cross-section method is based on the concept of a loss in timber section due to notional charring of any wood surfaces exposed to a standard heating regime of AS 1530.4. An effective residual section is determined using the notional charring results plus an assumed zero-strength layer to account for a reduction in strength or stiffness in uncharred wood that is affected by heat (typically to a depth of approximately 40 mm under the standard heating regime for periods up to 60 min). The effective residual section is assumed to have unchanged structural properties and the fire resistance for structural adequacy is determined by computing the capacity of the effective residual section.

A schematic showing the effective residual section concept is shown in Figure 46.

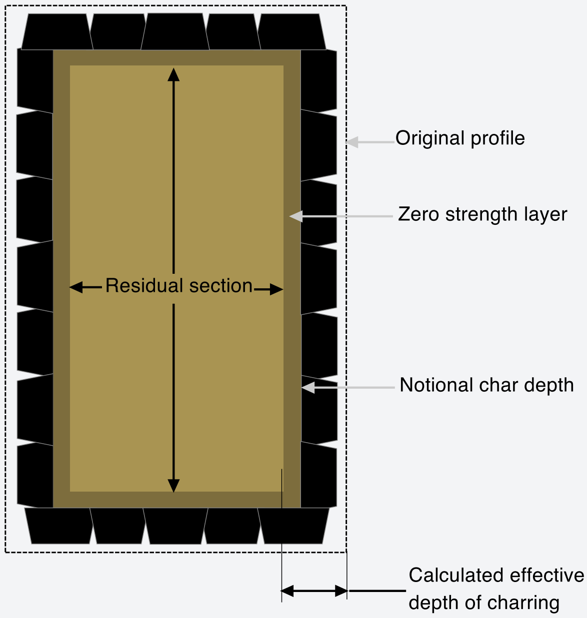


Figure 46: Schematic showing effective residual section concept.

A notional charring rate is calculated using the following relationship:

$c = 0.4 + (280/\rho)^2$

where:

c = the notional charring rate (mm/min)

ρ = timber density at 12% moisture content (kg/m^3)

Figure 47 shows typical char rates for some Australian timbers compared to the notional charring rates from AS 1720.4. The broken line defines the envelope of char rates from technical literature identified by Bartlett[11].

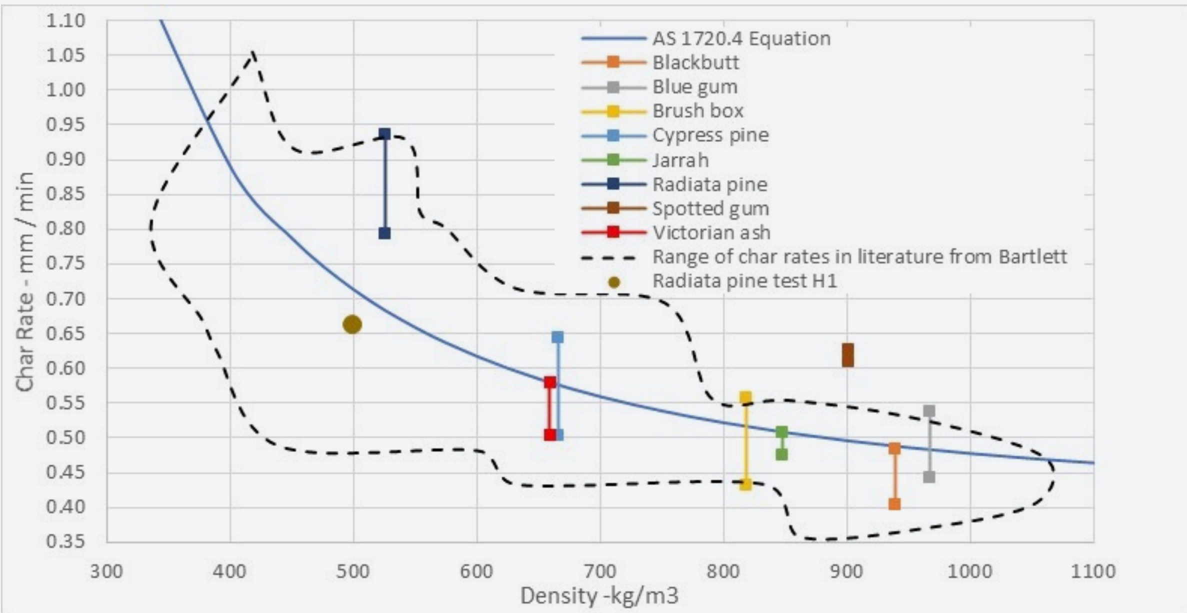


Figure 47: Density/char rate results for Australian-grown timber species subjected to a test following the procedures of AS 1530.4 1985 compared to the AS 1720.4 char rate equation.

The effective depth of charring, d_c(mm) should then be calculated at time t (min) using the following relationship:

$d_c = c\,t + 7.5$

The addition of a 7.5 mm zero-strength layer in the above equation is intended to account for the reduced structural capacity and elasticity of timber below the char layer that has increased in temperature but not exceeded 300°C (the notional temperature assumed for the onset of charring). The zero-strength layer has been rounded down to 7.0 mm in AS 1720.4:2019 for consistency with Eurocode 5 Part 1-2: 2004[46].

The validity of the use of a constant zero-strength layer thickness for a broad range of applications has been questioned, since the zero-strength layer thickness will vary with load conditions and the duration of the fire-resistance test heating regime, among other things. Useful background to the theory behind the effective residual cross-section (reduced cross-section) and sensitive to heating regimes and load conditions is provided by Schmid[135].

The application of the reduced cross-section approach to glulam timber exposed to non-standard fire curves was investigated by Lange[136], whose findings included:

> *"It is shown that the thickness of the zero-strength layer is dependent on the temperature time curve to which the timber is exposed in the furnace and that the 7 mm zero-strength layer prescribed in EN 1995-1- 2:2004 may be un-conservative for members in bending. For the cases studied, the zero-strength layer thickness in bending is shown to be around about 15 mm under standard fire exposure and 16 mm under exposure to a long cool parametric fire. Conversely, the zero-strength layer is only 8 mm deep under exposure to a short hot parametric fire."*

Modifications are intended to be included in the next revision of Eurocode 5 to address these matters but in the meantime the use of advanced calculation methods/test data for critical structural elements is recommended to provide additional confidence.

AZ/NZS 1720.4:2019 includes an informative appendix to provide general guidance on the use of advanced calculation methods.

AZ/NZS 1720.4 also includes more detail about the use of the reduced cross-section method for protected timber elements, which assumes no charring until the surface temperature of the timber exceeds 300°C and requires the time to be determined from a fire-resistance test with the protection (insulation) remaining in place. For the remaining time that the protection remains in place, the notional charring rate is taken as that for exposed timber but if the protection falls away the notional charring rate is doubled until a char depth of 25 mm is attained. Since this method requires test evidence of the protection time to be obtained in many instances, the test may be performed under load and/or temperatures of the timber cross-section measured through the test facilitating the use of advanced calculation methods and direct application of the test data as appropriate Evidence of Suitability.

6.5 Characterisation of Design Fire exposure for fully developed fires

6.5.1 Background

From a general consideration of the fire dynamics of enclosure fires the following can be observed:

- Maximum temperatures occur when the conditions within the enclosure are close to stoichiometric.
- If ventilation is restricted and/or the production of volatiles generates a strongly ventilation-controlled regime, maximum temperatures may be reduced.
- If the fire is fuel controlled, temperatures will tend to reduce as ventilation increases and increase if the fuel burning/ pyrolysis rate is increased until stoichiometric conditions are reached.
- As a fully developed fire progresses all the burning regimes described in the dot points above may occur.
- If it is assumed all combustion occurs within the enclosure with conditions close to stoichiometric, increasing the fire load will increase the duration of the fire. However, if the increase in fire load causes the fire to be strongly ventilation controlled (a high excess fuel factor) the enclosure temperatures may be reduced but flame extensions from openings and combustion outside the fire enclosure will be increased.
- Enclosure boundaries with high thermal inertias (high values of ($k\rho c$)), such as normal weight concrete, will exhibit lower temperatures during a fully developed fire compared to the same enclosure with the enclosure boundaries having low thermal inertias (e.g. autoclaved aerated concrete).

As a result, ventilation conditions, thermal properties of bounding constructions and fire load (magnitude and burning characteristics) all impact on the maximum enclosure temperatures, which generally vary within the range of 800°C to 1200°C during the fully developed fire stage. With increasing emphasis on sustainable construction materials and methods, systems providing high levels of insulation to external walls (low $\sqrt{(k\rho c)}$ values) are preferred. Therefore, it is unlikely that the fire exposure will approximate to the standard heating regime of AS 1530.4 for most enclosure fires even when there are no exposed timber structural elements.

This is demonstrated in Figure 48, which shows enclosure temperatures derived from 19 natural fire tests undertaken on non-combustible or fully encapsulated timber structures that are summarised in Appendix B. The natural fire temperatures are compared to the standard AS 1530.4 heating regime, the AS 1530.4 Appendix B Hydrocarbon heating regime and a modified hydrocarbon heating regime with a maximum temperature of 1200°C.

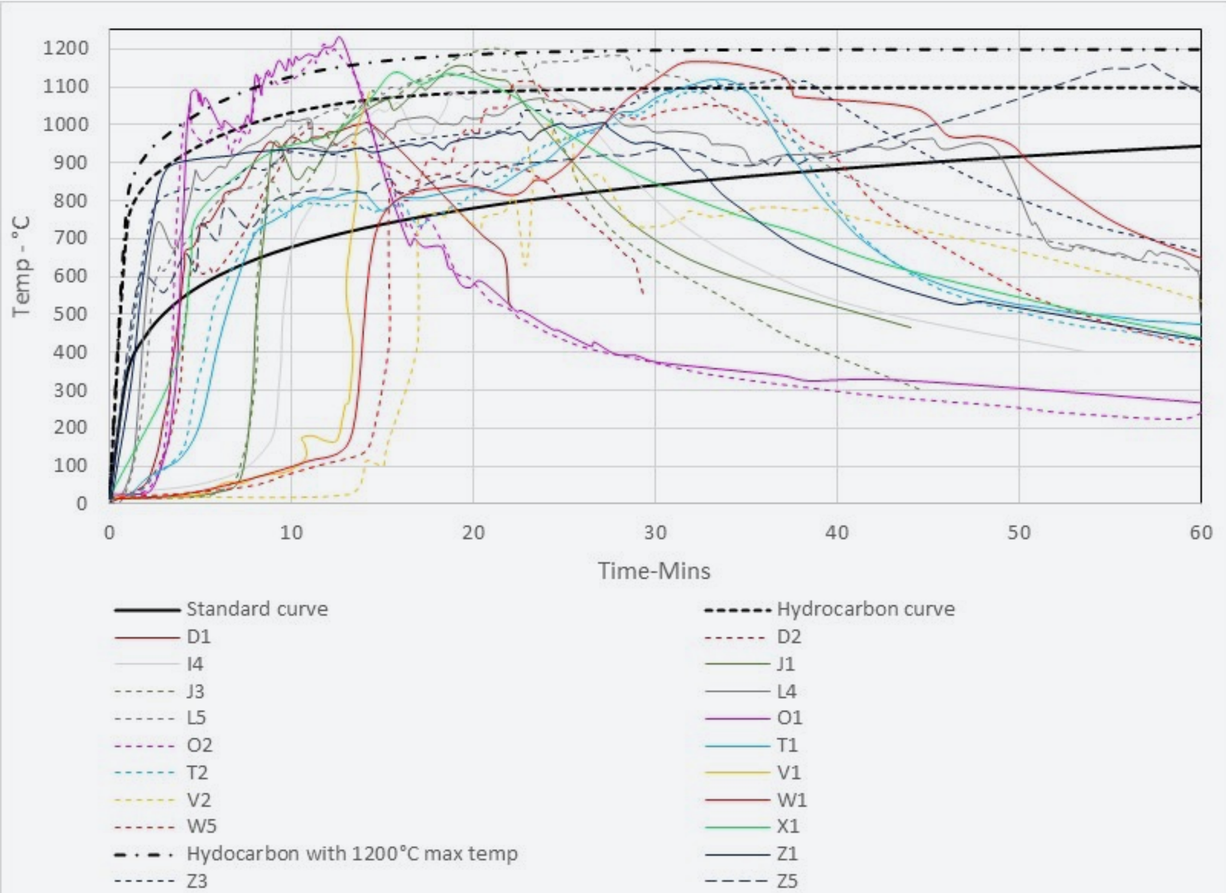


Figure 48: Natural enclosure fire temperatures for non-combustible construction and fully encapsulated timber constructions compared to standardised furnace test time/temperatures. Note: Refer to Appendix B for cross reference to source of natural fire test data.

It can be observed that for most of the fully developed fire stage, the enclosure temperatures were between the standard and hydrocarbon furnace temperatures. Therefore, if an element has been tested under the standard and hydrocarbon heating regimes, calculation methods used to determine times to failure can be verified against heating regimes that bracket a large proportion of exposure conditions.

6.5.2 Procedures and models for deriving enclosure temperature regimes

There are numerous correlations and models for deriving time/temperature regimes for post-flashover compartment fires which take account of the fire load, ventilation and thermal properties of boundaries, including:

- design charts (e.g. Magnusson and Thelandersson[70])
- parametric relationships (e.g. Eurocode 1 Part 1.2 Annex A[39])
- zone models (e.g. Babrauskas[71] – the Babrauskas model has been adapted for and developed further within the B-Risk Software package[72]).

A detailed review of these methods has been provided by Hurley[69] and the combinations of these inputs can provide an infinite distribution of Design Fires to which elements of construction may be exposed. This variability is also reflected in natural fire experiments.

In order to specify and evaluate products objectively and encourage innovation it is useful to have a standardised exposure and performance criteria. This is one of the major reasons that the standard fire-resistance test continues to serve a useful role. However, a review of natural fire experiments (and predicted fire exposures) indicates that enclosure temperatures may substantially exceed the AS 1530.4 standard heating regime particularly during a critical period for life safety following flashover.

More representative exposures of these scenarios can be obtained by adopting an alternate heating regime for evaluation of fire resistant construction. This has been recognised by Beyler[68], England[110] and numerous others. AS 1530.4 Appendix B incorporates an alternate hydrocarbon heating regime for this purpose but like the standard fire resistance heating regime it does not include a decay/cooling phase.

There are various methods that can be used to equate fire exposures to a time to exposure to the standard fire resistance heating regime. The time equivalence is generally calculated, based on the fire load, ventilation conditions and some of the methods include modifications to account for the thermal properties of the enclosure boundaries.

For example, Annex F of EN 1991-1-2 : 2002[39] is a typical example of a time equivalence approach and is described in NCC FSVM handbook Annex Data Sheet B3[14] with guidance relating to its application under the NCC Fire Safety Verification Method. The guidance in Data Sheet B3 can also be useful if other performance approval pathways, other than the Fire Safety Verification Method, are adopted.

There are a number of significant limitations with time equivalency methods, such as Annex F of EN 1991-1-2: 2002, including:

- These methods simply calculate the FRL expected to resist total burn-out of the combustibles within an enclosure and are not suitable as a standalone method for evaluation of exposed structural timber where the timing and potential for self-extinguishment requires consideration.
- If an element or component is expected to fail during a fire scenario, the fire scenario time at failure is not established.
- Sensitivities to higher temperatures and increased heating rates are not evaluated.
- Unless fire-protected structural timber elements are fully encapsulated (i.e. protection equivalent to the FRL required to resist total burn-out) the method will be unsuitable.

Some of these limitations can be addressed by a two-stage process defining enclosure time/temperature regimes and then using a target element to determine equivalent fire damage either by thermal analysis (e.g. equivalent temperatures of a component or at a specific depth), or by undertaking structural analysis and comparing the times to structural failure. An example of this approach is described in NCC FSVM handbook Annex Data Sheet C8[14]. Alternatively, more complex methods involving modelling heat transfer to and within each element of construction and then modelling the functional performance using material properties at elevated temperatures may be applied.

Greater confidence in these methods can be obtained if the methods and inputs can be validated against the performance achieved when exposed to heating regimes that effectively bracket the Design Fires being evaluated.

The standard heating regime of AS 1530.4 can be considered to approximate to the lower bound for many enclosure configurations. The following discussion relates to the identification of a reasonable upper bound and appropriate exposures for the decay and cooling phase.

6.5.3 Simple generic characterisation of the fully developed phase

A simple generic characterisation of fully developed fires can be obtained based on the Constant Compartment Temperature Method presented in the SFPE Engineering Standard S.01 2011[137] by assuming:

- a rapid growth rate
- a nominal peak temperature maintained until burnout
- fire is ventilation controlled and is burning under stoichiometric conditions.

Applying the above assumptions, the mass flow of air into the enclosure at stoichiometric conditions is approximately:

$\dot{m}_a = 0.5A_w H^{1/2}$

where:

$\dot{m}_a$ is the mass inward flow of air (kg/s)

A_w is the area of the opening (m^2)

H is the height of the opening (m)

The heat of combustion of air for most materials is of the order of 3 MJ/ kg.

Therefore, the heat release rate $\dot{q}_C$ within the enclosure will be approximately $1.5A_w H^{1/2}$ MW.

The total fire load in an enclosure is the product of the fire load density (E [MJ/m^2]) and floor area (A_f [m^2])

Therefore, the duration to burnout (D [min]) is given by:

$$D = \frac{E.A_f}{90A_W\sqrt{H}}$$

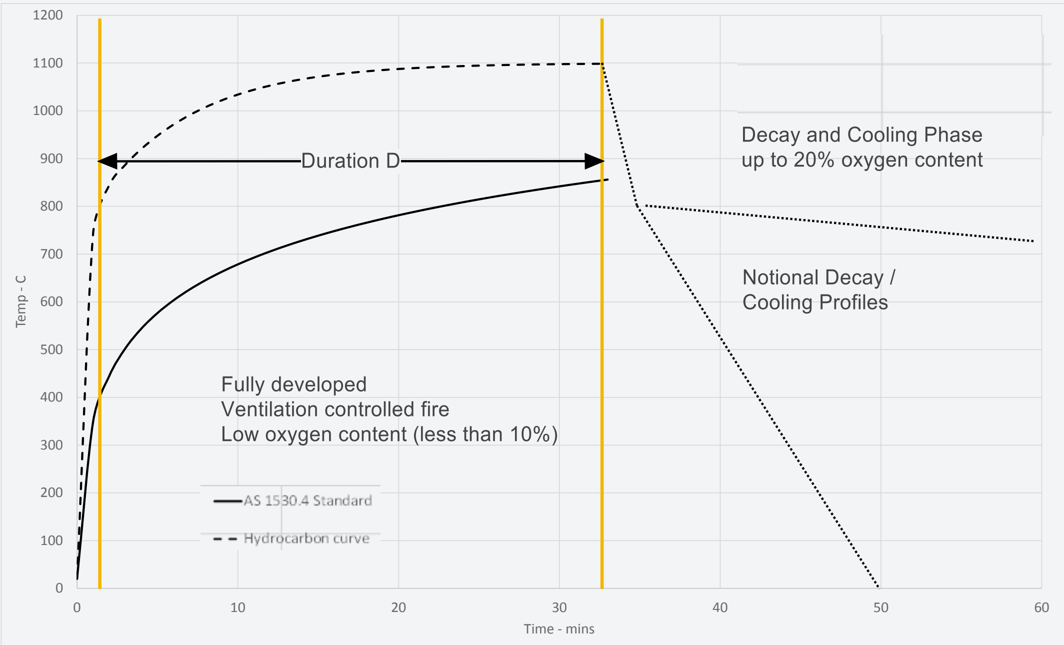
The SFPE Standard nominates a maximum constant temperature of 1200°C, which will provide a conservative exposure if maintained to burnout in most applications. However, there is a significant body of tests using the hydrocarbon regime specified in AS 1530.4 Appendix B[18] that maintains a constant maximum temperature of 1100°C. While peak enclosure temperatures greater than 1100°C can occur, particularly in enclosures with bounding construction having a low thermal inertia, a constant peak temperature of 1100°C maintained over the duration of a fully developed fire provides a reasonable representation of the fully developed phase.

An idealised time/temperature characterisation of a fully developed fire based on the hydrocarbon heating regime for the fully developed phase is shown in Figure 49 and compared to the standard AS 1530.4 heating regime.

The fire growth period is short, based on the AS 1530.4 hydrocarbon regime applying a more realistic thermal action in the initial stages of the fire than the standard AS 1530.4 heating regime.

The fully developed fire duration is assumed to commence after 3 min at temperatures above 800°C and is maintained until the moveable fire load is consumed. If the fire is ventilation controlled, oxygen concentrations will be low and can be considered to be reasonably represented by a fire-resistance furnace maintaining oxygen concentrations below 10%.

Figure 49: Generic characterisation of Design Fire exposure for fully developed fires.



The decay phase will generally be in an environment with relatively high oxygen concentrations. Further characterisation of a generic cooling phase with respect to temperature and/or heat flux will be sensitive to the thermal inertia of the enclosure boundaries, size of ventilation openings and nature of the fire load. Potentially, this can be addressed by nominating options for the decay/cooling phase and/or adjusting the fire duration to compensate for the cooling phase. These factors are considered in the following comparison against experimental data shown in Figure 50 to Figure 53.

6.5.4 Comparison of design exposure with typical data from natural fire tests without contribution from combustible walls and ceilings

In the past two decades numerous large-scale natural fire tests have investigated the performance of timber structures, including control experiments, in scenarios where all timber structural members are fully protected. Typical examples are summarised in Appendix B.

Various types of fuels and fuel configurations have been used in these tests, including gas and liquid fuels, timber cribs and representative furnishings to simulate moveable fire loads. The behaviour of the fuel can influence the outcomes of tests particularly if the potential for self-extinguishment of exposed timber members is being evaluated. The characteristics of the fire load will vary between occupancy types but in many instances there will be a mix of materials and elements with different surface area to mass ratios that will significantly impact burning rates.

A good example is residential occupancies where significant proportions of plastics and light furnishing will be present that will tend to burn rapidly, leaving heavier objects such as bookcases and furniture framing to continue burning over an extended period, potentially applying sufficient heat flux to any nearby exposed timber elements to maintain flaming and/or smouldering combustion.

The exposure of structural elements tends to be terminated rapidly and sometimes instantaneously when using gaseous and liquid fuels, which yields unrepresentative exposures during the decay phase. While not as extreme, timber cribs are commonly designed using constant stick dimensions throughout, which will tend to burn down at the same rate as the fuel is exhausted. Fortunately, there has been significant work characterising the fire load in residential occupancies and tests undertaken with representative furnishing configurations as shown in Figure 50. Refer to Appendix B for further details of these tests.

Due to the relatively low thermal inertia of the boundaries, high internal temperatures (exceeding 1100°C) were attained. Table 33 shows a comparison between the calculated duration and the duration estimated based on the time enclosure temperatures were above 800°C.

The temperatures and duration are also influenced by the available ventilation. Calculated durations varied from 16 min to 62 min whereas the time enclosure temperatures exceeded 800°C varied from 12 min to 39 min. In all cases the calculated duration exceeded the measured duration, providing conservative results.

Table 33: Comparison of calculated duration and duration enclosure temperatures were above 800°C in various experiments with contributions from moveable fire load only.

Test Refs	Opening factor O ($m^{1/2}$)	Fire Load Density E (MJ/m^2)	Open Area A_w (m^2)	Open Height	$A_w\sqrt{H}$ ($m^{3/2}$)	Floor Area A_f (m^2)	$E.A_f$ (MJ)	D_{calc} (min)	$D_{800\ act}$ (min)
O1, O2	0.084	570	3.87	2.1	5.6	14.48	8254	16	12
I4, J1	0.042	553, 614	2.14	2	3.0	15.75	9190	34	19
X1	0.03	550	1.52	2	2.1	10.8	5950	31	28
W1	0.03	550	3.6	2	5.1	41.86	23023	50	38
L5	0.039	976	2.25	1.5	2.8	15.96	15577	62	39

Notes: Fire loads comprise furnishings except test X1, which used timber cribs. Wall and ceilings were lined with plasterboard. Start times are offset to approximately align flashover times in the range of 0 to 3 min.

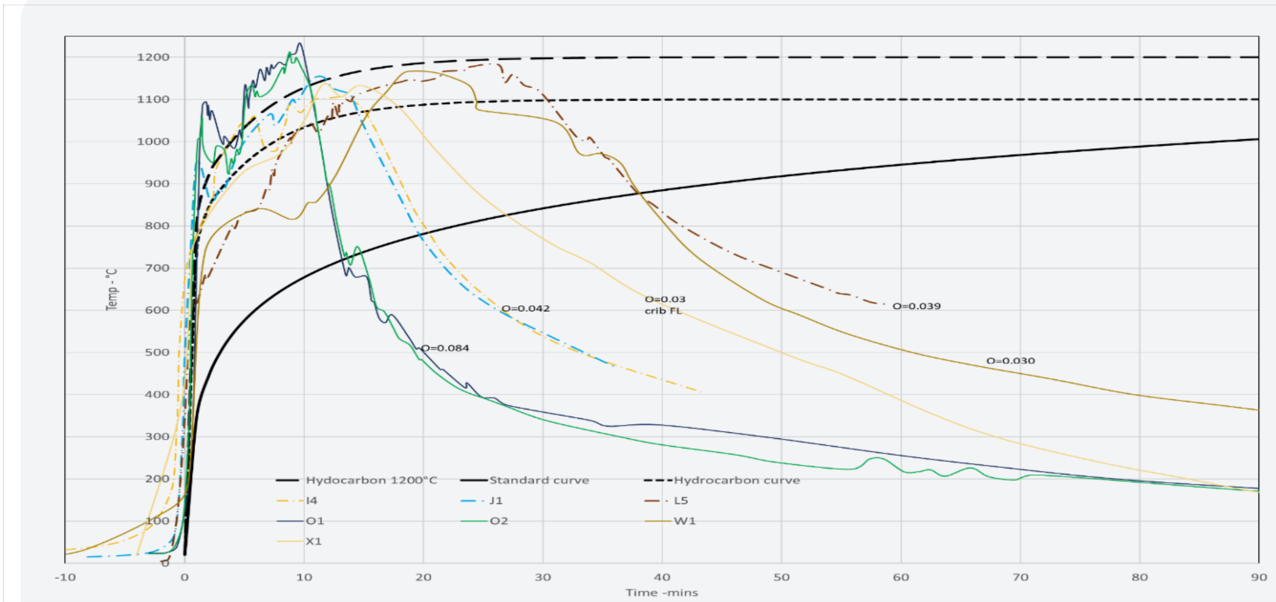


Figure 50: Typical fire test enclosure temperatures from natural fire tests with no contribution from the enclosure perimeter walls and ceiling.

The decay/cooling phase after the temperature has dropped below 800°C is shown in Figure 51 for fire loads comprising typical furnishings, except for test X1 which used timber cribs as the fire load.

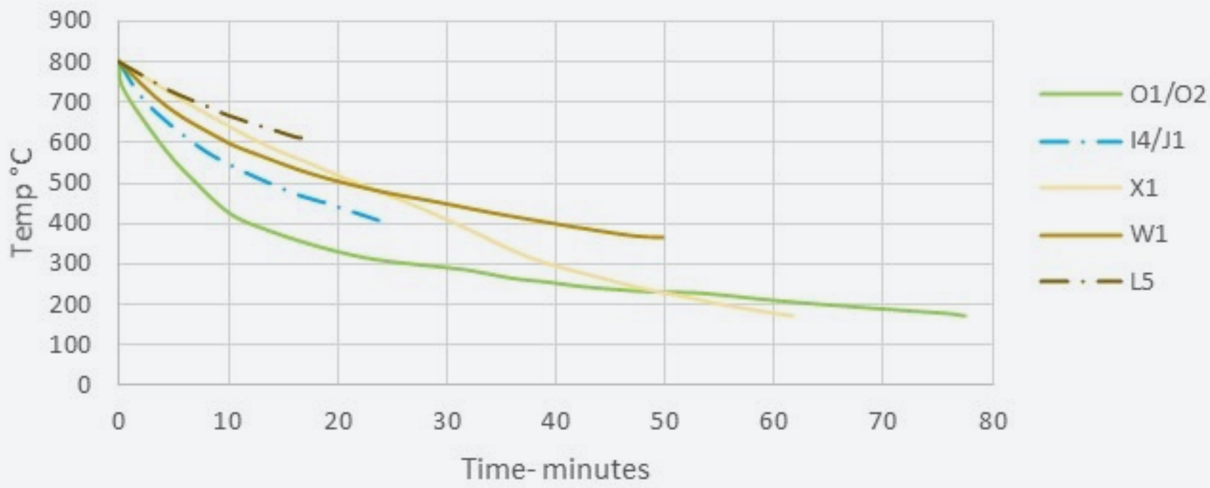
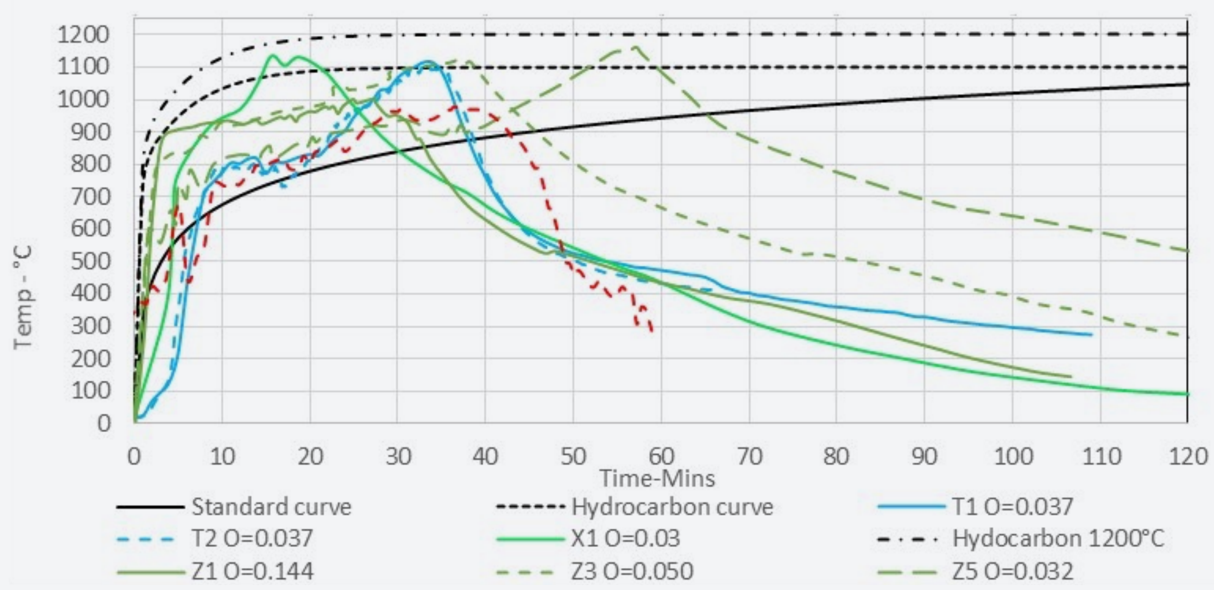


Figure 51: Decay/cooling phase temperatures from time enclosure temperature falls below 800°C. Note: Fire loads comprise furnishings except test X1, which used timber cribs.

Examples of enclosure temperatures obtained from tests performed with timber cribs simulating the moveable fire load are plotted against time in Figure 52. Refer Appendix B for further details of tests. Some of these enclosures (Z1, Z3 and Z5) had higher thermal inertia boundaries which, as expected, extended the cooling phase compared to enclosures with similar ventilation conditions but lower thermal inertia boundaries because of re-radiation and convective heat transfer of the heat absorbed by the boundary elements to the enclosure. Tests Z1, Z3 and Z5 also showed that the fully developed phase and decay/cooling phases reduced in duration as the ventilation to the enclosure was increased. It is also expected that the larger timber crib cross-section for tests Z1, Z3 and Z5 would tend to extend the duration of the fully developed fire phase.



Notes: Fire loads comprise timber cribs. Wall and ceilings lined with plasterboard except tests Z1, Z3 and Z5 with normal weight concrete slab and AAC walls. Start times for test G3 adjusted so that time to flashover occurs between 0 and 10 min.

Figure 52: Typical fire test enclosure temperatures from natural fire tests using timber cribs as the fire load with no contribution from the enclosure perimeter walls and ceiling.

Table 34 shows a comparison between the calculated duration and the estimated duration based on the time enclosure temperatures were above 800°C for tests using timber cribs to simulate the fire load. The conditions for tests Z1 and Z3 were fuel controlled and the burning rate was dependent on the crib configuration, which accounts for the underestimate of the fire duration.

Table 34: Comparison of calculated duration and duration enclosure temperatures were above 800°C in various experiments with timber cribs as the fire load.

Test Refs	Opening factor O ($m^{1/2}$)	Fire Load Density E (MJ/m^2)	Open Area A_w (m^2)	Open Height	$A_w\sqrt{H}$ ($m^{3/2}$)	Floor Area A_f (m^2)	$E.A_f$ (MJ)	D_{calc} (min)	$D_{800\ act}$ (min)	Crib X-section (mm x mm)
T1,T2	0.037	718	2.4	1.2	2.63	16	11488	48.5	27	40 x 40
X1	0.03	550	1.52	2	2.15	10.8	5940	30.7	26	38 x 89
G2	0.024	450	1.4	1	1.4	12	5400	42.9	31	50 x 50
Z1	0.144	891	10	2	14.14	24	21384	16.8*	30	90 x 90
Z3	0.050	891	4.5	2	6.36	24	21384	37.4*	46	90 x 90
Z5	0.032	891	2.2	2	3.11	24	21384	76.4	67	90 x 90

**The assumption of a ventilation-controlled fire did not apply to test and fuel configurations in tests Z1 and Z3 through significant parts of the test.*

The decay/cooling phase after the temperature has dropped below 800°C is shown in Figure 53.

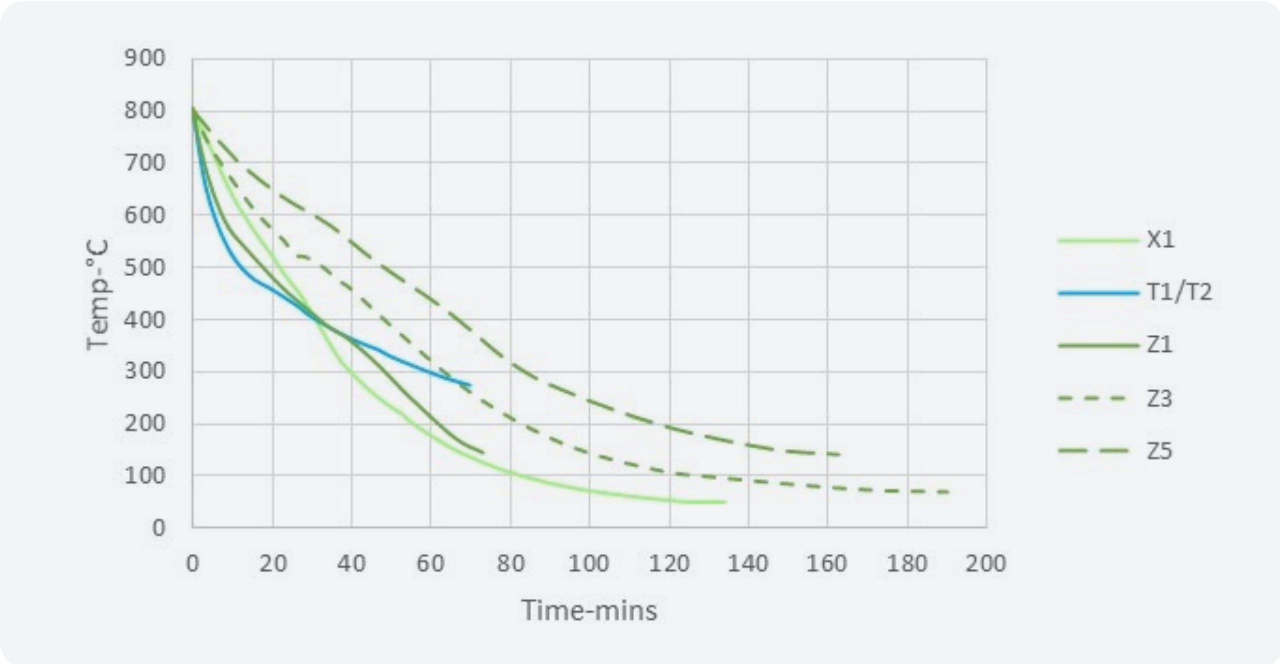


Figure 53: Decay/cooling phase temperatures from time enclosure temperature falls below 800°C. Fire loads comprise timber cribs. Wall and ceilings lined with plasterboard except tests Z1, Z3 and Z5 with normal weight concrete slab and AAC walls. Test G2 has been excluded because the fire may have been suppressed during the decay phase.

6.5.5 Typical natural fire tests with exposed timber elements

Potential fully developed enclosure fire scenarios that may occur with timber construction include:

a) Continuation of the fully developed phase after consumption of the moveable fire load due to the exposed timber until structural failure if there is no intervention.

b) Breakdown of fire-protective coverings, exposing timber elements prior to consumption of the moveable fire load leading to:

   i. Flaming combustion of timber elements and potentially secondary flashover or extended fully developed phase which may cause collapse if there is no intervention;
   or

   ii. Reduced combustion potentially transitioning to termination of flaming combustion of timber elements of construction as the moveable fire load is consumed. If this transition occurs and there is no intervention, the smouldering combustion may self-extinguish, continue, or re-establish flaming combustion depending on the details of the enclosure geometry, thermal properties, distribution of remaining combustibles and joint/connection details and airflows.

c) Fire-protective coverings remain intact and prevent a significant contribution to the fire throughout the fully developed phase and beyond burnout of the moveable fire load.

d) Partial exposure of Massive Timber (as an architectural feature) leading to:

   i. Flaming combustion of Massive Timber and potentially secondary flashover or extended fully developed phase;
   or

   ii. Termination of flaming combustion of the Massive Timber as the moveable fire load is consumed – smouldering combustion may self- extinguish, continue until structural failure or intervention, or flaming combustion may be re-established.

Figure 54 shows enclosure temperatures from natural fire tests that reflect the above scenarios.

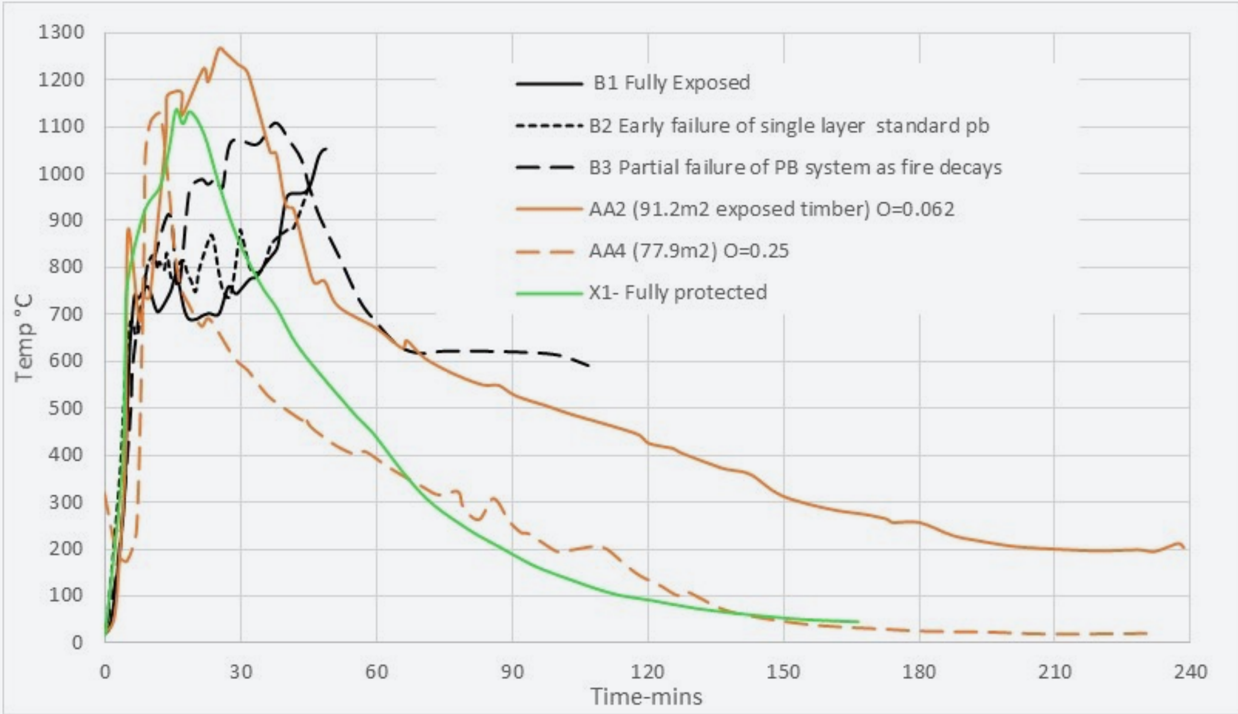


Figure 54: Enclosure temperatures from natural fire tests reported by Hakkarainen[57], Brandon[43] and Su[113].

Scenario a) was demonstrated in test B1 and scenario b)i was demonstrated in test B2. In both cases the excess volatiles produced tended to reduce enclosure temperatures until the volatiles produced by the moveable fire load reduced. The fully developed phase continued in these tests until the fire was manually supressed.

Scenario b)ii was demonstrated in Test B3, where a more-effective fire-protective covering system was selected compared to test B2. However, flaming combustion at enclosure temperatures of approximately 600°C continued until the fire test was terminated.

Scenario c) was demonstrated in test X1.

Scenario d)ii was demonstrated in tests AA2 and AA4 with flaming combustion ceasing. Smouldering combustion continued in test AA2 but in test AA4 the smouldering combustion self-extinguished.

These examples demonstrate the potential for substantial variability in decay scenarios, including extended fully developed phases, extended decay phases and rapid decay phases, as discussed in the next sub-section.

6.5.6 Variability of the decay/cooling phase

Overview

The rate of decay and cooling of enclosures has been shown in the review of natural fire tests to vary significantly with a number of factors such as:

- the thermal inertia of the boundaries
- ventilation
- combustion of timber structural elements
- duration and severity of the fully developed phase prior to decay/cooling.

Figure 55 shows this variability during the decay/cooling phase for typical residential type enclosures and fire loads.

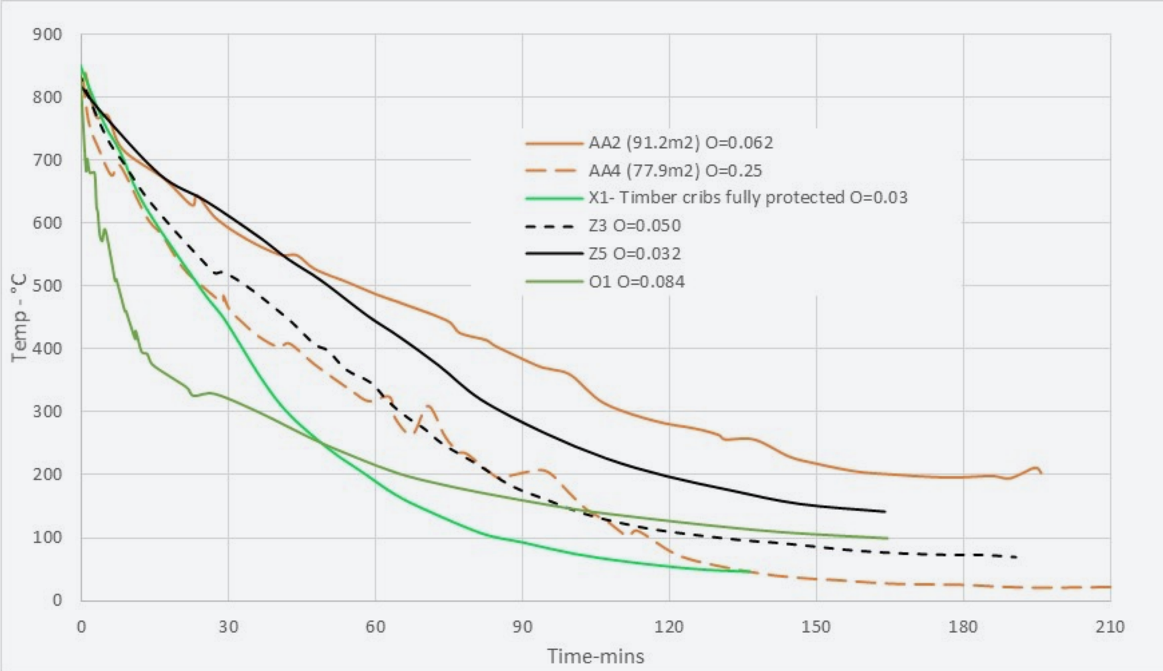


Figure 55: Representative decay phases for enclosures with exposed timber surfaces (AA2 and AA4) that cease flaming combustion without intervention, medium to high thermal inertia non-combustible construction (Z3 and Z5) and fully protected timber construction (O1 and X1).

Fire brigade intervention and the decay phase

In Australia, brigade intervention is likely to occur at some stage before the moveable and fixed fire load is fully consumed or self-extinction occurs. A holistic analysis of fire safety needs to consider scenarios where fire brigade intervention occurs prior to flashover, during the fully developed phase and during the decay phase, in addition to the rare occasions where there is no fire brigade intervention, to gain an understanding of the fire risks associated with a particular building.

The AFAC Fire Brigade Intervention Model[93, 94] provides a means to determine the initial response and estimated time to application of water for a fire scenario but the effectiveness of suppression activities will depend on variables such as:

- fire brigade response/fire ground resources
- available water supplies
- access to the fire
- fire severity
- stage of fire at time of suppression activities.

The following fully developed fire scenarios may need to be considered for multi-residential buildings within a sole-occupancy unit (SOU):

- Fire brigade suppression during early to mid-flashover stage.
- Fire brigade suppression as the fire starts to enter the decay phase (this may also address scenarios where the fire is initially controlled for a period before suppression.
- Gross defects and delayed fire brigade intervention leading to major structural and/or containment failures before fire brigade intervention.
- Delayed or no fire brigade intervention and fire enters the decay phase as moveable fire load is consumed. leading to the following potential scenario branches:
  - regrowth or continued flashover due to combustion of fixed fire load materials until structural and or major compartmentation failures
  - continued flaming combustion but at a reduced level until structural and or major compartmentation failures
  - transition from flaming to char oxidation/smouldering combustion (structural or compartmentation failures may still occur but after a longer time)
  - transition from flaming through char oxidation/smouldering combustion to self-extinction.

Which of these or other scenarios are relevant to a particular project should be determined and agreed during the PBDB process, together with the depth of analysis necessary for each scenario. In some cases, the outcomes may be self-evident and no further analysis is required other than determining the probability of occurrence. Consolidating scenarios into clusters can substantially reduce the volume of work required without compromising the quality of the analysis.

With the exception of gross defects affecting the structure and compartmentation, the fire is likely to be contained within the SOU of fire origin if:

- the structural and bounding construction can resist the fully developed fire for sufficient time to allow for fire brigade intervention or to resist burnout of the exposed fire load
- the 'reaction to fire' performance of external walls does not facilitate fire spread
- adequate separation between openings and other buildings is provided.

Under these circumstances the fire brigade will normally gain access through the SOU door to apply water to the fire.

The speed of suppression and exposure of the fire brigade personnel to hazardous conditions depends on the size of the fire and fire enclosure, among other things. For example, a fire that is in decay phase and has reduced so there is only smouldering combustion or small areas of flaming combustion presents less of a challenge to fire fighters than a fire with an extended fully developed phase.The smaller the fire, the less hazardous the conditions will tend to be for the fire fighters and the quicker a fire can be knocked down and any residual pockets of smouldering combustion can be extinguished.

An example of the impact of fire brigade intervention on a fully developed enclosure fire is the natural fire test undertaken as part of the TF 2000 project in the UK. A fire was ignited within an SOU that was part of a timber-frame mid-rise building with flashover occurring after 24 min. After 54 min, plasterboard fall-off of part of the ceiling system occurred, exposing the timber frame. The fire brigade opened the door to the SOU after 59.2 min and applied water to the fire after 64 min, which rapidly reduced the enclosure temperature from more than 900°C to less than 200°C in approximately 6 min. Further details of the test are summarised in Appendix B2. This is considered to provide a typical example of the accelerated decay if a fire is successfully supressed, although subsequent spread through the cavity highlighted the need to provide cavity barriers and for equipment to be available and procedures in place to locate and suppress smouldering combustion or combustion in concealed spaces.

Standard decay phase exposures

It is useful to define standard exposure conditions to evaluate and compare the performance of elements of construction during a simulated decay phase of a fire test that can be appended to an AS 1530.4 Hydrocarbon or Standard Heating regime or evaluated by other tests or analysis methods. Three simple multi-linear relationships are plotted in Figure 56 compared to plots of natural fire experiments where the fires were allowed to decay without intervention. Also included in the graph are:

- Enclosure temperatures from the TF 2000 fire test[138] where the fire brigade intervened at the end of the fully developed phase prior to entering the decay phase.
- Enclosure temperatures during the decay phases from tests AA2, AA4, X1, Z3 and Z5 (refer Appendix B for further details of tests)
- Exposure temperatures measured using plate thermometer below intermediate and full-scale fire-resistance test specimens raised above a furnace. The measurements were taken after the heating period to allow free access to air but maintaining a level of heat exposure from the furnace walls.

The decay profiles are further defined in Table 35.

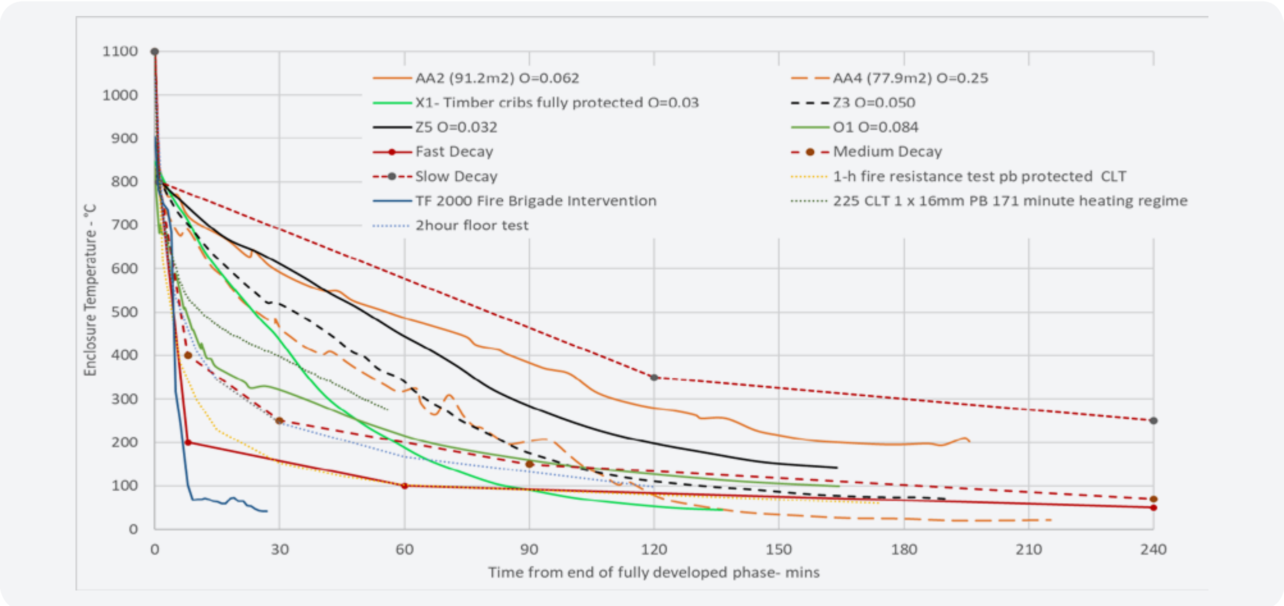


Figure 56: Proposed decay phase temperature profiles to supplement hydrocarbon heating regime.

Table 35: Decay profiles to supplement hydrocarbon heating regime tests.

Fast Decay		Medium Decay		Slow Decay	
Time (min)	Temp (°C)	Time (min)	Temp (°C)	Time (min)	Temp (°C)
0	1100	0	1100	0	1100
1	800	1	800	1	800
8	200	8	400	120	350
60	100	30	250	240	250
240	50	90	150		
		240	70		

Note: Time is from end of the 1100°C plateau if applied to the hydrocarbon heating regime or the end of the heating period for the standard heating regime.

The fast decay profile is intended to simulate well-ventilated enclosures with a low thermal inertia and no contributions from the fixed fire load or a fully developed fire that is manually suppressed by the fire brigade.

The slow decay profile is intended to simulate an enclosure with limited ventilation and a high thermal inertia, potentially with exposed timber elements smouldering with sporadic outbursts of flaming combustion. The temperature after 3 hours is compatible with performance criteria proposed by Brandon[43] that requires the plate thermometer temperatures to be below 300°C 240 min after ignition of a natural fire. Brandon indicated that the corresponding incident radiant heat flux is roughly 6 kW/m^2, which has previously been identified as one of the extinction criteria of smouldering in timber by Crielaard[31,95], Brandon also stated that achieving a complete stop of all smouldering was not an aim of the study, instead, the study aimed at assessing techniques for fire fighters of locating and extinguishing smouldering that is left after the fire.

A medium profile was defined that was representative of natural fires with a fully encapsulated structure of a short duration.

6.6 Performance of timber exposed to fully developed fires

6.6.1 Introduction

During the fully developed phase of a fire, in addition to fulfilling the required functional requirements (such as maintaining structural adequacy and/or compartmentation), exposed wood products will contribute fuel that may undergo combustion within the fire enclosure or within plumes venting through enclosure openings.

If adopting the Performance Solution pathway, it may be necessary to determine the ability of a member to satisfy its functional requirements when exposed to a fully developed fire for a required time or to withstand the entire fire scenario and continue to satisfy its functional requirements after the decay and cooling phases. In addition, it may be necessary to quantify the fuel contribution rate and duration, and determine if any continuing combustion presents an unacceptable risk. The need for, and depth of, analysis should be determined during the PBDB process, having regard for the fire hazards and holistic fire safety strategy for the building.

The NCC DTS Provisions allow the use of exposed timber for structural elements in low-rise buildings and also for specific applications in mid/high rise construction. Combustible linings are also permitted in most occupancies and therefore the DTS Provisions inherently account for some contribution from the fixed fire load.

The DTS Provisions rely on the standard fire-resistance test (AS 1530.4) and required performance is expressed in terms of Fire Resistance Levels when specifying the structural adequacy and fire separation performance that are required to provide an acceptable level of fire safety. Methods for determining the fire resistance of elements of construction in accordance with the DTS Provisions are described in the next section.

The detailed design and specification of lining materials is addressed in Chapter 5.

The DTS Fire-protected Timber provisions do not permit the use of exposed timber for structural and fire separating applications. Applications other than those described above need to follow the Performance Solution pathway.

6.6.2 Methods for design and specification of exposed timber

NCC DTS Methods – AS 1530.4 Fire Resistance Tests and AS/NZS 1720.4 calculation methods

General application of the AS 1530.4 test method and AS 1720.4 has been described in Sections 6.3 and 6.4.

Sole reliance on AS 1720.4 calculation methods for DTS Fire-protected Timber solutions for mid-rise buildings is not permitted by the NCC. Evidence of Suitability in the form of a fire-resistance test report from an Accredited Test Laboratory (ATL) based on an AS 1530.4 test or an equivalent or more severe test method is required.

In addition, AS/NZS 1720.4 places certain restrictions on its scope and application if calculation methods are used instead of an AS 1530.4 tests including:

- Determination of performance under the criteria of structural adequacy and insulation only (not integrity).
- The calculation methods apply only to; solid sawn timber and timber in pole form (circular cross-section), and to plywood, laminated veneer lumber (LVL) and glued-laminated structural timber elements fabricated in accordance with the Australian Standards nominated in AS/NZS 1720.4 using phenol, resorcinol, phenol-resorcinol or poly-phenolic structural adhesives.
- The calculation methods should not be applied to fire-retardant treated timber.
- The minimum width or thickness of any timber element before charring must be 75 mm.
- At the end of the required heating period, the minimum residual width or thickness must be 30 mm if the insulation criteria apply (a notional char depth of 23 mm plus the 7 mm thick residual char layer).

These limitations are based on the 2019 edition of AS/NZS 1720.4, but similar constraints apply to the AS 1720:2006 edition.

Notwithstanding the restrictions, it is common for many of the principles of AS/NZS 1720.4 to be considered by ATLs when defining test programs and/or assessing minor variations from tested prototypes, and by fire safety engineers if the Performance Solution pathway is used.

The primary calculation method defined in AS/NZS 1720.4 uses an empirical relationship that assumes a notional charring rate that is a function of timber density with an additional 7 mm or 7.5 mm (in the 2006 edition) allowance for a zero-strength layer to define an effective depth of charring. This is intended to account for the reduced strength of heated uncharred material. The residual load capacity is then calculated, based on the effective residual section using normal ambient temperature strength and stiffness properties. Worked examples of this effective residual section method are provided in WoodSolutions Technical Design Guide 15[139] in which it is applied to timber concrete composite (TCC) floors, timber cassette floors and post-tensioned timber beams without any fire-protective coverings.

Advanced calculation methods

Overview

Advanced calculation methods are also briefly mentioned in Informative Appendix B of AS/NZS 1720.4: 2019 where the char layer and cross-section temperature distribution of the residual section are determined, and the load capacity is calculated using thermal and structural material properties at elevated temperatures of the uncharred timber. Techniques such as finite element analysis can be used but it is generally necessary to use effective material properties to account for phenomena such as fissuring of the char layer, moisture migration and combustion. This approach can be successful if the properties are used within the validated ranges, but the use of empirical relationships still places a heavy reliance on the use of test/experimental data for validation. Appendix B of AS/NZS 1720.4 refers the reader to Annex B of Eurocode 5[42] for guidance on thermal properties of timber at elevated temperatures. General fire properties of wood including thermal properties of timber are discussed in detail in Chapter 2 of this Guide.

Generic Temperature Profiles

A relatively simple method can be adopted to define a generic temperature profile within a timber panel subjected to the standard heating regime based on an approach described by Janssens and White[140], which assumes the member behaves as a semi-infinite solid and adopts the following relationship.

$$T=T_i + (T_p-T_i)(1-x/a)^2$$

where:

T is the temperature at a distance of x from the char front (°C),

T_i is the initial temperature (20°C)

T_p is the char front temperature (300°C)

x is the distance from the char front (mm)

a is the thermal penetration depth.

This simple method relies on the assumption of a constant char rate where the temperature profile effectively moves through a timber element ahead of the char front at a constant rate. The profiles may not be applicable to other heating/char rates and will be affected if delamination occurs.

Best fit values for penetration depth (a) are provided in Table 36 for various species that were selected to investigate the relative effects of density, permeability and chemical composition. The test specimens were 230 mm × 510 mm with a thickness of 63 mm.

Table 36: Thermal penetration (best fit) depths estimated by Janssens and White[140].

Species	Dry density (kg/m³)	Thermal penetration depth best fit – a (mm)
Western Red Cedar	310	33
Red Wood	345	35
Basswood	400	32
Spruce	425	34
Yellow Popular	505	32
Southern Pine	510	33
Red Oak	665	32
Hard Maple	690	31

A general value of 40 mm is adopted if a conservative approach is necessary but a value of 35 mm or less would be expected for a line of best fit for commonly used structural timbers. The profiles for these penetration depths are plotted in Figure 57 together with the profiles for 30 mm and 50 mm thermal penetration depths to demonstrate the sensitivity to the assumed value.

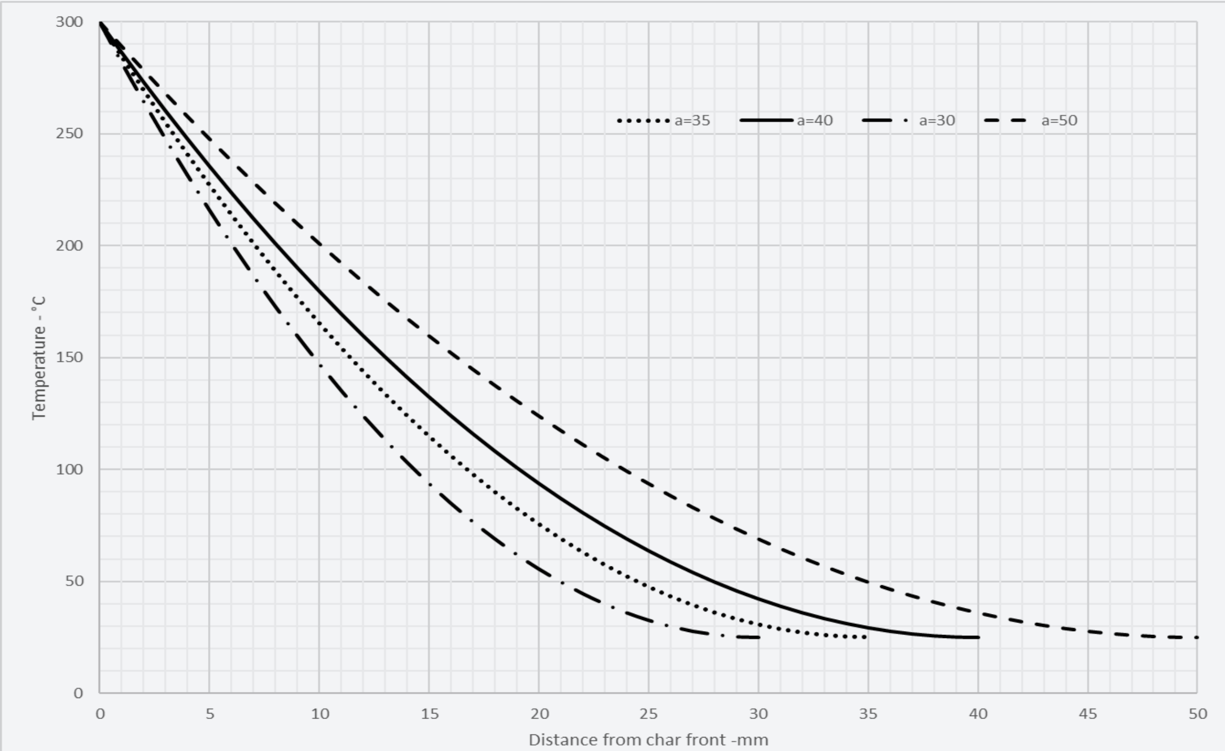


Figure 57: Generic temperature profiles for solid timber panels exposed to the standard AS 1530.4 heating regime based on approach described by Janssens and White.

Evaluation of systems prone to delamination

There are a number of innovative products that rely on structural adhesives. Some established products such as plywood, laminated veneer lumber (LVL) and glued-laminated structural timber elements, have used adhesives with moderate levels of temperature resistance such that the effective char rates of the products are similar to solid timber. This is recognised in AS 1720.4.

The remainder of this section focuses on cross-laminated timber (CLT) but many of the techniques can be applied to other systems.

Wood products such as CLT have been manufactured with a variety of adhesives, including polyurethane adhesives, that can be sensitive to elevated temperatures but have other desirable properties for manufacturers and users. Manufacturing techniques also vary with, for example, lamella being face bonded only or having sides bonded in addition to face bonding. These variables can have a significant impact on the fire-resistance performance. Figure 58 shows the cross-section of a CLT panel with face bonded lamella but no adhesive applied to the sides of the lamella.

Figure 58: Section through a CLT panel with lamella face bonded only.

There is currently no applicable Australian Standard for manufacture of CLT and therefore Evidence of Suitability for CLT and similar products tends to be specific to proprietary products. While this may lead to some repetition with respect to routine fire testing, it does provide an opportunity to design and evaluate systems to address their specific attributes.

The variability of adhesives and impact of delamination on char rates has been investigated by numerous researchers. For example, Frangi et al[141] studied fire tests at an intermediate scale in a horizontal orientation with the specimens exposed to the standard ISO 834 heating regime (similar to AS 1530.4). The study included tests on CLT panels, 60 mm thick with an additional 30 mm thick cover panel bonded to the upper surface of the CLT. Char rates were determined by measuring temperatures at the interfaces between lamella. Different adhesives and lamella thicknesses were evaluated. The combinations relevant to this discussion are summarised in Table 37.

Table 37: Charing rates from selected tests from Frangi et al tests with variations to panel make up and adhesives.

Test ref	Adhesive Type	Panel Depth (mm)	Panel make up	Parameter	Char Depth d_c (mm) at lamella interfaces				
					10	20	30	40	60
V1	MUF	60	10/10/10/10/20	t_{300} (min)	19	36	55	71	104
				c_{lam} (mm/min)	0.53	0.58	0.54	0.61	0.61
				c_{tot} (mm/min)	0.53	0.55	0.55	0.56	0.58
V2	PU1	60	10/10/10/10/20	t_{300} (min)	18	27	36	43	64
				c_{lam} (mm/min)	0.56	1.10	1.12	1.34	0.98
				c_{tot} (mm/min	0.56	0.74	0.83	0.92	0.94
V6	PU2	60	10/10/10/10/20	t_{300} (min)	18	28	36	43	67
				c_{lam} (mm/min)	0.55	1.01	1.22	1.39	0.85
				c_{tot} (mm/min	0.55	0.71	0.83	0.92	0.90
V7	PU3	60	10/10/10/10/20	t_{300} (min)	16	25	34	41	60
				c_{lam} (mm/min)	0.61	1.19	1.08	1.50	1.03
				c_{tot} (mm/min)	0.61	0.81	0.88	0.98	1.00
V9	PU4	60	10/10/10/10/20	t_{300} (min)	17	26	34	41	56
				c_{lam} (mm/min)	0.58	1.19	1.15	1.48	1.37
				c_{tot} (mm/min)	0.58	0.78	0.88	0.98	1.08
V10	PU4	60	20/20/20	t_{300} (min)	–	34	–	51	67
				c_{lam} (mm/min)	–	0.59	–	1.20	1.21
				c_{tot} (mm/min)	–	0.59	–	0.79	0.89
V4	PU1	60	30/30	t_{300} (min)	–	–	46	–	75
				c_{lam} (mm/min)	–	–	0.65	–	1.04
				c_{tot} (mm/min)	–	–	0.65	–	0.80
V5	MUF	60	30/30	t_{300} (min)	–	–	53	–	98
				c_{lam} (mm/min)	–	–	0.56	–	0.67
				c_{tot} (mm/min)	–	–	0.56	–	0.61

The lamella were fabricated from spruce boards with average densities varying from 405 kg/m^3 to 486 kg/m^3 and a mean moisture content of 10%.

Neither AS/NZS 1720.4 nor EN 1995-1-2 address CLT panels specifically. The element thickness may be regarded as less than 75 mm and therefore the general charring rates are not applicable but calculating the char rate using the approach that is permitted for glued laminated timber provides a useful benchmark for a similar material not prone to delamination.

The notional charring rates calculated in accordance with AS/NZS 1720.4 would range from 0.86 mm/min to 0.72 mm/min after adjusting the average densities to 12% moisture content (412-495 kg/m^3). These values are more conservative than the one-dimensional charring rate of 0.65 mm/min from EN 1995-1-2 but depending on interpretation of the code values up to 0.9 mm/min could be required by EN 1995-1-2.

A review of the results and reported observations in the Frangi et al[141] study indicates that the panels manufactured with melamine urea formaldehyde (MUF) adhesive did not show any evidence of delamination and fall-off of lamella while fall-off and accelerated charring was observed for all the PU adhesives.

A measure of the comparative performance can be obtained by comparing the times for the char front to progress to a depth of 60 mm, which confirms the significant deterioration in performance due to delamination:

- PU adhesives: 56-67 min
- AS 1720.4 notional char rates for solid timber (0.86-0.72 mm/min) yields: 70-83 min
- MUF adhesive: 98-104 min.

These results are consistent with the treatment of glued-laminated structural timber elements in AS/NZS 1720.4, which applies the notional char rates for solid timber, provided nominated adhesives that are not prone to causing delamination are used.

The test series described in Appendix C9 included a test on an intermediate-scale CLT panel 225 mm thick with five, 45 mm thick Radiata Pine lamella face bonded with a polyurethane adhesive with low resistance to elevated temperatures. The density of the pine was 500 kg/m^3 at a moisture content of 9% (514 kg/m^3 at 12% moisture content). The notional char rate calculated using the correlation in AS/NZS 1720.4 is 0.7 mm/min although it should be noted that application to CLT is not permitted in accordance with the current and previous editions. Delamination was observed and a review of the char rates in Table 38 confirms that the char rate after delamination increased significantly above the notional value.

Table 38: Charring rates from an intermediate-scale Radiata Pine CLT panel subjected to the AS 1530.4 Standard Heating Regime.

Test ref	Adhesive Type	Panel Depth (mm)	Panel make up	Parameter	Char Depth d_c (mm)			
					22.5	45	90	112.5
H1	PU	225	45/45/45/45/45 (Radiata Pine)	$t_{300\ (min)}$	38	60	92	110
				$c_{lam\ (mm/min)}$	0.59	0.75	1.41	1.25
				$c_{tot\ (mm/min)}$	0.59	0.75	0.98	1.02

There are two general approaches to manage the risk of delamination:

- Use adhesives that have sufficient high temperature performance to prevent delamination and if necessary, bond the edges of the lamella in addition to the faces. Evidence of Suitability for this solution is generally required to be in the form of a full-scale fire test on a loadbearing element supplemented by temperature measurements within timber elements to confirm char retention and charring rates for use in Australia.
- Use the preferred adhesive and management of the impact of delamination which may include increased effective char rates, potentially extension of the fire duration, increased severity and increased risk of failure compared to similar products that do not exhibit delamination.

A common approach to quantifying the impact of char fall-off on the fire resistance of an element of construction is to adapt the Eurocode 5 procedure for protected timber as proposed by Frangi[141]. After fall-off of the fire-protective coverings, the char rate is increased until the protective char layer is re-established. The charring rate then reverts back to the notional value.

A typical implementation of this process to determine the fire resistance of a CLT panel is described below but since this approach is outside the scope of AS/NZS 1720.4, additional fire test data relating to the specific materials, method of manufacture and with a similar arrangement of lamella would be required to validate the method and provide appropriate Evidence of Suitability:

1. Calculate the notional char rate for the element.
2. Apply the notional char rate until the first lamella bond line is reached.
3. Assume delamination occurs as the char front reaches the bond line and the effective char rate is then increased to 2 x the notional rate until the char layer is re-established. A char thickness of 25 mm is commonly suggested but should be checked as part of the validation process.
4. Once the char layer is re-established, apply the notional char rate until the next bond line is reached and repeat the process unless the heating period is exceeded
5. For the remainder of the lamella repeat steps 3 and 4.
6. When heating is terminated add the zero-strength layer and then calculate the residual load capacity using the effective cross-section or apply a more advanced method based on the temperature profile within the uncharred area.

This approach will be demonstrated and compared to the 60 mm panel results in Table 37 and the 225 mm results in Table 38.

For the 60 mm panels with 10 mm and 20 mm thick lamella it is not possible to re-establish a 25 mm char layer.

Therefore, the notional char rate applies to the first lamella only and 2x the notional char rate to the remainder of the panel. For the 2 x 30 mm layup the notional char rate applies to layer 1, and 2x the notional char rate applies to the first 25 mm of layer 2 before reverting to 1 x the notional rate for the remaining 5mm.

Calculation of the time for the char front to reach 60 mm (10/10/10/10/20 panel):

Notional char rate assumed to be 0.79 mm/min (centre of the range of values using the AS/NZS 1720.4 approach):

Lam 1:	10/0.79 =	12.7 min
Lam 2-5:	50/(2 x0.79) =	31.6 min
Time for char front to reach 60 mm =		44.3 min

Calculation of the time for the char front to reach 60 mm (20/20/20 panel):

Notional char rate assumed to be 0.79mm/min centre of the range of values using the AS/NZS 1720.4 approach:

Lam 1:	20/0.79 =	25.4 min
Lam 2 and 3:	40/(2 x0.79) =	25.3 min
Time for char front to reach 60mm:		50.7 min

Calculation of the time for the char front to reach 60 mm (30/30 panel)

Notional char rate assumed to be 0.79 mm/min centre of the range of values using the AS/NZS 1720.4 approach:

Lam 1:	30/0.79 =	38.0 min
Lam 2 Part 1:	25/(2 x0.79) =	15.8 min
Lam 2 Part 2:	5/0.79 =	6.3 min
Time for char front to reach 60mm =		60.1 min

Calculation of the time for the char front to reach 90 mm and 112.5 mm depth (45/45/45/45/45 panel)

For the 225 mm (45/45/45/45/45) CLT panel, the lamella are thick enough for the 25 mm char-insulating layer to be re-established in each lamella. Therefore, the notional char layer will be applied to the first lamella, 2x the notional rate to the first 25 mm and then 1x the notional rate for the remaining 20 mm for each of the subsequent lamella. The time to reach the bond line between the 2nd and 3rd lamella, and mid-depth of the third lamella will be calculated

Notional char rate assumed to be 0.7 mm/min for Radiata Pine with a density of 514 kg/m^3

Lam 1:	45 /0.70 =	64.3 min
Lam 2 Part 1:	25/(2 x0.70) =	17.9 min
Lam 2 Part 2:	20/0.70 =	28.6 min
Time for char front to reach 90 mm =		110.8 min

The additional 22.5 mm depth for the char front to reach 112.5 mm is less than 25 mm therefore the accelerated charring rate will apply to the first 22.5 mm of the third lamella.

Lam 3: mid-depth 22.5/(2 x 0.70) = 16.1 min

Time for char front to reach 112.5 mm = 126.9 min

Comparison of these results showed that the calculation method was conservative compared to the data in Table 37, which is to be expected because the accelerated char rates applied throughout the whole cross-section of the thinner lamella and the first 25 mm of the 30 mm lamella. Compared to the fire test results from Table 38 for the 225 mm thick CLT panel with 5 x 45 mm lamellae, the predictions were unconservative. There may be many explanations for this, including delamination occurring before the char front reaches the bond line or a need to build up a greater thickness of insulating char at higher Fire Resistance Levels to reduce the char rate. These examples highlight the need for requiring validation of empirical relationships for specific products and methods of analysis until the development and enforcement of manufacturing standards that include controls on features that affect fire properties of a system. In the case of the example in Table 38 a reasonable approach for further investigation could be to apply the notional char rate for the first lamella and 2x the notional char rate for the remaining lamella.

Note: Effective char rates of CLT can vary significantly depending on the efficacy of adhesives at elevated temperatures, configuration of panels and method of manufacture. If the CLT panels are not prone to delamination char rates may be similar to solid timber. If delamination occurs, the char rate can vary significantly depending on the CLT panel configuration, adhesives used and fabrication methods. Char calculation methods need to be validated and parameters adjusted to reflect the behaviour of each product until such time as standardised manufacturing methods and performance levels are specified. Generally, full-scale fire-resistance tests will be required on specific products to provide data for validation purposes. Delamination also affects the potential fire duration and length of the decay phase. There is a significant advantage in selecting adhesives, configurations and fabrication methods that can produce products that are not prone to delamination under fire conditions.

Charring rates for parametric heating curves

The char rates discussed above and the notional char rates from AS/NZS 1720.4 relate only to the standard heating regime specified in national and international standards such as AS 1530.4 and ISO 834 and the majority of information available relates to these fire exposures. There has been some work that has been codified in Eurocode 5 relating to charring rates for timber exposed to parametric heating regimes which assumes a steady state char rate throughout the fully developed fire based on the following relationships.

$$\beta_{par} = 1.5\,\beta_n \frac{0.2\sqrt{\Gamma} - 0.04}{0.16\sqrt{\Gamma} + 0.08}$$

$$t_o = 0.009\frac{q_{t,d}}{O}$$

Where:

β_{par} is the charring rate during the heating phase of a parametric fire curve

O is the opening factor, in m

β_n is the notional design charring rate, in mm/min

Γ is the modification factor

$q_{t,d}$ is the design value of the fire load density related to the total surface area (A_t) of the enclosure

t_0 is the time period with a constant charring rate, in minutes (approximate duration of fully developed fire)

Further details of the Eurocode 1[39] parametric curves and associated char rate calculation methods from Eurocode 5[42] are provided in Appendix F.

The charring rate reduces progressively to zero over a further period of $2t_0$. The decay and cooling phases are discussed in more detail in Section 6.8.

The following relationship has been proposed by Brandon[142] in lieu of the Eurocode 5 correlation based on review of more recent experimental data as well as previous studies by Hadvig and other subsequent researchers.

$\beta_{par} = \beta_n\,(\Gamma)0.25$

The application of these methods will be demonstrated in the following example, which is then compared to the outcomes from standard and hydrocarbon fire-resistance tests on a CLT panel 225 mm thick comprising five 45mm lamella.

Key inputs for the parametric curve are:

Opening factor, (O): 0.074m$^{0.5}$

Modification factor, (Γ): 4.757

Fire load density related to the total surface area of the enclosure, $q_{t,d}$: 443 MJ/m^2

Using the Eurocode 5 relationship, the constant charring rate during the heating phase of the parametric fire curve (β_{par}) would be 1.39β_n, where β_n is the notional design charring rate, in mm/min, and the constant char rate period t_0 would be 53.7 min.

Using the Brandon method to calculate β_{par} yields a value of 1.48 β_n, which is greater than the Eurocode value.

The above enclosure properties were selected such that the parametric curve would provide a similar fire exposure to the hydrocarbon heating regime after a 60 min period to facilitate comparison with the results of intermediate scale tests exposing CLT panels. This reflects a severe long duration fire with the duration extending considerably further than most of the natural fire experiments listed in Appendix B.

The parametric heating regime derived using the method described in Eurocode 1 and 5 is shown in Figure 59 and compared to the AS 1530.4 Standard and Hydrocarbon heating regimes. In order to compare the severity of the fire exposures the generic model for comparison of fire exposures described in Appendix G was used with the following properties for the target element.

Protection thickness (h): 0.02 m

Thermal conductivity of insulation (k_i): 0.25 W/mK

Heat capacity of insulation (c_i): 1,000 J/kgK

Density of Insulation (ρ_i): 900 kg/m^3

Heat capacity structural core (c_s): 550 J/kgK

Mass/unit length of core (W): 46 kg/m

Heated perimeter (D), 1.21 m

The resulting structural core temperatures are plotted as dashed lines in Figure 59.

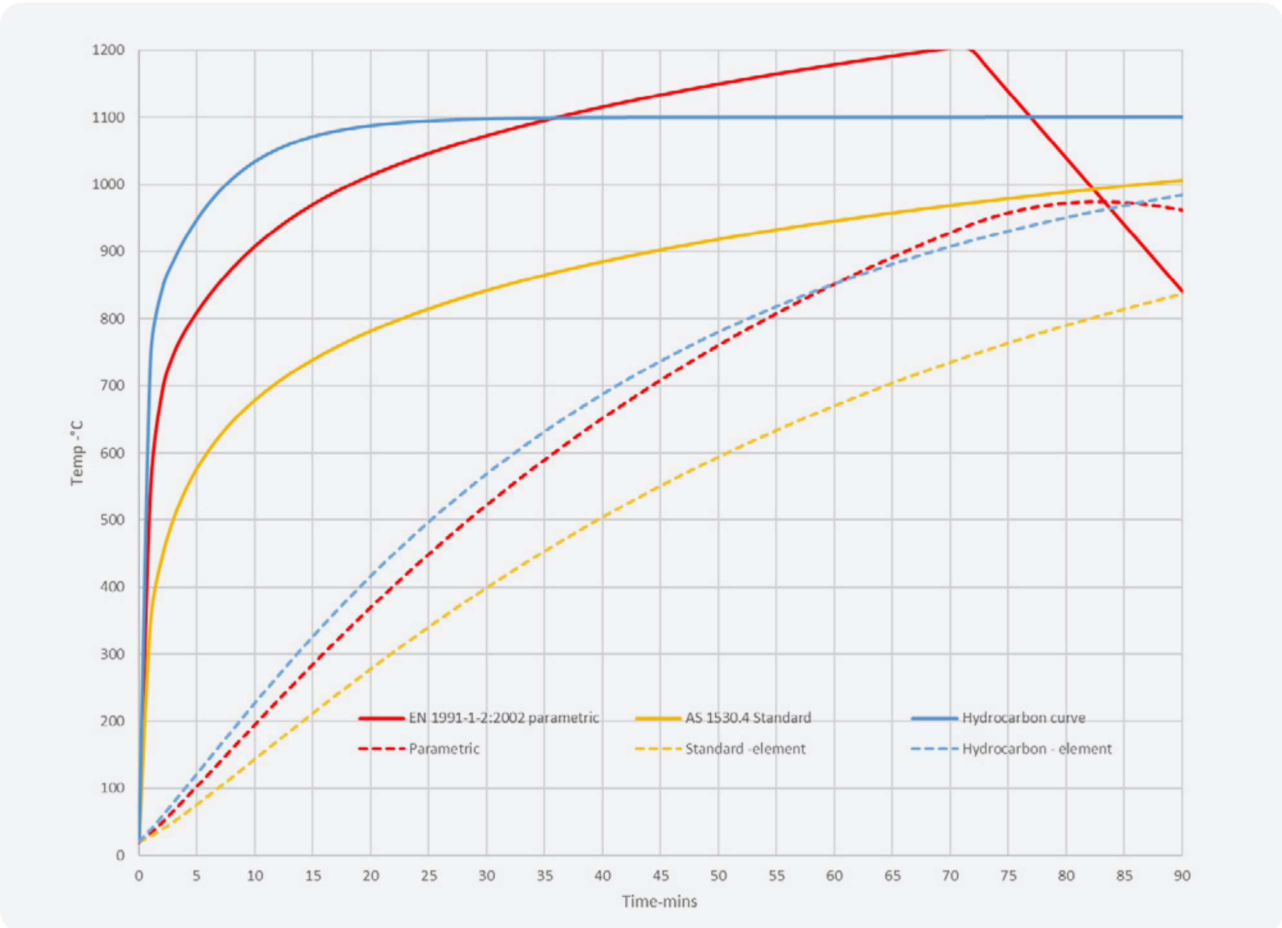


Figure 59: Comparison of a parametric curve with the AS 1530.4 Standard and Hydrocarbon Heating Regimes with predicted target element temperatures to compare exposures.

These results are compared to tests results and discussed in the following sub-section.

Application of the hydrocarbon heating regime

Tests on two similar CLT intermediate-scale non-loadbearing floor panel systems were undertaken. One specimen was subjected to the AS 1530.4 Standard heating regime and the other to the Hydrocarbon heating regime. Further details of the tests are provided in Appendix C9. The mean time for the char front to reach depths of 22.5 mm, 45 mm and 90 mm was derived from the time for embedded thermocouples in two similar arrays to exceed 300°C. The results are provided in rows H1 and H7 of Table 39. The char rate within the specific lamella and the char rate from commencement of the test were also calculated.

In the row identified as H7/H1 ratio, the ratio of the char rate averaged over the period from ignition to the nominated depth for the hydrocarbon regime compared to the standard regime are calculated. The hydrocarbon and parametric heating regimes were estimated to have similar exposures after approximately 61 min when the char depth was 90 mm.

The ratio of the time to the 90 mm char depth from commencement of the test under the hydrocarbon to standard heating regime at this stage was 1.51. This is comparable to the 1.48 ratio predicated by the Brandon equation but the Eurocode method with an estimated ratio of 1.39 will provide results that are more unconservative. Therefore, either the Brandon method and/or directly applicable test data would be preferred for this particular CLT / adhesive combination.

Table 39: Charring rates from an intermediate scale Radiata Pine CLT panel subjected to the AS 1530.4 standard heating regime.

Test ref	Heating Regime	Adhesive Type	Panel Depth (mm)	Panel make up	Parameter	Char Depth d_c (mm)		
						22.5	**45**	**90**
H1	Standard AS 1530.4	PU	225	45/45/45/45/45 (Radiata Pine)	t_{300} (min)	37	60	92
					c_{lam} (mm/min)	0.6	0.75	1.41
					c_{tot} (mm/min)	0.6	0.75	0.98
H7	Hydrocarbon AS 1530.4 Appendix B	PU	225	45/45/45/45/45 (Radiata Pine)	t_{300} (min)	18	35.5	61
					c_{lam} (mm/min)	1.25	1.27	1.76
					c_{tot} (mm/min)	1.25	1.27	1.48
H7/H1 ratio	Comparison Standard/ Hydrocarbon	PU	225	45/45/45/45/45 (Radiata Pine)	t_{300} (min) or c_{lam} (mm/min) ratios	2.05	1.69	1.51
Generic-Conv.	Hydrocarbon/ Standard Conversion	Target element for generic conversion			Std. time (min)	37	60	92
					Calc Hydro. equiv time	23.5	38	59
					Calc Std./Hydro. ratio	1.57	1.58	1.56
Parametric/standard char ratio					Eurocode 5 Parametric			1.39
					Brandon method			1.48

The target element temperature peaked after approximately 82 min of the parametric heating regime which was approximately equivalent to 90 min exposure to the hydrocarbon heating regime (refer Figure 59) based on the generic model for comparison of fire exposures described in Appendix G.

Quantification of production rates for volatiles and char from the fixed fire load

Overview of burning regimes

When wood products are exposed to a fully developed fire, moisture is vapourised followed by pyrolysis of the wood product releasing volatiles and leaving a predominantly carbon based char. If oxygen content of enclosure gases is limited (below approximately 10-15%) approximately 20-25% of the timber will be retained as char but if there is a more plentiful supply of oxygen, char oxidation will occur consuming the char leaving trace inorganic materials. Refer Section 2 for more detailed information.

If the burning regime is fuel controlled, based only on consumption of the moveable fire load, all or part of the volatiles released from the fixed fire load will burn within the enclosure while there is sufficient oxygen for efficient combustion. This will increase the temperature within the enclosure until temperatures peak close to stoichiometric conditions. If there is a sufficient area of the combustible elements of construction forming the fixed fire load exposed to alter the heating regime to a ventilation-controlled fire, any excess volatiles will be released through openings as part of the plume potentially burning outside the enclosure. Eventually, the moveable fire load will be progressively consumed and, as the rate of production of volatiles from the moveable fire load reduces, an increased proportion of the volatiles released from the fixed fire load will be consumed within the enclosure. This effectively extends the fully developed phase.

Depending on the extent and configuration of exposed wood product elements either the fully developed fire will continue until structural failure, or the elements are consumed or if the exposed surface area is limited and the enclosure configuration limits the risk of thermal feedback from opposing or adjacent faces the fire may enter into the decay phase.

If the burning regime is ventilation controlled, based on the contribution from the moveable fire load, initially all the volatiles produced by the fixed fire load will be ejected as part of the external plume and burn externally. In some circumstances the temperatures within the enclosure may be reduced due to the airflow into the enclosure being restricted by the additional outward flow of unburnt volatiles. Energy is also absorbed by heating the unburnt volatiles before they are expelled from the enclosure. Depending on the extent and configuration of exposed wood product elements either the fully developed fire will continue until structural failure or the elements are consumed or the fire may enter into the decay phase.

Quantification of production rates for ventilation-controlled, fully developed burning regime

The mass loss rate/per unit area from the fixed fire load can be estimated from the charring rate if the following assumptions are made for a ventilation-controlled burning regime:

- an oxygen constrained environment within the fire enclosure (less than 10% oxygen content)
- moisture is vapourised from the timber prior to charring
- approximately 20% of the timber remains as predominantly carbon char
- the remaining mass is converted to volatiles during the pyrolysis process
- energy from the combustion of the moveable fire load generates the heat to drive the pyrolysis of the fixed fire load.

Assuming an average charring rate 1.0 mm/min and initial density of wood at 12% moisture content is 560 kg/m^3. The density of dry timber will be 500 kg/m^3 at 0% moisture content.

If 20% of the original mass remains as char (112 kg/m^3)

Mass of volatiles produced by pyrolysis is 500-112 = 388 kg/m^3

Rate of production of volatiles = 388 x 0.001 = 0.388 kg/m^2/min

Heat of combustion for volatiles approximately16.6 MJ/ kg from Section 2.4

Assuming combustion efficiency if sufficient oxygen available is 80% (this will mainly occur outside the enclosure for a ventilation-controlled fire):

The maximum heat release rate from combustion of volatiles from fixed wood products/m^2

= 0.388 x16.6 x 0.8/60 x 1000

= 86 kW/m^2.

The remaining char can undergo predominately smouldering combustion/char oxidation, usually during the decay phase when there will be sufficient oxygen. For this process the heat of combustion is higher (approximately 34.3 MJ/ kg).

Assuming combustion efficiency is 80% and sufficient O_2 supply:

The maximum energy available from char oxidation from fixed wood products/m^3

= 112 x 34.3 x 0.8

= 3,073 MJ/m^3

Based on observations from a natural fire test, Brandon[143] estimated that char regression (consumption) caused by oxidation is most significant in the 30 min after switching from an oxygen poor to oxygen rich environment at the end of a ventilation-controlled fire. Afterwards the char regression slows down. An initial char regression of approximately 1.4 mm/min was estimated for the first 25 min and an average char regression rate of 0.25 mm/min was estimated over the following 185 min.

Based on these estimates, the heat release rate from char oxidation during the early stages of the decay phase would be:

3,073 x 1.4/60 ≈ 72 kW/m^2

This would then reduce to an average of 12.9 kW/m^2 over the following three-hour period.

Quantification of production rates for fuel-controlled, fully developed burning regime

For fuel-controlled fires there is sufficient oxygen for efficient combustion of the volatiles produced by both the moveable and fixed fire loads within the fire enclosure and therefore an effective heat of combustion of 14 MJ/ kg can be assumed from Section 2.4 can be applied to combustion process if a combustion efficiency of 80% is adopted.

With an assumed char rate of 1 mm/min this equates to a heat release rate contribution from a fixed fire load comprising wood products of:

560 x 14 x 1/60 ≈ 131 kW/m^2 that will be mostly released within the fire enclosure.

Impact on duration of the fully developed phase

Methods such as the Eurocode parametric curves assume that during the fully developed phase of the fire the conditions within the enclosure are close to stoichiometric. Therefore, based on the contribution of only the moveable fire load, all volatiles produced by the fixed fire load during this phase will burn outside the enclosure and the impact on enclosure temperatures can be ignored. However, there may be some minor increase in the rate of growth from the fixed fire load leading to a reduction in the time to flashover and the commencement of the decay phase may be delayed because the fixed fire load makes up the shortfall in the rate of production of volatiles as shown in the idealised plot in Figure 37.

An approximate estimate of the extended duration of the fire can be made by estimating the Heat Release Rate (HRR) within the enclosure assuming a stoichiometric burning regime and calculating the sum of the maximum theoretical heat release rates from the moveable and fixed fire loads if sufficient oxygen is available. While this sum is greater than the estimated HRR for stoichiometric conditions, the fully developed fire will not enter the decay phase. Eventually, the contribution from the moveable fire load will cease and, if the area of exposed timber is insufficient to maintain the fully developed fire, the fire will enter the decay phase.

The decay phase is discussed further in Section 6.8.

6.7 Encapsulated and Fire-protected Timber systems

6.7.1 Introduction

A common approach to manage the risks associated with combustible structural elements, such as wood products, is to encapsulate the element in a non-combustible fire-protective covering that can prevent the underlying element being directly exposed to fire and to provide sufficient insulation so that the underlying element is not ignited and/or its functional performance is not significantly compromised.

The use of encapsulation systems is not unique to timber. They are used extensively to enhance the fire resistance of steel elements and other materials when the inherent fire resistance needs to be increased.

The ideal encapsulation system is non-combustible, substantially reduces heat transfer to the protected element and will remain in position when exposed to fire. Separating elements also have other roles, such as thermal efficiency and the provision of acoustic separation. Encapsulation systems need to be optimised to achieve satisfactory performance for all the applicable functional requirements.

In addition, there needs to be ways to maintain and reinstate the encapsulation system at joints and service penetrations and to manage the incipient spread of fire within cavities.

There are a large range of encapsulation options, including various proprietary board systems, spray systems and composite systems comprising layers of non-combustible materials (e.g. calcium silicate boards in conjunction with mineral fibre insulation).

The performance of encapsulation systems is generally specified with reference to the standard fire-resistance test heating regime. When undertaking a fire engineering analysis, the performance may need to be determined with reference to other heating regimes.

The following critical performance criteria apply to encapsulation systems protecting wood products:

Time to commencement of charring (t_{ch})

This is commonly taken as the time for the surface temperature of a wood product to reach a defined charring temperature. In Australia, the defined temperature is either:

- 250°C on the non-fire-side surface of the fire-protective covering for lightweight timber construction or where there are cavities within the construction when applying the NCC DTS Provisions for Fire Protected Timber or other applications where the incipient spread of fire criteria apply, or
- 300°C on the surface of the wood product as defined in the NCC and AS 1720.4:2019 for Massive Timber DTS applications and other general applications.

Time to failure of protective covering – time of direct exposure of wood product (t_{pc})

This is the time at which a significant area of the wood product is directly exposed to the enclosure fire or test furnace and normally is taken to occur when an area of the base layer board falls away, exposing the timber.

Where cavities exist between the fire-protective coverings and wood products or within an element of construction, the following additional performance criteria apply to prevent uncontrolled incipient spread of fire.

Time-to failure of cavity barriers

This is the time from fire spread to the cavity to failure of a cavity barrier.

The majority of this section focuses on plasterboard encapsulation systems because of the relatively large amount of information available in technical literature and its treatment as a generic material in many applications. Other proprietary systems may be more suited to specific applications.

6.7.2 Fire-protected Timber – NCC DTS Provisions

This sub-section provides an overview of the Fire-protected Timber provisions that form part of the NCC Deemed-to-Satisfy requirements for mid-rise timber buildings, as well as a useful example of the encapsulation approach and the need to consider its application as part of a holistic analysis of the broader fire safety strategy for a building.

Details of the fire safety engineering risk assessment that underpins the NCC provisions is available in WoodSolutions Technical Design Guide 38 Fire Safety Design of Mid-rise Timber Buildings – Basis for the 2016 changes to the National Construction Code[12].

The following WoodSolutions Technical Design Guides provide detailed information relating to the application of the Fire-protected Timber requirements to various occupancies such as: requirements for cavity barriers, methods of managing service runs and penetrations through Fire-protected Timber elements, and construction details with references to appropriate supporting Evidence of Suitability. The details may also have more general relevance to the documentation and detailed design of Performance Solutions that include encapsulation systems.

- WoodSolutions Technical Design Guide 37R[4] – Mid-rise Multi-residential buildings
- WoodSolutions Technical Design Guide 37C[5] – Mid-rise Commercial and Education buildings
- WoodSolutions Technical Design Guide 37H[6] – Mid-rise health-care buildings

The following definitions from the NCC apply to the NCC Fire-protected Timber provisions:

Fire-protected Timber: fire-resisting timber building elements that comply with Volume One Specification C1.13a of the NCC.

Massive Timber: an element not less than 75 mm thick as measured in each direction formed from solid and laminated timber.

The definition for Massive Timber was introduced to allow relaxations to the Fire-protected Timber requirements for timber elements with large cross-sections that do not include cavities to account for the removal of the risk of cavity fires and the relatively large inherent fire resistance of timber with larger cross-sections compared to lightweight timber frame systems.

The NCC DTS Provisions for Fire-protected Timber are shown in Figure 60.

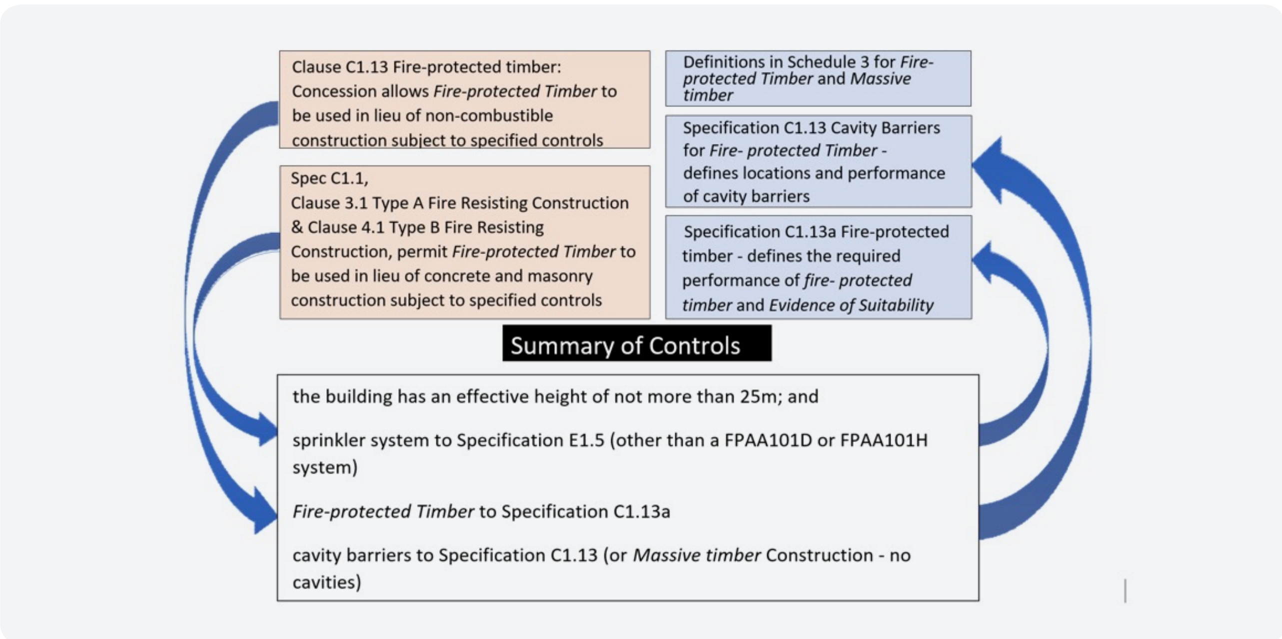


Figure 60: Fire-protected Timber concession structure.

NCC Clause C1.13 and Specification C1.1 Clauses 3.1 and 4.1 restrict the use of Fire-protected Timber construction under the DTS pathway to buildings with an effective height of not more than 25 m and apply the following additional controls:

- a sprinkler system to Specification E1.5 (other than a FPAA101D or FPAA101H system) must be provided
- Fire-protected Timber must comply with Specification C1.13a
- cavity barriers must be provided in accordance with Specification C1.13
- if cavity insulation is provided it must be non-combustible.

The general requirements for Fire-protected Timber construction are provided in Specification C1.13a Clause 2.1 which is presented in the following text box:

2.1 General requirements

(a) Fire-protected Timber must -

(i) utilise a non-combustible ***fire-protective covering*** fixed in accordance with the system requirements to achieve an FRL not less than that required for the building element; and

(ii) have a ***non-combustible fire-protective covering*** fixed in accordance with system requirements -

(A) to achieve a Resistance to the ***Incipient Spread of Fire*** of not less than 45 min when tested in accordance with -

(aa) for horizontal elements — Section 4 of AS 1530.4; and

(bb) for other elements – the relevant test procedures from Section 4 of AS 1530.4 applied to the element lining; or

(B) which consists of not less than two layers of 13 mm thick, fire-protective grade plasterboard.

(b) For the purposes of (a), the ***non-combustible fire-protective covering*** provided under (a)(ii) may form all or part of the ***non-combustible fire-protective covering*** provided under (a)(i).

The general requirements can be relaxed if Massive Timber elements are utilised. The Massive Timber requirements for Fire-protected Timber construction are provided in Specification C1.13a Clause 2.2 which is presented in the following text box:

2.2 Massive Timber

(a) ***Fire-protected Timber,*** where the timber is ***Massive Timber***, need not comply with Clause 2.1 if the Fire-protected Timber -

(i) utilises a ***non-combustible fire-protective covering*** fixed in accordance with system requirements to achieve an FRL not less than that required for the building element; and

(ii) has a non-combustible fire-protective covering fixed in accordance with system requirements -

(A) so as the temperature at the interface between the protection system and the timber does not exceed 300°C during a fire resistance test performed in accordance with Clause 3 for the application and periods listed in Table 1; or

(B) not less than that specified by Table 1; and

(iii) has either -

(A) any cavity -

(aa) between the surface of the timber and the fire-protective covering; or

(bb) between timber elements within the fire-protective covering,

filled with non-combustible insulation; or

(B) no cavity -

(aa) between the surface of the timber and the ***fire-protective covering***; or

(bb) between timber members within the ***fire-protective covering***.

(b) For the purposes of (a), the non-combustible ***fire-protective covering*** provided under (a)(ii) may form all or part of the ***non-combustible fire-protective covering*** provided under (a)(i).

Table 40 summarises the requirements for encapsulation with respect to the time to the onset of charring for Massive Timber when subjected to the standard fire-resistance test (AS 1530.4). The time to exceed an interface temperature of 300°C is specified to facilitate the use of proprietary systems and the corresponding Deemed-to-Satisfy thicknesses of fire-grade plasterboard have also been specified subject to confirmation that the required FRL can be achieved by the protected element.

Table 40: Interface temperature limit times and minimum fire-protective grade plasterboard thickness.

Application	Time – without timber interface exceeding 300°C (min)	Minimum thickness of fire-grade plasterboard (mm)
Inside a fire-isolated stairway or lift shaft	20	13
External walls within 1 m of an allotment boundary or 2 m of a building on the same allotment	45	2 x 13
All other applications	30	16

Note: This table is based on NCC 2019 Specification C1.13a Table 1.

6.7.3 Plasterboard fire-protective covering systems

Plasterboard types

Plasterboard comprises mainly gypsum with additives and paper facings. While there are numerous types of plasterboard with minor variations in composition for different applications, the following review looks at the two main types used extensively in Australia.

Standard or regular plasterboard is a basic, low-density board with little or no glass fibre reinforcement of the core and relies on the paper facings for its strength. This type is commonly referred to as Type A plasterboard in Europe. It has a low level of inherent fire resistance because once the paper facings are burnt and cracks develop in the core, large areas of board can fall away. White[144] indicated that the time assigned to standard plasterboard, 10 mm thick, in the Component Additive Method (CAM) for fire-resistance ratings of wood wall and floor assemblies was 10 min.

Fire-protective grade plasterboard has a higher density core with glass fibres reinforcing the core and controlling shrinkage, along with other minor additives such as vermiculite or perlite. It is not solely reliant on the paper facings to hold the core together. The glass fibres will tend to bind the core together for a considerable period of exposure to a fully developed fire or fire-resistance test after the paper facings have charred. They distribute any shrinkage over the whole surface of the board as small cracks rather than a few large cracks that could initiate large areas of boards falling away. Eventually, the temperature of the plasterboard may increase to the point where the glass fibres melt, and the core will lose strength and shrink; which increases the risk of fixing failures and fall-off. While there is no standardised specification of these plasterboards, and the term ‘fire-protective grade plasterboard’ is not directly defined in the NCC, the following levels of performance are inferred by the NCC DTS Fire-protected Timber applications and performance of proprietary systems available in the Australian market.

- Two layers of 13 mm thick fire-protective grade plasterboard: RISF greater than 45 min.
- A loadbearing timber stud wall faced with two layers of 13 mm thick fire-protective grade plasterboard each side with effective fixings: FRL 90/90/90.
- Two layers of 16 mm thick fire-protective grade plasterboard: RISF 60 min.
- A loadbearing floor with timber joists and a ceiling comprising two layers of 16 mm thick fire-protective grade plasterboard secured with effective fixings and 19 mm timber flooring applied to the upper surface: FRL 90/90/90.

Note: The fire-resistance performance of construction elements depends on a range of factors, including the quality of the fire-protective coverings and correct installation. Systems should be designed, as far as practicable, to be robust and insensitive to minor construction errors. Design documentation should also define appropriate Evidence of Suitability together with requirements for installation, supervision and inspection of installations.

Plasterboards with enhanced fire-resistance properties in the US and Canada are commonly classified as Type X plasterboards and in Europe as Type F.

Thermal properties of fire-protective grade plasterboard

Various researchers, including Mehaffey[145], Sultan[146], Clancy[147] and Thomas[148], have proposed thermal properties for plasterboard that can be considered effective values generally optimised for the standard heating regime and compatibility with various models. Table 41 summarises the values proposed by Thomas[148] that were validated with the finite element models TASEF and SAFIR against experimental data using New Zealand manufactured plasterboard.

These may provide a useful starting point but – due to variations between plasterboard compositions, sensitivity to rate of heating and modelling methods – any results should be validated against data relevant to the proposed applications. At temperatures above 300°C it is also necessary to start considering the physical performance of fixings and the board material to assess the likelihood of the covering remaining in place to continue protecting the structural elements.

A review of the effective specific heat values highlights the effect of the high percentage of combined water in gypsum (approximately 21% by weight) and a smaller proportion of free water that absorbs a large amount of energy as the gypsum is dehydrated and the released water is vaporised at a temperature of approximately 100°C. This enhances the fire protection provided by the plasterboard by slowing the rate of temperature rise of the board itself and heat flow to the elements being protected by the board, although the additional moisture could impact on the structural performance of the timber.

Table 41: Indicative thermal properties of fire-protective grade plasterboard.

T (°C)	Mass (%)	T (°C)	Specific heat smoothed (J/kg °C)	T (°C)	Specific heat calculated (J/kg °C)	T (°C)	Thermal conductivity (W/m °C)
0	100	0	950	0	950	0	0.25
80	100	100	950	100	5,000	70	0.25
125	95	110	52,450	110	52,450	130	0.13
540	93.5	110	18,120	120	950	300	0.13
650	91	140	950	200	950	800	0.18
1000	90	140	3,390	210	19,450	1,000	0.35
		220	3,390	220	950	1,000	0.78
		≥600	950	≥600	950	4,000	10

Note: The performance of fire-protective coverings is not just a material property but is also dependent of the method of support/fixing methods and the thermal properties of surrounding materials the board is in contact with or close to.

Performance of fire-protective grade plasterboard systems exposed to the standard fire-resistance heating regime

In addition to the fire-resistance test criteria of AS 1530.4 for structural adequacy, integrity and insulation, the following are important characteristics of a fire-protective covering system:

- Time to commencement of timber charring (t_{ch}). Typically assumed to occur at 300°C.
- Time to failure of protective covering (time of direct exposure of wood product) (t_{pc}).The term 'fall-off time' is commonly used in lieu of failure time.

These parameters are sensitive to the fire exposure and are generally stated and compared with reference to the standard fire exposure of AS 1530.4 for specification and evaluation of protection systems. This section focuses on the standard fire exposure but the performance under different fire exposures is considered in a following section.

Critical features identified in Canadian studies into fire resistant walls and ceilings

A series of full-scale fire-resistance tests described by Benichou[149] were conducted in Canada in accordance with the CAN/ULC-S101 standard on lightweight wall and floor systems. The Canadian test method imposes a similar heating regime and test procedures to AS 1530.4 and, although the wall and floor configurations vary somewhat from those in Australia, the general findings are relevant to the use of fire-protective coverings applied to lightweight timber elements.

Based on the test results, the effects of some design parameters on the fire-resistance performance of assemblies were investigated and the relevant conclusions are summarised below.

Wall assemblies:

- Fire resistance increases considerably with an increase in the number of gypsum board layers on each side. When using multiple board layers, it is recommended to stagger joints between sheets.
- With resilient channels beneath the single gypsum board layer, increasing the thickness of the gypsum board (GB) layer does not improve the fire resistance.
- The use of resilient channels reduces the fire resistance of stud walls, especially when fixed to a single gypsum board layer. To minimise this fire-resistance reduction, resilient channels should be installed under a double gypsum board layer.
- For loadbearing (1&2) wood-stud walls, the cavity insulation type has no effect on fire resistance.
- For loadbearing (1&2) wood-stud walls, there is no benefit in using staggered row studs (single plate) instead of single row studs.

Floor assemblies:

- Assemblies with screws located further from board edges (38 mm v 10 mm) provide higher fire resistance.
- In assemblies with wood joists and a single-layer gypsum board ceiling finish, the glass fibre reduced the fire resistance while the rock and cellulose fibre increased the fire resistance compared to a non-insulated assembly. In assemblies with a double-layer of 12.7 mm gypsum board finish, the glass, rock and cellulose fibre all reduced the fire resistance compared to a non-insulated assembly. In Australia, the Resistance to the Incipient Spread of Fire (RISF) criteria as well as the FRL of the system may apply and the impact of insulation needs to be considered for both these criteria.
- For floor assemblies with wood-I-joists and a single layer of 12.7 mm gypsum board ceiling finish, the rock and cellulose fibre insulation increased the fire resistance compared to a non-insulated assembly. In assemblies with a double-layer of 12.7 mm gypsum board finish, the glass fibre reduced the fire resistance while rock fibre increased the fire resistance compared to a non-insulated assembly.
- Assemblies with two layers of 12.7 mm gypsum board with staggered joints provided a significant increase in the fire resistance compared to an assembly with one layer of 12.7 mm gypsum board.
- For wood joist floor assemblies with glass fibre insulation and a double-layer of 12.7 mm gypsum board, the effects of changes in joist spacing and resilient channel spacing from 406 mm to 610 mm were significant, i.e. reduced fire resistance.

Analysis of database of international fire-resistance test results

Just[150] reported the findings of an analysis of a database of more than 340 full-scale fire-resistance tests undertaken internationally with the majority of tests performed in Europe.

In the Just study, the time to commencement of charring (tch) was taken as the time to 300°C on wooden surfaces behind the cladding and the failure time (fall-off time for coverings) was taken as the time from the start of the test to 1% of the covering falling away.

The report adopted a worst-case approach to provide estimates of board failure time and commencement of char. In some analyses, mixed data sets of Type F and Type A plasterboards were used to predict times to the commencement of charring in addition to different fixing methods and board manufacturers being included. Substantial variability in the results was expected but the approach was appropriate because the intention of the analysis was to adopt a conservative approach and provide information for design rules for standards to estimate the performance of systems if no tested systems with appropriate Evidence of Suitability were available.

In Australia, it is generally required that test evidence is provided as Evidence of Suitability for FRLs of elements of construction and the Resistance to the Incipient Spread of Fire performance under the DTS Provisions; but the data provided in the database is useful to indicate the potential variability in the performance of fire-protective plasterboard covering systems when risk-based fire engineering approaches are adopted and for preliminary design purposes. Fixings were not defined in detail in the Just report and systematic variations in performance resulting from changes in edge distances and centres of fixings could not be identified.

The values in Table 42 have been estimated from graphed data and are indicative only. Fall-off times for floors are based on larger spans between battens.

Table 42: Range of times for board fall-off and commencement of charring derived from Just for standard fire resistance heating regime[150].

Event	Parameter	Thickness of plasterboard covering (mm)			
		12.5	15	2 x 12.5[1]	2 x16[1]
		Time for event occurrence (min)			
Wall system board fall-off data	Min	31	45	57	82
	Mean	46	52	78	96
	Max	62	64	98	110
Wall systems fall-off prediction from proposed equations	First layer (equation)			51	63
	All layers (equation)	32	44	60	84
Floor systems board fall-off data[2]	Min	24	27	-	111
	Mean	34	32	112	116
	Max	45	37	-	120
Floor systems fall-off prediction from proposed equations	First layer (equation)			36	50
	All layers (equation)	23	25	47	59
Char commencement data (both layers of two layer system remain)	Min	16	23	47	58
	Mean	23	32	65	66
	Max	37	42	84	72
Char commencement prediction	Prop equation	16	20	36	50

1 Fall-off time for both layers.

2 Floor system fall-off data is very sensitive to fixing methods. The samples sizes are relatively small and the results show some inconsistencies.

Australian construction practices – Fire-resistant timber floor/ceiling assemblies

Typical Australian construction practices for fire-resistant timber/floor and ceiling assemblies include:

a) direct fix plasterboard to lightweight timber-frame members
b) lightweight timber-frame members with plasterboard applied to resilient mounted furring channels
c) joists with suspended grid and plasterboard applied to furring channels
d) Massive Timber with direct fix plasterboard
e) Massive Timber with plasterboard applied to resilient mounted furring channels
f) Massive Timber with suspended grid and plasterboard applied to furring channels.

Resilient mounts and suspended grid systems are commonly adopted where acoustic performance is important.

The following brief description of the systems is indicative only and in all cases requirements for installation should be checked against manufacturer's instructions and the Evidence of Suitability. As identified in the Canadian Study, small edge distances for fixings and greater spacing between joists or furring channels can significantly reduce the fire resistance of a system; particularly floor systems.

In Australia, most lightweight timber-frame floor/ceiling systems have been designed and fire tested for framing/support centres up to 600 mm although some systems may be restricted to lower centres.

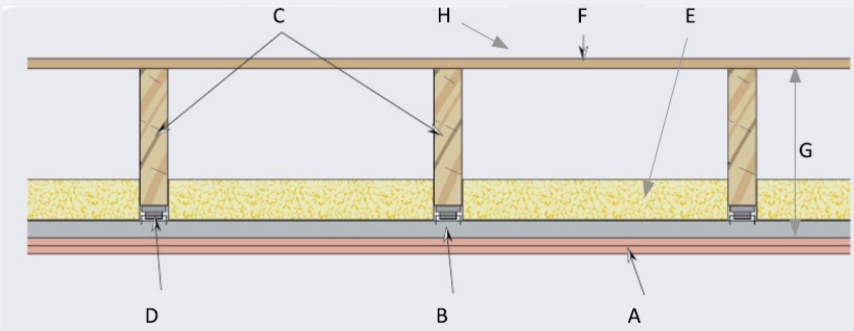
Massive Timber floors commonly comprise cross-laminated timber (CLT) panels. General information on CLT construction is provided in WoodSolutions Technical Design Guide 16[151] with typical details for acoustic walls provided in WoodSolutions Technical Design Guide 44[152]. LVL can also be used if the cross-section size requirements apply. Further information relating to the use of LVL systems is provided in WoodSolutions Technical Design Guide 15[139].

Only joints to external (face) layers of plasterboard are normally treated with paper tape, and joints and screw heads set with an appropriate jointing compound. Joints and fixing heads are generally not sealed in the inner layers.

Before specifying a system, the construction details should be checked against the Evidence of Suitability and the appropriate test reports and other documentary evidence referenced. Each of the systems listed above are described in more detail below using the same identifying letter

a) The direct fix systems under category a) generally apply to solid timber joists, including LVL products. Boards are nailed or screw fixed to the beams at 200 mm max centres in the field and 150 mm max centres at butt joints at the ends of sheets. Edge distances for the fixings at the butt joints are typically 10-15 mm, making the joints susceptible to pull out of fixings/tearing of the board edges, etc. Edge distances at the joints along the length of the boards are increased to 25 mm and 40 mm at the corner close to the sheet ends.

b) Furring channels are normally located at 600 mm centres. For the base layer and 2nd layer of plasterboard, the boards are secured to the furring channels with screws at 200 mm max centres in the field and 150 mm max centres at the board-end butt joints. Edge distances for the fixings at the butt joints are 15 mm, making the joints susceptible to pull out of fixings/tearing of the board edges, etc. Edge distances at the joints along the length of the boards are increased to 25 mm and 40 mm at the corner close to the sheet ends. These systems are frequently used with lightweight engineered trusses/beams. If a third layer of plasterboard is required, it is normally laminated to the two inner layers with laminating screws on a max 300 mm x 300 mm or 400 mm x 400 mm grid in the field and at 200 mm centres at the board ends. Edge distances at the butt joints at the board ends and along the length of the boards are increased to approximately 35-40 mm compared to systems a) and b), reducing the risk of board pull-out or tearing at the fixing location. A typical installation is shown in Figure 61.



Construction
A Linings 2 x 16 mm fire-protective grade plasterboard
B Steel furring channels at 600 mm max centres
C Timber Beams
Solid timber joists
LVL beams
I-section beams with OSB or LVL webs
I-section with steel web
Parallel chord steel web trusses
Parallel chord timber web truss
D Furring Channel Fixings
Direct fixing clips
Acoustic (resilient) mounts
Suspended ceiling (hanger support)
Suspended ceiling (acoustic hanger)
E Non-combustible cavity insulation may be added
F Flooring (minimum thickness)
Plywood – 15 mm
Cement sheet – 15 mm
Particle board – 18 mm
T& G flooring – 15 mm
Engineered flooring – 15 mm
Concrete applied over plywood
AAC – 50 mm
Calcium silicate sheets – 15 mm
G Minimum Cavity Depth – 288 mm from fire protective grade plasterboard.
H Floor finishes such as carpet, acoustic treatments may be added

Figure 61: Typical fire-resistant floor system with ceiling supported by steel furring channels.

c) Plasterboard fixings are similar to b) above for joists with suspended grid and plasterboard applied to furring channels.

d) Massive Timber Direct Fix. There are few systems available for general use with most tested systems being retained as proprietary information. A typical example is shown in Figure 62. Since the CLT forms a continuous surface there is substantial freedom in relation to fixing centres. Systems with fixing centres similar to the outer layer of 3-layer systems fixed with laminating screws have been shown to be very effective in intermediate scale tests including those described in Appendix C9.

The fixing method adopted for these tests was:

Bugle head needle point Type W 8 g x 65 mm long screws on a max 300 mm x 300 mm grid in the field and at 200 mm max centres at the board ends and edges. Edge distances at the butt joints at the board ends and along the length of the boards were approximately 38 mm to reduce the risk of board pull-out or tearing at the fixing location.

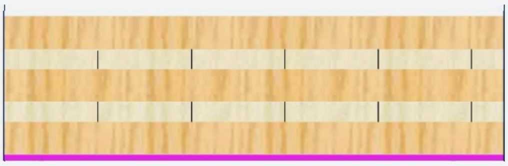


Figure 62: Typical CLT floor with direct fix fire-protective covering.

e) To economise on the fixings and for compatibility with other forms of construction, furring channels are commonly located at 600 mm centres with fixing methods similar to b) above. If these systems are adopted, the NCC DTS Massive Timber concession for Fire-protected Timber solutions may not be applicable because of the formation of a cavity between the fire-protective coverings and timber. To address this and achieve adequate acoustic separation, the fire-protective covering can be fixed directly to the CLT and a non-fire resistant false ceiling fitted below, as shown in Figure 63.

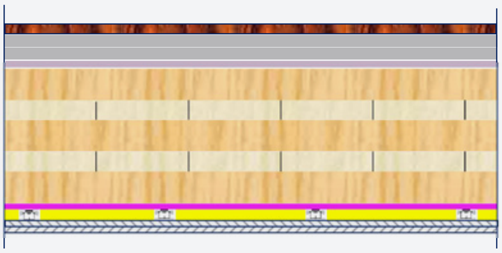


Figure 63: Typical CLT floor with direct fix fire-protective covering and non-fire resistant acoustic ceiling secured with furring channels and resilient mounts (from Technical Design Guide 44).

f) Plasterboard fixings are similar to e) above for Massive Timber elements with suspended grid and plasterboard applied to furring channels.

Table 43 summarises the indicative performance of timber-frame floor assemblies with differing configurations of plasterboard fire-protective coverings. Some of the systems are based on results from tests performed for the FWPA; others are based on public domain information/technical publications.

Summaries of the indicative performance of CLT floor systems are provided in Table 44 for systems with direct fix plasterboard fire-protective coverings and in Table 45 for systems with resilient mount and or suspended ceilings with furring channels and plasterboard fire-protective coverings. Due to limited Australian data, these have been predominantly based on international research programs supplemented by FWPA-sponsored research. Since there are no standardised construction requirements for CLT in Australia, a range of different adhesives with varying levels of temperature resistance are used and the configurations of lamella also vary substantial leading to potentially significant variations in performance.

Table 43: Indicative performance of timber-frame floor systems with plasterboard fire-protective coverings.

Type of construction	FPGPB (mm)	Time for event occurrence – min				Notes/sources
		FRL (min)	RISF (min)	Board fall-off (t_{pc}) (min)	Timber temp 300°C (t_{ch}) (min)	
a) Floor solid timber joists direct fix	13	30/30/30	-		20	FRL – proprietary systems. t_{ch} – NCC Spec C1.13 joist centres max 450 mm
	16	30/30/30	30		30	FRL & RISF – proprietary systems. t_{ch} – NCC Spec C1.13
	2x13	60/60/60	45		45	FRL – proprietary systems. RISF & t_{ch} – NCC Spec C1.13
	1 x 16 + 1 x 13	60/60/60	60	16 mm face 52-65 13 mm base 54-73	60	FRL, RISF & t_{ch} – proprietary sys. Board fall-off based on tests FSV0204 & FSV0205-refer Appendix C2
	2 x16	90/90/90	60		60	FRL, RISF & t_{ch} – proprietary sys.
	3 x16	120/120/120	60		60	FRL, RISF & t_{ch} – proprietary sys. RISF & t_{ch} are conservative refer lightweight engineered joist systems
b) & c) with solid timber joists. PB fixed to furring channels supported by resilient mounts or susp. grid	13	30/30/30	-		20	FRL – proprietary systems. t_{ch} – NCC Spec C1.13 furring centres max 450 mm
	16	30/30/30	30		30	FRL & RISF – proprietary systems. t_{ch} – NCC Spec C1.13
	2 x13	60/60/60	45		45	FRL – proprietary systems. RISF & t_{ch} – NCC Spec C1.13
	1 x 16 + 1 x 13	60/60/60	60	16 mm face 52-65 13 mm base 54-73	60	FRL, RISF & t_{ch} – proprietary sys. Board falloff based on tests FSV0204 & FSV0205-refer Appendix C2
b) & c) with lightweight engineered or solid joists. PB fixed to furring channels supported by resilient mounts or susp. grid	2 x 16	90/90/90	67	Face 86 Base layer joints opening up but PB in place at 90	67	Refer Appendix C7.1 t_{ch} temperatures were exceeded on some timber elements before 90 min
	3 x 16	120/120/120	120	All boards in place at 120 min. but face layer edges are sagging between fixings	120	Refer Appendix C7.2 No suppression undertaken and conditions monitored until cooled to ambient. Max RISF temperatures peaked 30 min after heating terminated just below 250°C.

Note:

1. The above information is indicative only and Evidence of Suitability should be obtained prior to specification of the systems.

2. PB Plasterboard

Table 44: Indicative performance of CLT floor systems with direct fix plasterboard fire-protective coverings.

CLT Configuration (mm)	Loading	FPGPB (mm)	FRL (min)	Board fall-off (t_{pc}) (min)	Timber temp 300°C (t_{ch}) (min)	Notes/ sources
165 (5-ply)	Inter-mediate	None	90/90/90 Integrity failure at 96			FRL indicative values based on Canadian CLT handbook[153]
185 (7-ply)	Low	None	120/120/120			FRL indicative values based on Canadian CLT handbook[153]
245 (7-ply)	High	None	120/120/120 SA 178			FRL indicative values based on Canadian CLT handbook[153]
100 (3-ply)	Low	12.5	60/60/60		20	FRL – proprietary systems t_{ch} – NCC Spec C1.13
140 (5-ply)		12.5	90/90/90		20	FRL – proprietary systems t_{ch} – NCC Spec C1.13
105 (3-ply)	Inter-mediate	16	60/60/60 Integrity failure at 86 SA imminent 86	52	30 (25)	FRL indicative values based on Canadian CLT handbook[153] t_{ch} – NCC Spec C1.13 (t_{ch} 25, board fall-off and integrity; Aguanno[154])
165 (5-ply)	High	16	120/120/120 Integrity failure at 124	26	30 (25)	FRL indicative values based on Canadian CLT handbook[153] t_{ch} – NCC Spec C1.13 (t_{ch} 25, board fall-off and integrity; Aguanno[154])
114 (3-ply)	Low	2 x 13	60/60/60 Test terminated 77	Face starting 60 Base starting 65-75	45 (61)	FRL indicative values based on Canadian CLT handbook[153] t_{ch} – NCC Spec C1.13 (t_{ch} 61, and fall-off; Osbourne[155])
225 (5-ply) Unloaded [1]	Inter-mediate Low	None	60/60/60 90/90/90			Estimates based on intermediate scale non-loadbearing tests refer Appendix C.9. Intermediate load estimate based on time for char depth to be equal to depth of lower lamella rounded down to the nearest 30 mm. Low load estimates are based on non-loadbearing performance.
225 (5-ply) Unloaded [1]	Inter-mediate	16	120/120/120	115	32	
225 (5-ply) Unloaded [1]	Inter-mediate Low	2 x 16	150/150/150 180/180/180	Face 92-110 Base 145	85	
225 (5-ply) Unloaded [1]	Inter-mediate Low	3 x 16	180/180/180 240/240/240	Face 110-128 Inter 150-156 Base 179	144	

Notes:

1 Some estimates were based on intermediate-scale tests performed on CLT panels constructed with an adhesive that was not temperature resistant, and delamination occurred during the tests, accelerating the char rate compared to solid timber. Higher FRLs may be achieved or load levels could be increased for CLT systems using adhesives less sensitive to increased temperatures. This should be demonstrated in full-scale tests under load to provide Evidence of Suitabiility.

2 The above information is indicative only and Evidence of Suitability should be obtained prior to specification of the systems.

Table 45: Indicative performance of CLT floor systems with resilient mount and or suspended ceiling with furring channels and plasterboard fire-protective coverings.

Type of construction	FPGPB (mm)	Time for event occurrence – min				Notes/sources
		FRL (min)	RISF (min)	Board fall-off (t_{pc}) (min)	Timber temp 300°C (t_{ch}) (min)	
225 mm 5-ply, furring centres max 450 mm	13	90/90/90	20		>20	FRL& RISF – proprietary systems for timber joists plus contribution of inherent CLT fire resistance based on data from Appendix C.9. t_{ch} – NCC Spec C1.13
225 mm 5-ply, furring centres max 600 mm	16	90/90/90	30		>30	
	2 x13	90/90/90	45		>45	
	1 x 16 + 1 x 13	90/90/90	60	16 mm face 52-65 min 13 mm base 54-73 min	>60	FFRL, RISF & t_{ch} – proprietary sys. plus contribution of inherent CLT fire resistance based on data from Appendix C.9. Board fall-off based on tests FSV0204 & FSV0205-refer Appendix C.2.
	2 x 16	120/120/120	67	Face 86 Base layer joints opening up but PB in place at 90 min	>80	t_{ch} limit exceeded between 80 min and 90 min by t/c on a section of CLT included in test ref 36474400 refer Appendix C.7.1 plus contribution of inherent CLT fire resistance based on data from Appendix C.9.
	3 x 16	180/180/180	120	All boards in place at 120 min but face layer edges are sagging between fixings	>120 temp 96°C at 120	Refer Appendix C.7.2 plus contribution of inherent CLT fire resistance based on data from Appendix C.9.

Notes:

1 These estimates were based on intermediate scale tests performed on CLT panels constructed with an adhesive which was not temperature resistant, and delamination occurred during the tests accelerating the char rate compared to solid timber. Higher FRLs may be achieved, or load levels could be increased for CLT systems using adhesives less sensitive to increased temperatures. This should be demonstrated in a full – scale tests under load to provide Evidence of Suitability..

2 The above information is indicative only and Evidence of Suitability should be obtained prior to specification of the systems.

Australian construction practices – fire-resistant wall assemblies

Typical Australian construction practices for fire-resistant timber stud wall assemblies include:

a) direct fix plasterboard to lightweight timber frame members
b) lightweight timber frame members with plasterboard applied to resilient mounted furring channels
c) Massive Timber with direct fix plasterboard
d) Massive Timber with plasterboard applied to resilient mounted furring channels.

The following brief description of typical systems is indicative only. In all cases, requirements for installation should be checked against manufacturer's instructions and the Evidence of Suitability.

In Australia, most lightweight timber-frame wall systems have been designed and fire tested for framing/support centres up to 600 mm although some systems may be restricted to lower centres. Noggings generally provide additional restraint to the studs minimising the likelihood of flexural buckling about the minor axis. This can make a significant difference to the load capacity and hence fire resistance of loadbearing wall systems. Resilient mounts or double stud walls are commonly adopted where acoustic performance is required.

Massive Timber walls commonly comprise cross-laminated timber (CLT) panels. General information on CLT construction is provided in WoodSolutions Technical Design Guide 16[151] with typical details for acoustic walls provided in WoodSolutions Technical Design Guide 44[152].

Joints to external (face) layers of plasterboard only are normally treated with paper tape and joints and screw heads set with an appropriate jointing compound. Joints and fixing heads are generally not sealed on the inner layers.

Before specifying a system, the required construction details should be checked against the Evidence of Suitability and the appropriate test reports and other documentary evidence referenced.

a) The direct fix systems under category a) generally apply to solid timber studs. For single layer systems, the face layer of two-layer systems and the intermediate layer of three-layer systems, the plasterboard is typically screw fixed to the studs at 300 mm to 400 mm max centres in the field and 200 mm max centres at butt joints that are backed by studs or noggings. For multilayer system fixing, centres may be increased to 600 mm centres for the base layer if the increased spacing was adopted for the fire-tested system. Edge distances for the fixings at the butt joints at the ends of sheets depend on the stud widths and may vary from 10 mm to 16 mm depending on the stud width, making the joints susceptible to pull out of fixings/tearing of the board edges, etc, although walls are less susceptible to board fall-off than floor/ceiling systems. Where three-layer systems are used, the face layer is generally fixed to the two lower layers with laminating screws at 300 mm or 400 mm centres with edge distances increased to approximately 38 mm centres, reducing the susceptibility to pull out/tearing at fixing points.

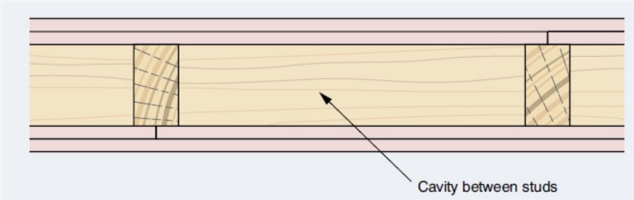


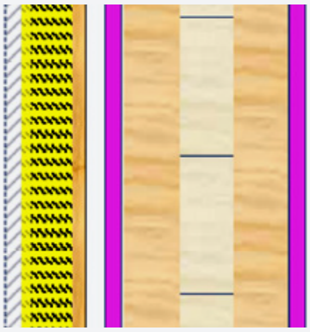
Figure 64: Typical direct fix fire-protective covering applied to timber stud wall.

b) Furring channels are normally fixed and run parallel to the timber studs. They may be fixed to one or both sides of the timber stud depending on the required acoustic performance, among other things. It is good practice for horizontal butt joints to be backed by furring channels fixed to timber noggings and may be required as part of a fire-tested systems. Screw fixing centres are similar to a).

c) Massive Timber Direct Fix. There are few systems available for general use, with most tested systems being retained as proprietary information. Since the CLT forms a continuous surface there is substantial freedom in relation to fixing centres. Systems with fixing centres similar to the outer layer of 3-layer systems fixed with laminating screws have been shown to be effective in intermediate tests including those described in Appendix C9. The fixing method adopted for these tests was: Bugle head needle point Type W 8 g x 65 mm long screws on a max 300 mm x 300 mm grid in the field and at 200 mm max centres at the board ends and edges. Edge distances at the butt joints at the board ends and along the length of the boards approximately 38 mm to reduce the risk of board pull-out or tearing at the fixing location.

Figure 65: Typical direct fix fire-protective covering applied to CLT wall.

d) To economise on the fixings and for compatibility with other forms of construction, furring channels are commonly located at 600 mm centres with fixing methods similar to b).



Lining
Stud frame
75mm glasswool insulation
Gap
16mm fire-rated plasterboard
90mm Cross-Laminated Timber (CLT)
16mm fire-rated plasterboard

Figure 66: Typical direct-fix fire-protective covering applied to CLT wall with additional acoustic treatment.

Table 46 summarises the indicative performance of timber frame wall assemblies with differing configurations of plasterboard fire-protective coverings. Some of the systems are based on results from tests performed for the FWPA; others are based on public domain information/technical publications.

Table 46: Indicative performance of timber frame wall systems with plasterboard fire-protective coverings directly fixed to timber studs.

FPGPB (mm)	Time for event occurrence				Notes/sources
	FRL (min)	RISF (min)	Board fall-off (t_{pc}) (min)	Timber temp 300°C (t_{ch}) (min)	
13	30/30/30	18	–	20	FRL – proprietary systems. t_{ch} – NCC Spec C1.13, RISF refer Appendix C3 test F91767 and F91769. Joist centres max 450 mm
16	60/60/60	27	>60	30	FRL & RISF – proprietary systems. t_{ch} – NCC Spec C1.13, RISF and fall-off estimated from Clancy[147] from series described in Appendix C.4
2 x13	90/90/90	48-54	>90	60	FRL – proprietary systems. RISF & t_{ch} – test series Appendix C.8. Fall of test ref 32190200[156]
2 x 16	120/120/120	>60	Face layer >90	85	FRL & RISF– proprietary sys. Face layer all off conservative est. based on Appendix C.9 and C.7 data
3 x 16	180/180/180	136	Face ≈110 Int 160-165 Base 172-196	158	FRL, RISF & t_{ch} and Board fall-off –from test F3 Appendix C7.3. Min stud 140 mm x 45 mm with stone wool insulation lamella fitted between studs

Notes:

1 Similar performance expected with furring channels fitted.

2 The above information is indicative only and Evidence of Suitability should be obtained prior to specification of the systems.

Table 47 summarises the indicative performance of CLT wall systems. Due to limited Australian data these have been predominantly based on international research programs supplemented by FWPA-sponsored research. There are no standardised manufacturing requirements for CLT in Australia, so a range of adhesives with varying levels of temperature resistance are used. The configurations of lamella also vary, causing substantial variations in performance. Therefore, Evidence of Suitability should be obtained for the specific form of CLT being used.

Table 47: Indicative performance of CLT wall systems with direct fix plasterboard fire-protective coverings.

CLT Configuration (mm)	Loading	FPGPB (mm)	FRL (min)	Board fall-off (t_{pc}) (min)	Timber temp 300°C (t_{ch}) (min)	Notes/ sources
105 (3-ply)	Inter-mediate	NA	30/30/30 SA 32	NA	NA	FRL indicative values based on Canadian CLT handbook[153]
105 (5-ply)	Low	NA	30/30/30 Integrity (57) SA ≈57	NA	NA	FRL indicative values based on Canadian CLT handbook[153] SA. Osbourne[155]
175 (5-ply)	Low	NA	90/90/90 SA 113	NA	NA	FRL indicative values based on Canadian CLT handbook[153] SA. Osbourne[155]
175 (7-ply)	Low	NA	120/120/120 SA 132	NA	NA	FRL indicative values based on Canadian CLT handbook[153]
100 (3-ply)	Inter-mediate	12.5mm	90/90/90	Unknown	20	Proprietary Systems, t_{ch} NCC Spec C1.13
100 (5-ply)	Inter-mediate	12.5mm	90/90/90	Unknown	20	Proprietary Systems t_{ch} NCC Spec C1.13
105 (3-ply)	Inter-mediate	16mm	60/60/60 SA 76	Unknown	30	FRL indicative values based on Canadian CLT handbook[153] t_{ch} – NCC Spec C1.13
175 (5-ply)	Low	16mm	180/180/180 SA 185	Unknown	30	FRL indicative values based on Canadian CLT handbook[153] t_{ch} – NCC Spec C1.13
82 (3-ply)	Low	16mm	SA 61	>61	32	Results from Schmid[157] based on tests on reduced width specimens. Representative joints not included so SA only stated
121 (5-ply)	Low	16mm	SA 140	114	29	
95 (3-ply)	Low	16mm	SA 114	>114	30	
114 (3-ply)	Inter-mediate	2 x 13mm	90/90/90 SA 106	Face layer 75-85, ¼ of base layer 100	60	FRL indicative values based on Canadian CLT handbook[153] (t_{ch} 60 board fall, off and SA. Osbourne[155])
175 (5-ply)	Inter-mediate	2 x 16mm	180/180/180 SA 219	Unknown	>60	FRL indicative values based on Canadian CLT handbook[153] t_{ch} based on horizontal intermediate scale test from Appendix C9

Notes:

1. These estimates were based on intermediate scale tests performed on CLT panels constructed with an adhesive that was not temperature resistant, and delamination occurred during the tests accelerating the char rate compared to solid timber. Higher FRLs may be achieved, or load levels could be increased for CLT systems using adhesives less sensitive to increased temperatures. This would be demonstrated in full-scale tests under load.

2. SA = structural adequacy

3. The above information is indicative only and Evidence of Suitability should be obtained prior to specification of the systems.

Performance of fire-protective grade plasterboard systems when exposed to alternative fully developed fire exposures

Introduction

The performance of some fire-protective grade plasterboard systems has been demonstrated when exposed to the natural fire experiments (summarised in Appendix B). In addition, various research projects have imposed parametric heating regimes using furnaces. However, a process is needed to evaluate the performance of systems in a consistent manner to determine their fitness for purpose and provide Evidence of Suitability when exposed to a range of fully developed fire exposure conditions in addition to the standard heating regime of AS 15030.4, which is applicable to the NCC DTS pathway.

As identified in Section 6.5, for the majority of the fully developed phases of many natural fires, enclosure temperatures are maintained within a range effectively bounded by the standard and hydrocarbon heating regimes. Therefore, a useful approach to verify the performance of a system for fire-engineering applications is to undertake tests using the standard and hydrocarbon heating regimes.

A database of tests of fire-protective grade plasterboard systems that have been subjected to both the standard and hydrocarbon heating regimes of AS 1530.4 is provided below. As a typical example, the database has been used to compare equivalent hydrocarbon exposure time predictions obtained using the simple generic model for conversion of fire resistance times described in Appendix G with hydrocarbon test results from the database.

Comparative database of fire-protective grade plasterboard systems exposed to AS 1530.4 Standard and Hydrocarbon Heating Regimes

Intermediate scale – timber stud wall systems faced on each side with 13 mm fire-protective grade plasterboard (Ref Appendix C3).

WarringtonFire undertook this test series in 1999 to compare the likely performance of timber-frame plasterboard partitions exposed to different heating regimes which was reported for FWPA in 2014.

The series comprised four intermediate-size timber-frame partitions (1.2 m x 1.2 m) faced on each side with one layer of 13 mm fire-protective grade plasterboard. Two specimens were subjected to the standard AS 1530.4 heating regime and two to the hydrocarbon heating regime. One comparative set included cavity insulation the other did not.

Additional instrumentation was provided to record the temperature distribution across the wall. An extract of this data for key events is provided in Table 48. For further details refer to Appendix C3.

Table 48: Intermediate-scale timber stud partitions faced with 13 mm fire-protective grade plasterboard.

Test	Heating regime	Cavity insulation	Est RISF[1] (min)	Est t_{ch}[2] (min)	Mean char time (min)		Sig.crack in PB		PB fall-off[4]		Non-fire side face of PB @ 600°C (min)
					7.5 mm depth	15 mm depth	time (min)	temp (°C)	time (min)	temp (°C)	
F91767	Standard	None	18.5	26	46	55	60	553	99	711	70
F91768	Hydrocarbon	None	12	19	32	41	45	648	88	740	35
F91769	Standard	Glass wool	19	23	37	50	48	722	68	720	29
F91770	Hydrocarbon	Glass wool	11.5	15	25	30	21	737	27	843	16

Notes:

1 The Resistance to the Incipient Spread of Fire (RISF) estimated based on time of thernocouples fitted to plasterboard in cavities between studs exceeding 250°C.

2 Estimated t_{ch} commencement of charring based on time interface between stud and plasterboard exceeds 300°C.

3 All specimens were faced on each side with one layer of 13 mm thick fire-protective grade plasterboard.

4 Board fall-off times may be earlier for full-size specimens.

Intermediate scale – steel framed ceiling system faced on underside with 2 x 13 mm fire-protective grade plasterboard (Ref Appendix C5).

WarringtonFire undertook these tests in 1998-99 to compare the performance of plasterboard faced elements with lightweight steel framing exposed to different heating regimes and was reported for FWPA in 2014.

The tests were performed in the horizontal orientation at intermediate scale (1.2 m x 1.2 m). The specimens were faced on the fire-exposed face with 2 x 13 mm layers of fire-protective grade plasterboard. The cavity was open for one half of the specimen and enclosed by a layer of 13 mm thick plasterboard applied to the upper surface of the studs creating a 64 mm deep cavity over the remaining specimen. The two areas were separate by a central steel stud with an insulated packing to minimise heat transfer between the enclosed and unenclosed cavities.

The data includes plasterboard face temperatures from which estimates of the RISF performance can be derived.

Table 49: Intermediate-scale steel-framed ceiling faced on the underside with 2 x 13 mm fire-protective grade plasterboard (PB).

Test	Heating regime	Cavity Open	Est RISF[1] (min)	Est PB temp >300°C[2] (min)	Est PB temp >400°C[2] (min)	PB fall-off[3]		600°C PB Interface temperature between base and face layers (min)
						time (min)	temp (°C)	
F91780	Standard	No	57.5	61	73.5	Face 72	676	60
		Yes	67	77	80.5			
F91782	Hydrocarbon	No	37	38.5	40.5	Face 35 Base 55	631 552	34 -
		Yes	39	40	41.5			

Notes:

1 The Resistance to the Incipient Spread of Fire (RISF) estimated based on time of thermocouples fitted to plasterboard fire side base layer upper surface exceeding 250°C.

2 Estimated t_{ch} commencement of charring based on time plasterboard surface exceeds 300°C.

3 Board fall-off times are approximate and boards fell away progressively.

Full-scale lightweight timber frame floor system with furring channels supporting 2 x 16 mm fire-protective grade plasterboard sheets (Ref Appendix C7.1and C7.4).

Two tests were performed on similar lightweight timber-frame floor system with furring channels supporting 2 x 16 mm fire-protective grade plasterboard sheets.

The first test was undertaken in 2015 (Test ref 36474400[158]) with the specimen exposed to the standard heating regime of AS 1530.4. The second test was undertaken in 2020 (Test Reference FRT 200150[159]) to investigate the sensitivity of plasterboard ceilings at full-scale to fires of greater severity than the AS 1530.4 standard heating regime.

The specimens comprised the following lightweight engineered beam systems protected by a plasterboard ceiling system:

- I-section with OSB web
- Parallel chord steel web truss
- Parallel chord timber web truss
- I-section with steel web.

The ceiling system comprised two layers of fire-grade plasterboard (each 16 mm thick) fixed to furring channels spaced at 600 mm centres that were supported from the beams by direct fixing brackets. The ceiling was constructed using normal industry installation methods. Key time-related data relevant to the performance of the plasterboard is summarised in Table 50. Other timber elements were incorporated in the system test to provide additional data (e.g. solid timber, CLT sample).

Table 50: Full-scale timber-framed ceiling faced on underside with 2 x 16 mm fire-protective grade plasterboard.

Test	Heating regime	RISF (min)	Member	Time to 300°C max temp (min)[1]	EPB time to fall-off (min)[2]	Time max upper surface of PB ceiling exceeded (min)			FRL Structural Adequacy/ Integrity/ Insulation (min)
						300°C	400°C	500°C	
EWFA 36474400	Standard	67	LWT Joist Solid Joist CLT soffit Furring Channel	87 86 83 68	86 face	71	81	90	SA NF 90 Integrity NF 90 Insulation 90
FRT 200150 R1.1	Hydro-carbon	44	LWT Joist Solid Joist CLT soffit Furring Channel	51.5 >57 >57 53.5	33-45 face 53.5 base	45	49	53	SA NF 57 Integrity 57 Insulation 57

1 Estimated t_{ch} commencement of charring based on time to 300°C on surface of timber elements

2 Board fall-off times are approximate and boards fell away progressively.

In the standard heating regime test (36474400) the base layer of plasterboard remained in place until the end of the test but was sagging between screw fixings (Figure 67).

Figure 67: Exposed face of test (36474400) after the end of the heating period showing base layer of plasterboard sagging between fixings.

In the hydrocarbon test a localised early failure of the face layer of plasterboard at a joint position accelerated the deterioration and a localised failure in the base board allowed hot gases to penetrate the floor cavity, which was reflected in the temperature data. This further highlights the sensitivity of the results to the edge distances of fixings.

Intermediate scale – timber-frame wall protected with two layers of 13 mm thick fire-protective grade plasterboard applied to each side (Ref Appendix C8).

This series, undertaken for the FWPA, was an extension of the work examining the impact of different heating regimes but with additional instrumentation provided and procedures to examine the behaviour of the partitions after the end of the heating period. Only data from the standard and hydrocarbon heating stages are summarised in this section.

The specimens comprised intermediate-scale (1.2 m x 1.2 m) timber-frame/plasterboard partitions with 90 mm x 45 mm Radiata Pine framing and two layers of 13 mm thick fire-protective grade plasterboard applied to each side of the framing. Half the specimen was provided with non-combustible glass fibre cavity insulation and the other half was not provided with cavity insulation.

Timber stud temperatures were measured, and comparative data is available from the measurements taken at a depth of 7.5 mm.

Table 51: Intermediate-scale timber-frame wall protected with two layers of 13 mm thick fire-protective grade plasterboard applied to each side.

Test	Heating Regime	RISF (min) Glass Fibre Insulation	RISF (min) No Insulation	Est t_{ch} (min)	Mean char time (min) @7.5mm
55676500	Standard	48	54	63	77
55676600	Hydrocarbon	30	33	42	53

Intermediate-scale Massive Timber tests with direct fix fire-protective grade plasterboard (Ref Appendix C9)

As part of an intermediate-scale series of tests on CLT panels performed in the horizontal orientation, comparative tests used the standard and hydrocarbon heating regimes of AS 1530.4 on panels protected by one and two layers of 16 mm thick fire-protective grade plasterboard. Interface temperatures were measured in all the tests, providing useful comparative data relating to the times to reach critical temperatures. In addition, temperatures at various depths within the CLT were measured in the tests except for the specimen protected by one layer of plasterboard that was subjected to the hydrocarbon heating regime. For this case, when the test was stopped, the specimen was quickly extinguished and the char depth measured; which could then be compared to the estimated time to reach the same char depth for the specimen subjected to the standard heating regime based on internal temperature measurements to provide a data point for a long-duration fire. Table 52 summarises key time-related data relevant to the performance of the plasterboard and further details of the tests are provided in Appendix C.9.

Table 52: Intermediate-scale results from CLT panels with direct fix fire-protective grade plasterboard.

Test	FPGPB facings (mm)	Duration (min)	Time max upper surface of PB ceiling exceeded (min)			PB Fall-off (min)	Fall-off temp (°C)	Thermocouple ref	Time to 300°C (min)			
									Char depth (mm)			
			t_{ch}^2 =300	500	600				22.5	45	90	125
H2 Standard 49385300	1 x16	171	32	52	75	Face 115	≈ 700	1	118	121	132	
								2	115	132	138	
								Mean	117	127	136	175[1]
H9 Hydro – carbon 54455301	1 x 16	120	18	30	49	Face 67-69	820		-	-	-	-
								-	-	-	-	-
								-	-	-	-	120[2]
H3 Standard 49385400	2 x 16	191	85	115	127	Face 92-110	≈ 500	1	153	170	191	-
						Base 145	672	2	150	165	186	-
								Mean	152	168	189	-
H5 Hydro – carbon 49385500	2x 16	153	60	77	92	Face 53-65	551	1	111	119	142	-
						Base 101	676	2	111	116	150	-
								Mean	111	117	146	-

Notes:

1 Estimate of 175 min obtained by extrapolation based on prevailing char rate at end of 171 min test.

2 Char depth measured after test (reduced by 5 mm to allow for additional charring prior to suppression).

Comparison of database results with simple generic model for conversion of fire-resistance times

In most instances the time to failure, or of a critical event associated with an element of construction ascertained in a standard fire-resistance test, will differ from the time of occurrence if the element is exposed to a real or simulated fire scenario, such as a parametric heating curve based on the Annex A of EN 1991-1-2:2002[39] because the fire exposures differ.

If an element of construction is made up of homogeneous materials with known thermal and mechanical properties at elevated temperatures, it is possible to determine the time to failure using simple correlations or more complex methods; such as finite element analysis. It is complex to reliably model many fire-resistant elements or components, such as fire doors, penetration seals, composite systems, connections, board fixings, adhesion of sprayed materials, etc. For many applications, a simple general method for conversion of fire-resistance times to scenario times will be adequate for preliminary design purposes if validated appropriately. If necessary, more detailed analysis and/or other Evidence of Suitability can be sourced during the detailed design stage.

Predictions based on an insulated thermal mass equal temperature method, described in Appendix G, have been compared to the comparative database from the previous sub-section and are presented below.

The main limitation with this method is that it considers thermal performance only. Other factors – such as thermally induced deflections and/or stresses, degradation of structural materials and materials used for protection, e.g. spalling, shrinkage, thermal shock, smouldering combustion and other chemical reactions – may need to be taken account of separately if they are not indirectly accounted for in the thermal analysis. Validation over a range of fire exposures can help identify factors that require additional consideration.

The material properties selected for the target element(s) are summarised in Table 53. In this simple model, the material properties are constant throughout a fire scenario but could be varied in a more complex implementation.

Table 53: Inputs for target elements for conversion plots for standard to hydrocarbon heating regimes.

Parameter	Symbol	Value(s)	Units
Thickness	h	0.016, 0.020, 0.026, 0.032	m
Thermal conductivity of insulation	k_i	0.25	W/mK
Heat capacity (insulation)	c_i	1000	J/kgK
Density Insulation	p_i	900	kg/m^3
Heat capacity (core)	c_s	550	J/kgK
Mass/unit length of core	W	30	kg/m
Heated perimeter	D	1.21	m

Using the Table 53 inputs, the equivalent hydrocarbon heating regime time has been calculated and plotted against the corresponding standard heating regime times for target elements with four thicknesses of protection in Figure 68. The lower thicknesses are more suited to elements designed for shorter fire-resistance test durations. Events from the database of results have been plotted on the graph. The events with equivalent hydrocarbon heating regime times above the prediction plots are conservative if performance is being predicted based on standard fire-resistance test exposures.

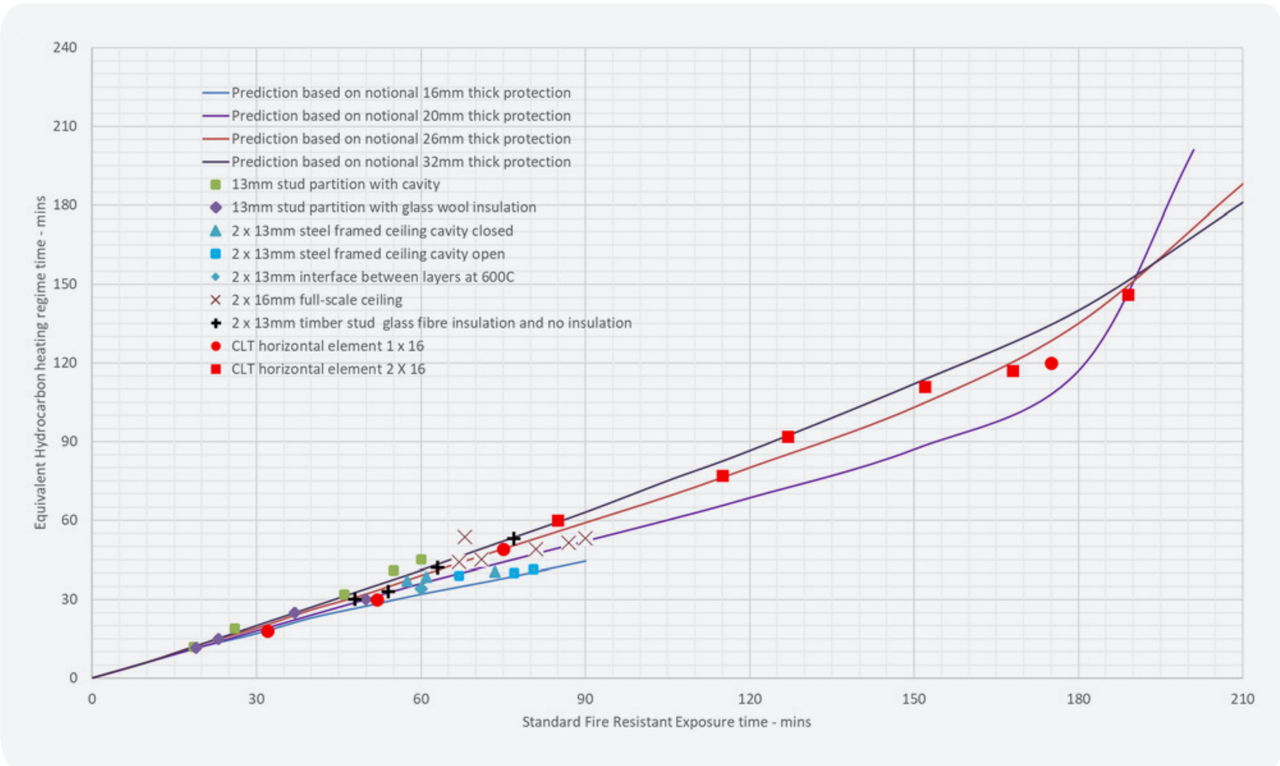


Figure 68: Comparison of database results with predictions from the insulated thermal mass equal temperature method described in Appendix G.

If conservative results are likely to be required for design purposes, the blue line based on a 16 mm thickness may be appropriate for standard fire-resistance periods up to 90 min and the purple line based on the 20 mm protection thicknesses for fire-resistance periods from 90 min to approximately 180 min.

If a probabilistic analysis or other method is adopted and more typical values are required, with safety factors being applied at the end of an analysis, the purple plot (20 mm thickness) would be more appropriate for fire-resistance periods below 90 min and the orange plot (26 mm thickness) for periods above 90 min.

Comparison with other exposures

The same technique can be applied to transpose fire-resistance test data to other natural fire exposures or fire scenarios derived theoretically, e.g. using Eurocode 1 Appendix A Parametric Curves[39]. This application is demonstrated in Appendix B2.3.

6.8 Response during decay and cooling phase

6.8.1 Overview

The response of elements of construction during the decay and cooling phase can be an important consideration, particularly in applications such as high-rise buildings where fire brigade intervention and evacuation of occupants may be difficult during some fire scenarios.

Generally, for these applications a building will be protected by automatic sprinklers and a number of components of the fire protection system for the building will need to fail for a scenario to end in structural failure. For example, failure of the automatic sprinkler system, fire-protective coverings and detection and alarm systems may need to occur in addition to a relatively slow fire brigade response.

A meaningful evaluation of these events will generally require some form of quantified risk assessment to determine scenario probabilities and consequences. Such an approach is consistent with the NCC holistic approach and should be applied to all structural forms. Refer to Section 1.2 for further discussion.

In addition to premature structural failures, structural failures can also occur sometime after exposure due to a number of causes, including:

- temperatures of structural elements may continue to increase during the decay period of a fire due to the thermal inertia of the enclosure fabric and fire protection systems
- stresses may be induced on cooling
- material properties may change on cooling
- smouldering combustion and incipient spread of fire may continue.

It is important to consider the fire decay and cooling period when undertaking a fire-safety engineering design. This is not a unique requirement for combustible construction; it applies equally to all structural materials.

6.8.2 Behaviour of elements of construction during the decay and cooling phase

In many instances, both natural and furnace fire-resistance tests are terminated at the end of a nominated exposure time and so there is relatively limited data on their behaviour during the decay and cooling phases. Even when the performance of an element is monitored the exposure conditions may be unrealistic or not fully documented.

Some recent studies, such as the Epernon Series (refer Appendix B25) and Fire Safe Implementation of Visible Mass Timber (refer Appendix B26), have monitored conditions at the end of tests to evaluate performance during the decay phase.

In addition, some recent fire-resistance tests performed for the FWPA have included monitoring of simulated decay phases in conditions with normal concentrations of oxygen by removing specimens from the furnace and, in some cases, continuing to expose the specimen to heat from the furnace walls. Details of the tests are summarised in Appendix C with the most relevant tests summarised below.

Full encapsulation of a floor system by a plasterboard ceiling

This was a fire-resistance test on a lightweight engineered timber floor to determine the fire resistance of various types of lightweight engineered beam systems protected by a plasterboard ceiling system. The specimen was subjected to the AS 1530.4 standard heating regime for 122 min. Further details are provided in Appendix C7.2.

The ceiling system comprised three layers of fire-protective grade plasterboard (each 16 mm thick). The first two layers were fixed to furring channels that were supported from the beams by direct fixing brackets using normal industry installation methods. The third layer was laminated to layers 1 and 2 with 50 mm long laminating screws at 200 mm centres along the edges, 35 mm from the board edge and 300 mm max centres in the board field. Butt joints between the ends of boards were within 50 mm of centre line between framing and fixed with laminating screws at 35 mm from sheet edges, 35 mm from sheet ends and at 200 mm max centres.

- The specimen achieved the following performance: (FRL 120/120/120)
- Resistance to the Incipient Spread of Fire: 120 min.

The heating was terminated after 120 min, and the specimen was raised 600 mm above the furnace, allowing free access to the laboratory atmosphere while being exposed to heat from the furnace floor and walls to simulate the decay and cooling phases under natural convection for a further 17 hours without intervention. The temperatures measured below the ceiling during the fire test exposure and for the first two hours of the cooling phase are plotted against time in Figure 69. The specimen continued to support the full test load while cooling to ambient temperatures over the remaining 15 hours of the monitoring period. Figure 70 shows the fire-exposed face at the end of the monitoring period.

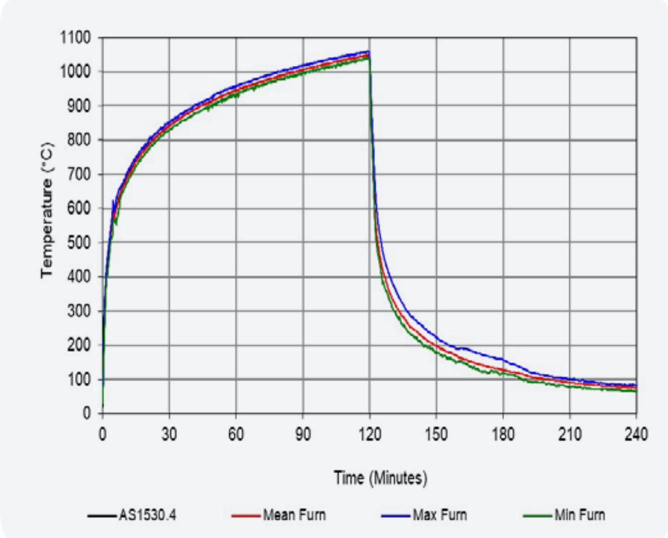


Figure 69: Complete heating and first two hours of cooling exposure measured by exposed thermocouples.

Figure 70: Layer 2 of PB still in place after monitoring period.

There was no evidence of combustion of the timber elements during the test and throughout the monitoring period. The temperatures on the upper surface of the plasterboard sheeting peaked after approximately 150 min, as shown in Figure 71 (30 min after termination of heating) but the temperatures did not exceed 250°C.

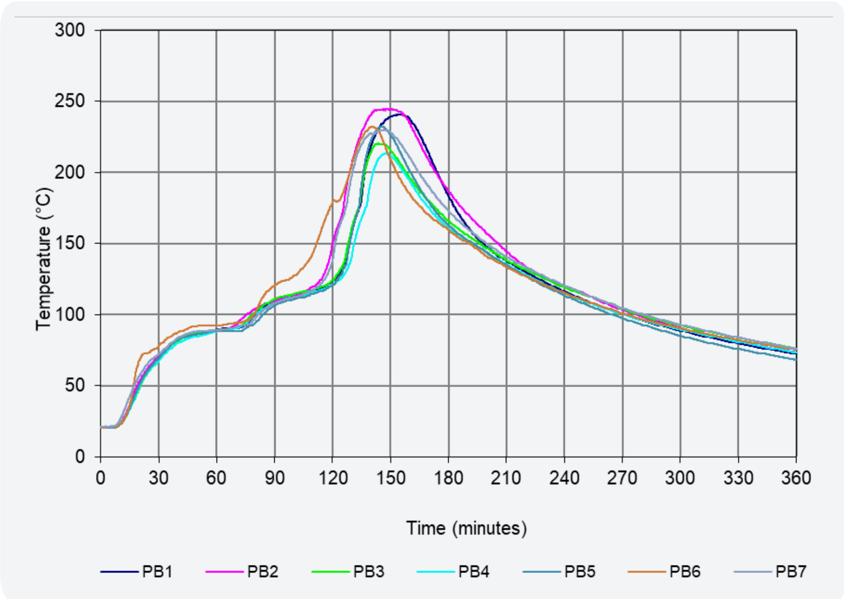


Figure 71: Temperatures of upper surface of the plasterboard.

A section of CLT was included within the floor cavity and temperatures were measured at various positions within and adjacent to the CLT element. These temperatures are summarised in Table 54 and Figure 72, which illustrates that a thermal wave passed through the CLT with temperatures at depths of 20 mm and 55 mm peaking at 94°C and 84°C more than 90 min after the end of the heating period.

Table 54: Peak CLT specimen temperatures and temperatures after 120 min.

Ref	Description	T (°C) @120 min	Max temp(°C)
CL-1	On the upper surface of plasterboard directly under CLT	120	226
CL-2	19 mm below CLT soffit air temperature	109	161
CL-3	Soffit of CLT	96	151
CL-4	10 mm depth	77	105
CL-5	20 mm depth (lower glue line)	52	94
CL-6	55 mm depth (upper glue line)	58	84

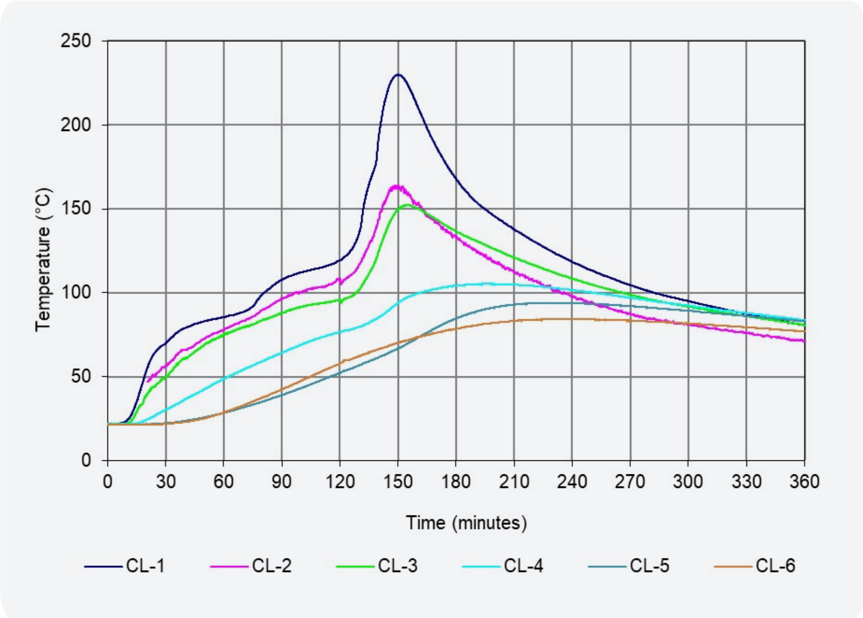


Figure 72: CLT specimen temperatures recorded during120 min fire test and first four hours of monitoring.

Self-extinguishment of CLT panel protected by one layer of 16 mm fire-protective grade plasterboard

Two standard fire-resistance tests were performed on CLT panels protected by one layer of 16 mm fire-protective grade plasterboard. The first test was of 45 min duration and the second of 60 min duration. The time for the CLT plasterboard interface to reach 300°C was expected to be approximately 30 min and this was confirmed in both tests. Also, in both tests the CLT panels ignited but self-extinguished during the monitoring period. Further details of the tests are provided in Appendix C.9. The test with a 60 min heating period will be discussed below.

The specified and measured furnace temperatures are plotted in Figure 73 for the heating period. At the end of the heating period after 60 min, the area under the mean furnace temperature/time plot exceeded the prescribed standard heating regime plot by approximately 1.5%. At the end of the heating period the specimen was raised approximately 320 mm above the furnace to allow natural airflow across the surface of the specimen and data monitoring was continued for 23 hours.

The furnace thermocouple data is presented for the first 60 min of the monitoring period in Figure 74. During this period the temperatures measured by the furnace thermocouples reduced to approximately 100°C. The furnace thermocouple data is presented for the 23 hour monitoring period in Figure 75. During this period the CLT panel temperatures had effectively reduced to ambient temperatures with no evidence of continuing smouldering combustion.

The incident heat flux to which the underside of the specimen was exposed is plotted for the first 3 hours of the monitoring period in Figure 76. Approximately 11 min after completion of heating, the measured heat flux had reduced to approximately 10 kW/m^2; 42 min after completion of heating, it had reduced to approximately 4 kW/m^2 and 108 min after completion of heating, it had reduced to approximately 2 kW/m^2.

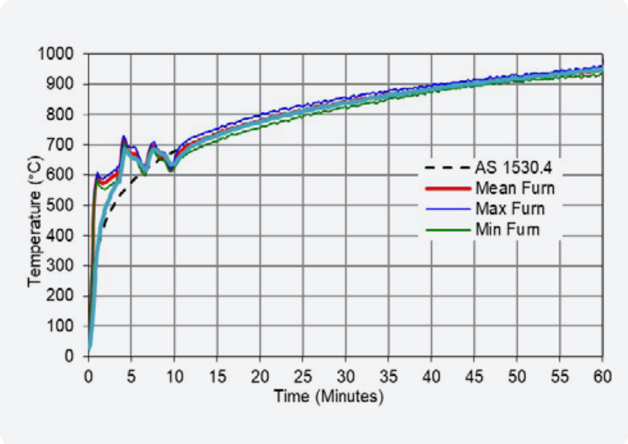


Figure 73: Furnace temperatures during 60 min heating period.

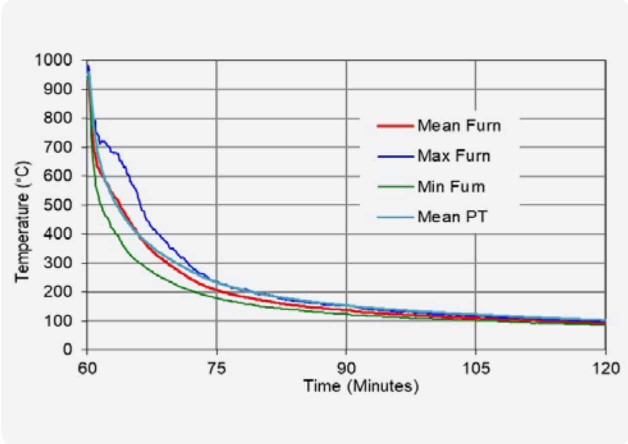


Figure 74: Temperatures recorded by furnace thermocouples during the first 60 min of the monitoring period.

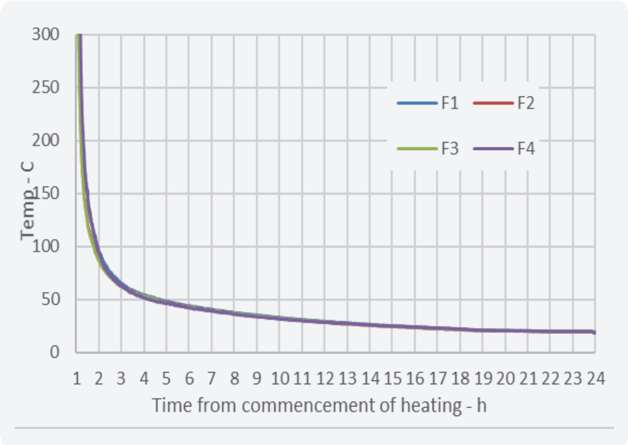


Figure 75: Temperatures recorded by furnace thermocouples throughout the monitoring period.

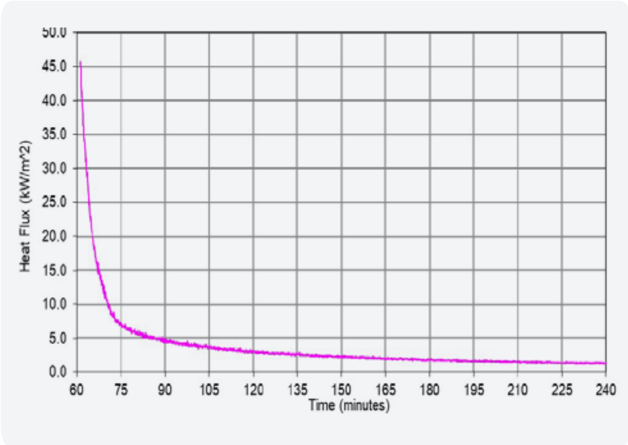


Figure 76: Heat flux from furnace and from specimen for 180 min after heating.

Visual observations from the test are provided in Table 55.

Table 55: Visual observations of CLT panel protected by one layer of 16 mm fire-protective grade plasterboard.

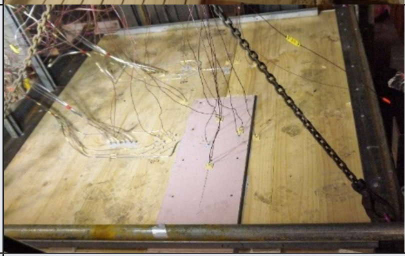
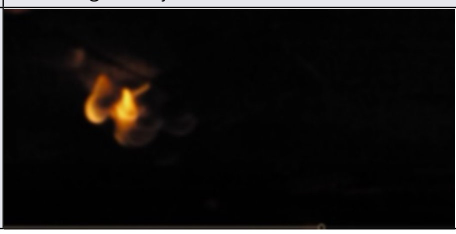
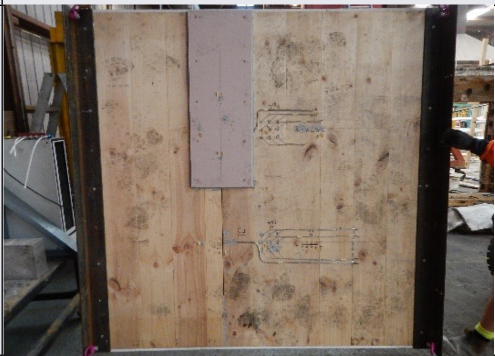
Time h:mm:ss	Observation test started	Comments
Pre-test		Fire-exposed face before test
0:58:00		Non-fire side showing no visible degradation or smoke release through specimen
1:00:00	Heating terminated	
1:00:30		Fire-exposed face showing flaming from joint and additional furnace thermocouple penetrations
1:01:30		Fire-exposed face showing flaming from joint and additional furnace thermocouple penetrations
1:03:30		Fire-exposed face showing flaming from joint
1:04:30		Fire-exposed face showing flaming from joint
1:07:00		Fire-exposed face showing flaming from joint
1:09:30	Flaming from joint intermittent	
1:10:40		Intermittent flaming from joint continuing

Table 55: Visual observations of CLT panel protected by one layer of 16 mm fire-protective grade plasterboard (continued).

Time h:mm:ss	Observation test started		Comments
1:11:30	Intermittent flaming stopped – no further flaming combustion		
1:13:00			Fire-exposed face – no flaming
1:36:00			Fire-exposed face – no flaming
24:00:00	Monitoring period ended – no evidence of ongoing combustion		
Post test			Non fire side showing no evidence of degradation
Post test			Fire-exposed face with plasterboard removed showing charred zone. No significant delamination but the timber strips making up the lower layer had shrunk opening up the joints between lower lamella boards which were not glued on the side faces.

The external flaming occurred due to the venting of volatiles, which mixed with the unconstrained air supply as the specimen was raised from the furnace. The impact was localised and had a minor influence as indicated by the measured heat fluxes and temperatures.

No recurrence of flaming combustion was observed after 11.5 min of the monitoring period.

Internal temperatures were monitored for 23 hours to identify any residual smouldering combustion. Details of typical thermocouple positions are shown in Figure 77.

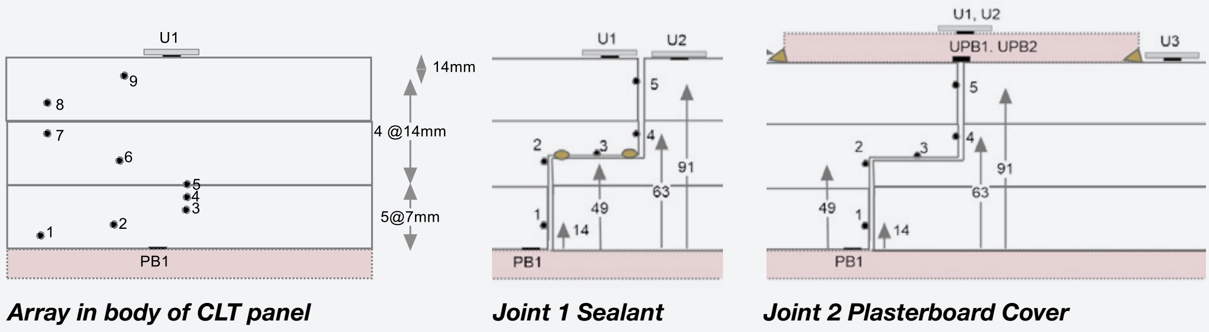


Figure 77: Sections through CLT panels showing joint details and thermocouple positions.

The data recorded by these thermocouples is presented in Figure 78 to Figure 80. Temperatures on the non-fire side of the specimen peaked below 35°C, approximately 2.5 hours after termination of heating.

The interface temperatures between the plasterboard and CLT peaked at approximately 500°C, with the highest measured peak of 520°C.

The temperatures within the CLT at a depth of 7 mm from the fire-exposed face peaked below 280°C but the temperatures measured within the joints at a depth of 14 mm from the fire-exposed face peaked at approximately 330°C for joint 1 (sealant applied to single rebate) and 430°C for joint 2 (plasterboard applied to non-fire side of joint). This indicates that joint details will provide a potential for premature fire spread without adequate protection.

In all cases the internal thermocouples cooled exponentially towards ambient conditions confirming no ongoing smouldering combustion was occurring.

The two tests of 45 min and 60 min heating duration demonstrated that fire-protected Massive Timber elements can self-extinguish if exposed to the standard heating regime of AS 1530.4 for periods greater than the estimated time to commencement of charring under some circumstances.

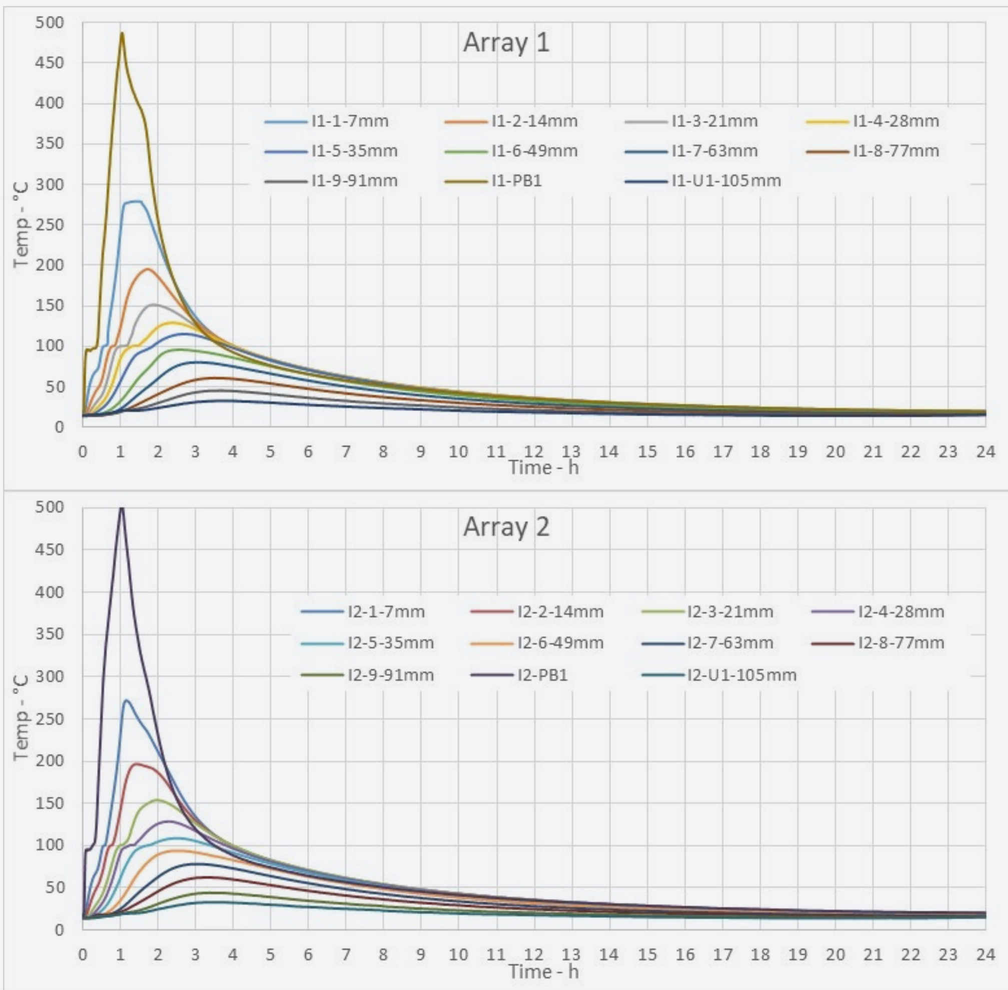


Figure 78: Thermocouple array temperatures in body of the CLT panels.

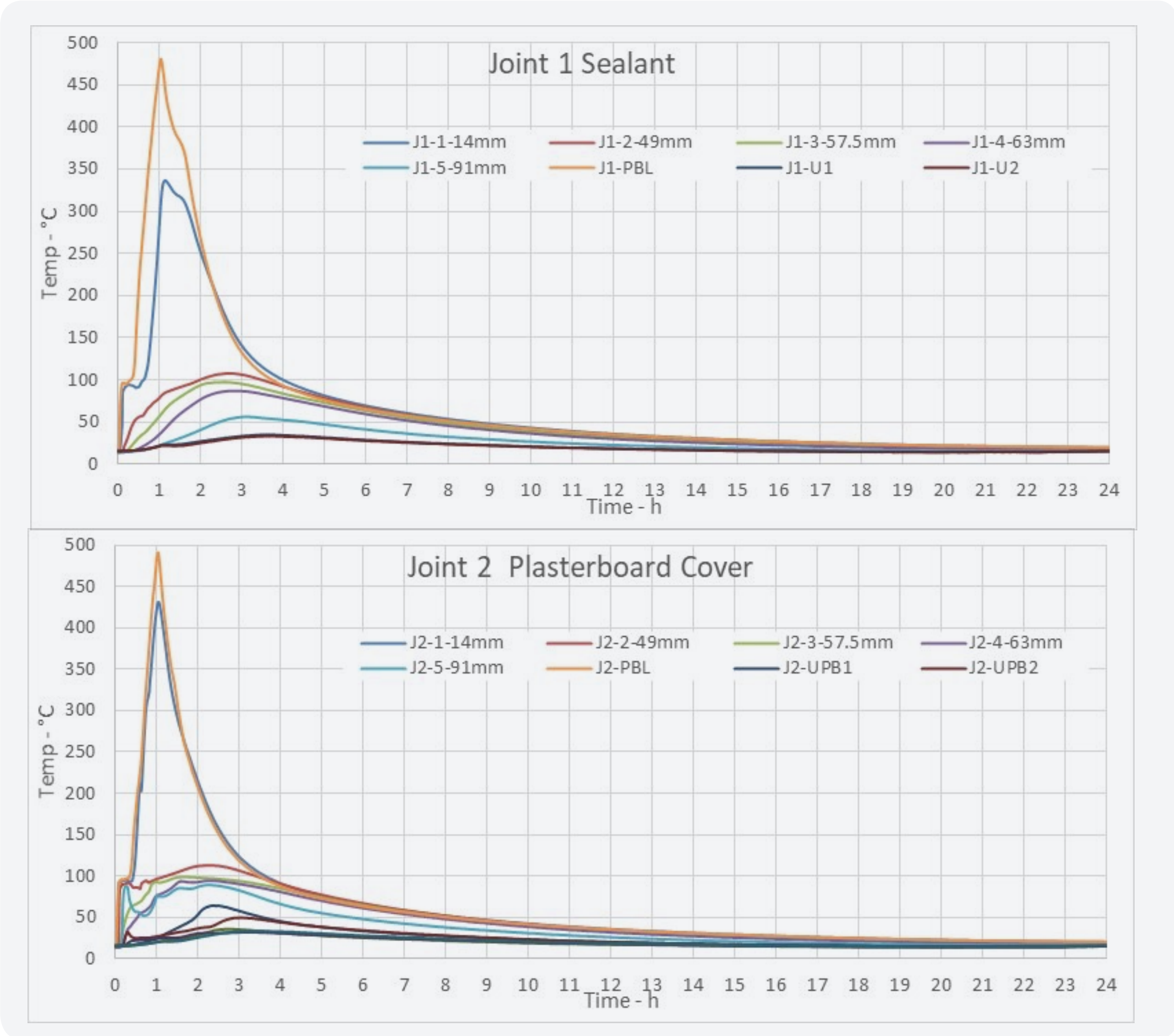


Figure 79: Thermocouple temperatures at joint positions.

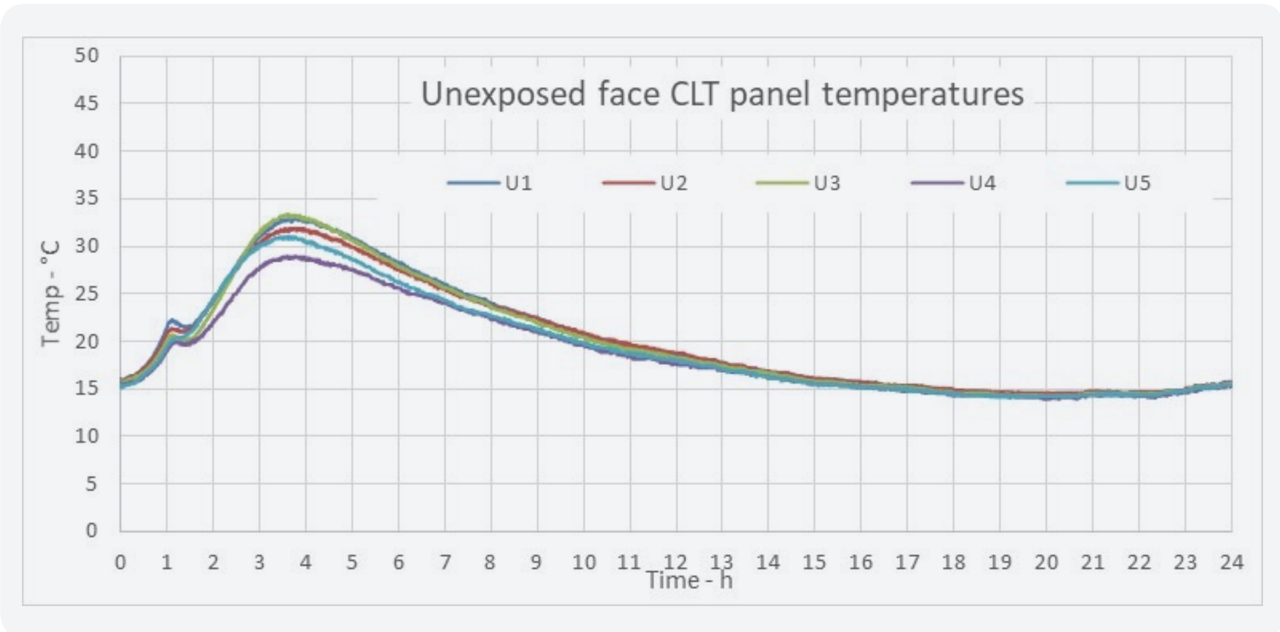


Figure 80: Non-fire side thermocouple data.

Decay after longer-duration fire tests on CLT panels

The behaviour of the Massive Timber elements after the longer duration fire tests was also investigated. The most relevant comparison with the shorter tests was Test 2, a 225 mm thick CLT panel protected by a single layer of 16 mm plasterboard subjected to the standard heating regime. The conditions were monitored for a relatively short period of 59 min since the element showed evidence of continuing char oxidation, albeit at a reduced rate. A comparison of the tests is provided in Table 56.

Table 56: Comparison of tests with single layer of 16 mm plasterboard protection.

Test	CLT depth (mm)	Furnace heating (h:min)	Monitoring period (h:min)	Time (min) CLT -PB interface > 300°C (t_{ch})	PB. Fall-off (min)
6-49385700	105	0:45	15:00	34	No fall-off
8-54455500	105	1:00	23:00	32	No fall-off
2-49385300	225	2:51	0:59	32	115

The heating period for Test 2 (49385300) was terminated after approximately 171 min when failure at the joint positions was considered imminent. Subsequently, failures under the criterion of insulation occurred for Joint 1, Joint 2 and in the body of a CLT panel 5, 22 and 29 min after termination of heating, respectively.

Heat flux measurements from Test 2 during the decay period are presented in Figure 81. It is noteworthy that, despite evidence of some ongoing combustion, the decay of measured heat flux from the specimen (purple plot) reduced to approximately 11 kW/m^2 after 60 min and the measured heat flux received by the specimen from the furnace walls and floor (green plot) is comparable.

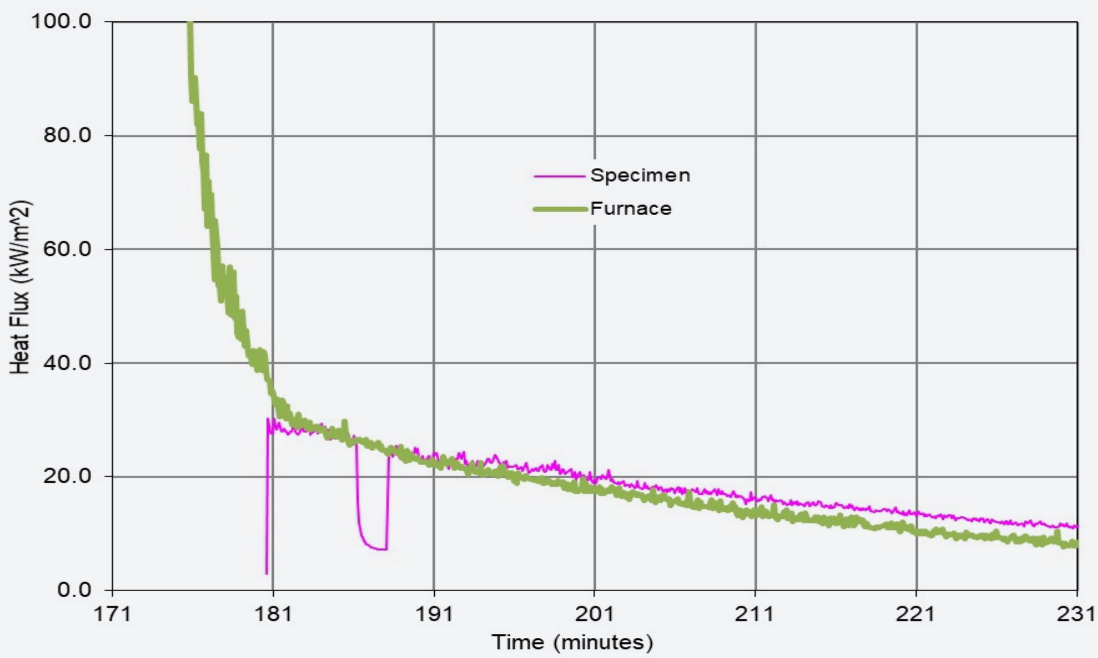


Figure 81: Heat flux from furnace and from specimen for 60 min after heating.

Figure 82 shows the fire-exposed face after 6, 10, 18 and 60 min of the post-heating monitoring period.

Image	Description
	Fire side 6 min after completion of heating period
	Fire side 10 min after completion of heating period
	Fire side 18 min after completion of heating period
	Fire side after monitoring period (approximately 60 min after completion of heating period)

Figure 82: Fire-exposed face during the post heating monitoring period.

A substantial reduction in the combustion rate is visible, confirming the thermal data, however combustion was ongoing at the joint positions and the exposed perimeter of the specimen at the end of the 60 min monitoring period. Significant delamination occurred such that 90 mm or more of the specimen face had been lost over the heated area, creating a detail at the perimeter where a horizontal face meets a vertical face of timber, facilitating radiative feedback. These observations indicate that as heat penetration into timber elements increases, intersections and joint details will become more critical if self-extinguishment is an objective. It may also be important to maintain fire-protective coverings in place if used to reduce radiant heat interchanges at intersections of elements.

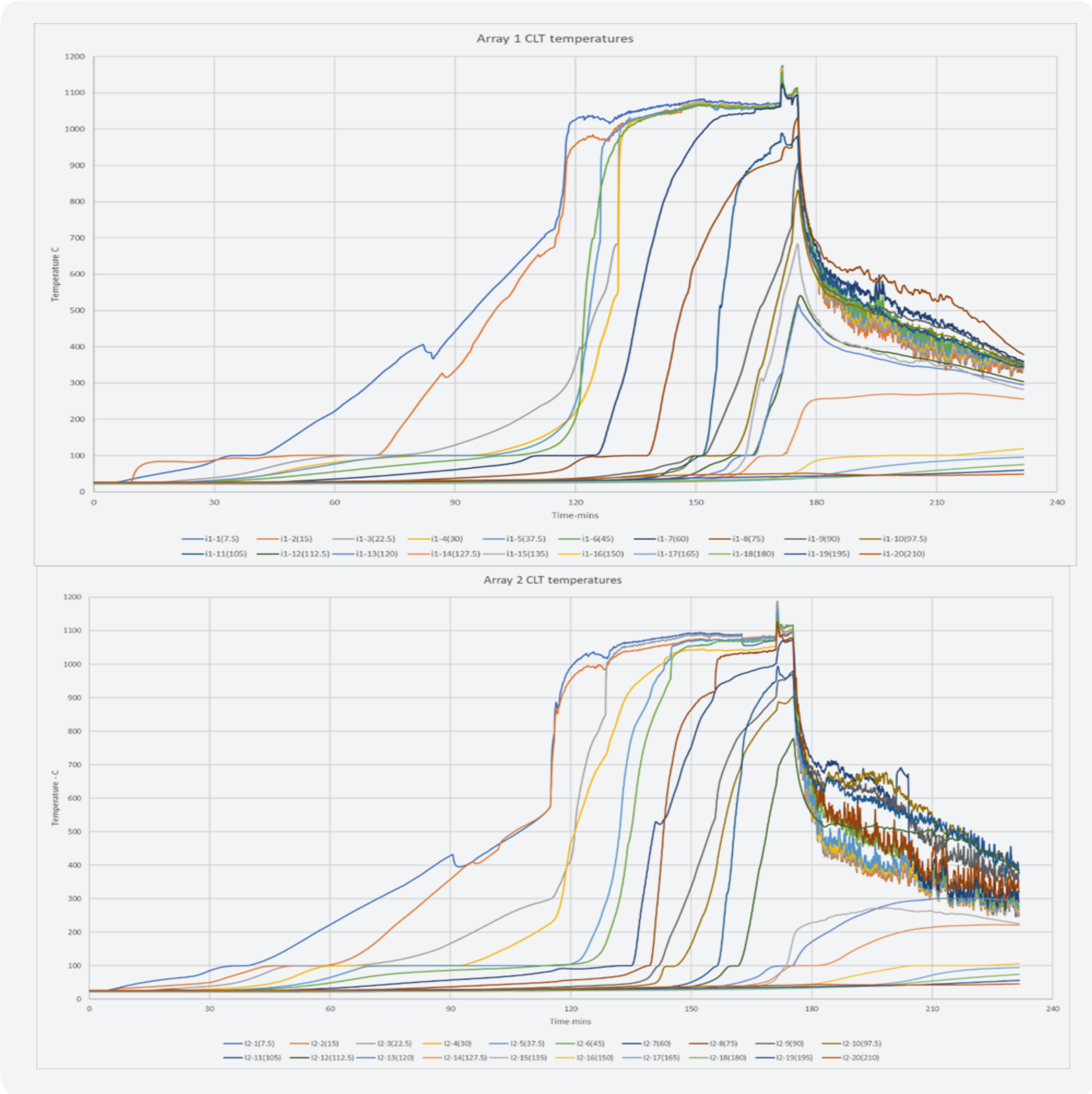


Figure 83: Thermocouple array temperatures in body of the CLT panels.

Decay after long duration fire tests on timber stud partition

This was a fire-resistance test on a loadbearing timber-frame wall system with three layers of fire-protective grade plasterboard 16 mm thick applied to each face of 140 mm x 45 mm studs with cavities filled with non-combustible stone wool.

The stone wool insulation was installed in lamella form to provide a practical way to reliably install the insulation in intimate contact with the timber studs with a controlled level of compression. The high-temperature performance specification and compression was intended to maintain one-directional heating of the timber studs by avoiding heat transfer through the cavity. The temperature data from the test indicated this was effectively achieved. Figure 84 shows the internal structure of the wall system.

Figure 84: Internal structure of high-performance timber frame wall system.

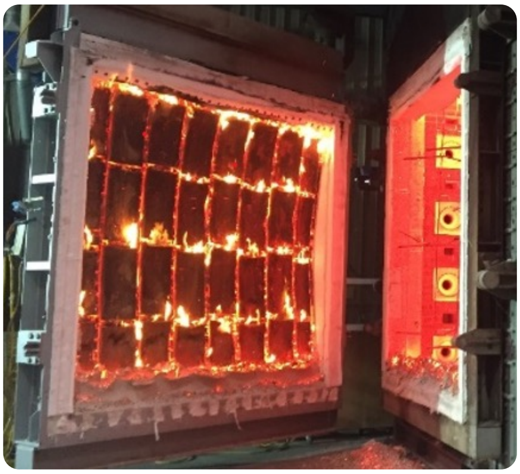
The use of laminating screws to secure the outer layer of plasterboard facilitated the positioning of fixings 38 mm from board edges and reduction of fixing centres over the board area, which is expected to significantly improve the retention time for the outer layer of board.

The specimen was subjected to the AS 1530.4 standard heating regime for 227 min, after which the specimen was removed from the furnace and conditions were monitored for a further 30 min. Further details are provided in Appendix C.7.3.

The specimen achieved an FRL in excess of 180/180/180 and Resistance to the Incipient Spread of Fire (RISF) rating in excess of 120 min. The full test load was applied until 198 min and then progressively reduced until heating was terminated after 227 min (due to the risk of damage to the loading equipment) with no failures under the criteria for insulation and integrity. The RISF criteria were exceeded after 135 min.

At the end of the heating period the specimen was removed from the furnace. To enable observation and the fitting of a heat flux meter to measure radiant heat released from the specimen, the specimen was rotated at an angle to the furnace as shown in Figure 85.

Visual observations confirmed continuing combustion and char oxidation with a slight reduction in intensity further away from the furnace, which can be explained by the lower incident radiant heat from the adjacent furnace. Temperatures measured within the char were generally in the range of 500°C to 600°C thoughout this period, indicating continued combustion. An average char rate of approximately 0.43 mm/min was maintained throughout the 30 min monitoring period.



Approximately 4 min after end of heating period

Approximately 26 min after end of heating period

Figure 85: Exposed face of partition during the monitoring period.

Heat flux measurements were taken 500 mm from the specimen to measure the radiant heat released from the specimen from 235 min to 257 min. The measured heat flux remained reasonably constant within the range of 8-10 kW/m^2 except for isolated peaks not greater than 13 kW/m^2.

6.9 Joints, connections and other interfaces

6.9.1 Overview

Within timber structures there are many joints, connections and interfaces with other forms of construction and building elements, such as services penetrations, which if not properly treated may compromise the performance of a structural element or fire barrier.

With timber elements there can be an added complication in that continued combustion at joint, connections and interface positions may compromise the fire resistance of the joint/connection and/or adjoining elements.

If the DTS pathway is followed, the adequacy of joints, connections and other interfaces is generally determined assuming exposure to the standard heating regime of AS 1530.4[18]. AS 1530.4 does not include specific test methods for connections, except to require representative joints to be included when testing elements of construction and features such as service penetrations, fire doors and the like to be tested in conjunction with a representative element of construction. While AS 1530.4 does not currently include specific test procedures for interfaces between elements of construction and connections, the fire exposure and general performance criteria can be applied to these features with representative test configurations being determined by the Accredited Test Laboratory in conjunction with the test sponsor.

AS/NZS 1720.4[19] includes additional guidance with respect to the assessment of joints and metal connectors:

- The fire resistance of joints fabricated with unprotected metal connectors shall be determined in accordance with AS 1530.4 using the standard heating regime. Without test evidence, the fire resistance shall be assumed to be negligible.
- Embedded fixing should be embedded to a minimum depth equal to the calculated effective depth of charring with the remaining holes filled with timber plugs glued in place.
- Fire-protective coverings can be locally applied around joint positions, in which case AS/NZS 1720.4 requires that the temperature under the insulation shall not exceed 120°C or 300°C for dowel type testing.
- The general use of the fire-resistance test method of AS 1530.4 is permitted in addition to the above options.

Figure 86 shows an example of the general use of the fire-resistance test for evaluation of fire-protected lightweight engineered timber floor systems with nail plate connections for the floor trusses and metal web to timber flange connections for composite I-beams. Refer to Appendix C.7 for further details of tested lightweight floor systems.

Figure 86: View within cavity showing connections after a fire test of the floor system protected by fire-protective coverings.

Further details relating to the treatment of joints, particularly under exposure to the standard heating regime are provided in Buchanan[17]. Interface details are provided in the following WoodSolution Technical Design Guides.

Applicable to applications where the Fire-protected Timber provisions do not apply:

- WoodSolutions Technical Design Guide 2[160] – Timber-framed Construction for Multi-residential Buildings Class 2 & 3
- WoodSolutions Technical Design Guide 3[161] – Timber-framed Construction for Commercial Buildings Class 5, 6, 9a & 9b
- WoodSolutions Technical Design Guide 6[162] – Timber-framed Construction. Sacrificial Timber Construction Joint

Applicable to fire protected timber:

- WoodSolutions Technical Design Guide 37R[4] – Mid-rise Multi-residential buildings
- WoodSolutions Technical Design Guide 37C[5] – Mid-rise Commercial and Education buildings
- WoodSolutions Technical Design Guide 37H[6] – Mid-rise health-care buildings

The performance and effect of adhesives is discussed in Sections 2.9 and 6.6 under various fire exposures.

When evaluating potential Performance Solutions, reference should ideally be made to test data for connections, joints and interfaces, performed under a range of fire exposures; but where this is not available reliance may have to be placed on elements exposed to the standard heating regime of AS 1530.4 supplemented by the application of engineering judgement. Where there remains doubt about the potential performance, additional test data may need to be obtained to provide satisfactory Evidence of Suitability.

Some general principles that should be considered when designing connections joints and interfaces are summarised below:

1. Conduction of heat through metal components may accelerate charring around fixings. This can be reduced by minimising the exposed surface area of the fixing, embedding fixings or providing fire-protective coverings over fixing positions.
2. The depth of char for the end of the time a connection needs to maintain its loadbearing capacity should be estimated and the fixing should be designed to support the required load based on the residual embedment length within uncharred timber only and with the load capacity of the uncharred timber adjusted based on modified timber properties at elevated temperatures.
3. The loadbearing capacity of metal components as well as the interface with wood should be checked because these can be the critical.
4. Fixings with shallow embedment, such as nail-plates, will tend to provide low levels of fire resistance unless adequately protected.
5. Connections and joints should be designed to withstand thermally induced stresses at the fixing positions in addition to applied loads.
6. Connection, joint and interface details that allow air flow through an element should be avoided where practical. Air flow may tend to accelerate charring locally and potentially initiate failure under the criteria of integrity and/or insulation.
7. Connection, joint and interfaces should be evaluated with a positive pressure differential which will promote the flow of hot gases from the fire-exposed face to the non-fire side. (Note: Some older test methods may not have required positive differentials and the performance obtained may be unconservative).
8. Charring will be accelerated in locations where there are opposing timber faces separated by a small gap due to radiative feedback between the opposing faces. Depending on the timber properties, if the end grain is exposed further acceleration of the char rate may occur. This can be addressed by filling or packing the joint/interface with a fire-resistant seal. The configuration and seal should be selected to ensure excessive stresses are not induced.

6.9.2 Comparative performance of half-lap joints

The test series described in Appendix C.9 included fire tests at an intermediate scale on cross-laminated timber (CLT) panels 225 mm thick, comprising five 45 mm deep Radiata Pine lamella. Each test specimen included a 50 mm half-lap joint secured with countersunk head HSB 8 mm diameter x 200 mm long wood screws at 300 mm centres fixed from above. The tests were performed unloaded and the length of joint exposed to the furnace was 1200 mm. The joint was sub-divided into two or three sections by a fire-resistant sealant in most tests to evaluate different joint protection methods as described below.

In tests 1 and 7, three half-lap joint treatments were evaluated:

- Joint 1 (Unprotected)
- Joint 2 (joint sealed with two beads of sealant between the bearing services
- Joint 3 (plasterboard cover on the fire-exposed side).

In tests 2 to 5 two half lap joint treatments were evaluated:

- Joint 1 (plasterboard cover on the non-fire-exposed side)
- Joint 2 (joint sealed with two beads of sealant between the bearing services).

In test 9, one half-lap joint treatment was evaluated. The joint was sealed by with two beads of sealant between the bearing services.

Typical details are shown in Figure 87.

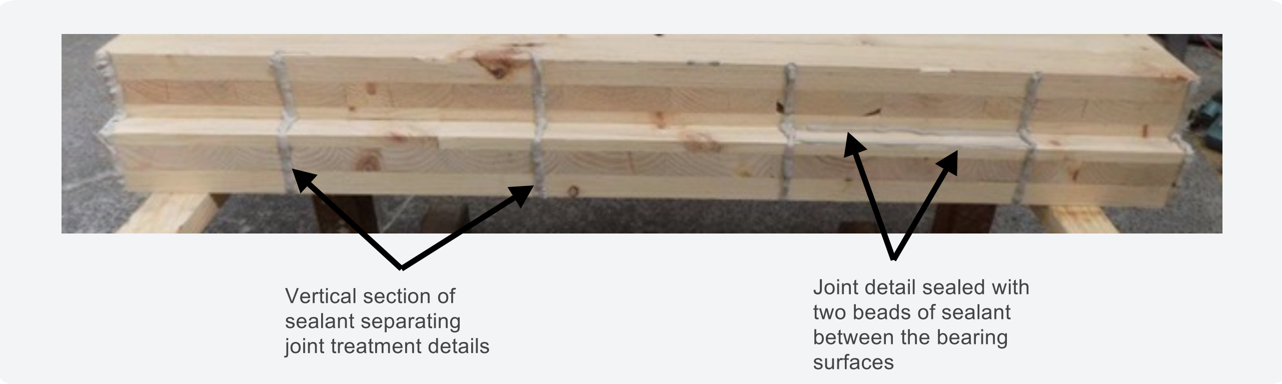


Figure 87: Mastic applied to specimen 1 during construction.

In all cases the half lap bearing surfaces were in contact and a 3 mm gap was provided between the ends of the joint to represent typical site installations where the joints are not tight fitting.

Cross-sections through each of the joint types are shown in Figure 88.

The results for the unprotected CLT specimens are summarised in Table 57.

Table 57: Performance of joints in unprotected CLT panels.

Joint treatment	Joint Integrity (min)		Ratio Standard to Hydrocarbon Integrity
	Standard	Hydrocarbon	
Unprotected	94	68	1.38
Two beads of mastic	131	75	1.75
Plasterboard cover	143	No failure at 109	-
CLT Panel excluding joint	No failure at 151	No failure at 109	-

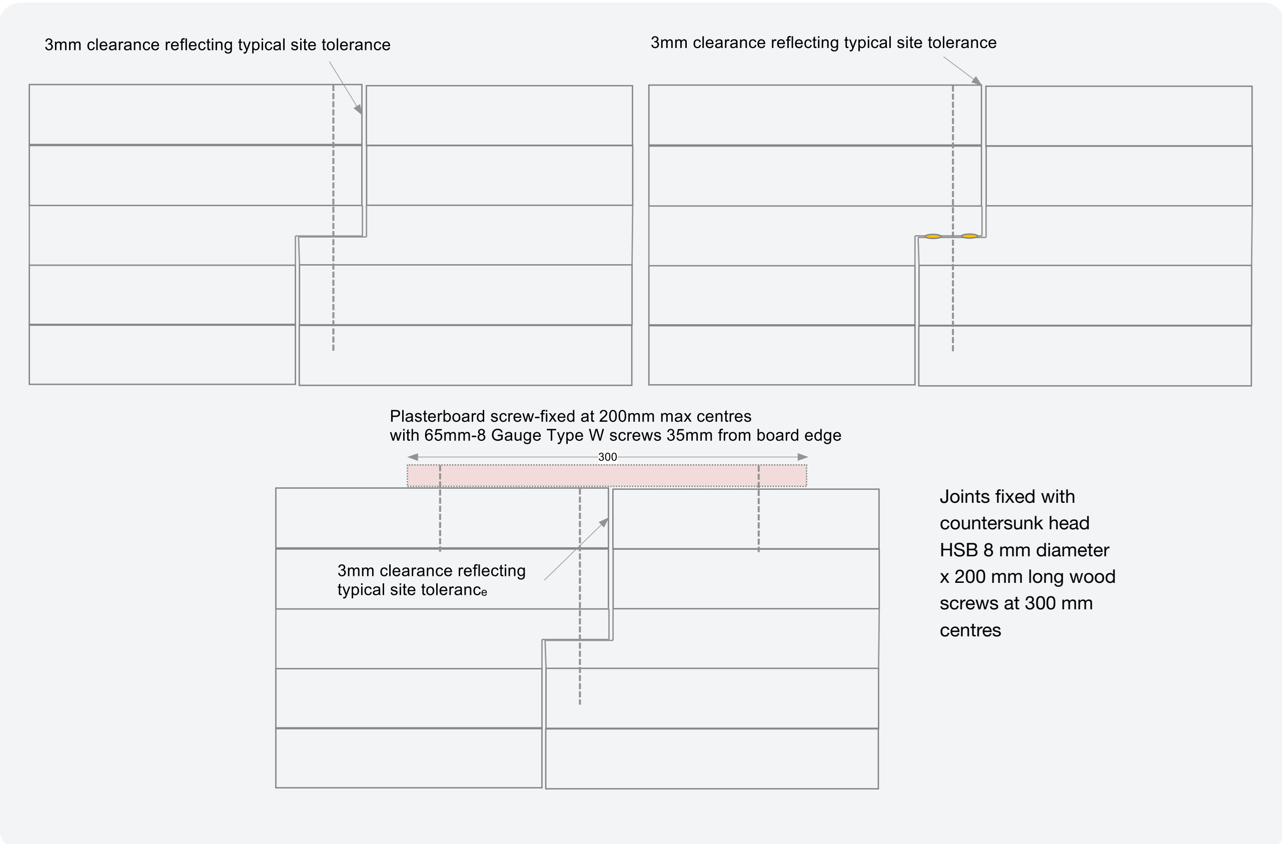


Figure 88: Cross-sections through half lap joint treatments evaluated.

The tests with the plasterboard protection to the soffit of the CLT panels were terminated before failures of the joints.

6.10 Modelling fire exposure from enclosure fires with exposed timber elements of construction

6.10.1 Overview

Common methods for modelling fully developed fires and the associated decay and cooling phases, such as general empirical correlations, parametric curves, zone models and CFD models, may not adequately model the impact of exposed timber elements. Some adjustments to the methods may be required or alternative methods adopted.

A brief recap of the potential impact of exposed timber elements is provided below.

Exposed timber elements may contribute to the fire load and the rate of production of volatiles, which may affect the heat release rate within an enclosure (unless the fire is already ventilation controlled based on the contribution from the moveable fire load). The heat release rate from combustible gases in fire plumes released from openings in the enclosure boundaries may also increase.

Depending on the timing of release of the volatiles from the fixed and removeable fire loads, the duration of the fire may also be increased. Therefore, the transition from the fully developed phase to decay phase needs to be considered.

The transition to the decay phase is not a clearly defined event but is commonly taken as the time at which 80% of the available fire load has been consumed or at an arbitrary enclosure temperature, which may be defined as a proportion of the sustained peak temperature (e.g. 70%). If timber structural members contribute to the fire load, it is more useful to adopt a temperature benchmark, particularly if self-extinguishment is being considered.

In most applications, the transition to the decay phase will occur when most of the moveable fuel load has been substantially consumed with only the residual parts of larger and/or slower-burning elements continuing to contribute to the fire. An idealised HRR plot is shown as the green line in Figure 89.

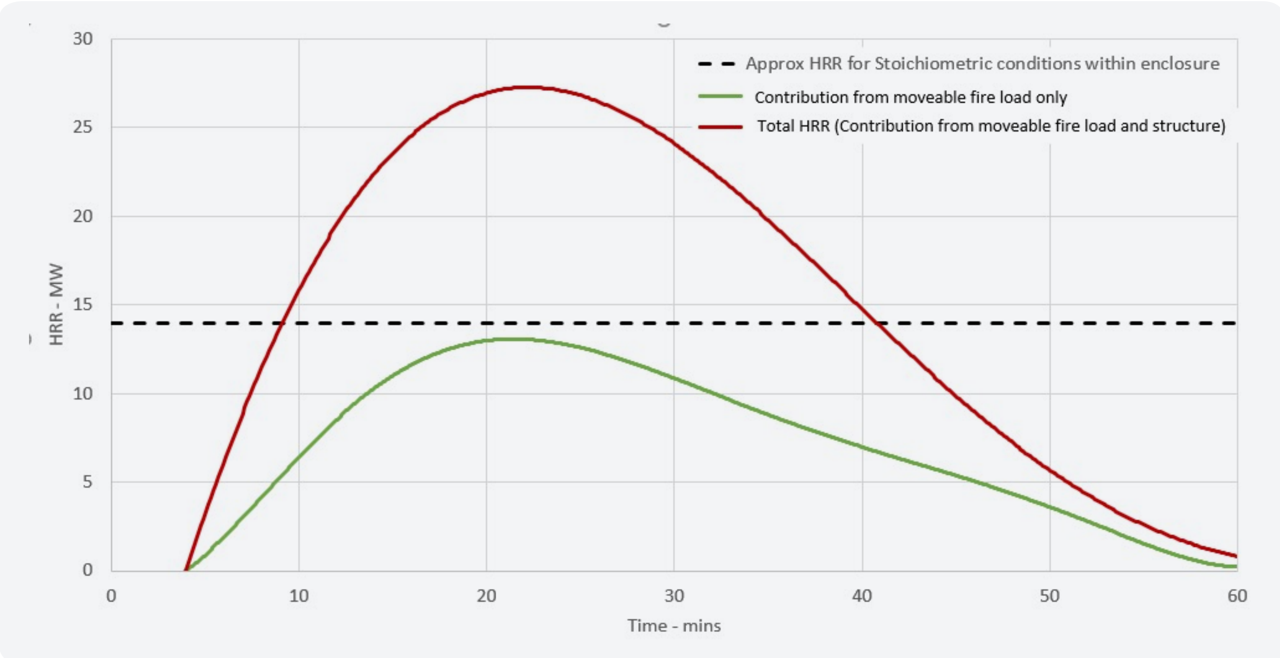


Figure 89: Idealised HRR v time graph for a residential enclosure with exposed timber structural elements self-extinguishing. Note: HRR values include external combustion of volatiles vented from the enclosure. The maximum HRR within the enclosure will be limited to nominally 14 MW by the available ventilation.

In this idealised example, the surfaces of some structural elements are exposed but the area of exposed timber is controlled. The exposed timber structural elements will increase the severity and duration of the Design Fire but flaming of the exposed timber will transition to smouldering combustion and eventually the elements will self-extinguish as the fire enters the cooling phase. The red line in Figure 89 is a plot of the combined contribution from the moveable fire load and structure. If the design achieves its goal of self-extinguishment, the red line will attain a zero heat release rate.

In this example, the fully developed fire duration would be of the order of 20 min, with the burning regime being fuel controlled but close to stoichiometric conditions. The impact of the exposed timber is to change the burning regime within the enclosure to ventilation controlled and the fire duration to approximately 40 min. Flame extension of the fire plumes outside the enclosure would be expected to increase significantly due to the excess volatiles produced.

Other decay/cooling scenarios that may need evaluating in order to check the robustness of the design, particularly in relation to low-probability high-consequence events, include:

- Additional areas of timber structural members being exposed.
- Delamination of exposed timber panels leading to regrowth of the fire.
- Premature failure of protection systems applied to timber elements increasing the surface area of exposed timber.
- Failure of the timber to self-extinguish, leading to eventual failure of structural elements if fire brigade intervention is not successful. Causes can include changes in air flow and detailing of connections and joints with opposing surfaces and exposed end grain that promote continuing combustion.
- The impact of a thermal wave during the cooling phase initiating structural failure.

The first four points may prevent self-extinguishment and the total HRR may not tend to zero. In some cases regrowth and secondary flashover could occur.

The last point reflects the potential for ongoing deterioration after heating has stopped and/or the passage of a thermal wave through a member. It is not unique to timber or combustible materials and applies equally to most structural materials, including steel and concrete. The potential for this mode of failure should be checked as part of the design process and, provided extinguishment occurs (either by one or a combination of manual or automatic suppression or self-extinguishment), it can normally be addressed by adjusting the size of a structural member and/or levels of protection.

6.10.2 Empirical correlations for fire exposures in terms of time equivalence

A typical example of this method is Annex F of EN 1991-1-2[39]. Further information on the method and its application is provided in the data sheets within the Fire Safety Verification Method Annex[14].

Methods such as this calculate the equivalent fire-resistance period to resist total burnout of the contents of an enclosure.

The use of this type of method in relation to timber construction is limited to:

- Evaluation of fully encapsulated timber structural elements and fire-resistant barriers that are protected such that they will not be ignited during the fire scenario or make any contribution to the fire severity; or
- Fixed fire loads that are not part of structural elements or fire barriers, such as combustible wall and ceiling linings that do not contribute to the fire resistance of the element to which they are applied. In this application, the fire load for the enclosure needs to be increased to allow for the entire fire load associated with the combustible linings in addition to the moveable fire load.

Note: Some current DTS Solutions allow combustible linings. Where this is the case, it is reasonable to assume the prescribed DTS FRLs take account of this contribution. This assumption should be confirmed during the PBDB process if a Performance Solution pathway is being adopted.

6.10.3 Parametric temperature time curves

One of the most well-known parametric temperature-time curves is the method provided in Annex A of EN 1991-1-2[39], which has the added advantage of its ability to be used in conjunction with the corresponding timber char rates that can be derived for a parametric curve using the method provided in Annex A of EN 1995-1-2:2004[42]. These methods are described in Appendix F and discussed in more detail in Section 6.6. A modification to the relationship for the parametric char rate has been suggested by Brandon and should be considered when using the method.

Application of the method requires the addition of an iterative approach to quantify the impact of continuing flaming combustion, char oxidation and potential for self-extinguishment during the decay phase. A typical iterative approach that applies procedures similar to those outlined in Figure 90 in conjunction with the parametric curves of EN 1991-1-2 was suggested by Barber et al[163], based on the earlier work of Crielaard[31, 95]. Supplementary checks are made to ensure that the area of timber is not sufficient to maintain a fully developed fire and that the fire will self-extinguish. The method initially required self-extinguishment to occur before the char layer reached the second lamella but, if adhesives that are shown not to be prone to delamination are used, this constraint may not be critical.

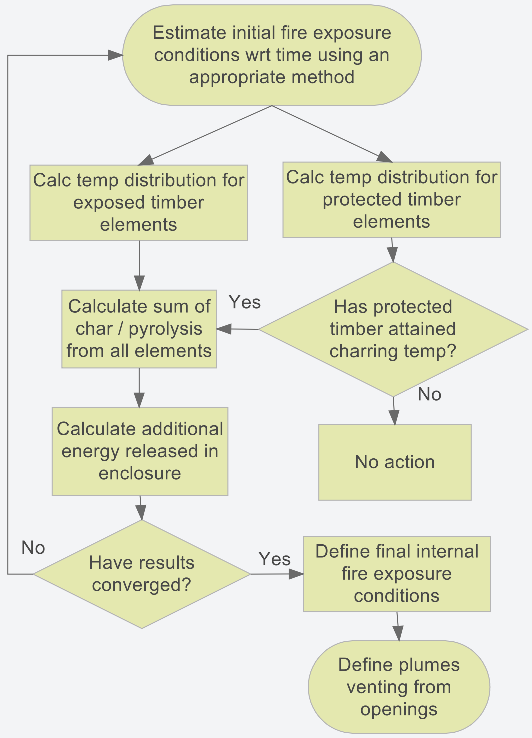


Figure 90: Flow chart for calculating enclosure time/temperature fire exposure regime with exposed timber elements.

6.10.4 Application of single zone models

Brandon[143] demonstrated and documented the application of an approach that applies a single zone model. In the example, a single-zone model adopted an energy equilibrium approach to obtain gas temperatures and surface temperatures of compartment boundaries.

The energy contribution of charring timber is included, based on the calculated char depth and experimental correlations for the combustion rate.

The comparisons with test results indicated that the total heat is underestimated in some cases and surface temperatures were underestimated in the decay phase. Local effects due to radiative feedback between surfaces with significant char oxidation occurred in a part of the tests, and this phenomena was not incorporated in the model.

The method adopts a similar iterative procedure to that shown in Figure 90.

Brandon included a detailed description of an implementation of the iterative approach.

6.10.5 SFPE constant compartment temperature and variants

A simple generic characterisation of fully developed fires can be obtained based on the Constant Compartment Temperature Method presented in the SFPE Engineering Standard S.01 2011[137] by assuming:

- a rapid growth rate
- a nominal peak temperature maintained until burnout
- a ventilation-controlled fire burning under stoichiometric conditions.

The SFPE method nominates a constant temperature of 1200°C and the duration is calculated using the following relationship:

$$D = \frac{E.A_f}{90A_W\sqrt{H}}$$

Where:

D is the duration at constant temperature (min)

E is the fire load density (MJ/m^2)

A_f is the floor area (m^2)

A_w is the area of the opening (m^2)

H is the height of the opening (m)

A cooling rate of 7°C/min is assumed.

The following is a brief description of an adaption of the SFPE method using the hydrocarbon heating regime included in AS1530.4. The fire growth period for the AS 1530.4 hydrocarbon regime is faster in the initial stages than the AS 1530.4 standard regime, applying a more realistic thermal action in the initial stages of the fire test.

The fully developed fire duration is assumed to commence after 3 min at temperatures above 800°C and is maintained until the moveable fire load is consumed. If the fire is ventilation controlled, oxygen concentrations will be low and can be considered to be reasonably represented by a fire-resistance furnace maintaining oxygen concentrations below 10%.

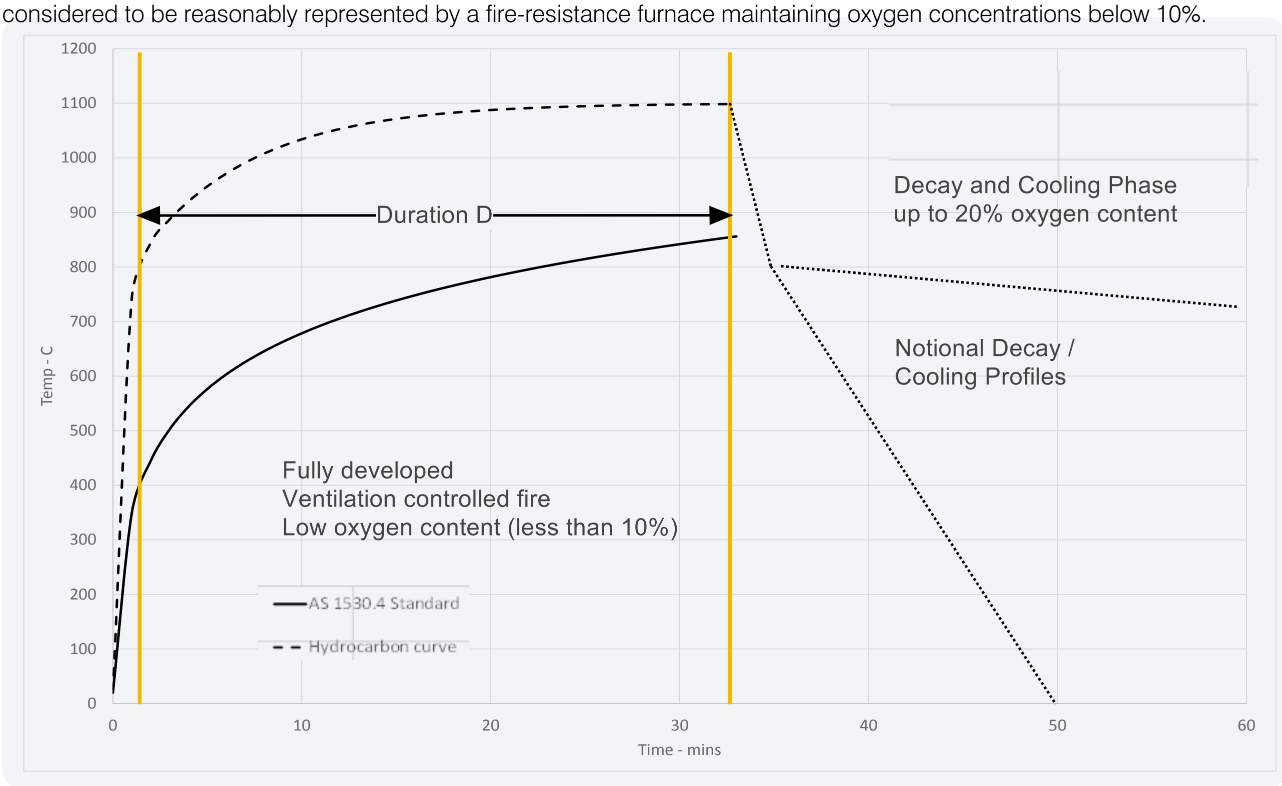


Figure 91: Generic characterisation of Design Fire exposure for fully developed fires.

The decay phase will generally be in an environment with relatively high oxygen concentrations. Further characterisation of a generic cooling phase with respect to temperature and/or heat flux will be sensitive to the thermal inertia of the enclosure boundaries, size of ventilation openings and nature of the fire load. Potentially, this can be addressed by nominating options for the decay/cooling phase and/or adjusting the fire duration to compensate for the cooling phase.

Supplementary calculations based on the extent of exposed timber elements are necessary to check if the fire will transition to the decay phase and the likelihood that it will eventually self-extinguish.

6.10.6 B-RISK

Significant development of the zone model B-RISK[72] has been undertaken to incorporate an integrated approach to evaluating the impact of exposed timber elements on enclosure temperatures and model vent flows from the enclosure. It has recently been updated to incorporate the outcomes from Wade[44, 164].

Essentially B-RISK allows the contribution of exposed timber surfaces to the fire development to be included, adding the mass released from the char layer to the moveable fire load at each time step during the simulation.

During the flashover phase, the moveable fire load is represented as wood cribs and the total fire load is increased to account for the additional fuel from exposed timber surfaces. The global equivalence ratio can also be manually adjusted to allow for burning or excess volatiles outside the enclosure.

Two options are available to calculate the additional fuel released from the surface of timber elements:

- calculating the char depth using a one-dimensional wall/ceiling heat transfer model
- using a kinetic pyrolysis model for the decomposition of the surface of the timber element.

Further details and validation against some natural fire tests is included in Wade[44].

6.10.7 CFD models

Dixon[165] also presented a preliminary implementation of an integrated approach using the CFD model FDS to simulate a fire within a compartment containing exposed timber. The methodology utilises the pyrolysis model within FDS that was calibrated against Heat Release Rate (HRR) data from cone calorimeter tests. Char rates were determined within FDS and benchmarked against full-scale experimental fire test data. An FDS model was developed for an example open plan floor area and then used to predict the fire dynamics within the compartment and quantify the response of the exposed timber structure.

The need for further development was indicated, including:

- Improvement to the initial fire characteristics, including re-radiation to investigate the potential for accelerated burning or alterations to fire dynamics.
- The effect of key input assumptions such as:
  - window breakage
  - initial fire location
  - initiating fire spread rate
  - charring rate assumptions.

6.10.8 Screening for delamination

The above approaches do not have an effective method of modelling the impact of delamination of lamella for products such as CLT that use adhesives that are prone to delamination. Instead, the risk of delamination is minimised by restricting charring to the outer lamella such that the first glue line does not increase to critical delamination temperatures.

Alternatively adhesives can be selected that are less sensitive to temperature and thus reduce the risk of delamination. Test procedures such as those described by Janssens[60] can be used for screening/verification purposes. In Australia, full-scale fire-resistance tests are currently used to provide useful information on the tendency for products such as CLT to delaminate.

6.10.9 Application of test data

The brief review of methods for modelling the impact of exposed timber elements, particularly during the decay phase, highlights that the methods tend to be modifications of established calculation methods and often use empirical calculation methods and/or effective properties of materials. Therefore, the methods should be validated against available experimental or test data.

Alternatively, appropriate test data, if available, may be suitable for direct application and as a major component of the Evidence of Suitability for a Performance Solution.

The following summaries of test data are included in the Appendices to this Guide:

- Appendix B Natural Fire Tests Relevant to Timber Construction
- Appendix C Australian Fire Resistance Tests
- Appendix D Wall and Ceiling Lining Tests.

A Appendix A - Abbreviations and Definitions

A.1 Abbreviations

ABCB	Australian Building Codes Board
ATL	Accredited Test Laboratory
CFD	Computational Fluid Dynamics
DTS	Deemed-to-Satisfy
FPT	Fire-protected Timber
FRL	Fire Resistance Level
FSVM	Fire Safety Verification Method (specified in the NCC)
FWPA	Forest & Wood Products Australia
HOC_{eff}	Effective heat of combustion
MRISF	Modified Resistance to the Incipient Spread of Fire
NCC	National Construction Code
PBDB	Performance-based Design Brief
RISF	Resistance to the Incipient Spread of Fire
SOU	Sole-occupancy unit
TFC	Timber Framed Concession

A.2 Frequently used symbols

k	Thermal conductivity (kW/m·K)
c	Heat capacity (J/ kg·K)
ρ	Density (kg/m^3)
$k\rho c$	Thermal Inertia
O	Opening factor (m$^{1/2}$)
A_v	Total area of vertical openings on all walls (m^2)
h_{eq}	Weighted average of window heights on all walls (m)
A_t	Total area of enclosure (walls, ceiling and floor including openings) (m^2)

A.3 Definitions

Definitions in italics are defined terms within the NCC.

Appropriate Authority: the relevant authority with the statutory responsibility to determine the particular matter.

Assessment Method: a method that can be used for determining that a Performance Solution or Deemed-to-Satisfy Solution complies with the Performance Requirements.

Combustion: an exothermic reaction of a substance with an oxidising agent.

Critical heat flux (for piloted ignition): the minimum external heat flux required to achieve piloted ignition of an exposed material.

Deemed-to-Satisfy Provisions: provisions that are deemed to satisfy the *Performance Requirements*.

Deemed-to-Satisfy Solution: a method of satisfying the *Deemed-to-Satisfy Provisions*.

Encapsulated timber: timber that is encapsulated by *fire-protective coverings* to prevent the underlying timber igniting for either a prescribed time period when exposed to a prescribed fire exposure, or in relation to fully encapsulated timber, for the entire fire duration, including the fire growth, fully developed, decay and cooling phases.

Encapsulation (in general usage when not directly related to timber): encapsulated by fire-protective coverings to prevent the underlying element reaching a critical temperature or functional failure occurring (e.g., structural failure), for either a prescribed time period when exposed to a prescribed fire exposure, or for the entire fire duration, including the fire growth, fully developed, decay and cooling phases.

Evidence of Suitability (in the context of the NCC): one of the types of Evidence of Suitability nominated as being acceptable in the NCC for the relevant application(s)

Expert Judgement: the judgement of an expert who has the qualifications and experience to determine whether a *Performance Solution* or *Deemed-to-Satisfy Solution* complies with the *Performance Requirements*.

Explanatory Information: Contemporary and relevant qualifications and/or experience are necessary to determine whether a *Performance Solution* complies with the *Performance Requirements*. The level of qualification and/or experience may differ depending on the complexity of the proposal and the requirements of the regulatory authority. Practitioners should seek advice from the authority having jurisdiction or *Appropriate Authority* for clarification as to what will be accepted.

Note: In engineering disciplines, the term engineering judgement is commonly used when making decisions or judgements rather than expert to indicate that the judgements made are typical of those made routinely by a competent professional engineer. The process may be formal, intuitive, or deliberate or, in most cases, a combination of the three.

Fire exposure: the exposure of an element of construction, material, object or person to thermal and other environmental or fire-related actions including variations to oxygen concentrations and other gas species concentrations, air flows and pressure differentials, as appropriate to the application.

Fire-hazard Properties: General definition from Guide to the National Construction Code Volume One:

A material's fire hazard properties are an indication of its susceptibility to the effects of flame or heat, particularly during the early stages of a fire.

Specific definition from National Construction Code Volume One: the following properties of a material or assembly that indicate how they behave under specific fire test conditions:

(a) Average specific extinction area, critical radiant flux, and Flammability Index, determined as defined in Schedule 3.

(b) Smoke-Developed Index, smoke development rate and Spread-of-Flame Index, determined in accordance with Schedule 6.

(c) Group number and smoke growth rate index (SMOGRA), determined in accordance with Specification C1.10 of Volume One.

Fire Load: The quantity of heat that could be released by the complete combustion of all the combustible materials in a volume. It is generally based on the gross heat of combustion. The fire load generally comprises the permanent or fixed fire load and the moveable fire load and is expressed directly in terms of energy (MJ) or as an equivalent mass of timber (kg).

Fire load density: The fire load per unit area and is generally expressed in terms of energy per unit area (MJ/m^2). Depending on the application, the fire load density may be expressed as the fire load per unit floor area or the fire load per unit area of the bounding construction.

Fire-protected timber: Fire-resisting timber building elements that comply with Volume One Specification C1.13a of the NCC.

Fire-protective covering (in the context of fire-protected timber in the NCC): A non-combustible covering complying with the requirements of specification C1.13a. Note: This differs from the standard definition provided within the NCC for fire-protective coverings.

Fire-protective grade plasterboard: Used to identify plasterboards with glass fibre and other additives to enhance the fire safety performance. Typically, timber elements constructed as described below with appropriate fixings will be able to achieve as a minimum the following Resistance to Incipient Spread of Fire (RISF) performance and FRLs when tested in accordance with AS 1530.4 as a wall or floor system:

- Two layers of 13 mm thick fire-protective grade plasterboard – RISF 45 min
- A loadbearing timber stud wall faced with two layers of 13 mm thick fire-protective grade plasterboard each side – FRL 90/90/90
- Two layers of 16 mm thick fire-protective grade plasterboard – RISF 60 min
- A loadbearing floor with timber joists and a ceiling comprising two layers of 16 mm thick fire-protective grade plasterboard and 19 mm timber flooring applied to the upper surface – FRL 90/90/90.

Note: the term fire grade plasterboard is sometimes used to refer to fire-protective grade plasterboards.

Fire-resistance level (FRL): The grading periods in minutes determined in accordance with Schedule 5 of the NCC, for the following criteria:

(a) structural adequacy; and
(b) integrity; and
(c) insulation,

and expressed in that order.

Note: A dash means that there is no requirement for that criterion. For example, 90/–/– means there is no requirement for an FRL for integrity and insulation, and –/–/– means there is no requirement for an FRL.

Fire resisting (for the purposes of Volume One of the NCC, applied to a building element): Having an FRL appropriate for that element.

Fire safety strategy: A strategy that defines the combination of measures that are required to satisfy the fire safety objectives and includes physical and human measures.

Fire Safety Engineer or Fire Engineer: A professional fire engineer with appropriately qualifications and experience.
Note: National and State based accreditation of fire safety engineers is available. When relying on a certificate or report from a fire engineer it is prudent to check the credentials of the relevant engineer and recognition of the accreditation within the State or Territory in which the building work is to be undertaken. Legislation within a State or Territory often includes requirements for insurance of practitioners such as Fire Safety Engineers.

Flashover: The transition from a localised fire to a fully developed fire, simultaneously involving all exposed combustible surfaces within a fire enclosure.

Gross heat of combustion: The heat of combustion of a material when any produced water is in liquid form.

Governing Requirements: Rules and instructions for using and complying with the NCC.

Heat of Combustion: The thermal energy produced by unit mass of a material.

Massive Timber: An element not less than 75 mm thick as measured in each direction formed from solid and laminated timber as defined by the NCC.

Modified *Resistance to the Incipient Spread of Fire*: The modified criteria used to determine the performance of fire-protective coverings applied to Massive Timber.

Moveable fire load: The fire load that is not permanent and is likely to vary over the life of the building and includes the fire load associated with free-standing furniture, soft furnishings, electrical equipment such as computers, books, stationary and stored combustible materials.

Net heat of combustion: The heat of combustion when any water produced is in the gaseous state.

Opening factor: A factor representing the amount of ventilation relative to the area of compartment walls and is calculated as the area of openings multiplied by the square root of the effective height of the openings, divided by the total area of the enclosure surfaces (i.e. $O = A_v(h_{eq})^{1/2}/A_t$).

Performance Solution: A method of complying with the Performance Requirements other than by a Deemed-to-Satisfy Solution.

Performance Requirement: a requirement that states the level of performance which a Performance Solution or Deemed-to-Satisfy Solution must meet.

***Performance-based Design Brief* (PBDB):** The process and the associated report that defines the scope of work for the performance-based analysis, the technical basis for analysis, and the criteria for acceptance of any relevant *Performance Solution* as agreed by stakeholders.

Permanent fire load: The fire load that is part of the structure, non-loadbearing walls, linings, coverings and other attachments including fixed furniture that is unlikely to vary over the life of the building.

Pyrolysis: The thermal decomposition of materials at elevated temperatures.

Reaction to fire: Response of a product in contributing by its own decomposition to a fire to which it is exposed, under specified conditions.

Resistance to the Incipient Spread of Fire: The ability of the membrane to insulate the space between the ceiling and roof, or ceiling and floor above, so as to limit the temperature rise of materials in this space to a level that will not permit the rapid and general spread of fire throughout the space. Note: This definition is expanded to include walls in Specification C1.13a.

Self-extinguish: To cease combustion without being affected by any external agent.

Sole-occupancy unit: A room or other part of a building for occupation by one or joint owner, lessee, tenant, or other occupier to the exclusion of any other owner, lessee, tenant or other occupier and includes:

(a) a dwelling; or

(b) a room or suite of rooms in a Class 3 building which includes sleeping facilities; or

(c) a room or suite of associated rooms in a Class 5, 6, 7, 8 or 9 building; or

(d) a room or suite of associated rooms in a Class 9c building, which includes sleeping facilities and any area for the exclusive use of a resident.

Standard Fire Test: The Fire-resistance Tests of Elements of Building Construction as described in AS 1530.4

Stoichiometric conditions: in the context of natural fires is where the ratio of air to other reactants (fuel) is in accordance with the equation for complete combustion.

Thermal Inertia: The product of thermal conductivity, density and heat capacity or in some applications it is defined as the square root of the product of thermal conductivity, density and heat capacity.

Verification Method: A test, inspection, calculation, or other method that determines whether a *Performance Solution* complies with the relevant *Performance Requirements*.

B Appendix B - Natural fire tests relevant to timber construction

B1 Introduction

A substantial number of natural fire test series have been undertaken since 2000 to investigate the performance of timber elements of construction when exposed to fully developed fires with and without various levels of protection. A summary of these is provided in Table 58 with further details being provided in the following sections of this Appendix. The depth of discussion differs between programs with greater emphasis being placed on test programs that yielded interesting results and where access to data from the series is readily available.

This forms a useful resource for validation of design methods and for some applications a natural fire test may be able to be applied directly as Evidence of Suitability. Where appropriate the body of this Guide has referred to the content of this Appendix to illustrate the fire dynamics associated with timber construction.

It should be noted that there are ongoing test programs, and it is recommended that users regularly check on the release of data from these test programs.

Table 58: Summary of natural fire tests relevant to timber structures. *(Superscripts in bold type refer to notes at the end of the table. Superscripts in a light type refer to references provided in Appendix H)*

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
A1	Lennon et al. (2000)[78, 138, 166] [14]	TF 2000	19.8[14]	3.36[14]	0.043[14]	LTF	Ceiling 19 mm Gyproc Plank, 12.5 mm Gyproc Wall Board (system fire resistance 60 min) Fire resistant walls 2 x 12.5 mm Wall Board (system fire resistance 60 min) Glass fibre insulation	wood cribs	391	wood crib
B1	Hakkarainen (2002[57])	test 1	15.75	2.76	0.042	HTC	None	wood cribs	720[1]	wood crib
B2		test 2	15.75	2.76	0.042	HTC	12.5 mm Type A	wood cribs	720[1]	wood crib
B3		test 3	15.75	2.76	0.042	HTC	12.5 mm Type A 15.4 mm Type F	wood cribs	720[1]	wood crib
B4		test 4	15.75	2.76	0.042	LTF	12.5 mm Type A 15.4 mm Type F	wood cribs	720[1]	wood crib
C1	Frangi and Fontana (2005)[167]	BE bb g	18.04	2.55	0.041	LTF	None	cribs & bed	N.F.	mattress
C2		BE bb o I	18.04	2.55	0.041	LTF	None	cribs & bed	N.F.	mattress
C3		BE bb o II	18.04	2.55	0.041	LTF	None	cribs & bed	N.F.	mattress
C4		BU nbb	18.04	2.55	0.041	LTF	18 mm plasterboard	cribs & bed	234 (363)[7]	mattress
C5		BU bb	18.04	2.55	0.041	LTF	None	cribs & bed	211[8]	mattress
C6		nbb demo	18.04	2.55	0.041	LTF	15 mm non-comb.	cribs & bed	237[9]	mattress
D1	Chen (2008)[168]	test 1	15.72	2.25	0.040	LSF	Ceil. 2 x 15.7 mm Type X Walls 1 x 15.7 mm type X+ 1 x 12.7 mm cement board + 1 x 15.7 mm Type X	furniture	397	bed
D2		test 2	15.72	2.25	0.040	LSF		furniture	366	bed
E1	Frangi et al. (2008)[169]	none	11.16	2.00	0.032	CLT	12 mm standard 12 mm fire proof[2]	cribs & bed	790	wood crib
F1	Kampmeier (2009)	none	14.44	N.F.	N.F.	CLT	31% of CLT K215 or K230	gas	N.F.	gas

Table 58: Summary of natural fire tests relevant to timber structures (continued).

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
G1	Lennon et al. (2010)[170]	solid floor joist	12.00	1.40	0.024	LTF	12.5 mm Type F 12.5 mm Type F	wood cribs	450	wood crib
G2		OSB web I joist	12.00	1.40	0.024	LTF	15 mm Type F 15 mm Type F	wood cribs	450	wood crib
G3		steel truss web joist	12.00	1.40	0.024	LTF	12.5 mm Type F 12.5 mm Type F	wood cribs	450	wood crib
H1	Peng et al. (2011)[171] Sprinkler protection for test 1	1	17.10	1.8[4]	N.F.	N.F.	N.F. (Ceiling provided)	wood	N.F.	wood
H2		2	17.10	1.8[4]	N.F.	N.F.	N.F. (Ceiling provided)	wood	N.F.	wood
H3		3	17.10	1.8[4]	N.F.	N.F.	N.F.	furniture	N.F.	N.F.
H4		4	17.10	1.8[4]	N.F.	N.F.	N.F. (Ceiling provided)	furniture	N.F.	N.F.
H5		5	17.10	1.8[4]	N.F.	N.F.	N.F.	wood	N.F.	wood
H6		6	17.10	1.8[4]	N.F.	N.F.	N.F.	wood	N.F.	wood
I1[3]	McGregor (2013)[58]	test 1	15.75	2.14	0.042	CLT	2 x 12.7 mm fire rated p.b.	propane	486	prop. burner
I2[3]		test 2	15.75	2.14	0.042	CLT	2 x 12.7 mm fire rated p.b.	furniture	533	bed
I3[3]		test 3	15.75	2.14	0.042	CLT	None	propane	182	prop. burner
I4[3]		test 4	15.75	2.14	0.042	CLT	2 x 12.7 mm fire rated p.b.	furniture	553	bed
I5[3]		test 5	15.75	2.14	0.042	CLT	All surfaces exposed CLT (55.75 m^2)	furniture	529	bed
J1	Li (2014)[172]	test 4	15.75	2.14	0.042	LTF	2 x 12.5 mm Type C	furniture	614	bed
J2		test 5	15.75	2.14	0.042	LTF	12.5 mm Type C	furniture	610	bed
J3		test 6	15.75	2.14	0.042	LSF	12.5 mm Type C	furniture	601	bed
K1	Medina Hevia (2014)[59]	test 1	15.75	2.14	0.042	CLT	Back & 1 side wall exposed CLT (20 m^2): 2 x 12.7 mm Type X [5]	furniture	532	bed
K2		test 2	15.75	2.14	0.042	CLT	Both side walls exposed CLT (22.5 m^2) 2 x 12.7 mm Type X[5]	furniture	532	bed
K3		test 3	15.75	2.14	0.042	CLT	One side wall exposed CLT (11.25 m^2) 2 x 12.7 mm Type X[5]	furniture	532	bed
L1	Su and Lougheed (2014)[6] [173, 174]	LWF1	52.54	4.5[10]	0.031	LTF	2 x 12.7mm Type X except 1 x 12.7 mm regular non-loadbearing internal partitions	furniture	≈550[4]	bed
L2		CLT	52.54	4.5[10]	0.031	CLT	2 x 12.7 mm Type X except 1 x 12.7 mm stand. non-load-bearing internal partitions	furniture	≈550[4]	bed
L3		LSF	52.54	4.5[10]	0.031	LSF	1 x 15.9 mm Type x except 1 x 12.7 mm, regular non-loadbearing internal partitions and external walls and 1 x 12.7 mm Type X ceiling	furniture	≈550[4]	bed
L4		LWF2	52.54	4.5[10]	0.031	LTF	2 x 12.7 mm Type X except 1 x 12.7 mm regular non-load-bearing internal partitions and exterior wall	furniture	≈550[4]	bed
L5	Bwalya et a PRF-03[175]	PRF-03	15.96	2.25	0.039	NA fully protected	Type X plasterboard	furniture	976 include. floor	bed

Table 58: Summary of natural fire tests relevant to timber structures (continued).

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
M1	Su and Muradori[11] (2015)[176]	none	23.72	4.70	0.064	CLT	Walls 2 x 16 mm Type X[2] Add protection to shaft Ceiling 1 x 16 mm plus insulation attached to double furring channels	furniture & wood cribs	790	seat
N1	Kolaitis et al (2014)[177]	none	4.93	0.42	0.015	CLT & LTF	12.5 mm Type DF 12.5 mm Type DF	wood cribs	420	wood crib
O1	Janssens (2015)[192]	test 1	14.48	3.87	0.084	CLT & NLT ceiling	2 x 16 mm Type X	furniture	570	sofa
O2		test 2	14.48	3.87	0.084	CLT	2 x 16 mm Type X	furniture	601	sofa
P1	Hox [91, 92] (2015)	test 1- sprinkler activation	13.30	3.27[6]	0.070[6]	HTC	15.8 m^2 of wall & 13.2 m^2 ceiling exposed CLT: 13 mm Type A PB 15 mm Type F PB	desk, mattress, wood cribs	660	desk
P2		test 2	13.30	3.27[6]	0.070[6]	HTC	15.8 m^2 of wall & 13.2 m^2 ceiling exposed CLT: 13 mm Type A PB 15 mm Type F PB	desk, mattress, wood cribs	660	desk
Q1	Hadden et al [178.] (2017)	Beta 1	7.4	1.40	0.042	CLT	Back wall and ceiling exposed. Other walls 1 x 12.5 mm Type F + 25 mm high-density stone wool + 2 x 12.5 mm type F.	wood cribs	132	wood crib
Q2		Beta 2	7.4	1.40	0.042	CLT	Back wall and ceiling exposed. Other walls 1 x 12.5 mm Type F + 25 mm high-density stone wool + 2 x 12.5 mm Type F	wood cribs	132	wood cribs
Q3		Alpha-1	7.4	1.40	0.042	CLT	Back and one side wall exposed. Other walls and ceiling 2 x 12.5 mm Type F	wood cribs	132	wood cribs
Q4		Alpha-2	7.4	1.40	0.042	CLT	Back and one side wall exposed other walls and ceiling – 1 x 12.5 mm Type F + 25mm high-density stone wool + 2 x 12.5 mm Ttype F	wood cribs	132	wood cribs
Q5		Gamma-1	7.4	1.40	0.042	CLT	Back and one side wall + ceiling exposed other walls – 1 x 12.5 mm Type F + 25 mm high-density stone wool + 2 x 12.5 mm Type F	wood cribs	132	wood cribs
R1	Janssens (2017)[60]	test 1	15.9	1.74	0.033	CLT	Ceiling: unprotected CLT Walls: non-combustible	Propane burners	456	burner
R2		test 2	15.9	1.74	0.033	CLT	Ceiling: unprotected CLT Walls: non-combustible	Propane burners	456	burner
R3		test 3	15.9	1.74	0.033	CLT	Ceiling: unprotected CLT Walls: non-combustible	Propane burners	456	burner
S1	Just et al [179] (2018)	none	15.75	4.50	0.072	CLT	37% of walls exposed: 2 x15 mm Type F ceiling: 3 x 15 mm Type F	furniture	600	sofa
T1	England and Eyre (2011)[73, 74]	Timber frame test	16	2.4	0.037	LTF	Walls 2*12.5 mm fire-protective grade PB Ceiling 2 x 16 mm fire-protective grade PB	wood cribs	718	wood crib
T2		Steel frame test	16	2.4	0.037	LSF	Walls 2*12.5 mm fire-protective grade PB Ceiling 2 x 16 mm fire-protective grade PB	wood cribs	718	wood crib

Table 58: Summary of natural fire tests relevant to timber structures (continued).

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
U1	Emberley et al (2017)[180]	Large scale cross-laminated timber fire test	12.25	1.79	0.042	CLT	Walls 2*12.5 mm fire-protective grade PB Ceiling and one side wall exposed CLT	wood cribs	118[12]	wood crib
V1	Zelinka et al (2018)[c 89]	Test 1 Lounge/ kitchen	41.13	8.93	0.089	CLT	Walls and ceilings 2 x 16 mm Type X	furniture	550	Within base kitchen cabinet
V2		Test 1 Bed	27.00	8.93	0.125	CLT	Walls and ceilings 2 x 16 mm Type X	furniture	550	Spread from lounge/ kitchen
V3		Test 2 Lounge/ kitchen	41.13	8.93	0.089	CLT	Walls and ceilings 2 x 16 mm Type X 8.36 m^2 ceiling exposed CLT	furniture	550	Within base kitchen cabinet
V4		Test 2 Bed	27.00	8.93	0.125	CLT	Walls and ceilings 2 x 16 mm Type X 8.36 m^2 ceiling exposed CLT	furniture	550	Spread from lounge/ kitchen
V5		Test 3 Lounge/ kitchen	41.13	8.93	0.089	CLT	Walls and ceilings 2 x 16 mm Type X Wall B exposed (25m^2)	furniture	550	Within base kitchen cabinet
V6		Test 3 Bed	27	8.93	0.125	CLT	Walls and ceilings 2 x 16 mm Type X Wall D exposed (16.4 m^2)	furniture	550	Spread from lounge/ kitchen
V7*	Zelinka et al (2018)[89] Sprinkler Protected V7 and 8 normal activation 2:37 min V9 and V10 delayed activation – 23 min after ignition	Test 4 Lounge / Kitchen	41.13							Within base kitchen cabinet
V8*		Test 4 bed	27							Spread from lounge/ kitchen
V9*		Test 5 Lounge / Kitchen	41.13				Lounge exposed CLT walls and ceiling Kitchen 2 x 16 mm			
V10*		Test 5 Bed	27							
W1	Su et al (2018) Fire Safety Challenges of Tall Wood Buildings Fire Tests [181, 182]	Test 1-1	41.86	3.6	0.03	CLT	Walls and ceilings 3 x 16 mm Type X	furniture	≈550[13]	Sideboard in room corner
W2		Test 1-4	41.86	3.6	0.03	CLT	Walls 3 x 16 mm Type X – Ceiling exposed (41.86m^2)	furniture	≈550[13]	Sideboard in room corner
W3		Test 1-5	41.86	3.6	0.03	CLT	Walls & ceiling 3 x 16 mm Type X except wall W1 (24.56 m^2) exposed	furniture	≈550[13]	Sideboard in room corner
W4		Test 1-6	41.86	3.6	0.03	CLT	Walls 3 x 16 mm Type X except ceiling (41.86 m^2) & wall W1 (24.56 m^2) exposed	furniture	≈550[13]	Sideboard in room corner
W5		Test 1-2	41.86	7.2	0.06	CLT	Walls and ceilings 2 x 16 mm Type X	furniture	≈550[13]	Sideboard in room corner
W6		Test 1-3	41.86	7.2	0.06	CLT	Walls 2 x 16 mm Type X and Ceilings 3 x 16 mm Type X except wall W1(24.56m^2) exposed	furniture	≈550[13]	Sideboard in room corner

Table 58: Summary of natural fire tests relevant to timber structures (continued).

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
X1	Su et al (2018) Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction [113]	CLT-1	10.8	1.52	0.03	CLT	Walls and Ceilings 1 x 16 mm Type X and 2 x 13 mm Type X	wood cribs	550	wood cribs
X2		CLT-2	10.8	1.52	0.03	CLT	Walls and ceiling 2 x 13 mm Type X except 10% of ceiling and Wall A (33% of perimeter)	wood cribs	550	wood cribs
X3		CLT-3	10.8	1.52	0.03	CLT	Walls and ceiling 2 x 13 mm Type X except 10% of ceiling with Glulam beam (4.54 m^2 -11.5% of perimeter) & Glulam Column (9.62 m^2 -24.5% of perimeter)	wood cribs	550	wood cribs
X4		CLT-4	10.8	1.52	0.03	CLT	Walls 2 x 13 mm Type X except for Ceiling, Glulam Beam (2.46 m2 -6.4% of perimeter) & Glulam Column (4.81 m^2 -12.6% of perimeter)	wood cribs	550	wood cribs
X5		CLT-5	10.8	1.52	0.03	CLT	Walls 2 x 13 mm Type X except ceiling and two short walls (35% of perimeter)	wood cribs	550	wood cribs
Y1	Su et al (2019) Nail-laminated timber compartment fires[183]	NLT-1	10.8	1.52	0.03	NLT	Walls 2 x 13 mm Type X; Ceilings, Beam and Column exposed (19% of perimeter)	wood cribs	550	wood cribs
Y2		NLT-2	10.8	1.52	0.03	NLT	Walls 2 x 13 mm Type X Ceilings, beam and column exposed (19% of perimeter).	wood cribs	550	wood cribs
Y3		NLT-3	10.8	1.52	0.03	NLT	Walls 2 x 13 mm Type X except ceiling and two short walls (35% of perimeter)	wood cribs	550	wood cribs
Y4		NLT-4	10.8	1.52	0.03	NLT	Walls 2 x 13 mm Type X except ceiling and two short walls (35% of perimeter)	wood cribs	550	wood cribs
Z1	Collignon & Tessier[184-189]	Scenario 1 Concrete 010615	24	10	0.144	Conc	Walls 300 mm thick AAC Floor 180 thick concrete slab with pp fibres	wood cribs	891	wood cribs
Z2		Scenario 1 CLT 010617	24	10	0.144	CLT	Walls 300 mm thick AAC Floor 165 mm CLT unprotected	wood cribs	891	wood cribs
Z3		Scenario 2 Concrete 013598	24	4.5	0.050	Conc	Walls 300 mm thick AAC Floor 180 thick concrete slab with pp fibres	wood cribs	891	wood cribs
Z4		Scenario 2 CLT 013597	24	4.5	0.050	CLT	Walls 300 mm thick AAC Floor 165 mm CLT unprotected	wood cribs	891	wood cribs
Z5		Scenario 3 Concrete 013600	24	2.2	0.032	Conc	Walls 300 mm thick AAC Floor 180 thick concrete slab with pp fibres	wood cribs	891	wood cribs
Z6		Scenario 3 CLT 013599	24	2.2	0.032	CLT	Walls 300 mm thick AAC Floor 165 mm CLT unprotected	wood cribs	891	wood cribs

Table 58: Summary of natural fire tests relevant to timber structures (continued).

Test	Reference	Name in ref.	Floor area (m^2)	Vent opening area (m^2)	Opening factor ($m^{1/2}$)	Main struct. members	Thickness and type of gypsum board protection (exposed layer last)	Fuel type	Movable fire load MJ/m^2	First item ignited
AA-1	Fire Safe Implementation of visible mass timber in tall buildings – compartment fire testing – Brandon et al[43, 190]	Test 1	48	8.0	0.062	CLT/ GLULAM	All walls and columns protected by two layers of 16 mm Type X PB Ceiling/beam exposed	Furniture / wood cribs and timber flooring	560	635 g crumbled paper close to centre of rear wall
AA-2		Test 2	48	8.0	0.062	CLT/ GLULAM	Back wall and front wall protected by three layers of 16 mm Type X PB Ceiling/beam side walls exposed	Furniture/ cribs and timber flooring	560	635 g crumbled paper close to centre of rear wall
AA-3		Test 3	48	8.0	0.062	CLT/ GLULAM	Back wall and back 1.5 m of right wall protected by three layers of 16 mm Type X PB. Ceiling/beam and remaining walls exposed	Furniture/ cribs and timber flooring	560	635 g crumbled paper close to centre of rear wall
AA-4		Test 4	48	31.1	0.25	CLT/ GLULAM	Back wall protected by two layers of Type X PB, Ceiling/ beam and remaining walls exposed	Furniture/ cribs and timber flooring	560	635 g crumbled paper close to centre of rear wall
AA-5		Test 5	48	8.0	0.062	CLT/ GLULAM	Back wall and 0.7 m of left and right of the front wall protected by three layers of Type X PB	Furniture/ cribs and timber flooring	560	635 g crumbled paper close to centre of rear wall

Notes:
LTF: Lightweight timber frame
HTC: Heavy timber construction (including CLT and similar wood products)
LSF: Lightweight steel frame
CLT: Cross-laminated timber
NF: Data/information not found
NLT: Nailed laminated timber
Conc: Concrete
GLULAM: Glued laminated timber
PB: Plasterboard

1 Fire load calculated assuming a combustion efficiency of 0.8 and a net heat of combustion for wood products of 15.5 MJ/ kg/
2 The ceiling had only one layer of 16 mm Type X gypsum boards.
3 Additional lining applied to walls compared to earlier series sandwiching cement sheet board/
4 Moveable fire load density based on survey results:
   i. bedroom 510 MJ/m^2
   ii. living area 380 MJ/m^2
   iii. kitchen dining area 970 MJ/m^2
   iv. average living/dining/kitchen 575 MJ/m^2
   v. whole apartment average 550 MJ/m^2.
5 All protected walls and ceilings protected by two layers of 12.5 Type X plasterboard.
6 Opening areas are approximate estimates allowing for framing around the door and window remaining in place. Window is assumed broken for these estimates.
7 Value in brackets includes contribution of fixed fire load from floor. There was a transient peak recorded from 20-22 min which was not reflected in any other data in the reviewed documentation. These data points were therefore omitted.
8 Temperature measurements through whole fire scenario not reported. Possible equipment malfunction.
9 Time-temperature data not reported.
10 The direct external opening from the room was 1.5 x 1.5 m but the estimated ventilation including the window from the adjoining room (also 1.5 x 1.5m). The rooms were connected by a hollow core timber door. While this would burn through within a few minutes, fully developed fires occurred in both spaces and therefore the oxygen from the adjoining enclosure during the fully developed phase may have been relatively low. An opening area of 2.25m^2 and an opening factor of 0.039 $m^{1/2}$ may be more representative.
11 Data logging failure after approx 30 min due to collapse of the ceiling.
12 Assumed heat of combustion of timber crib 18MJ/kg. Calculations based on base CLT enclosure ignoring linings.
13 Also includes combustible flooring and plasterboard paper.
14 Dimensions scaled and based on lounge/kitchen area only with estimates of the kitchen and lounge window openings being used to determine ventilation conditions.

B2 Test A1 Lennon TF 2000 Timber frame natural fire test

B2.1 General information

The following information was predominately obtained from the Fire Resistance of Timber Frame Buildings – Closing Report, Results and Observations[166]. Other sources of information are referenced below:

An apartment in a full-scale 6-storey timber-framed building was fire tested to determine the structural performance and resistance to fire spread of protected light timber frame elements of construction forming the bounding construction to the apartment when subjected to a fully developed fire.

The bounding and loadbearing construction was protected by standard grade plasterboard with systems capable of achieving a fire resistance rating of 60 min. Walls were protected with two layers of 12 mm thick plasterboard, and the floor was protected by a direct fix ceiling comprising a base layer of 19 mm thick plasterboard and a outer layer of 12 mm plasterboard. Glass fibre insulation was provided with systems based on the manufacturer's literature. Internal walls not serving a loadbearing function were covered with a single layer of plasterboard[138].

A fire door with intumescent seals was provided at the main entrance to the flat separating the flat from the lobby

The following instrumentation was included:

- temperature measurements in the compartments and of the bounding construction
- load cells were provided to obtain an indication of the heat release rate
- gas analysis 200 mm below the ceiling in the living area
- heat flux meters
- timber cubes were included to provide data on charring behaviour for comparison with fire-resistance test data.

The fire load density (ignoring any contribution for the building elements) was stated to be: 391 MJ/m^2 of the floor area: and comprised timber cribs. The fire was ignited in the living area of an apartment. Based on fuel mass measurements the peak heat release rate was estimated to be 6 MW (some of this energy is expected to have been released outside the enclosure.

B2.2 Relevant test observations and data

Relevant test observations are summarised in Table 59.

Table 59: Relevant observations.

Time (min)	Observations
0	Test ignited
21.5	Window in kitchen area broken to provide additional ventilation
24	Flashover
35	Window frame to living room burnt away
54	Ceiling boards falling away in living area exposing timber flooring members
59.2	Fire brigade opened door to apartment from lobby. Visibility in lobby outside the apartment of fire origin before door opened was 30 m
64	Water applied to fire in the living room and kitchen areas
70	Enclosure temperatures generally below 200°C

The fire loads in the bedrooms within the apartment of fire origin were not ignited during the test and the measured temperatures in the voids were only above 100°C where the timber was directly exposed to the fire for some time. There was no structural failure or significant deflection observed during the test but there was extensive charring of timber members enclosing the corridor within the apartment.

Tenable conditions were maintained in all other apartments and the lift lobby until the door to the fire apartment from the lobby was opened for firefighting purposes temporarily reducing visibility to a minimum of 6 m.

Pressure differential at head of the apartment door was approximately 5.5 Pa during fully developed stage.

Maximum temperatures measured within the living area are plotted in Figure 92 together with the oxygen content 200 mm below the ceiling and external temperatures measured 1 m from the living area window on the fire floor level and 100 mm from the living room window opening on the floor above.

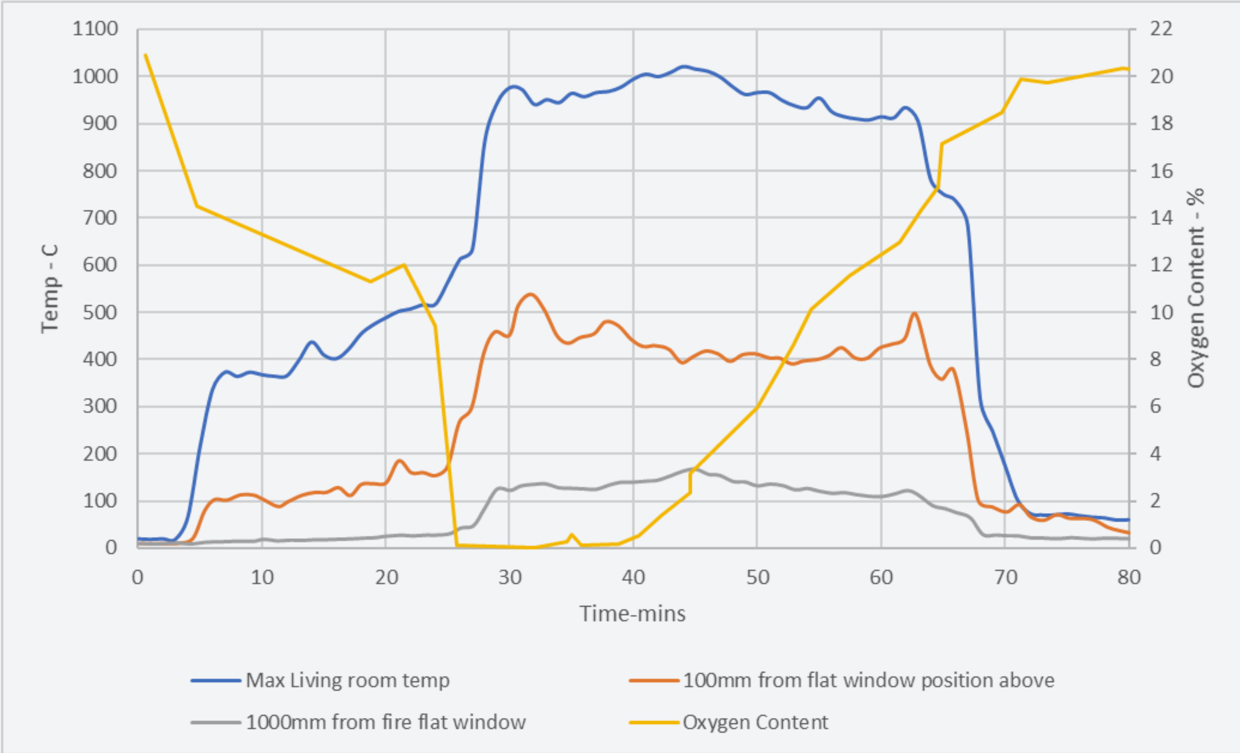


Figure 92: Maximum living room enclosure temperatures, external temperature data and enclosure oxygen content.

The peak temperatures opposite the window on the level above (approximately 540°C) occurred shortly after flashover before there would have been any contribution from the timber elements covered with plasterboard. It was indicated that the heat flux incident on the window at this position was approximately 30 kW/m^2, which was considered sufficient to cause fire spread. Therefore, in this particular fire scenario and building configuration, the timber elements would be unlikely to significantly increase the risk of fire spread to the level above due to external fire spread. The lower temperatures 1m from the window on the fire floor indicate that the fire plume did not extend 1 m from the window and that the thermocouple temperature increase was predominantly caused by radiant heat.

The oxygen content was maintained below 14% throughout the fully developed fire stage which would substantially reduce the extent of char oxidation and corresponding reduction in the mass of char. Thus, the low oxygen contents within furnace tests will be representative of conditions that occurred during the fully developed stage of this fire.

Following the fire test, a cavity fire developed and spread through cavities due to a lack of cavity barriers and an opening to the cavity allowing ventilation. The fire was contained within the cavity and eventually suppressed without generating untenable conditions within potentially occupied areas. This is not relevant to the analysis of fully developed fires but is discussed in more detail in Appendix I of WoodSolutions Guide 38[12].

B2.3 Comparison with parametric and standard heating curves

The fully developed fire was contained within the living area and kitchen with some fire spread down the corridor towards the bedrooms and bathrooms within the apartment. Since the apartment door to the lobby was closed the available ventilation for the post flashover phase was based on the areas of windows in the living and kitchen areas and the enclosure dimensions were based also on the combined living and kitchen areas. This was considered to be a reasonable approximation for the purposes of this study.

During the fire some timber elements were directly exposed to the fire when the plasterboard sheets fell away, and some elements were charred beneath plasterboard facings that remained in place. Additional observations were made regarding the depth of charring in order to estimate the potential contribution to the overall fire load from combustion of timber elements[191]. This investigation estimated the total mass of timber from the structural elements to have been consumed based on visual observations to be 141 kg. If this had undergone combustion within the living and kitchen areas the effective fire load would be increased by approximately 28.5%. However, for considerable periods the fire was ventilation controlled with significant combustion occurring outside the fire enclosure.

Observations during the test indicated that the internal non-loadbearing partition separating the kitchen and living area had been fully consumed and that an area of the ceiling fell away exposing joists and the underside of the timber flooring during the test. The contribution from these areas has been estimated to be approximately 11.8%.

A fire load modification factor of 12% was therefore applied to evaluate the significance of the potential contribution. All required dimensions of the relevant enclosures were not available in literature and where necessary values were scaled from drawings and photographs yielding the values provided in Table 60. Assumed materials for boundaries are summarised Table 61.

Table 60: Inputs for Eurocode 1 Appendix A Parametric Curves.

Parameter	Symbol	Value	Units
Enclosure height	H	2.3	m
Enclosure length	L	6	m
Enclosure width	W	3.3	m
Floor area	A	19.8	m^2
Vent opening effective height	h_{eq}	1.12	m
Vent opening total width	b_o	3	m
Vent area	A_v	3.36	m^2
Opening factor	O	0.043	$m^{1/2}$
Fire load from cribs	q_{fd}	391	MJ/m^2
Fire load modification factor	q_{factor}	12	%

Table 61: Assumed material for boundaries.

Boundary Construction	Symbol		Value	
	Mat.Code	Thick (s_1)	Mat.Code	Thick (s_2)
Units	-	m	-	m
Wall (j=1)	GBP	0.032	LDF	0.1
Wall (j=2)	GBP	0.032	LDF	0.1
Wall (j=3)	GBP	0.032	LDF	0.1
Wall (j=4)	GBP	0.032	LDF	0.1
Floor(j=5)	WOOD	0.015	WOOD	0
Ceiling (j=6)	GBP	0.032	LDF	0.1

The derived parametric curves are plotted in Figure 93 and compared to the experimental heating regime and standardised heating regimes.

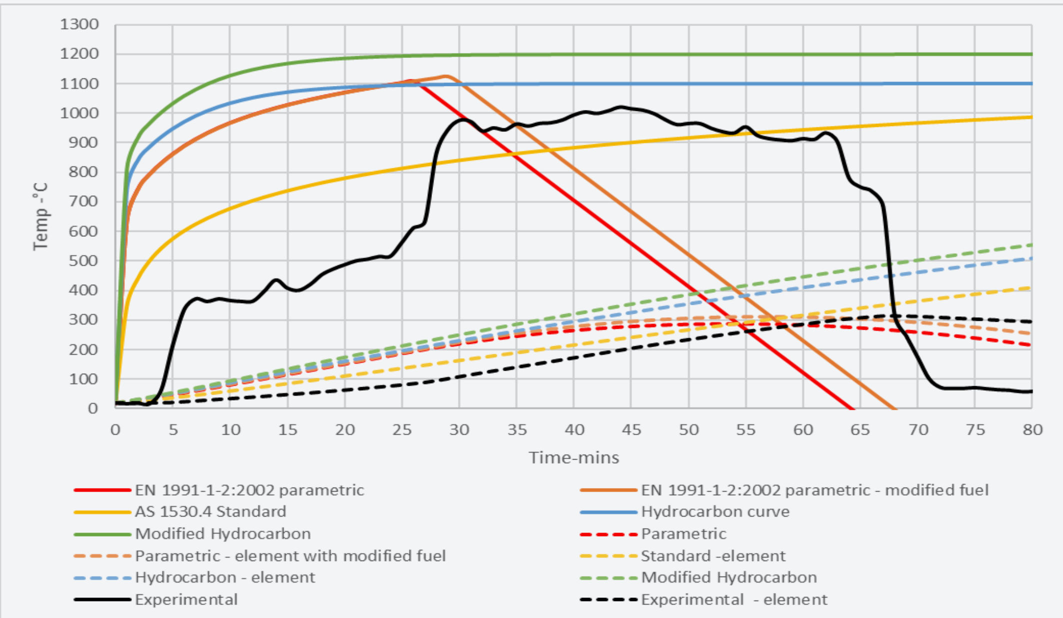


Figure 93: TF 2000 test compared to EN 1991-1-2 parametric curves and standard heating regimes and target element temperatures.

The fire severity can be expressed in terms of the temperature attained by the lumped thermal mass of a target element as described in Appendix G. This allows for comparison of the potential thermal impact of the various heating regimes. Table 62 compares the times for the target to reach a critical temperature associated with significant events.

Table 62: Comparison of times for the target element to reach maximum temperatures and critical temperatures associated with significant events when exposed to different heating regimes.

Event	Max target Parametric	Max target Parametric with increased fuel	Max target Peak TF 2000	Max target 60-min. std. fire test	Target temp @ Partial PB fall-off TF 2000
Critical Target Temp. (°C)	**289**	**310**	**313**	**317**	**255**
Heating Regime	**Time to reach equivalent target temperature (min)**				
TF 2000	60	66	67	-	54
AS 1530.4 Standard	54	58	59	60	47
Hydrocarbon	39	42	42	42	33
Modified Hydrocarbon	35	38	39	39	30
Parametric	52	-	-	-	36
Parametric fuel modified	43	55	35	-	-

A standard fire-resistance test was performed on the same ceiling system and exhibited very little charring of the joists when the test was terminated after 60 min which was similar to observations where the plasterboard remained in place in the TF 2000 test but some areas of the ceiling fell away during the natural fire experiment leading to increased charring.

However, the retention of non-fire-grade plasterboard sheets is very variable, as noted by Buchanan[17] who observed that:

"Regular gypsum board can fall off a wall or ceiling as soon as the gypsum plaster has dehydrated, at about the same time as charring of the timber studs begins. The falling off of regular gypsum board is unpredictable because single large cracks can cause large sections to fall prematurely."

Timber cubes were also included in both tests for comparison yielding the results shown in Table 63. These have been compared to the notional char rates calculated in accordance with the following relationship from AS/NZS 1720.4[19] when exposed to the standard heating regime for densities of 450 and 550 kg/m^3 representing the typical range for structural softwoods and 600 and 800 kg/m^3 representing the typical range for structural hardwoods.

$c = 0.4 + (280/\rho)^2$

where

c is the notional charring rate, (mm/min)

ρ = timber density at a moisture content of 12% (kg/m^2)

Table 63: Timber cube char results from TF 2000 natural fire test compared to fire resistant test data and calculated estimates when exposed to the standard heating regime.

Cube type	Depth of charring – mm					
	TF 2000 after test	Standard Heating regime @ 60 min	AS 1720.4 ρ=450 kg/m³ @ 60 min	AS 1720.4 ρ=550 kg/m³ @ 60 min	AS 1720.4 ρ=600 kg/m³ @ 60 min	AS 1720.4 ρ=800 kg/m³ @ 60 min
Hardwood	33	24			37	31
Softwood	45	41	47	40		

The char rates from a softwood cube included in the TF 2000 natural fire test and a softwood cube included in a standard fire-resistance test are comparable to the range of notional char depths calculated for typical structural softwood with a density in the range of 450 to 550 kg/m^3 in accordance with AS 1720.4. The results are therefore consistent with the estimate of an equivalent standard fire test exposure period of 59 min using the lumped thermal mass conversion method.

The average char rate for the hardwood cube measured in the standard test was 0.4 mm which is unexpectedly low for exposed timber yielding a total char depth of 24 mm after 60 min compared to the range of 31-37 mm predicted by as 1720.4 calculation methods. The TF 2000 char depth for the hardwood cube was 33 mm which is consistent with exposure to the standard heating regime for approximately 60 min.

Insufficient information is available to explain the unusual low char rate for the hardwood cube in a fire-resistance test in the UK but it is noted that the primary reason for the test was evaluation of a fire-resistant floor system with the cubes located within the furnace wall potentially distant from temperature measurements.

Reports relating to the TF 2000 series concluded that the charring depth of softwood was approximately 10% higher in the ignited room (living room) than in a standard fire test of 60 min duration implying that the TF 2000 heating regime in some parts of the enclosure was more severe that the standard heating regime. Details of the respective densities of the cubes were not reported nor furnace temperature data close to the cube positions therefore it can only be concluded that the exposure during the TF 2000 test was likely to be approximately equivalent or greater than 60 min exposure to the standard heating regime.

The experimental results were offset by 25 min in Figure 94 such that the times to flashover were similar to facilitate comparison of the fully developed stages.

It can be observed that the experimental fire temperatures generally lie between the standard and hydrocarbon heating regimes and that the parametric curves are reasonably similar to the experimental curve.

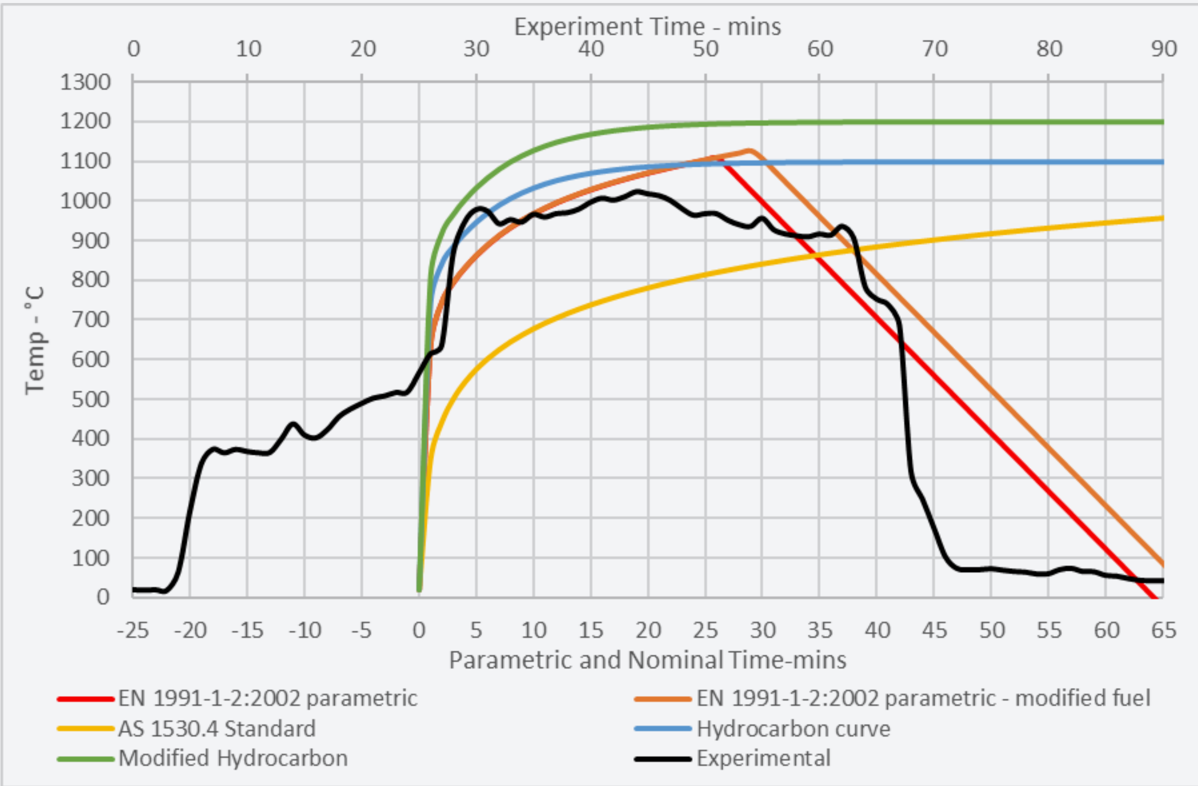


Figure 94: TF 2000 test with 25 min offset compared to EN 1991-1-1-2 parametric curves and target element temperatures to provide similar times to flashover.

B3 Series B Hakkarainen Massive Timber and timber framed tests

Hakkarainen[57] presented four fire tests of compartments, of which three (Tests B1, B2 and B3) were constructed using heavy laminated timber and one Test B4 was constructed using light timber framing. The flooring in all compartments was made of 22 mm thick particleboard. The inner dimensions of all compartments were 3.5 x 4.5 x 2.5 m and there was a single opening of 2.3 x 1.2 m. The fire load consisted of wood cribs and particleboard flooring. The reported fuel load density was 720 MJ/ m^2 assuming a net heat of combustion of 15.5 MJ/ kg and a combustion efficiency of 0.8.

The first heavy timber compartment comprised fully exposed walls and ceiling. The heavy laminated timber elements of the second test were protected using a single layer of 12.5 mm Type A gypsum plaster board. The structure of the other two compartments was protected using a layer of 12.5 mm Type A and a layer of 15.4 mm Type F gypsum plasterboard.

Gas temperatures were measured using three thermocouple trees. Timber element temperatures and char rates were measured in the ceiling and a wall and a heat flux meter was positioned in a mock facade 2.2 m above the upper edge of the window opening.

Results of test B1 and test B2 showed relatively low gas temperatures of around 700^{0}C for the majority of the time. It was stated that this was caused by under ventilation of the fire. Both fires did not show decay and were stopped after approximately 50 min due to excessive flaming outside the compartment and a fault in the smoke venting system. In test B2 the gypsum plasterboard (Type A) started to fall down after 13 min. This explains the similarity between the fires of test B1, which involved only unprotected timber elements, and test B2.

The gas temperatures in test B3 and B4 were significantly higher as the moveable fire load burned, peaking at approximately 1200°C. Hakkarainen stated that the ceiling and walls did not contribute to the fire during the most intense period, as the layers of gypsum plaster boards remained intact during that period. A decay of the fire was seen, evidenced by a temperature drop and a drop of measured heat flux in the mock facade. Test B4 was stopped after 48 min because the ceiling started to burn through. During the decay phase of test B3 parts of the CLT ceiling were exposed and impacted the decay phase.

B4 Series C Frangi and Fontana (2005)

Frangi and Fontana[167] reported three pre-flashover and three post-flashover fire tests of light timber-frame compartments. The three pre-flashover tests focussed on the effect of sprinklers on fires in compartments with combustible linings. The three post-flashover tests were each conducted on a 2-storey setup.

The outer dimensions of each compartment were 6.6 x 3.1 x 2.8 m. A window of 1.5 x 1.7 m was positioned in the short wall and a door (with unknown fire rating) was positioned in the opposing wall.

The structural frames of all compartments comprised timber studs in the walls and ceilings and timber joists in the floors, all insulated using wood based fibreboards. The inner lining was different for each compartment.

The lower (ignited) compartments of test C5 had an exposed layer of 18 mm OSB. The timber frames of test C4 and C6 were protected by a layer of 18 mm plasterboard and two layers of 15 and 12.5 mm plasterboard, respectively. An additional facade which surrounded the window was made of 19 mm timber board that was fixed leaving a 20 mm air gap.

The pre-flashover tests showed that sprinklers were activated in 2 min or 3 min after ignition and that the sprinkler location and ventilation conditions had no significant influence on the effectiveness of the sprinklers. Furthermore, it was concluded that the combustible linings were not involved during the fires and that flashover did not occur in these tests.

Temperatures were measured inside the room, inside the surrounding materials and on the glass surfaces of the windows. Gas analysis was performed and the weight of the entire unit was logged using four load cells. Observations are included with respect to external fire spread to the upper levels.

The plasterboard linings in tests C4 and C6 were observed to start falling way after approximately 30 min of the tests exposing timber elements that contributed to the fire load and prolonged the decay phase.

B5 Series D Chen (2008)

Chen[168] reported two tests using fire loads derived from a fire load survey conducted in Canadian motels, one representing a bedroom with one bed and the other a bedroom with two beds.

The dimensions of the test room for both tests were 3.77 m x 4.17 m x 2.37 m with an opening of 1.5 m x 1.5 m. The test room was built on a concrete slab with a thickness of 15.2 cm. The walls and roof were constructed using lightweight steel frame. The internal linings comprised:

Floor: 12.7 mm cement sheet over the concrete slab.

Ceiling: two layers of 15.9 mm Type X plasterboard fixed to steel framing with plywood flooring above the ceiling.

Walls: inner layer – 12.7 mm cement sheet, face layer – 1 layer of 15.7 mm Type X plasterboard.

The first test had a fire load density of 397 MJ/m^2, and the second test had a fire load density of 366 MJ/m^2.

Test measurements included HRR, temperatures, heat flux and oxygen concentrations within the enclosure. A summary of relevant observations that were reported by Chen is provided in Table 64.

Table 64: Observation from Chen (2008) series of tests.

Observation	Time (s)	
	Test 1	Test 2
Ignition	0	0
Flame reach ceiling	195	140
Smoke flow out of window	210	160
Flame issues out of window	240	180
Flashover	240	180
Decay starts	780	900
Door infill open (changed ventilation)	1500	-
Test stopped	1785	1325

The tests were terminated before the end of the decay phase.

B6 Series E Frangi et al. (2008)

A full-scale fire test of a three-storey building was reported by Frangi et al[169]. Prior to the fire test, the test building withstood a shaking table test to simulate exposure to an earthquake. The aim of the research was supplying documentation and information regarding the use of CLT.

The fire room was surrounded by two rooms on the same floor, one room at the ground floor and one room at the top floor. The inner dimensions of the ignited room were 3.34 x 3.34 m and the room had two windows of 1.0 x 1.0 m and a 60 min fire-resistant door. All except one wall were made of 85 mm thick CLT panels. The inner surfaces of these walls were insulated using 27 mm mineral wool and protected using one layer of 12 mm standard gypsum board and an exposed layer of 12.5 mm fire-protective grade plasterboard. The other wall was a room dividing wall made of 142 mm thick CLT panels, which was only protected by mineral wool insulation and a layer of 12 mm standard plasterboard. The floors were constructed using 142 mm thick CLT panels and were covered with 60 mm sand, 50 mm concrete topping and wooden flooring. Mineral wool and a single layer of 12 mm fire-protective grade plasterboard insulated the ceiling. The exterior walls were insulated on the outside using 120 mm wood fibre finished with 10 mm plaster.

In addition to measurements of gas temperatures, temperatures were measured in the interfaces of the different layers in the walls, floor and ceiling. The gas was analysed at a single point at 2.2 m above the floor. Air pressure measurements were made at the top and bottom of both windows. Two heat flux meters were positioned 3.0 m outside the window. Additionally, the temperature of the reinforced glass of the upper floor windows was measured.

The results showed a rapid increase of gas temperatures in the first 10 min and after approximately 35 min. The latter was caused by the failure of the single layer of standard gypsum board protection that was applied on the thickest CLT wall. Increased flaming outside of the apartment confirmed an increased intensity. Temperatures behind the two layers of gypsum plasterboard rapidly increased at approximately 50 min after ignition. The results suggested that the insulation behind the gypsum boards fell off almost immediately after the gypsum board failed. Decay of the fire was observed after approximately 55 min and the fire was manually extinguished after 60 min. The windows of the upper floor did not fail and there was no fire and smoke spread to the upper floor.

The authors concluded that the fire spread in timber buildings could be limited to one room using only passive fire protection. They also concluded that the damage on the CLT panels was relatively small after the test.

B7 Series F (L5) Bwalya et al. 2014

Bwalya[175] summarised experiments and fire load analyses conducted to characterise fires in multi-suite residential dwellings. The project was initiated by NRC, Canada.

The project focused on fires that can occur in apartments, semi-detached houses, duplexes, row houses, secondary suites, and residential care facilities.

The average fire load densities in various rooms were estimated from surveys to be:

- Kitchens – 807 MJ/m^2
- Dining rooms – 393 MJ/m^2
- Living rooms – 412 MJ/m^2
- Basement living rooms – 288 MJ/m^2
- Primary bedrooms – 534 MJ/m^2
- Secondary bedrooms – 594 MJ/m^2.

In Phase 2, 14 full-scale tests were performed in a test facility that was representative of a single storey of a multifamily dwelling, having a floor area of approximately 48 m^2.

One of the main conclusions was that, in rooms lined primarily with gypsum board, regardless of other variables (such as, ventilation, fuel load, ignition method and room size), the mean maximum hot layer temperatures during the post-flashover period fell within a narrow range of approximately 1050°C to 1200°C.

However, test variables and particularly ventilation, first-ignited-item and composition of the fuel load had a significant effect on the time of attainment and duration of the fully-developed phase.

Test PRF-03 was a typical example of a higher fire load (976 MJ/m^2 including a contribution from timber flooring in additional to the moveable fire load).

B8 Series G Lennon et al. (2010)

Lennon et al.[170] performed three compartment tests in order to assess protected engineered timber floor systems in a natural fire. The compartments were made from concrete blocks and an engineered timber floor protected on the underside. The inner dimensions of the compartments were 4.0 x 3.0 x 2.4m and the dimensions of the two ventilation openings were 0.7 x 1.0 m. The tested floors were solid timber floor joists (test G1), engineered I-section joists (test G2) and engineered truss joists (test G3). A uniformly distributed load of 0.75 kN/m^2 was placed on top of the floor to resemble a typical load of a residential building during a fire.

This project aimed to compare the structural failure caused by fire between engineered floor joists and more conventional solid timber joists. The floors were designed to achieve 60 min fire resistance. The solid timber joists and engineered steel truss web joist were protected from below (the exposed side) using two layers of 12.5 mm type F gypsum board and the engineered OSB web joists were protected using two layers of 15 mm type F gypsum board.

Gas temperatures and temperatures in the floors were measured using thermocouples. Wood cribs were used as fuel for the fire, resulting in a fire load density of 450 MJ/m^2. Failure of the gypsum board was reported in all tests and occurred fastest in the solid timber joist floor (after 30 min).

From this work it was concluded that the two-layers of 15 mm gypsum board protecting the engineered joists were very effective and offered protection until the decay phase. The thinner layers of gypsum protecting the solid timber floor joists were significantly less efficient.

The OSB I-section joists may be capable of resisting 60 min of natural fire, considering it is protected using two layers of 15 mm type F gypsum board. The engineered (steel) truss joint showed large deflections of up to 90 mm, which was almost three times as much as the deflections of the solid timber joists.

B9 Series H Peng et al. (2011)

Peng et al[171] reported an experimental study of fires in an old building comprising six rooms, each with a floor area of 3.0 x 5.7 m, with a single door opening. The walls were stated to be entirely made from wood and the fuel for the fire was either raw wood or furniture. Six tests were performed in order to assess the influence of locations of the ignition, the fuel type and the presence of a ceiling under the gable roof on the fire spread. A sprinkler system was included in one test (Test 1) to demonstrate the performance of sprinkler systems. Gas temperatures were measured in the centre of the ignited room and in the centre of the adjacent room. A summary of the tests is provided in Table 65.

Table 65: Summary of tests reported by Peng.

Test No	Fuel	Location of Fire	Ceiling	Sprinkler	Door	Spread time to adjoining room
1	Raw Wood	Corner	With	With	Open	N/A
2	Raw Wood	Corner	With	Without	Open	N/A
3	Furniture	Corner	Without	Without	Open	15 min
4	Furniture	Corner	With	Without	Open	27 min
5	Raw Wood	Corner	Without	Without	Open	23 min
6	Raw Wood	Corner	Without	Without	Open	33 min

The authors concluded that the fire spread was faster if the ignition source is near a wall and that the fire spread to adjacent rooms can be postponed by the presence of a ceiling under a gable roof. They also concluded that the sprinkler effectively limited the fire spread. Information, such as fire load density and a description of the structural materials, was not reported in the referenced paper.

A series of tests have been undertaken at Carleton University Fire Research Laboratory, to investigate the contribution of CLT to compartment fires that have been reported by:

- Series I McGregor, 2013[58]
- Series J Li et al., 2014[172]
- Series K Medina Hevia, 2014[59].

The inner floor dimensions of all tested compartments were 3.5 x 4.5 m and the inner room height was 2.5 m. One door opening of 2.0 x 1.1 m allowed ventilation in the room during the fire. The walls, floors and ceilings of all compartments were made of 105 mm thick three-ply CLT comprising lamellas of 35 x 89 mm.

McGregor performed separate propane fuelled and furniture fuelled tests. The tests included measurements of the gas temperature as well as measurements of temperatures of the walls and ceiling at varying depths. A plate thermometer was positioned 0.1 m from a wall without an opening at a height of 1.5 m. Gas analysis of all extracted gas was undertaken to determine the heat release of the fire.

In McGregor's propane fuelled fire tests, the propane flow was controlled and the heat release rate corresponding to propane was calculated. The contribution of the CLT to the heat release rate was then calculated by excluding the heat release rate corresponding to propane from the measured heat release rate. In the propane fuelled tests, the CLT was protected using two layers of 12.7 mm fire-grade plasterboard (test I1), and the CLT was exposed in test I3.

McGregor also performed three furniture-fuelled tests of which all CLT surfaces in two tests were protected by two layers of plasterboard and the CLT surfaces were exposed in one test.

The publication by Li et al. (2014) included information on the three furniture fuelled tests described in the McGregor thesis. In addition, Li et al. presented three tests including light timber frames and light steel frames of the same size and with comparable moveable fire loads. The light steel or timber framing was attached inside a CLT compartment in order to maintain structural stability during the test. One compartment comprised of light steel frame protected by a single layer of 12.5 mm Type C gypsum board attached directly onto the studs. A similar test was performed using timber studs instead of steel studs and a third test was presented using a second layer of gypsum board to protect a similar timber frame. All frames were filled with fiberglass.

The authors showed that the temperatures and the heat release rates were similar for all protected tests (I2, I4, J1, J2 and J3). In these tests, the fully developed phase was reached approximately10 min after ignition and lasted for approximately 15 min. The mean heat release rate measured during the tests was between 3.6 and 4.1 MW. Decay started 25 min after ignition and the fire became fuel controlled during the decay phase instead of ventilation controlled.

Medina performed three tests of similar compartments comprising different extents of protected area. The aim of the work was studying the contribution of CLT to a compartment fire corresponding to several configurations of protected and unprotected CLT surfaces. Furniture was used to fuel the tests and the fire load density, and the positions of furniture were the same as in McGregor's furniture fuelled tests. This allowed straight forward comparisons between tests of both authors.

It was concluded that unprotected CLT contributes to the fire growth rate, the intensity and the duration of the fire and that the contributions are generally more significant if more surface is exposed.

Typical enclosure temperatures from specimens with exposed CLT have been compared to fully encapsulated CLT and timber frame bounding construction in Figure 95. The commencement times were adjusted slightly to align the commencement of the fully developed phase.

The results demonstrated that the fire tested compartment comprising one unprotected wall exposing 11.25 m^2 of CLT, slightly increased the severity and duration of the exposure and the fire was decaying prior to termination. The compartments comprising two exposed walls exhibited delamination of CLT lamellas, which resulted in secondary flashovers. It was found that two opposing walls that were unprotected led to higher heat release rates than two adjacent walls.

Furthermore, it was concluded by McGregor that CLT protected by two 12.7 mm layers of fire rated gypsum plaster board did not noticeably contribute to the duration or intensity of compartment fires if fall-off of gypsum did not occur. Once the gypsum board failed, the CLT increased the intensity of the fire and a second flashover occurred. In the same way delamination of the CLT has led to a second flashover.

In the early stages of the fire the room temperatures were similar for all tests and substantially higher than the standard heating regime of AS 1530.4. The exposed CLT seemed to delay the temperature drop or decay of the fire but did not appreciable increase the enclosure temperatures while the moveable fire load was being consumed.

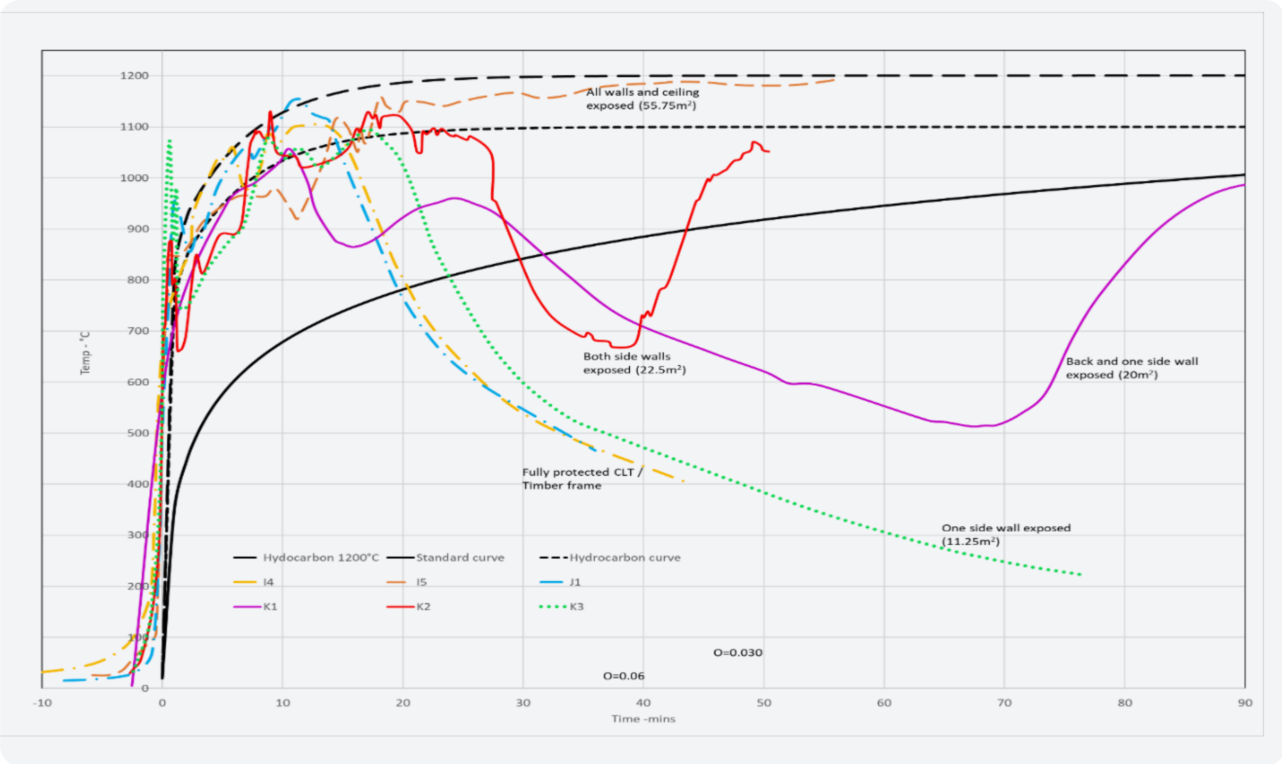


Figure 95: Comparison between fully exposed CLT and fully encapsulated timber construction.

B11 Series L Su and Lougheed (2014)

Su and Lougheed[174] reported four tests of furnished compartments. The test facility comprised three storeys with the middle storey simulating a typical furnished apartment with inner dimensions of 6.3 x 8.3 x 2.4 m. It comprised a living room, bathroom and bedroom. The living room and the bedroom both had a window of 1.5 x 1.5 m and there was a steel entrance door with a 45 min fire protection rating in the hallway.

The compartments were built using different forms of construction summarised below:

Test L1 and L4 – lightweight timber-frame with closely spaced studs and a 15.9 mm OSB panel on one side. Glass fibre insulation was applied in all timber frames and two layers of plasterboard were applied on both sides of the walls. The floor and ceiling were constructed using I-joists with a depth of 241 mm and 15.9 mm OSB subfloor sheathing. The ceiling comprised of two layers of 12.7 mm Type X gypsum board that protected the I-joists. At locations where the walls met the I-joist floor, the layers of gypsum board were interrupted. Glass fibre insulation was applied in the ceiling and the floors.

Test L2 – CLT comprising 105 mm thick 3-ply CLT walls, insulated using a 38 mm thick layer of glass fibre and protected using two layers of 12.7 mm Type X gypsum board on the exposed side. The floor and ceiling comprised 175 mm thick 5-ply CLT panels. The exposed ceiling was protected on the underside with two layers of 12.7 mm Type X gypsum board. The exposed floor was covered with two layers of 12.7 mm cement board and a floating hardwood floor.

Test L3 – light steel-frame, comprising cold formed metal studs. All surrounding walls of the compartment were insulated using glass fibre. The walls were protected by one layer of 15.9 mm Type X gypsum. The floor and ceiling were constructed using cold formed steel joists and a galvanized steel and concrete composite floor. All apartments tested had a hardwood floor finish. The ceiling comprised a single layer of 12.7 mm Type X gypsum board that protected the steel joists. At locations where the walls met the ceiling, the layer of gypsum board was interrupted. The ceiling and the floor of the compartment were not insulated.

Measurements included:

- HRR calorimetry
- heat flux was measurements outside the enclosure
- air temperatures
- temperatures inside the floor, walls and ceiling
- the encapsulation times.

The shortest encapsulation times occurred in test L3 with the lightweight steel frame compartment within 20 min.

The shortest encapsulation times in the lightweight timber frame compartments concerned the ceiling of the bedrooms and were 30 and 23 min for Test L1 and L4, respectively.

Temperature measurements in the cavities indicated that the low fire performance of a non-loadbearing and non-fire rated wall led to a decrease of the encapsulation performance of the ceiling, highlighting the importance of adequate detailing of these features. Failure of the encapsulation led to an increase of heat release rate in steel frame and timber frame assemblies.

The encapsulation times corresponding to the CLT compartment were highest, e.g. 65-99 min for wall panels. After 170 min visible flames at the ceiling CLT panels and an increase of the heat release rate were observed.

B12 Series M Su and Muradori (2015)

Su and Muradori[176] undertook a single large scale fire test of compartments that represented a section of a 13-storey residential building. The setup comprised an apartment that was located next to an elevator shaft.

The inner dimensions of the apartment were 5.2 x 4.6 x 2.7 m and the inner dimensions of the elevator shaft were 4.6 x 2.5 x 8.8 m. The apartment had a window opening of 2.5 x 1.9 m and a door with a 45 min fire protection rating. All walls were made from 175 mm thick 5-ply CLT and the apartment shared a wall with the elevator shaft. The surfaces of the CLT were protected using two layers of 16 mm Type X gypsum board directly applied on the CLT. The ceiling was insulated using 90 mm thick non-combustible fibreglass and protected using one layer of 16 mm Type X gypsum plasterboard. The wall separating the apartment room from the elevator shaft was additionally protected using non-combustible rigid mineral wool and an additional 13 mm gypsum board. Concrete blocks were put on top of the ceiling assembly to induce a total load (including the self-weight) of 4.74 kPa.

Temperatures were measured at the interface between CLT and the plasterboard sheets and on the unexposed sides. Additionally, gas temperatures were measured at several heights in the room using two separate thermocouple trees. In the elevator shaft the gas temperatures were measured and an optical density meter was installed at a height of 7 m to monitor the smoke development in the shaft during the fire.

Results showed that the CLT ceiling panels started to be involved in the fire, after cladding fell away, approximately 15 min after ignition. Based on the temperature measurements at the CLT surface, the encapsulation time corresponding to the wall between the apartment and the shaft was 91 min and the lowest encapsulation time measured in another wall was 57 min. No changes of temperature and smoke density were observed in the shaft, leading to the conclusion that the fire had no impact on the conditions in the shaft.

B13 Series N Kolaitis et al

Kolaitis et al[177] reported a compartment fire test to assess plasterboard encapsulation systems for the fire protection of light timber-frame and massive timber elements.

The fire load was simulated with wood cribs.

Instrumentation comprised air temperature and wall temperature measurements.

A free-standing wall inside the test compartment, protected by wood-based panels, partially collapsed.

B14 Series O Southwest Research Institute & Marc Janssens

Two tests were undertaken on furnished living rooms and reported by Janssens[192].

The inner dimensions of both tested compartments were 4.1 x 3.6 x 2.4 m each having a single 1.9 x 2.1 m opening. The first tested compartment comprised 5-ply CLT walls and a nail laminated timber (NLT) ceiling. The second compartment was constructed using 5-ply CLT for the walls and the ceiling. All interior surfaces were protected using two layers of 15 mm thick Type X plasterboard.

Instrumentation included:

- heat release rate calorimetry
- gas temperatures and internal wall and ceiling temperatures measurements
- plate thermometers measurements.

A structural load of 1.82 kPa was applied.

Both tests showed similar results, with a peak temperature of approximately 1200°C.

The first test was terminated after 3 hours and the second test was terminated after 2:15 h providing useful data on encapsulation data and decay rates.

B15 Series P SP Fire Research Hox

Hox[91, 92] reported two fire tests on a 5.75 x 2.3 x 2.75 m compartment, which represented a bedroom with bathroom in a 9-storey student accommodation building.

A nominally 2.0 m x 0.9 m door that was set in the open position between the compartment and a corridor. A (triple-glazed) window was installed in the wall opposite the door.

In the first test the effect of sprinklers and the activation time of a fire alarm in a fire with rapid fire growth was observed.

In the second test, there was no intervention until after flashover and failure of CLT panels had occurred during the post flashover period. The sprinklers were disabled in the main enclosure but were operational in the corridor. Further details of this second test are summarised below:

The moveable fire load was approximately 660 MJ/m^2 of floor area, excluding the CLT elements. The fire load comprised a mattress, desk wooden pallets and wood cribs.

The compartment was constructed from 100 mm CLT panels (5 x 20 mm lamella) and comprised:

- An exposed CLT ceiling (13.2 m^2)
- An exposed CLT wall (15.8 m^2)

An enclosed bathroom area close to the enclosure entry that was separated from the remainder of the room by a steel stud plasterboard partition.

The remaining CLT walls, except for those enclosed by the bathroom, were protected with one layer of 15 mm Type F and one layer 13 mm Type A plasterboard, and 50 mm mineral wool insulation

A triple glazed window of overall size 1.6 m high x 1.2 m wide was initially closed but broke during the test.

The temperature was measured with encapsulated thermocouples at two places in one of the longer walls that was unprotected.

The temperature was measured in the opposite wall at one position, which was protected with one layer of 15 mm Type F and one layer 13 mm Type A plasterboard, and 50 mm mineral wool insulation.

Temperatures were also measured in the middle of the unprotected CLT elements in the ceiling and below the sound reduction board in the floor. The temperature in the room was measured with a plate thermometer in the middle of the room and also with thermocouples below the ceiling, inside the bedsit and in the corridor.

Enclosure temperatures between approximately 900 and 1100°C were maintained within the enclosure after flashover until collapse of the ceiling and termination of the test after 96 min. Key observations are summarised in Table 66.

Table 66: Observations from SP student accommodation fire test.

Time after ignition (min:sec)	Observation
02:50	First sprinkler head in corridor activates
04:10	Flashover
05:45	All three layers of the window glass are broken
08:30	The suspended ceiling in the corridor fell down
25:00	The one layer of plasterboard around the bathroom fell off
47:00	First parts of the double layered plasterboard wall fell off
70:00	Burn through CLT element on unprotected wall near the window.
85:00	Large parts of the unprotected wall burnt through
96:00	The ceiling in the enclosure collapsed

B16 Series Q Hadden et al (2017)

Hadden[178] et al described a series of compartment fire experiments evaluating the impact of combustible cross-laminated timber on compartment fire behaviour.

Compartment heat release rates and temperatures were reported for three configurations of exposed timber surfaces undertaken using enclosures 2.72×2.72×2.77 m. The moveable fire load was simulated using timber cribs.

For configurations with larger areas of exposed timber, flaming combustion continued after the timber cribs were consumed. Fall-off of the charred timber layers was found to be a key contributor to continuing combustion.

B17 Series R Janssens (2017)

Janssens et al[60] reported a series of three full-scale room fire tests designed for assessing the performance of cross-laminated timber adhesives. The test enclosure was plasterboard lined with additional ceramic fibre protection applied and was approximately 2.75 m x 5.80 m x 2.44 m with a 0.92 m wide x 1.91 m high opening. The test specimen comprised a 4.88 x 2.44 m CLT floor/ceiling panel that was simply supported and subjected to an imposed load of 0.96 MPa. A propane gas diffusion burner was used as the fire source which was controlled to follow a pre-defined HRR profile.

Enclosure temperatures and heat fluxes were monitored. Different glue types were used, and the test method differentiated the differences in delamination performance between CLT manufactured with different glue types.

B18 Series S Just et al (2018)

Just et al[179] described a compartment test of a two-storey building made of CLT to study delamination behaviour and consequences in compartments with realistic ventilation conditions. Solutions to limit fire spread from the first floor into the second floor were included. Connections and service penetration systems through the compartment boundary and the facade were incorporated in the test.

The test building was 3.5 x 4.5 m in plan with the two longer walls being of exposed timber (CLT). The remaining walls were protected by two layers of 15 mm fire rated plasterboard cladding and the ceiling was protected by three layers of 15 mm fire rated plasterboard cladding. The opening factor was 0.072 $m^{1/2}$ (achieved by the provision of two windows [total area of 4.5 m^2]).

The upper levels had fire-resistant glazing fitted to protect the upper level window openings from external flame spread from the fire on the floor below.

The longer walls were the full height of the two storeys and the shorter walls supported the intermediate floor panels. The fire-exposed lamella (face layer within the fire enclosure) was (40 mm), with the CLT panel comprising five lamella (40, 30, 20, 20, 20 mm).

Temperature measurements were taken in the room of fire origin, in-between the CLT lamella and behind the cladding. Different types of protected joints and service penetrations were included for evaluation.

A moveable fire load of 600 MJ/m^2 was provided based on typical domestic furnishings and a sofa was ignited on the ground floor.

External cladding systems were evaluated which incorporated fire-retardant treated timber as part of the system.

Key observations are summarised in Table 67 including secondary flashover.

Table 67: Observation from Just (2018 test).

Time after ignition (min)	Observation
0	Ignition of the sofa
20	Small amounts of smoke continuing to be released. First window broken
23	Flames increasing in height within compartment
25	Second window broken
46	Flashover
58	Fire begins to decay
65	Fire in building decayed but CLT inside continues burning
69	Exposed CLT panels were smouldering with no visible flames
111	Charred layer of CLT fell off and the CLT started to burn
120	Second flashover
132	Second decay phase begins
136	Fire extinguished by Fire Brigade

B19 Series T England and Eyre (2011)

England and Eyre[73, 74] reported two natural fire experiments undertaken to determine if there was any appreciable contribution to the fire severity from protected timber framing and combustible insulation. These tests were undertaken in Melbourne in 2011 to address issues raised regarding the potential contribution from timber structural framing elements when protected by common Australian fire-protective grade plasterboard walls used for bounding construction of sole occupancy units (SOUs) in residential buildings.

The tests were undertaken as part of a project seeking the extension of a concession within the NCC (BCA at the time) allowing the use of timber-frame construction in low-rise Class 2 (apartment buildings) to be extended to Class 3 buildings which includes buildings used for accommodation of the aged and other vulnerable occupant groups. As a result of a submission supported by the experimental results the concession was extended to Class 3.

The test enclosures were 4 m x 4 m x 2.4 m constructed with either timber-frame or steel-frame walls protected by 2 x 13 mm thick fire-grade plasterboard on each face and a ceiling system comprising two layers of 16 mm fire-grade plasterboard fixed to steel furring channels.

The total area of enclosure (including openings) (A_t) is 70.4m^2:

- opening dimensions: 2 m wide x 1.2 m high with the sill 500 mm above floor level
- opening area 2.4 m^2
- opening factor 0.037 m$^{1/2}$.

The moveable fire load was simulated using 16 Radiata Pine cribs providing a total fire load of 656 kg (41 kg/m^2) – approximately 718 MJ/m2. The cribs were constructed from 40 mm x 40 mm x 440 mm sticks with a 1:1 air to stick ratio.

Compartment temperatures and interface temperatures within the walls and ceilings were reported. Other features included in the tests were:

- An instrumented insulated steel column to compare the fire exposure within the enclosure.
- An instrumented fire door and corridor at the back of the enclosure.
- An instrumented facade fitted above the opening. A 600 mm horizontal projection was mounted above the opening of the timber framed specimen to demonstrate the reduction in radiant heat transfer to the wall above compared to a vertical facade without a horizontal projection.

A control test was performed on a specimen with lightweight steel framing and non-combustible insulation, protected by fire-protective grade plasterboard and a second test was performed with timber framing and combustible insulation, protected by fire-protective grade plasterboard with all other variables within the enclosure the same. Similar instrumentation was provided in each test. The results indicated that there was no appreciable contribution to the fire load from the timber framing and the enclosure temperatures from both tests were closely aligned.

B20 Series U Emberley et al (2017)

Emberley[180] et al described a large-scale fire test conducted on a compartment constructed from cross-laminated timber (CLT) with internal dimensions nominally 3.5 × 3.5 × 2.7 m and a 0.85 × 2.1 m opening.

The CLT was 150 mm thick comprising the following lamella 45 × 20 × 20 × 20 × 45 mm. The internal faces of the compartment were lined with two layers of 13 mm thick fire-grade plasterboard, with the exception of one wall and the ceiling which had exposed CLT surfaces.

Above the opening to the enclosure, the front wall was extended vertically by 2.7 m using a light timber-frame construction faced with two layers of 13 mm thick fire-grade plasterboard.

A fire load density of approximately 115 MJ/m^2 of floor area was provided in the form of two timber cribs with 25 mm x 25 mm x 1000 mm sticks with a 1:1 air to stick ratio.

The instrumentation included the following:

- thermocouples for enclosure temperature measurements
- thin skin calorimeters within the compartment
- thermocouples within the CLT sections
- bidirectional probes at the opening to measure air flows.

Key observations are summarised in Table 68.

Table 68: Observations from Emberley et al test (2017).

Time after ignition (h:mm:ss)	Observation
0:00:00	Test started
0:10:00	Cribs fully involved
0:12:15	Involvement of ceiling
0:12:30	Flames reach base of CLT wall
0:23:30	Flaming at base of wall stopped
0:28:00	Flaming of top of wall and ceiling stopped
5:32:00	Test stopped

In this Guide, the term self-extinction refers to the termination (i.e. stopped) of both flaming and smouldering combustion, therefore the above observations have been modified to refer to termination of flaming combustion rather than self-extinction. The Emberley paper did not identify if smouldering combustion had terminated prior to the test termination after 5.5 hours.

B21 Series V Zelinka et al (2018)

Zelinka[89] et al reported five full-scale experiments on a two level apartment style massive timber structure using balloon frame type construction with the CLT walls continuous from top to bottom and the CLT floors and ceilings supported by concealed ledgers and a glulam beam. The beam was supported by Glulam columns. Each level comprised a one bedroom apartment and a 1.5 m wide corridor linked to the other level by a stair.

The apartment can be considered to comprise the following two main areas and ancillary areas:

- a living room kitchen – 4.75 m wide x 9.14 m deep x 2.74 m high with a drop ceiling over the kitchen area
- a bedroom – 4.75 m wide x 6.1 m deep x 2.74 m high.

The general arrangement is shown in Figure 96.

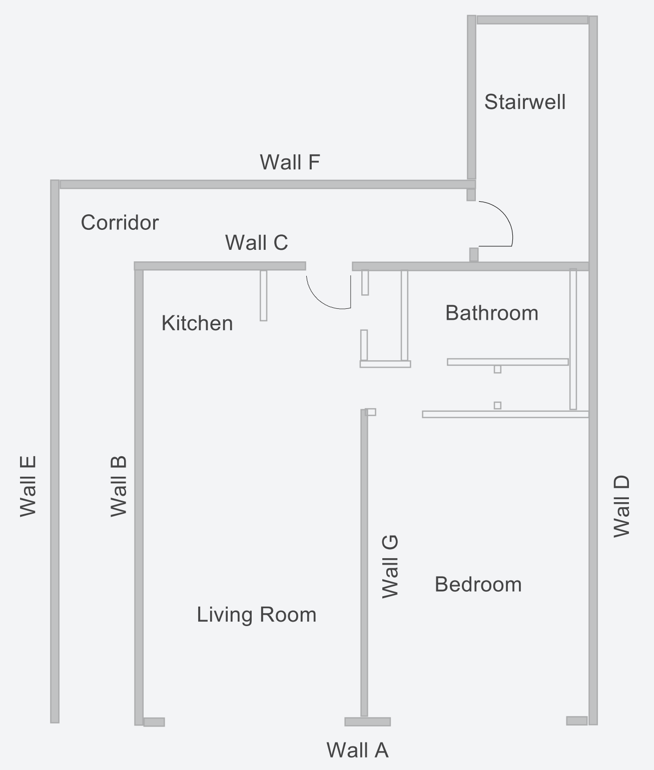


Figure 96: General arrangement of fire test apartment adapted from Zelinka et al[89].

Walls A through F and the floor/ceiling assemblies comprised 175 mm thick 5-ply CLT panels manufactured from Douglas Fir/Larch with a polyurethane adhesive. Interior non-loadbearing walls/partitions were constructed with steel studs and faced with one layer of standard plasterboard 13 mm thick.

The opening factor for the kitchen and living room enclosure area, assuming all ventilation was through the front opening, was calculated to be nominally 0.089 $m^{1/2}$ ignoring the drop ceiling.

The opening factor for the bedroom enclosure area, assuming all ventilation was through the front opening, was calculated to be 0.125 $m^{1/2}$ ignoring the fitted wardrobes.

One of the useful features of this test is that the spread of fire within an apartment was simulated forming two enclosure fires as the fire spread from the lounge /kitchen to the bedroom.

Glazing was fitted to the openings in Wall A for tests 4 and 5. Test 4 was terminated after the automatic activation of the sprinklers which confined the fire to within the kitchen cabinetry. Any continued burning within the cabinet was manually extinguished at the end of the test.

The automatic sprinkler system was manually activated after approximately 23 min in test 5 with peak temperatures in the range of 700-800°C and rapidly controlled the fire, reducing the enclosure temperatures to less than 100°C within 30 s of activation. The fire was later fully extinguished using the deluge system.

The door between the apartment and corridor was stated to be a 20 min solid core door that remained closed for tests 1 through 4 but was left open in test 5.

Internal doors within the apartment were hollow core timber doors.

Protected service penetrations between the floors were included in the kitchen and bathroom areas

If the timber elements were protected, two layers of 16mm Type X plasterboard was applied.

The fire load density was approximately 570 MJ/m^2 of floor area and consisted of furniture, books, and cabinets supplemented by timber cribs. All fires were started in a lower kitchen cabinet on wall C.

The instrumentation/data recorded included:

- thermocouples measuring enclosure air temperatures and temperatures within the building elements
- oxygen consumption calorimeter to estimate the HRR
- internal and external heat flux meters
- optical density and gas analysis
- bidirectional probes fitted in openings to measure air velocities.

A summary of some key observations is provided in Figure 69.

Table 69: Summary of test observations.

Test ref	Sprinkler system status	Exposed CLT surfaces	Time to flashover (mm:ss)	Flames in corridor (mm:ss)	General observations
1	Not activated	None	LR: 13:27 BR: 17:20	26:51	Fully developed phase 15 to 18 min peak enclosure temps approx 1200°C
2	Not activated	30% exposed on bedroom ceiling; 30% exposed in living room	LR: 11:42 BR: 17:20	30:38	Fully developed phase 15 to 18 min peak enclosure temps approx 1200°C
3	Not activated	Wall B in the living room area Wall D in the bed-room	LR: 12:37 BR: 17:00	33:06 (door installation error)	Fully developed phase 15 to 18 min peak enclosure temps approx 1200°C
4	Automatic activation 2:37 min	All CLT walls, ceilings, glulam beams & columns in the living room and bedroom exposed.	No flash-over	Did not occur	Max temp before sprinkler activation ≈ 100°C then reduced rapidly on activation
5	Delayed activation – 23 min after ignition	All CLT walls, ceilings and glulam beams and columns in the living room and bedroom exposed	No flash-over before sprinkler activation at 23 min	9:00 (door open throughout test)	Main opening was glazed reducing ventilation and hence delaying the time to flashover compared to tests 1 to 3. Peak temp 700-800°C in living room and bedroom before reducing to less than 100°C within 30s of activation of the sprinkler.

Data was monitored for up to 4 hours after the start of the test. At the end of the test period a deluge system was turned on to extinguish the fire.

The HRR profile for tests 1-3 was similar with low heat release rates being recorded at 4 hours after ignition shortly before termination of the experiment. The enclosure temperatures also reduced significantly, and flaming combustion terminated before the end of the test. As the deluge system was switched on at the end of the tests it is not possible to confidently determine if localised smouldering combustion was ongoing at this stage.

Detailed information is provided in the project report.

B22 Series W Su et al (2018a) Fire safety challenges of tall wood buildings

Su et al[181] reported a series of fire tests undertaken for the Fire Protection Research Foundation (FPRF) to quantify the contribution of mass timber elements to compartment fires and to characterise the fire protection of the CLT structural elements using physical barriers (e.g. plasterboard) for delaying or preventing their involvement in the fire.

Six CLT compartment fire tests were conducted without any sprinklers and without firefighting intervention until the end of the tests in order to quantify the CLT contribution to compartment fires.

CLT test compartments (9.1 m long x 4.6 m wide x 2.7 m high) were constructed using 175 mm thick 5-ply CLT structural panels. The CLT panels were manufactured using spruce-pine-fir lumber glued with a polyurethane structural adhesive stated to conform to American National Standard ANSI/APA PRG 320 manufacturing standard. The compartment had an opening of 1.8 m wide x 2.0 m high in four tests and 3.6 m wide x 2.0 m high in two tests, with ventilation factors of 0.03 $m^{½}$ and 0.06 $m^{½}$, respectively.

The tested configurations are summarised in Table 70:

Table 70: Summary of Tests reported by Su – Fire safety challenges of tall wood buildings.

Opening size in W2 wall	1.8 m wide x 2.0 m high				3.6 m wide x 2.0 m high	
Test	**1-1**	**1-4**	**1-5**	**1-6**	**1-2**	**1-3**
W1 wall	3x16 mm GB	3x16 mm GB	exposed	exposed	2x16 mm GB	exposed
W2, W3 and W4 walls	3x16 mm GB	3x16 mm GB	3x16 mm GB	3x16 mm GB	2x16 mm GB	2x16 mm GB
Ceiling	3x16 mm GB	exposed	3x16 mm GB	exposed	2x16 mm GB	2x16 mm GB
Exposed CLT surface versus total ceiling and wall area (%)	0	36%	21%	57%	0	21%
Flashover (min)	14.9	11.5	11.5	9.8	15.3	12.5
Fully developed fire stage(min)	14.9 – 45	11.5 – 57[1]	11.5 – 50[1]	9.8 – 160	15.3 – 37	12.5 – 35

Notes:

GB refers to Type X Gypsum board used as a fire-protective covering to the CLT.

[1] Secondary flashover occurred during the cooling phase.

Representative residential contents and furnishings were used in the compartment tests with a moveable fire load density of 550 MJ/m^2.

The instrumentation/data recorded included:

- thermocouples measuring enclosure air temperatures and temperatures within the building elements
- oxygen consumption calorimeter to estimate the HRR
- internal and external heat flux meters
- optical density and gas analysis
- pressure differentials and bi-directional velocity probes.

Two baseline tests (Test 1-1 and Test 1-2) with all CLT surfaces protected in the compartments were undertaken. Protecting the CLT surfaces using the physical barrier was demonstrated to be an effective means to delay and/or prevent the ignition and involvement of the timber structural elements in the fires, limiting and/or eliminating their contribution to the fires.

In test 1-1 the maximum interface temperatures between the plasterboard and CLT for the ceiling was approximately 180°C and for the walls was 120°C. The test was terminated after 134 min and the debris on the floor hosed down.

In test 1-2 the temperatures at the gypsum board base layer and CLT interface reached 300°C at 53-67 min in the rear and middle sections of the ceiling assembly and increased to a peak temperature of 450°C afterwards. This indicated that CLT ceiling panels started charring behind the base layer board in the rear and middle sections of the ceiling assembly. The CLT interface temperatures in the front section of the ceiling were less than 185°C. In the wall assemblies, the maximum temperature measured at the CLT interface with gypsum board was 263°C on wall W1 at the 1.8 m height; at other measurement locations, the CLT wall interface temperatures were below 170°C. The test lasted for 104 min and was terminated after continuous fire decay (the heat release rate falling to below 500 kW at the end). A fire hose was used to lightly spray water over the debris on the floor to terminate the test. One of the interface temperatures between the CLT and ceiling plasterboard had not peaked at the termination of test but dropped quickly from 400°C to less than 200°C as the enclosure temperature was cooled.

The report noted that, although there was some charring of the CLT ceiling panels, it did not contribute to the compartment fire as the fire conditions in the compartment were not affected. The depth of char generally varied from 0 mm to 15 mm but was a maximum of approximately 50 mm at two joint positions.

In tests 1-4 and 1-5, char layer fall-off during the cooling phase of the fire resulted in secondary flashover.

Ventilation conditions had significant impacts on the fire development in the compartments. The smaller opening, which was used in four of the six tests, provided a longer duration of interior compartment fire than the larger opening.

B23 Series X Su et al (2018b) fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction

Su et al[113] reported a series of fire tests undertaken for Natural Resources Canada and the Province of Ontario performed by the National Research Council Canada. This was a follow-up to the Fire Safety Challenges of Tall Wood Buildings to evaluate the impact of alternate adhesives on char fall-off.

Five room fire tests were conducted, incorporating mass timber structural elements of Glulam beams and columns and second generation CLT panels (with adhesives less susceptible to char layer fall-off than first generation CLT).

The second generation CLT panels were manufactured using 38 mm x 89 mm spruce-pine-fir lumber glued with a new thermal resistive polyurethane adhesive (with a brand name of HBX2).

The test rooms were 4.5 m long x 2.4 m wide x 2.7 m high, constructed using 175 mm thick 5-ply CLT structural panels. Each test room had a rough opening of 0.76 m wide x 2.0 m high with a ventilation factor of 0.03 $m^{½}$. Three wood cribs, made of 38 mm x 89 mm x 900 mm spruce pieces were used as the fuel load for each test. Each wood crib had ten layers with eight spruce pieces per layer. The wood cribs were designed to provide a fire load density (FLD) of 550 MJ/m^2.

The CLT surfaces in the test rooms were fully or partially covered using multiple layers of Type X gypsum board. Two of the test rooms incorporated Glulam beams and columns. The tested configurations are summarised in Table 71.

Table 71: Summary of Tests reported by Su – Fire safety challenges of tall wood buildings.

Test Ref	CLT Wall A 4.5 m x 2.7 m	CLT Wall B 2.4 m x 2.7 m	CLT Wall C 4.5 m x 2.7 m	CLT Wall D 2.4 m x 2.7 m	CLT Ceiling 4.5 m x 2.4 m	CLT Floor 4.5 m x 2.4 m	Glulam Beam 327 mm x 457 mm	Glulam Column 457 mm x 457 mm
1	3 GB	3 GB	3 GB	3 GB	3 GB	3 GB	-	-
2	exposed (= 33% of perimeter)	2 GB	2 GB	2 GB	10% exposed	2x16 mm GB	2x16 mm GB	
3	2 GB	2 GB	2 GB	2 GB	2 GB	2 GB	exposed (4.54 m^2 = 11.5% of perimeter) GB	exposed (9.62 m^2 = 24.5% of perimeter)
4	2 GB	2 GB	2 GB	2 GB	100% exposed	0	exposed (2.46 m^2 = 6.4% of perimeter)	exposed (4.81 m^2 = 12.6% of perimeter)
5	2 GB	exposed (= 17.5% of perimeter)	2 GB	exposed (=17.5% of perimeter)	100% exposed	2 GB	-	-

Notes:

3 GB: one layer of 15.9 mm thick Type X gypsum board + two layers of 12.7 mm thick Type X gypsum.

2 GB: two layers of 12.7 mm thick Type X gypsum.

The instrumentation/data recorded included thermocouples measuring enclosure air temperatures and temperatures within the building elements.

For the fully encapsulated configuration test 1, no charring of the CLT was observed after a test duration of 167 min. Enclosure temperatures had dropped to below 400°C after 60 min and 100°C after 160 min. Measured interface temperatures with the CLT and plasterboard show that the ceiling temperatures peaked at approximately 150°C and the wall temperatures peaked at approximately 100°C after approximately 120 min.

In all tests with exposed mass timber, the peak room temperatures were similar to the baseline (fully encapsulated) but the fully developed fire stages were longer than the baseline as the exposed timber added more fuel load to the rooms.

In tests 3 and 5 secondary flashover occurred after the first fully developed fire phase.

In tests 2 to 4 there was substantial decay with enclosure temperatures falling to below 400°C after four hours. There was no substantial regrowth of the fire but there was some evidence of smouldering combustion continuing as temperatures within the body of the CLT panels continued to rise at some locations after 240 min and had exceeded 300°C. A longer monitoring period could have determined whether the CLT would have eventually self-extinguished with the general definition of self-extinguishment that requires combustion to cease.

The char was observed to remain on the exposed CLT surfaces long after the char front had passed the first glueline.

B24 Series Y Su et al (2019) Nail-laminated timber compartment fires

Su et al[183] reported a series of room scale fire tests of Encapsulated Mass Timber Construction with nail laminated timber (NLT) and Glulam structural elements to quantify the contribution of NLT elements to compartment fires and to provide additional data as the technical basis for the amount of mass timber elements that can be exposed without significantly increasing the fire severity and duration.

Four room fire tests were conducted that incorporated mass timber structural elements of Glulam beams and columns and NLT panels. The test rooms were 4.5 m long x 2.4 m wide x 2.7 m high, constructed using NLT structural panels. The NLT panels were fabricated using spruce-pine-fir laminations. Each test room had a rough opening of 0.76 m wide x 2.0 m high with a ventilation factor of 0.03 $m^{½}$.

The test configurations are summarised in Table 72.

Table 72: Summary of tests reported by Su – nail-laminated timber compartment fires.

Component	Test NLT-1	Test NLT-2	Test NLT-3	Test NLT-4
NLT Walls A and C with interior lining	2x6 laminations with 2 x 12.7 mm Type X	2x6 laminations with 2 x 12.7 mm Type X	2x6 laminations with 2 x 12.7 mm Type X	2x6 laminations with 3 x 12.7 mm Type X
NLT Walls B and D with/without interior lining	2x6 laminations with 2 x 12.7 mm Type X	2x6 laminations with 2 x 12.7 mm Type X	2x8 laminations exposed	2x8 laminations exposed
NLT Ceiling without interior lining	2x8 laminations exposed	2x8/2x10 alternate laminations exposed	2x8 laminations exposed	2x8 laminations exposed
Glulam Beam (327 mm x 457 mm)	exposed (2.46 m^2)	exposed (2.46 m^2)	-	-
Glulam Column (457 mm x 457 mm)	exposed (4.81 m^2)	exposed (4.81 m^2)	-	-

Wood cribs were used to simulate residential room contents with a fire load density of 550 MJ/m^2 in the room.

The instrumentation/data recorded included:

- thermocouples measuring enclosure air temperatures and temperatures within the building elements
- oxygen consumption calorimeter to estimate the HRR.

The fire dynamics in tests NLT1 and NLT 2 were similar with flashover occurring just before 4 min and temperatures peaking at 1170 °C during the fully developed stage before decreasing after approximately 30 min of the test to 800/850°C after 50 min and then increasing again when the NLT wall panels started to char behind the plasterboard causing flaming at the cracks and joints in the plasterboard. Temperatures within the enclosures up to approximately 800°C at a height of 2.4 m were maintained until the tests were terminated after 240 min.

In test NLT-4, with the same amount of exposed timber surface but enhanced encapsulation (three layers of gypsum board) on the two long walls, substantial decay of the fire and much reduced contributions of the timber to the fire during the four-hour monitoring period were observed although there was a slight upward trend from 180 to 240 min. The maximum enclosure temperatures at a height of 2.4m marginally exceeded 300°C during the monitoring period but below this height temperatures were below 300°C. Flaming combustion was stated to have ceased in NLT-4 during the monitoring period.

Test NLT-3 was terminated after 120 min and the fire extinguished. The enclosure temperatures peaked at 1200°C during the fully developed stage then decreased slightly after 30 min but remained above 1000°C for the remainder of the test. This was caused by the contribution from the initially protected timber in Walls C and D once the protection began to breakdown exposing the timber.

B25 Test Series Z (Epernon Fire Test Program) Collignon & Tessier

B25.1 General information

The Epernon Fire Test Program comprised three standard fire-resistance tests and six natural fire experiments.

The information relating to the test program was obtained from nine test reports, Collignon & Tessier[184-189] and the following papers; McNamee[193]. Mindeguia[194], and Bartlett[195].

The natural fire experiments were performed on compartments 6000 x 4000 mm x 2520 mm high. The walls of the fire compartment were constructed from aerated concrete (nominal density of 350 kg/m^3) and the floor was covered with calcium silicate boards and a layer of mineral fibre.

Three tests were performed on 165 mm CLT floors/ceilings assemblies (5 x 33 mm lamella) with the CLT exposed. The glue used was a single-component polyurethane resin.

The remaining three natural fires were performed on normal-weight concrete floor/ceilings 180 mm thick, with a welded reinforcement mesh and a cover of 20 (axis distance of 24 mm). Polypropylene fibres were incorporated in the concrete mix which would be expected to significantly reduce the risk of concrete spalling and therefore the results may not apply to concretes without equivalent mitigation measures to limit spalling.

CLT and concrete slabs were loaded during the test.

The fuel load during the tests was 891 MJ/m^2 of the floor area and consisted of spruce wood cribs with a small amount of heptane accelerant. This value excludes any contribution from the exposed CLT.

The CLT elements and concrete elements were tested with the following opening factors calculated in accordance with EN 1991-1-2: 0.144, 0.050 and 0.032 m$^{1/2}$. The opening factor of 0.144 m$^{1/2}$ corresponds to a fuel-controlled fire ignoring any contribution from the CLT panels, and the opening factor of 0.032 m$^{1/2}$ corresponds to a ventilation-controlled burning regime. The contribution from the CLT panel will tend to move the burning regime towards a ventilation-controlled regime and in some cases change the burning regime.

In addition, two fire-resistance tests using the standard heating regime were performed on the CLT floor/ceiling system and one fire-resistance test on the concrete floor system. The specimens were similar to those used for the natural fire test providing a useful benchmark.

B25.2 Relevant test observations and data

The mean temperatures measured by plate thermometers from the three natural fire tests, are plotted in Figure 97 based on results reported by Mindeguia[194]. These are compared against the standard and hydrocarbon heating regimes specified in AS 1530.4 and a modified hydrocarbon regime where the maximum temperature is increased from 1100°C to 1200°C. It can be observed that the plate thermocouple temperatures during the fully developed phases of the natural fires are effectively bounded by the modified hydrocarbon and standard heating regimes. Also included in Figure 97 are plots of plate thermocouple temperatures measured during:

- A standard fire test with a CLT panel – Epernon test series.
- Test H1 – Intermediate standard fire test with a CLT panel – FWPA furnace test series.
- Test H7 – Intermediate hydrocarbon fire test with a CLT panel – FWPA furnace test series.
- For scenario 1 No failure occurred and the CLT self-extinguished.
- For scenario 2 No failure occurred during the combustion of the timber crib but the specimen collapsed after 29 hours.
- For scenario 3 Structural failure occurred after 108 min.

In the Epernon fire-resistance tests Z1 and Z5 structural failure occurred after termination of heating although deflection limits were exceeded between 121 and 141 min depending on the deflection criteria adopted.

If the time for limiting deflection from EN 13501 is adopted for comparison it is possible to compare the scenario 3 time of 107 min to the values of 121 and 125 obtained in the standard exposure tests.

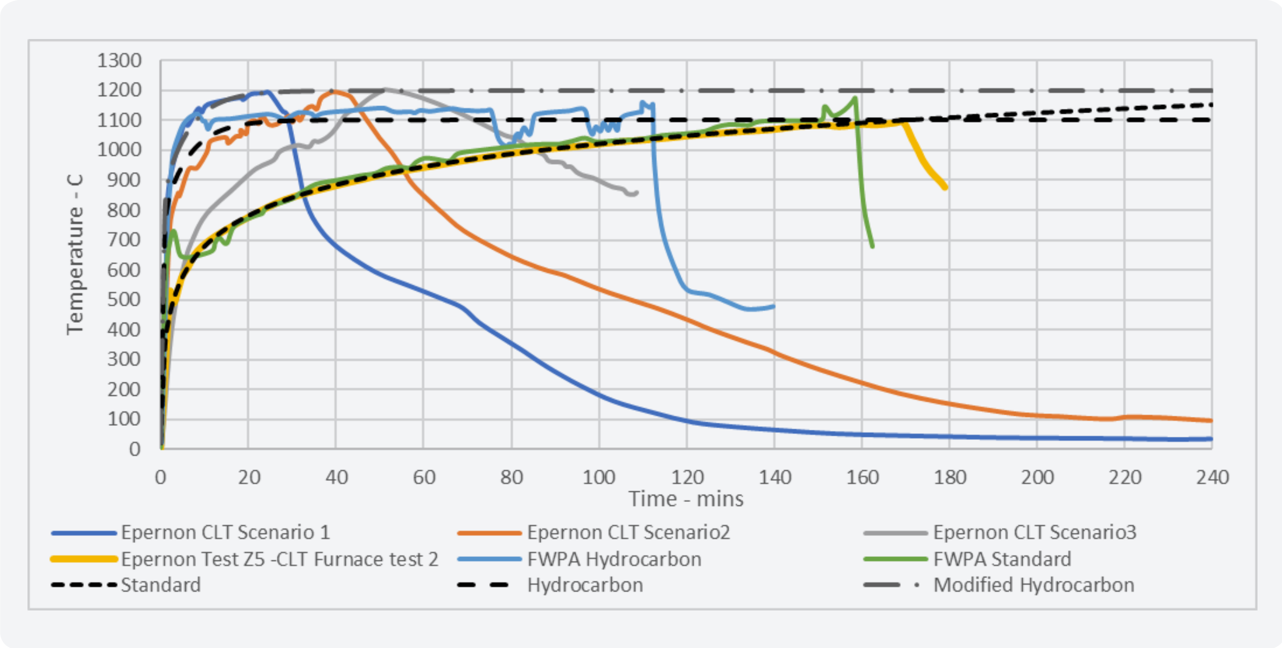


Figure 97: Plate thermometer temperatures comparing natural fire test exposures with standard and hydrocarbon furnace test exposures.

A review of the enclosure temperatures shows slow decay rates. This would have been due at least in part to the combustion of the CLT once the timber cribs had been consumed.

The time for the char depth to reach the first lamella (i.e. 33mm) is a useful benchmark to compare the damage to the CLT element when exposed to the various fire scenarios prior to a significant influence of delamination. Char data after which delamination is likely to have occurred are also shown in Table 73.

Table 73: Comparison of char data from Epernon natural fire scenarios and furnace tests adopting the standard heat regime.

Nominated Char Depth (mm)	Estimated exposure time to achieve nominated char depth (min)			
	Scenario 1	Scenario 2	Scenario 3	Mean Standard (tests Z1 and Z5)
33	23	28	39	52
44	46	49	60	70
66		69	75	87
77			95	118

Char data based on estimates of the position of the 300^0 C isotherm are plotted against time in Figure 98 and compared to data from FWPA furnace tests. It should be noted that the FWPA tests were performed with specimens manufactured from a different timber species, lamella thicknesses and the lamella were only face bonded rather than the face and edge bonding adopted in the Epernon tests. Therefore, delamination would be expected to be more likely and extensive with the FWPA tests. The measured temperatures confirmed this expectation, however the time to attain a char depth of 33 mm was similar for the FWPA and Epernon tests exposed to the standard heating regime since delamination would be expected to be relatively limited at this char depth.

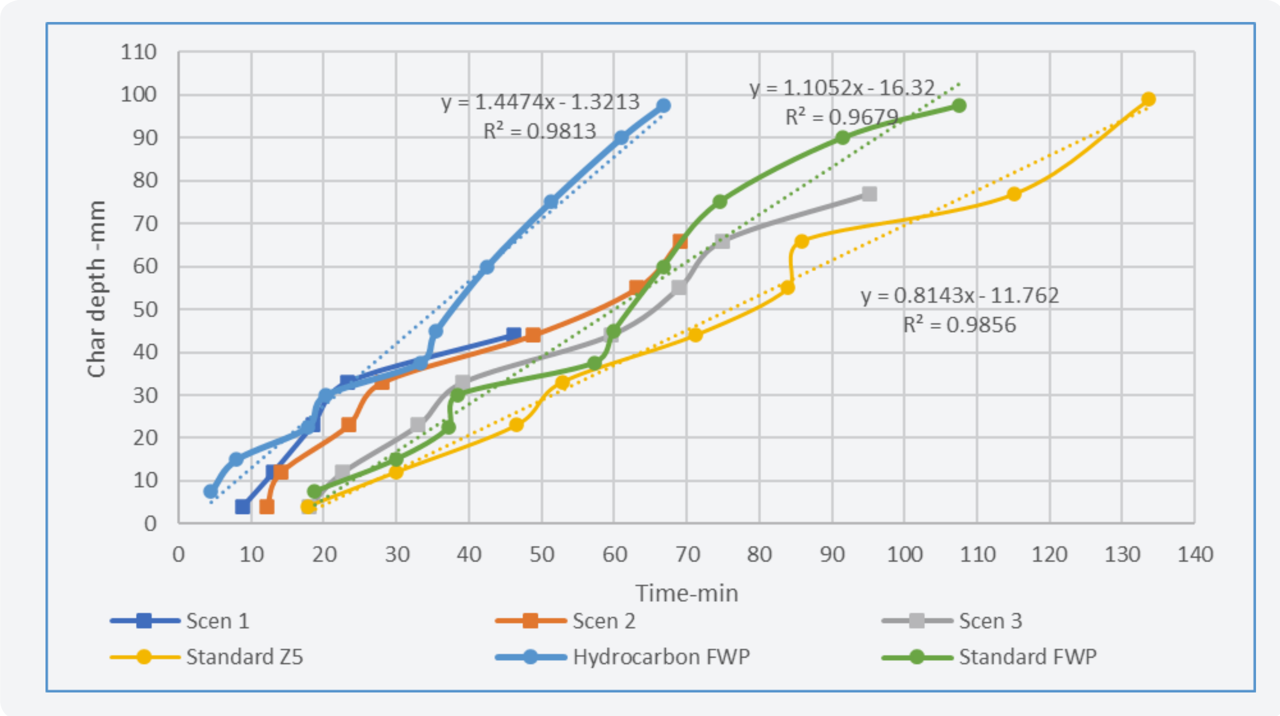


Figure 98: Comparison of Epernon CLT char rates with FWPA furnace test data.

B26 Series AA Brandon et al Fire safe implementation of visible mass timber

Brandon et al[43,190] reported five fire tests of compartments constructed of cross-laminated timber (CLT) and glued laminated timber, compliant with product standards specified in current (at the time of testing in 2020) US model building code.

Tests 1, 2, 3 and 5 were designed to represent a residential fire compartment. Test 4 had additional openings yielding a greater opening factor, which was intended to be more representative of buildings designed for business (office) occupancy.

Representative residential contents and furnishings were used in the compartment tests with a moveable fire load density of 560 MJ/m^2.

The instrumentation/data recorded included:

- Thermocouples measuring enclosure air temperatures and temperatures within the building elements
- oxygen concentrations at locations of interest,
- exposure to exterior surfaces of the wall and facade above the openings.
- HRR based on mass loss measurements.

The configurations tested are summarised in Table 74.

Table 74: Test Configurations for Brandon et al fire safe implementation of visible mass timber tests.

Component	Test 1	Test 2	Test 3	Test 4	Test 5
Ceiling	100% exposed	100% exposed	100% exposed	100% exposed	100% exposed
Back wall	2 x 15.9 mm Type X PB	3x 15.9 mm Type X PB	3x 15.9 mm Type X PB	2 x 15.9 mm Type X PB	3x 15.9mm Type X PB
Front wall	2 x 15.9 mm Type X PB	3 x 15.9 mm Type X PB	100% exposed	100% exposed	60% exposed
Left wall	2 x 15.9 mm Type X PB	100% exposed	100% exposed	100% exposed	100% exposed
Right wall	2 x 15.9 mm Type X PB	100% exposed	78% exposed Back 1.5m prot. 3 x 15.9 mm Type X PB	100% exposed	100% exposed
Column	2 x 15.9 mm Type X PB	3 x 15.9 mm Type X PB	100% exposed	100% exposed	100% exposed
Beam	100% exposed	100% exposed	100% exposed	100% exposed	100% exposed
Vent area	8.0 m^2	8.0 m^2	8.0 m^2	31.2 m^2	8.0 m^2
Opening factor	0.062 $m^{1/2}$	0.062 $m^{1/2}$	0.062 $m^{1/2}$	0.25 $m^{1/2}$	0.062 $m^{1/2}$
Exposed CLT	53.8 m^2	91.2 m^2	96.2 m^2	77.9 m^2	97.2 m^2
Full developed phase duration	22 min	28 min	31 min	5 min	30 min
Total heat release from structure and floor – (GJ) during flashover phase	29 ± 5	47 ± 5	44 ± 5	26 ± 5	44 ± 5

Excluding test 4 with the large opening factor, all the other tests had similar enclosure temperatures for approximately the first 10 min after flashover. The compartment with only the ceiling (including the glued laminated timber beam) exposed started to decay after 22 min of post-flashover conditions and continued to decay until the end of the test at 4 hours after ignition.

The other three tests had, in addition to the ceiling, significant areas of exposed wall and column surfaces. The additional exposed surface areas of walls led to an increase of the fully developed fire duration by 6-9 min.

Test 3 included corners where two exposed walls intersect. Significantly increased damage was observed in the lower part of these wall corners, and an overall higher radiative exposure in the test with such corners would be expected. After more than three hours of decay, surface flaming developed on the walls in this test. The fires in the tests without such corners exhibited continual decay for the full 4-hour test duration. Post-test analysis showed that the structural damage was lower in the exposed ceilings than at the bottom of the exposed walls for all tests.

After the tests, remaining smouldering and hot spots were extinguished using relatively small amounts of water mist. Overnight measurements to study the thermal wave going through the loadbearing structure indicated no post-test reduction of structural capacity.

Test 4 (largest opening factor) had two layers of fire-rated gypsum board protection on the back wall and all other surfaces of CLT and glued laminated timber exposed. Despite having the highest peak combustion rate, this compartment fire had the least severe internal and external fire exposure. The fire decayed relatively quickly after flashover and continued to decay until the test was stopped at 4 hours after ignition. This fire resulted in less structural damage than the fires in compartments with fewer and smaller openings.

C Appendix C - Australian Fire Resistance Tests

There is a substantial body of work that has been undertaken in Australia relating to the performance of elements of construction when exposed to fire-resistance tests and to a lesser extent, various parametric heating regimes using furnaces. Standard fire-resistance tests have been used extensively through most of the last century for the grading and classification of elements required to resist fully developed fires (including timber elements) and continue to be used successfully for this purpose. Fire-resistance test methods have evolved to improve repeatability with options to obtain additional data to facilitate fire engineering design and continue to provide a useful tool for the verification and classification of elements of construction. The use of other heating regimes such as the hydrocarbon heating regimes also facilitate the sensitivity of elements to different fire exposures to be evaluated. The following is a summary of tests sponsored by FWPA or other industry bodies or data that is in the public domain that has relevance to the construction of timber buildings in Australia.

C1 Summary of furnace fire-resistance tests relating to Australian timber industry

The fire tests summarised below include tests performed in Australia that the FWPA have access to or commissioned or have been published in technical literature. This listing does not include proprietary test data owned by product suppliers.

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry. *(Superscripts in bold font refer to notes at the end of the table. Superscripts in a light font refer to references provided in Appendix H)*

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insulation	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
A1 - NAFI	FSH 0204 [196]	CSIRO (1992)	AS 1530.4: 1990/ Standard	Floor/ ceiling	4.6 x 3.7	3.6 kPa	250 mm x 50 mm Douglas Fir joists @ 450 mm centres	13 mm and 16 mm fire-protective grade PB nailed directly to joists (Boral Firestop/CSR Super Fire Check)	Mineral Fibre (MF) 85 mm thick density 30 kg/m^2 (upper part of cavity)	L1 46-74 L2 85	57 (48**[1]**)	125/125/125
A2 - NAFI	FSH 0205 [197]	CSIRO (1992)	AS 1530.4: 1990/ Standard	Floor/ ceiling	4.6 x 3.7	3.3 kPa	250 mm x 50 mm Douglas Fir joists @ 450 mm centres with steel furring channels @ 600 mm centres	13 mm and 16 mm fire-protective grade PB fixed to steel furring channels @ 200 mm cts (Boral Firestop/ CSR Super Fire Check)	MF 85 mm thick density 30 kg/m^2 (upper part of cavity)	L1 52 L2 54	53 (52**[1]**)	66/66/66
A3 - NAFI	FSV 0187 [198]	CSIRO (1992)	AS 1530.4: 1990/ Standard	Wall	3 x 3 x 0.257	108 kN total	2 x 100 x 50 Douglas Fir F7 timber studs @ 450 mm centres. Frames separated by 25 mm	1 x 16 mm fire-protective grade PB each side (Boral Firestop/CSR Super Fire Check)	MF 85 mm thick density 30 kg/m^2 Non-fire side	No fall-off observed	No data	76/76/76
A4 - NAFI	FSV 0189 [199]	CSIRO (1992)	AS 1530.4: 1990/ Standard	Wall	3 x 3 x 0.289	108 kN total	2 x 100 x 50 Douglas Fir F8 timber studs @ 450 mm centres. Frames separated by 25 mm	2 x 16 mm fire-protective grade PB each side (Boral Firestop/CSR Super Fire Check)	MF 85 mm thick density 30 kg/m^2 Non-fire side	L1 87-110 L2 120	No data	134/134/134

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insulation	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
A5 - NAFI	FSV 0190 [200]	CSIRO (1992)	AS 1530.4: 1990/ Standard	Wall	3 x 3 x 0.266	54 kN total	2 x 100 x 50 Douglas Fir F5-8 timber studs @ 450 mm centres.	1x 16 mm fire-protective grade PB to fire side (Boral Firestop/CSR Super Fire Check). 6 mm plywood bracing on NFS of stud, 34 mm cavity and 110 mm Brick Veneer	MF 75 mm thick density 36 kg/m^2 Fire-side	L1 83-85	No data	94/94/94
A6 - NAFI	FSV 0194	CSIRO (1992)	AS 1530.4: 1990/ Standard	Wall	3 x 3 x 0.266	54 kN total	2 x 100 x 50 Douglas Fir F5-8 timber studs @ 450 mm centres.	1x 16 mm fire-protective grade PB to fire side (Boral Firestop/CSR Super Fire Check). Steel bracing on NFS of stud, 40 mm cavity and 110 mm Brick Veneer	MF 75 mm thick density 36 kg/m^2 Fire-side	L1 59-63	No data	88/88/88
B1	F91767	WF (1999)	AS 1530.4: 1990/ Standard	Wall	Int. 1.2 x 1.2	NL	90 x 45 mm studs @580 centres	1 x 13 mm fire-protective grade PB applied to both faces no joints fixed at 300 mm in the field and 200 mm at perimeter /studs	None	99-100	18/ 26[2,5]	-/120/69[2]
B2	F91768	WF (1999)	Hydro carbon	Wall	Int 1.2 x 1.2	NL	90 x 45 mm studs @ 580 centres	1 x 13 mm fire-protective grade PB applied to both faces no joints fixed at 300 mm in the field and 200 mm at perimeter /studs	None	88-93	11 / 19[2,5]	-/101/53[2]
B3	F91769	WF (1999)	AS 1530.4: 1990 / Standard	Wall	Int 1.2 x 1.2	NL	90 x 45 mm studs @ 580 centres	1 x 13 mm fire-protective grade PB applied to both faces no joints fixed at 300 mm in the field and 200 mm at perimeter /studs	Glasswool	68-minor 103-108 significant[3]	19/ 26[2,5]	-/122/82
B4	F91770	WF (1999)	Hydro carbon	Wall	Int 1.2 x 1.2	NL	90 x 45 mm studs @ 580 centres	1 x 13 mm fire-protective grade PB applied to both faces no joints fixed at 300 mm in the field and 200 mm at perimeter /studs	Glasswool	28-35	11.5/ 16[2,5]	-/45/37[2]

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insula-tion	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
C1	BFT 668	BHP Results reported by Young[61] and Clancy[147]	AS 1530.4 :1990 Standard	Wall	3x1.6	NL	90 x 45 mm Radiata Pine studs @380 centres	1 x 16 mm fire-protective grade PB each side nailed at 100 mm spacing at joints	None	None before failure	RISF≈ 28 MRISF ≈32 based on stud interface	-/87/87 to -/89/89 Structural failure (major integrity failure due to all studs fully charred)
C2	BFT 669			Wall		NL						
C3	BFT 676			Wall		NL						
C4	BFT 679			Wall Pin ends		8 kN/ Stud						34/34/34 to 35/35/35 Stuc failure. Less than 3 mm char. Significant part of cross-section at 100°C
C5	BFT 680			Wall Pin ends		8 kN/ Stud						
C6	BFT 681			Wall Fixed ends		8 kN/ Stud						58/58/58
C7	BFT 682			Wall Pin		8 kN/ Stud						40/40/40[4]
C8	BFT 683			Wall Pin		8 kN/ Stud						28/30/30
D1	F91780	WF (1999)	AS 1530.4: 1990/ Standard	Ceiling	Int 1.2 x 1.2	NL	64 x 32 Steel Studs	2 x 13 mm fire-protective grade PB applied to fire-exposed face and 1 x 13 mm applied to non-fire side (half specimen)	None	Face layer 72	Cavity 57[2] Open 67[2]	-
D2	F91782	WF (1999)	Hydro carbon			NL				Both layers 55	Cavity 37[2] Open 39[2]	-
D3	R9112	WF (1998)	AS 1530.4: 1990/ Standard	Wall	Int 1 x 1	NL	64 x 32 Steel Studs	2 x 13 mm fire-protective grade PB applied to fire-exposed face and 2 x 13 mm applied to non-fire side (half specimen)	None	Face layer 123 @ Base layer 147	52[2]	-
D4	R9113	WF (1998)	Hydro carbon		Int 1 x 1	NL				Face layer < 50 Base layer 91	33-38[2]	-
E1 – E8	Tec Rpt 5	Fire Technology Lab Weyerhaeuser USA reported by Gardner and Syme (1991)[55]	AS 1530.4: 1985 Standard	Beams 3-sided exposure	Int 0.9m length exposed	NL	Glued-Laminated Beams 1.2m x 270 mm x 150 mm Blackbutt Blue gum Brush box Cypress pine Jarrah Radiata Pine Spotted Gum Victorian ash	None	None	Not Applicable	Not Applicable	60 min tests
E9-16								None				120 min tests
E17-24								1x 13 mm fire-protective grade PB applied to exposed faces with 50 x 2.8 mm Clout nails (softwood specimens and 40 mm x 2.6 mm hardwood specimens at 100 mm nominal centres. Mouldings applied to corners and joints treated with paper tape and cornice cement		Generally remained in place for 120 min	MRISF typically 27-30	120 min tests with PB protection

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insulation	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
F1	3647 4400	WF (2015)[201]	AS 1530.4: 2014 Standard	Floor/ Ceiling	4 x 3 x .334	Total Load for beams 1.28-1.72 kN/m[6]	Following engineered lightweight timber elements supporting 15 mm timber plywood flooring[7] Composite I-section with steel web Timber truss with nail plate connections Timber truss with steel diagonal webs Composite I-section with OSB web	2 x 16 mm fire-protective grade PB fixed to steel furring channels provided at 600 mm centres supported from the beams	None	L1>76-86 L2 remained in place with gaps forming at joints	67	90/90/90
F2	TST 180021	WF (2019)[202]	AS 1530.4: 2014 Standard	Floor/ Ceiling	4 x 3 x .351	Total Load for beams 1.06-1.57 kN/m[8]	Following engineered lightweight timber elements supporting 15 mm timber plywood flooring[9] Composite I-section with steel web Timber truss with nail plate connections Timber truss with steel diagonal webs Composite I-section with OSB web	3 x 16 mm fire-protective grade PB. First two layers fixed to steel furring channels provided at 600 mm centres supported from the beams. Outer layer fixed to first two-layers with laminating screws	None	All PB layers in place after 120 but PB edges sagging between fixings	No failure at 120[10]	120/120/120
F3	4938 5100	WF (2017)[203]	AS 1530.4: 2014 Standard[12]	Wall	3 x 3 x 0.236	Total load 12.3kN/ stud[11]	140 mm deep x 45 mm wide MGP10 timber framing at nominal 400 mm centres	3 x 16 mm fire-protective grade PB First two layers fixed to timber studs Outer layer fixed to first two-layers with laminating screws	Rockwool® RockTech S 400SPL stone wool uncompressed density 81.4 kg/m³ filling cavity. Applied as 130 x 100 mm lamella with four lamellae compressed to fit within 355 mm wide cavity between frame members	L1>110 L2 150-165 L3 172-186	136	198/198/198 (Based on time at which load reduced – heating was continued under reduced load)[13]
F4	FRT 200150	WF (2020)[159]	AS 1530.4: 2014 hydro carbon	Floor/ Ceiling	4 x 3 x 0.334	Total Load for beams 1.28-1.72 kN/m[6]	Following Engineered lightweight timber elements supporting 15 mm timber plywood flooring[7] Composite I-section with steel web Timber truss with nail plate connections Timber truss with steel diagonal webs Composite I-section with OSB web	2 x 16 mm fire-protective grade PB fixed to steel furring channels provided at 600 mm centres supported from the beams	None	L1 33-46 L2 53.5	44	57/57/57

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insulation	Board fall-off time (min)	RISF/MRISF	Structural Adequacy/ Integrity/ Insulation (min)
G1	5567 6400	WF (2018) [204]	AS 1530.4: 2014 Standard	Wall	Internal 1.2 x 1.2 exposed to furnace	NA	90 x 45 mm MGP10 @ 450 mm centres	2 x 13 mm fire-protective grade PB applied to fire-exposed face and 2 x 13 mm applied to non-fire side	East cavity R2.5 non-combustible glass wool insulation 90 mm thick West Cavity None	PB remained in place but joints opened	49-53 with insulation 56 min without insulation Timber interface temp[14]	-/60/60[2] Heating terminated at 60 min
G2	5567 6500	WF (2018) [205]	AS 1530.4: 2014 Standard							PB remained in place but joints opened and board split	48-50 with insulation 54-56 min without insulation Timber interface temp[15]	-/90/90[2]
G3	5567 6600	WF (2018) [206]	AS 1530.4: 2014 Hydro carbon								30 with insulation 33-36 min without insulation Timber interface temp[16]	-/75/75[2]

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insul ation	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
H1	4938 5200	WF (2018) [207]	AS 1530.4: 2014 Standard	Floor/ Ceiling	Internal 1.2 x 1.2 exposed to furnace	NA	225 mm thick CLT comprising 5 x 45 mm Radiata Pine lamella face bonded with Purbond polyurethane adhesive	Exposed CLT	None	NA	NA	Base -/151/151[17] Joint Integrity Unprotected 94 2 beads -119 PB Cover 143
H2	4938 5300	WF (2018) [208]	AS 1530.4: 2014 Standard					1x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field.		L1 = 115	MRISF 32	Base -/171/171[17] Joint Integrity 2 beads – 171[17] PB cover 171[17]
H3	4938 5400	WF (2018) [209]	AS 1530.4: 2014 Standard					2 x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field		L1≈92-110 L2=145	MRISF 85	Base -/191/191[17] Joint Integrity 2 beads – 191[17] PB cover 191[17]
H4	4938 5500	WF (2018) [210]	AS 1530.4: 2014 Standard					3 x 16 mm fire-protective grade PB. Layers 2 and 3 direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field. L1 outer layer laminated to L2 and 3 with 50 mm bugle head screws with fixing centres as above.		L1≈110-128 L2≈150-156 L3=179	MRISF 144	Base -/240/240[17] Joint Integrity 2 beads – 240[17] PB cover 240[17]
H5	4938 5600	WF (2018) [211]	AS 1530.4: 2014 Hydro carbon					2 x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field		L1≈56-65 L2=102	MRISF 60	Base -/153/153[17] Joint Integrity 2 beads – 153[17] PB cover 153[17]
H6	4938 5700	WF (2018) [212]	AS 1530.4: 2014 Standard				105 mm thick CLT comprising 3 x 35 mm Radiata Pine lamella face bonded with Purbond polyurethane adhesive	1x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field.		No fall-off	MRISF 34	No failures when heating terminated at 45 min and during subsequent monitoring period
H7	5445 5300	WF (2018) [213]	AS 1530.4: 2014 Hydro carbon				225 mm thick CLT comprising 5 x 45 mm Radiata Pine lamella face bonded with Purbond polyurethane adhesive	Exposed CLT		NA	NA	Base -/109/109[17] Joint Integrity Unprotected 69 2 beads -75 PB Cover 109

Table 75: Australian furnace fire-resistance tests accessible to the Australian timber industry (continued).

Test	Ref	Lab/ year	Test Standard /Heating Regime	Spec type	Nom Size (m)	Load	Main struct. Members	Thickness and type of gypsum board protection (exposed layer last)	Insul ation	Board fall-off time (min)	RISF/ MRISF	Structural Adequacy/ Integrity/ Insulation (min)
H8	5445 5500	WF (2018) [214]	AS 1530.4: 2014 Standard				105 mm thick CLT comprising 3 x 35 mm Radiata Pine lamella face bonded with Purbond polyurethane adhesive	1x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field.		No fall-off	MRISF 32	No failures when heating terminated at 60 min and during subsequent monitoring period
H9	5445 5301	WF (2018) [215]	AS 1530.4: 2014 Hydro carbon				225 mm thick CLT comprising 5 x 45 mm Radiata Pine lamella face bonded with Purbond polyurethane adhesive	1x 16 mm fire-protective grade PB direct fix to CLT with W8g x 65 mm screws at 200 mm centres around the perimeter with minimum edge distance 38 mm and 300 mm centres in the field.		L1=69	MRISF 18	Base -/120/120[17]

Notes:

1 RISF estimated under AS 1530.4:2014 Criteria.

2 Results stated are indicative estimates since tests were intermediate scale and/or interpretation of temperature data required.

3 Estimated from temperature data.

4 Due to furnace malfunction results from the test may not be reliable after the malfunction.

5 MRISF estimated based on thermocouple at interface of stud and partition.

6 The load ratios of the beams varied from 0.52 to 0.81 for the beams (maximum load ratio for fire limit state if designed to Australian Standards is approximately 0.5).

7 Additional unloaded elements and design features were included together with additional instrumentation enabling a broad range of configurations to be assessed in WF report 37600400[216].

8 The load ratios of the beams varied from 0.53 to 0.58 for the beams (maximum load ratio for fire limit state if designed to Australian Standards is approximately 0.5).

9 Additional unloaded elements and design features were included together with additional instrumentation enabling a broad range of configurations to be assessed in WF report FAS 190034[217].

10 At the end of the test, the specimen was raised above the furnace to expose the underside of the specimen to the laboratory atmosphere while maintaining an imposed heat flux for a further 17 hours with the full test load applied. No suppression was undertaken with the specimen cooling to ambient conditions under full test load and no evidence of combustion of the specimen.

11 The load ratio for the studs was 0.5 for the first 198 min of the the test based on calculations to AS 1720.1 and then was progressively reduced during the remainder of the test.

12, 13 Additional instrumentation was included, and heating continued until 227 min had elapsed at which point heating was terminated because test equipment was at risk due to breakdown of the furnace seals. The specimen was removed from the furnace and monitored for a further 30 min before water was applied to the wall system to suppress any residual combustion. Based on the supplementary data obtained assessments were able to be provided for variations to the system for FRLs of 120/120/120 and 180/180/180 and -/240/240[218-220].

14 Temperatures measured between timber frame and plasterboard max 298^{0}C at 60 min.

15 Temperatures measured between timber frame and plasterboard max 303^{0}C at 60 min.

16 Temperatures measured between timber frame and plasterboard max 300^{0}C at 39.5 min.

17 Specimen did not fail during heating period – test duration stated.

A series of six full-scale fire-resistance tests were included as part of the submission to AUBRCC (the predecessor of the Australian Building Codes Board (ABCB)) supporting a proposal for change to include a DTS Pathway for Low Rise (up to 3 or 4 storeys) Multi-Residential Timber Frame Construction within the Building Code of Australia (Appleton[221]). The submission incorporated a quantitative risk assessment which facilitated the inclusion of the Class 2 and 3 buildings: Concession, the current version of which is included in NCC 2019 Specification C1.1 Cl 3.10 and Cl 4.3[2].

The tests provided supporting data for typical forms of construction that could be adopted for timber-frame construction incorporating typical Australian Building Products. Basic instrumentation consistent with the minimum requirements of AS 1530.4 1990 was provided enabling the structural adequacy, integrity and insulation criteria and for floor systems the Resistance to Incipient Spread of Fire criteria of AS 1530.4:1990 to be determined. The observations also noted plasterboard fall-off times.

These tests have been largely superseded by more recent tests including proprietary systems from various plasterboard suppliers however the performance of ceiling systems comprising a base layer of 12.5mm fire-protective grade plasterboard and a face layer of 16 mm fire-protective grade plasterboard provides some useful data.

A brief summary of the two floor tests is provided below:

FSV 0205[197] Fire resistant timber floor with plywood flooring protected by a ceiling system comprising a layer of 13 mm and a layer of 16 mm thick fire-protective grade plasterboard screw fixed to resilient channels at 600 mm centres fitted to the soffit of the joists.

The timber floor comprised a loadbearing floor/ceiling construction with timber joists nominally, 250 x 50 mm, spaced at 450 mm centres. The floor was protected by a ceiling that comprised two layers of fire-protective grade plasterboard attached to steel resilient channels at right angles to the joists at 600 mm centres. The base layer of 13 mm thick fire-grade plasterboard was screwed to the steel channels using 25 mm long bugle-head screws at 200 mm centres in the field of the board and the board butt joints. All butt joints in the first layer of plasterboard were aligned with the steel channels. The face layer of 16 mm thick fire-grade plasterboard was screw fixed along the butt joints at 200 mm centres using 40 mm long steel laminating screws. The face layer plasterboard was fixed to the steel resilient channels using 45 mm long screws at 200 mm centres in the field of the board. The butt joints in the second layer of plasterboard were located centrally between the steel resilient channels. All joints between the plasterboard sheets and between plasterboard layers were staggered. The joints in the plasterboard sheets were taped and set and all screw heads were caulked using plasterboard jointing cement.

The flooring comprised sheets of 14 mm thick tongue and groove waterproof plywood glued and nailed to the timber floor joists. The ceiling cavity incorporated 85 mm thick mineral fibre batts with a density 30 kg/m^3, friction fitted between the timber joists and supported by a polypropylene string, directly below the plywood floor sheet.

FSV 0204 Fire resistant timber floor with plywood/acoustic layer and reinforced RC upper layer flooring protected by a ceiling system comprising a layer of 13 mm and a layer of 16 mm thick fire-protective grade plasterboard directly nail fixed to joists at 450 mm centres joists.

The specimen comprised a loadbearing floor/ceiling system with nominal 250 mm x 50 mm timber floor joists at 450mm centres.

The floor was protected by a ceiling comprising a base layer of 13 mm and a face layer of 16 mm fire-protective grade plasterboard, nail fixed directly to the underside of the timber floor joists. The flooring comprised sheets of 14 mm thick tongue and groove waterproof plywood glued and nailed to the timber floor joists and a 25 mm thick 60 kg/m^3 acoustic mineral fibre layer over which a 45 mm thick reinforced lightweight concrete slab was laid.

The ceiling cavity incorporated 85 mm thick mineral fibre batts with a density 30 kg/m^3, friction fitted between the timber joists and supported by a polypropylene string, directly below the plywood floor sheet.

Table 76: Summary of results from tests FSV 0204 and FSV0205.

Test	Cavity Insulation	Flooring	Ceiling Construction	FRL (Structural Adequacy/ Integrity/ Insulation)	Est RISF1 (min)	Time to fall-off of significant section of ceiling (min)	
						Face layer 16 mm	Base layer 13 mm
FSV 0205	Mineral fibre	14 mm T&G plywood	Steel resilient channels at 600 mm centres – screw fix	66/66^1/66	≈53	52	54
FSV 0204	Mineral fibre	14 mm T&G plywood, plus 25 mm acoustic insulation plus 45 mm RC slab	Direct nail fix to joists at 450 mm centres	125^3/125^2/125	>50	65	73

Notes:
1 Integrity failure due to burn through of floor
2 Integrity failure due to flaming at end of specimen.
3 Some load redistribution due to the concrete slab is expected to have occurred.

C3 Series B Comparative tests on intermediate scale plasterboard faced timber stud partitions exposed to hydrocarbon and Standard AS 1530.4 heating regimes

This test series was undertaken by WarringtonFire in 1999 to compare the likely performance of timber frame plasterboard partitions exposed to different heating regimes and was reported for FWPA in 2014.

The series comprised four intermediate size timber frame partitions (1.2 m x 1.2 m) faced on each side with one layer of 13 mm fire-protective grade plasterboard. Two specimens were subjected to the standard AS 1530.4 heating regime and two to the hydrocarbon heating regime. One comparative set included cavity insulation the other did not.

Additional instrumentation was provided to record the temperature distribution through the specimen. An extract of this data is provided in Table 77. Board fall-off times may be earlier for full-size specimens.

Table 77: Extract of data from tests F91767 to F91770[222-225].

Test	Heating Regime	Cavity Insulation	Est RISF[1] (min)	Est t_{ch}[2] (min)	Mean char time (min)		Sig.crack in PB		PB fall-off		Non fire side PB @ 600°C (min)
					7.5 mm depth	15 mm depth	time (min)	temp (°C)	time (min)	temp (°C)	
F91767	Standard	None	18.5	26	46	55	60	553	99	711	70
F91768	Hydrocarbon	None	12	19	32	41	45	648	88	740	35
F91769	Standard	Glass wool	19	23	37	50	48	722	68	720	29
F91770	Hydrocarbon	Glass wool	11.5	15	25	30	21	737	27	843	16

Notes:

1 The Resistance to the Incipient Spread of Fire (RISF) estimated based on time of thermocouples fitted to plasterboard in cavities between studs exceeding 250°C.

2 Estimated t_{ch} commencement of charring based on time interface between stud and plasterboard exceeds 300°C.

3 All specimens were faced on each side with one layer of 13 mm thick fire-protective grade plasterboard.

C4 Series C fire-resistance tests on timber stud partitions protected by one layer of 16 mm fire-protective grade plasterboard to provide data for validation of fire models.

These tests were undertaken by BHP Melbourne Research Laboratories (a NATA accredited laboratory) in the mid to late 1990s for Victoria University of Technology to provide data for validation of fire models for protected timber-frame construction which were being developed as part of a multi-scenario Quantitative Risk Assessment (QRA) model. The results were reported within the PhD theses of Young[61] and Clancy[147]. The additional instrumentation applied enabled estimates to be made of the Resistance to the Incipient Spread of Fire performance and charring rate likely to be achieved. All specimens comprised 90 x 45 mm Radiata Pine timber studs with one layer of 16 mm thick fire-protective grade plasterboard applied to each face. Structural restraint conditions were varied through the test program.

Structural adequacy tended to limit the performance of the walls with unloaded specimens achieving integrity and insulation levels of in excess of 80 min. For loadbearing specimens, structural failures occurred between 28 and 58 min as a result of high loading levels and varying restraint conditions.

Proprietary timber stud systems protected by single layers of 16 mm thick fire-protective grade plasterboards capable of achieving FRLs of 60/60/60 are readily available. Evidence of Suitability should be obtained from the supplier prior to use to ensure the systems are used within their field of application.

Although the instrumentation and tested configurations varied from current requirements of the NCC for Fire-protected Timber, indicative estimates for the following have been made:

- Resistance to the Incipient Spread of Fire (RISF) ≈ 28 min
- t_{ch} ≈ 32 min based on stud interface temperatures.

C5 Series D Comparative tests on intermediate scale plasterboard faced elements with lightweight steel framing exposed to Hydrocarbon and Standard AS 1530.4 heating regimes

This test series was undertaken by WarringtonFire in 1998-9 to compare the performance of plasterboard faced elements with lightweight steel framing exposed to different heating regimes and reported for FWPA in 2014.

The series included:

- two intermediate scale horizontal elements (1.2 m x1.2 m) faced on the fire-exposed face with 2 x 13 mm layers of fire-protective grade plasterboard. The cavity was open for one half of the specimen and enclosed by a layer of 13 mm thick plasterboard applied to the upper surface of the framing creating a 64 mm deep cavity over the remaining specimen. The two areas were separate by a central steel stud with an insulated packing to minimise heat transfer between the enclosed and unenclosed cavities.
- two intermediate scale vertical partitions (1.0 m x1.0 m) faced on each side with 2 x 13 mm layers of fire-protective grade plasterboard.

One specimen of each pair was subjected to the standard AS 1530.4 heating regime and the other to the hydrocarbon heating regime.

The data includes plasterboard face temperatures from which estimates of the RISF performance can be derived. As hybrid forms of construction using timber structural members and lightweight steel elements to support plasterboard protective coverings are common in Australia, comparative data under different heating regimes is relevant to Fire-protected Timber construction if the performance pathway is adopted to demonstrate compliance with the NCC.

The results are summarised in Table 78. Fall-off times may be earlier for full size specimens and RISF values are indicative estimates because tests were intermediate scale and interpretation of temperature data was required.

Table 78: Extract of data from tests F91780, F91782, R9112 and R9113[226-229].

Test	Heating Regime	Orienta-tion	Fire-protective coverings	Cavity Insul.	Board fall-off time (min)	Estimated RISF
F91780	Standard	Ceiling	2 x 13 mm fire-protective grade PB applied to fire-exposed face and 1 x 13 mm applied to non-fire side (half specimen)	None	Face layer 72	Cavity 57 Open 67
F91782	Hydrocarbon				Both layers 55	Cavity 37 Open 39
R9112	Standard	Wall	2 x 13 mm fire-protective grade PB applied to fire-exposed face and 2 x 13 mm applied to non-fire side	None	Face layer 123 Base layer 147	52
R9113	Hydrocarbon				Face layer <50 Base layer 91	33-38

C6 Series E charring of glued-laminated beams manufactured from Australian timber species with and without 13 mm plasterboard protection

These tests were undertaken in the US and reported by Gardner and Syme in 1991[55]. The series comprised 24 tests on intermediate scale non-loadbearing glued-laminated structural timber beam sections 270 x 150 mm with nine, 30 mm deep lamella glued with resorcinol adhesives.

Three specimens for most of the Australian timbers listed in Table 79 were tested.

Table 79: Densities and moisture content of Australian timber species used in the test series.

	Density kg/m³			Moisture content %		
	Range	Mean	SD	Range	Mean	SD
Blackbutt	827- 986	939	48	10.9 – 12.7	12.2	0.6
Blue Gum	780 – 1049	968	96	12.8 – 15.0	14.1	0.8
Brush Box	787 – 843	819	23	10.7-11.8	11.4	0.3
Cypress Pine	630 – 720	666	37	10.2 – 11.4	10.9	0.5
Jarrah	706 – 961	848	83	11.2 – 12.9	12	0.5
Radiata Pine	443 – 565	526	37	8.3 – 9.9	9.2	0.6
Spotted Gum	823 – 958	901	65	11.5 – 12.4	12	0.2
Victorian Ash	568 – 739	659	56	10.3 – 10.7	10.5	0.2

Two specimens of each group were unprotected with the tests being terminated after 1 or 2 hours and the third specimen was protected by a single layer of 13 mm-thick fire-protective grade plasterboard.

The plasterboard was fixed in position with nails around the perimeter of the boards at 81 mm to 100 mm centres with a butt joint in the side of one face of the beam. Steel corner mouldings were applied to the corners and set in Gyprock cornice cement applied to the edges as well as the butt joint. The boards remained in place throughout the 2-hour test but since the scale was intermediate and specimens unloaded, additional evidence of the ability of the plasterboard to remain in place at full-scale under load should be obtained before applying the results.

Typical interface temperatures between the timber and plasterboard are plotted in Figure 99. Assuming a temperature of 300°C represents the onset of charring, charring typically commenced between 27 min and 30 min of the test (288°C was adopted for the onset of charring in the study).

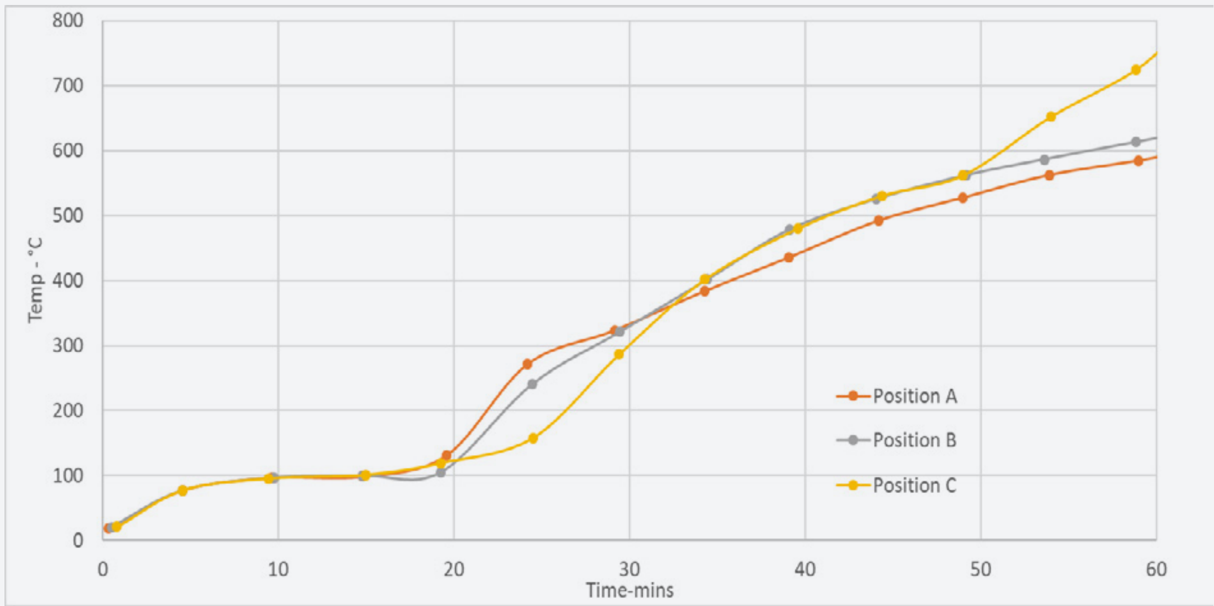


Figure 99: Typical interface temperatures with plasterboard and timber element derived from Gardner and Syme[55] (Positions A and B indicate interface temperatures measured on the side of the specimens and Position C the base).

Char rates were also determined, and correlations provided for the various timbers tested and generalised correlations based on timber density were also provided. Figure 100 plots the correlations for Radiata Pine LVL beams.

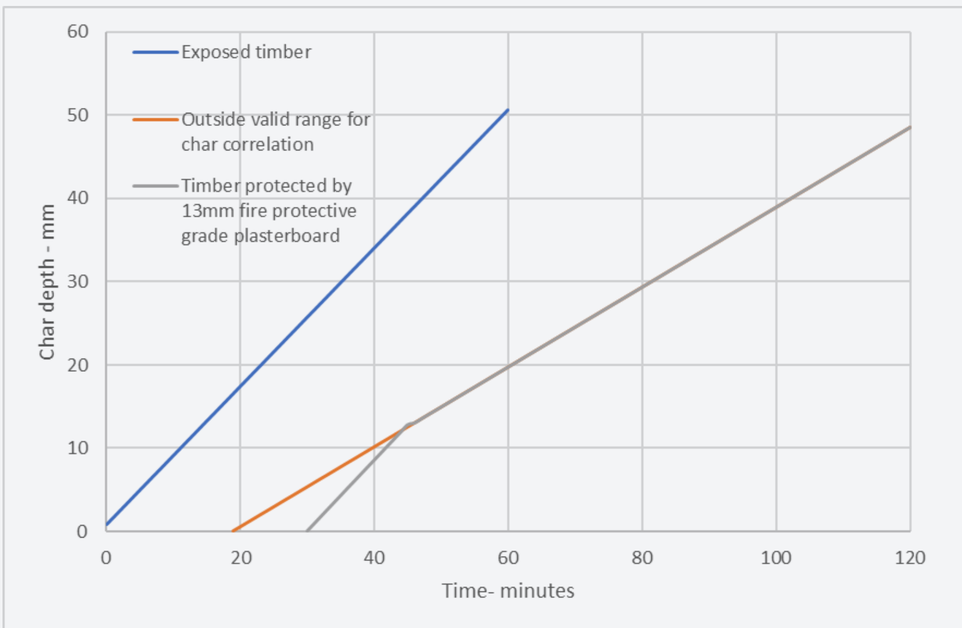


Figure 100: Char rates for Radiata Pine LVL beams exposed to the fire exposure and protected by 13 mm fire-protective grade plasterboard.

Note: The correlation for the protected beam is not applicable prior to commencement of charring and for a period after charring commences because of the pre-heating of the timber. The invalid range is highlighted in orange and the grey plot modified to show no charring prior to approximately 30 min and the char rate for fully exposed timber is assumed until the plot intersects with the plot of the protected timber correlation.

C7 Series F FWPA Standard Fire Tests for high FRLs and engineered timber framing systems

Gap analyses were undertaken to check the coverage provided by proprietary gypsum board-based fire-protective coverings to lightweight timber-frame construction when mid-rise timber framed construction Deemed-to-Satisfy solutions were planned for introduction into the NCC 2016 and 2019 editions. Data was limited with respect to Evidence of Suitability for lightweight engineered timber floors required to achieve 90/90/90 and for FRLs greater than 90/90/90 generally for lightweight timber-frame construction. A series of three standard tests (AS 1530.4) were undertaken to, among other things, determine practical limits for the use of fire-protective grade plasterboard systems for timber framed elements required to achieve FRLs greater than 90/90/90. Supplementary instrumentation and additional procedures were adopted to maximise the field of application for the data and provide supplementary information for fire engineering purposes. A full-scale test using the hydrocarbon heating regime was also undertaken to investigate the sensitivity of plasterboard ceilings to fires of greater severity than the AS 1530.4 standard heating regime to support Performance Solutions.

Methods of construction were typical of Australian industry practices except for the fitting of the insulation within the wall where lamella of mineral fibre were used to facilitate installation with a consistent level of compression. For systems with three layers of plasterboard the outer layer was fixed to the base and intermediate layers with laminating screws allowing increased edge distances and increased fixing centres to be adopted.

Table 80: Summary of Series F test results.

Test ref	Heating Regime	Orienta-tion	Fire-protective coverings	Cavity Insul.	Board observation/ fall-off time (min)	RISF (min)	FRL (min)
EWFA 36474400.2 [201]	Standard	Ceiling	2 x 16 mm fire-protective grade PB applied to steel furring channels spaced at 600mm centres	None	86: large area of face layer fell	67	90/90/90
TST 180021.2 [202]	Standard	Ceiling	3 x 16 mm fire-protective grade PB applied to steel furring channels spaced at 600mm centres	None	125[1]: PB sheet in face layer fell	120 NF	120/120/120
EWFA 49385100.3 [203]	Standard	Wall	3 x 16 mm fire-protective grade PB applied to timber studs	Lam. mineral fibre	Face layer ≈ 110 Int. layer 150-165 Base layer 172-186	136	180/180/180
FRT 200150 R1.1[159]	Hydro carbon	Ceiling	2 x 16 mm fire-protective grade PB applied to steel furring channels spaced at 600 mm centres	None	Face layer 33-46 Base layer 53.5	44	Structural Adequacy No failure @ 57/ Integrity 57/ Insulation 57

Note:

1 PB fell away 5 min after the end of the heating period after thermal shock as specimen lifted from furnace for monitoring.

C7.1 Test F1 Lightweight engineered timber floor protected by two layers of 16 mm fire-protective grade plasterboard secured to steel furring channels (FRL 90/90/90) RISF 60

A fire-resistance test was undertaken in accordance with AS 1530.4:2014 to determine the fire resistance of the following types of lightweight engineered beams incorporated in a floor assembly protected by a fire-protective grade plasterboard ceiling system:

- I-section with OSB web
- Parallel chord steel web truss
- Parallel chord timber web truss
- I-section with steel web.

The ceiling system comprised two layers of fire-protective grade plasterboard (each 16mm thick) fixed to furring channels which were supported from the beams by direct fixing brackets using normal industry installation methods. The furring channels were spaced at 600 mm centres. The flooring was 15 mm thick tongue and groove plywood sheeting.

The test also included the following short, unloaded elements and components to provide supplementary data.

- a sample of CLT
- a solid timber beam section
- a parallel sided flanged steel channel
- a through steel 6mm threaded bar simulating a hanger or similar fixing that could be used to support non-fire rated ceilings and services such as sprinkler pipes below fire resistant ceilings
- a range of acoustic fixing brackets and ceiling supports to facilitate the assessment of alternate support systems for the furring channels.

The floor system during construction and viewed from the underside before fire testing is shown in Figure 101.

Figure 101: Timber floor test with lightweight engineered beam systems during construction and viewed from the underside before fire testing.

The test was terminated after 90 min with the floor/ceiling system achieving the following performance:

- FRL 90/90/90 (test terminated – no failure)
- RISF 67 min.

Images of the fire-exposed face after test are shown in Figure 102 and Figure 103, which show limited flaming of volatiles from joints in plasterboard reducing as the specimen cools. Figure 104 shows the application of water 6 min after the end of the test.

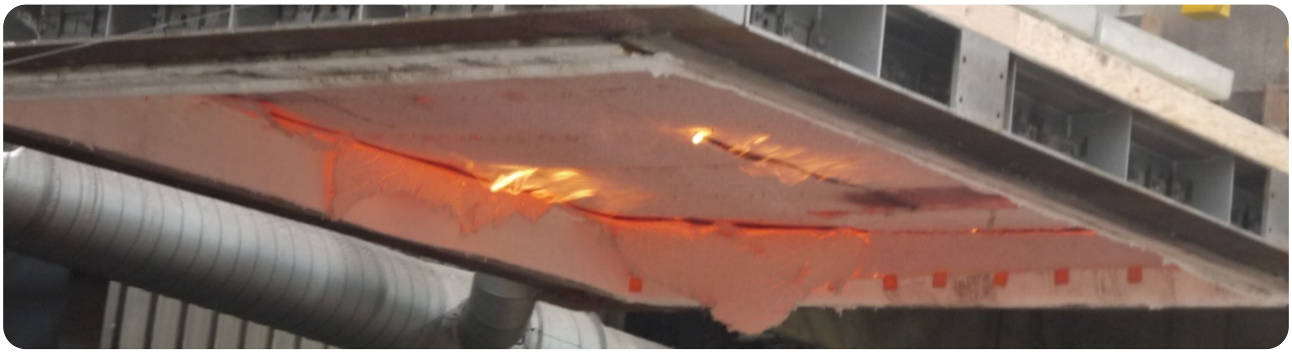


Figure 102: Specimen in process of removal from furnace 4 min after end of test (load still applied).

Figure 103: Exposed face showing loss of the face layer of plasterboard and opening of joints in remaining layer.

Figure 104: Application of water to specimen 6 min after test – specimen still under load.

C7.2 Test F2 Lightweight engineered timber floor protected by three layers of 16 mm fire-protective grade plasterboard secured to steel furring channels (FRL 120/120/120) RISF 120.

A fire-resistance test was undertaken in accordance with AS 1530.4:2014 to determine the fire resistance of the following types of lightweight engineered beam systems incorporated in a floor assembly protected by a fire-protective grade plasterboard ceiling system:

- I-section with OSB web
- Parallel chord steel web truss
- Parallel chord timber web truss
- I-section with steel web.

The ceiling system comprised three layers of fire-protective grade plasterboard (each 16 mm thick). The first two layers were fixed to furring channels which were supported from the beams by direct fixing brackets using normal industry installation methods as for test F1. The third layer was laminated to layers 1 and 2 with 50 mm long laminating screws at 200 mm centres along the edges, 35 mm from the board edge and 300 mm max centres in the board field. Butt joints between the ends of boards were within 50mm of the centre line between framing and fixed with laminating screws at 35 mm from sheet edges, 35 mm from sheet ends and at 200 mm max centres.

Paper tape was applied to joints in Layer 3 and the screw heads and joints sealed following manufacturer's instructions. The joints and screw heads in Layers 1 and 2 were not sealed representing current industry practices for not sealing covered layers.

The test also included the following short, unloaded elements and other components to provide supplementary data.

- a sample of CLT
- a solid timber beam section
- a parallel sided flanged steel channel
- a through steel 6mm threaded bar simulating a hanger or similar fixing that could be used to support non-fire rated ceilings and services such as sprinkler pipes below fire resistant ceilings
- a range of electrical and plumbing services that penetrate the timber flooring at one end of the specimen – run through the ceiling cavity before penetrating the flooring at the opposite end of the specimen.

The floor system from the underside before fire testing and during construction is shown in Figure 105 and Figure 106.

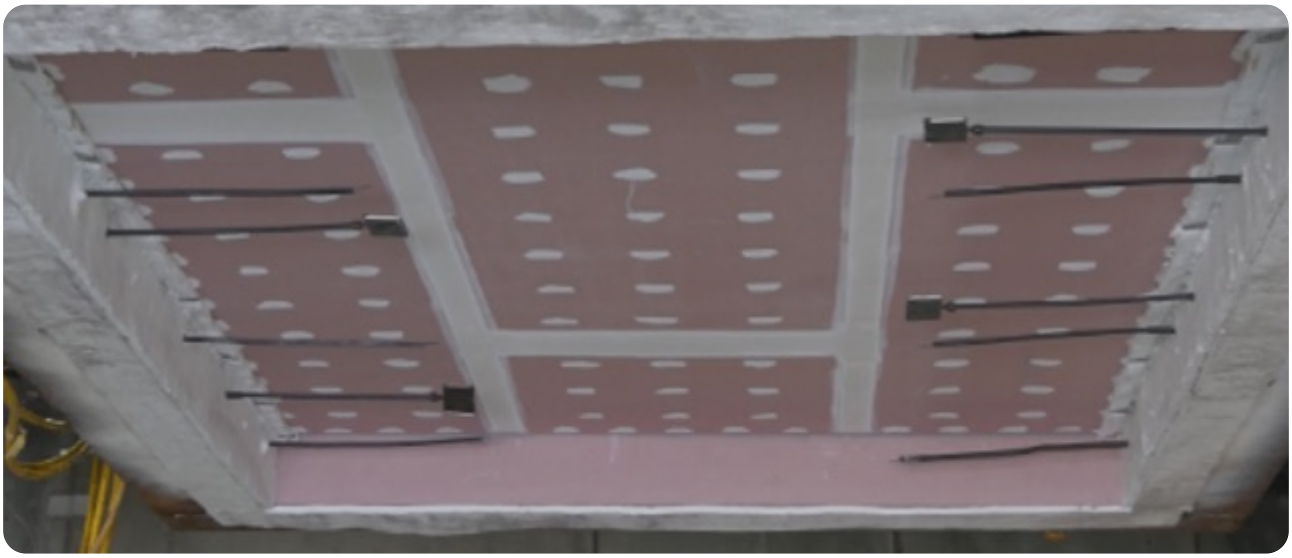


Figure 105: FRL 120/120/120 Timber floor test viewed from the underside before fire testing.

Figure 106: FRL 120/120/120 Timber floor test with lightweight engineered beam systems during construction.

The test was terminated after 120 min with the floor/ceiling system prior to failure under any of the AS 1530. 4 criteria and therefore achieved the following performance:

- FRL 120/120/120 (test terminated – no failure)
- RISF 120 min (test terminated – no failure).

At the end of the heating period the specimen was raised 600 mm above the furnace (see Figure 107) allowing free access to the laboratory atmosphere while being exposed to heat from the furnace floor and walls to simulate the decay and cooling phases under natural convection for a further period of 17 hours without intervention. The temperatures measured below the ceiling during the fire test exposure and for the first two hours of the cooling phase are shown in Figure 108. The specimen continued cooling to ambient temperatures over the remaining 15 hours of the monitoring period.

Figure 107: Specimen located 600 mm above furnace 122 min after the start of the fire test showing all layers of plasterboard in position but edges of boards sagging between fixings.

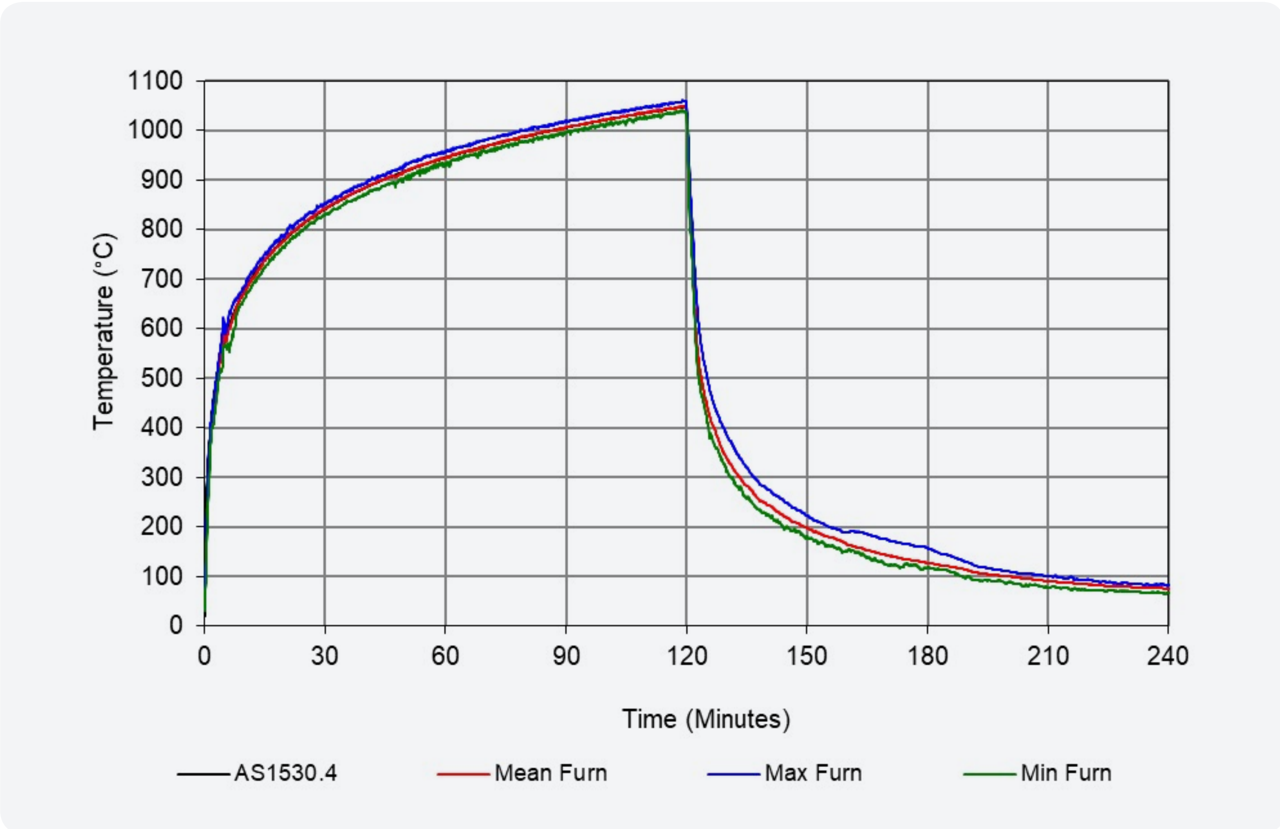


Figure 108: Complete heating and first two hours of cooling exposure measured by exposed thermocouples.

The full test load was supported by the specimen throughout the 1020 min (17 hour) monitoring period following the AS 1530.4 test. The specimen during this period is shown in Figure 109 and Figure 110. There was no evidence of combustion of the timber elements during the test and throughout the monitoring period. Figure 111 shows the ceiling cavity with flooring removed after the end of the cooling period confirming that the beams and paper facing to the plasterboard were still intact except for minor charring at the joint positions and around screws.

Figure 109: Most of Layer 3 of PB fallen from ceiling 2 hours after start of monitoring period.

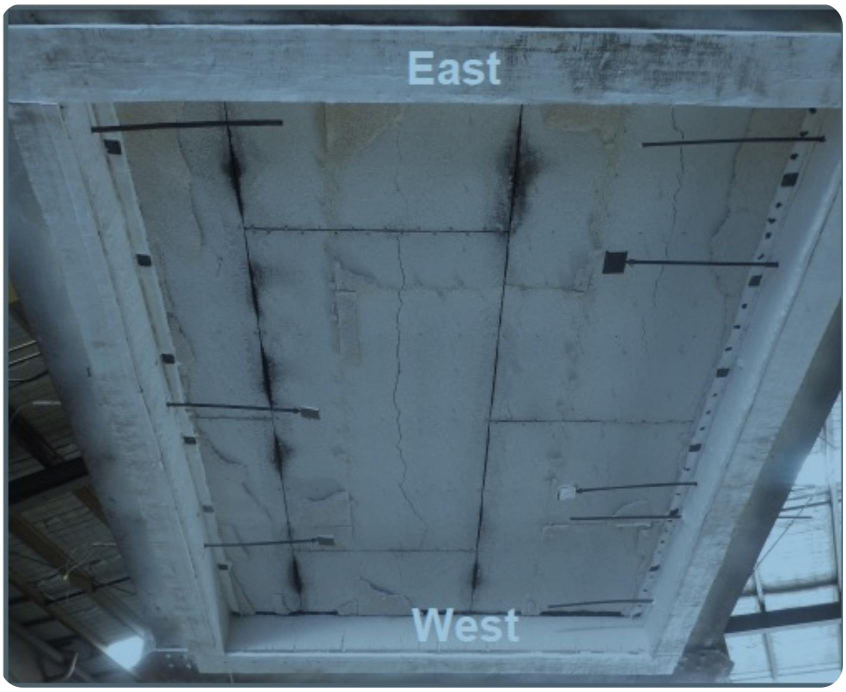


Figure 110: Layer 2 of PB still in place after monitoring period.

Figure 111: Upper surface of floor cavity with flooring removed showing no visible damage to the floor.

Throughout the decay/cooling phase temperature data was recorded. The temperatures on the upper surface of the plasterboard sheeting peeked after approximately 150 min as shown in Figure 112 but the temperatures did not exceed 250°C.

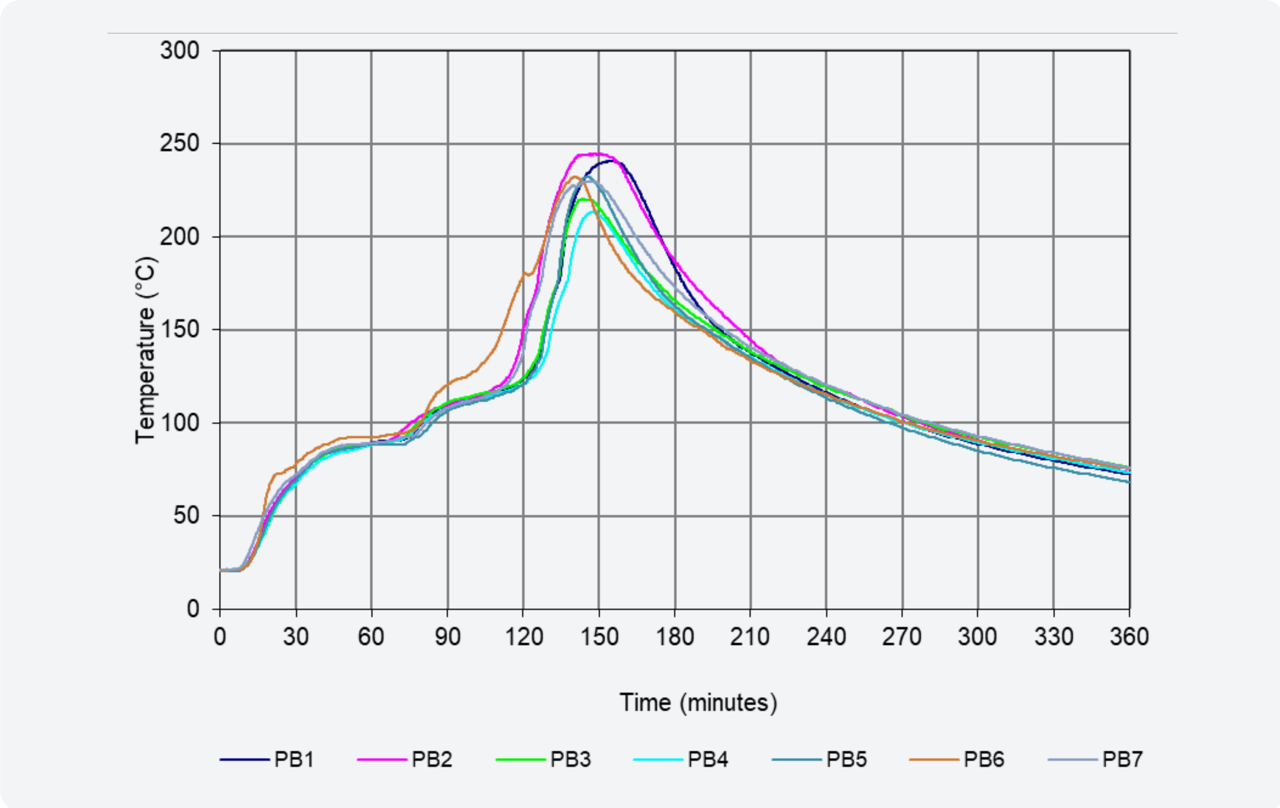


Figure 112: Temperatures of upper surface of the plasterboard (PB1-PB5 used to determine RISF).

A supplementary innovative feature of the test was the use of the floor cavity to run services from above such that the services only penetrate the flooring and potentially a shaft. This avoids the need to penetrate the fire-protective grade plasterboards but the risk of cavity fires involving services will need to be considered as part of the fire safety strategy. A detailed inspection was undertaken as the specimen was dismantled. Some softening of plastic services and discoloration as shown in Figure 113 and Figure 114 was noted but no evidence of combustion was observed.

Figure 113: View within cavity showing service penetrations between beams.

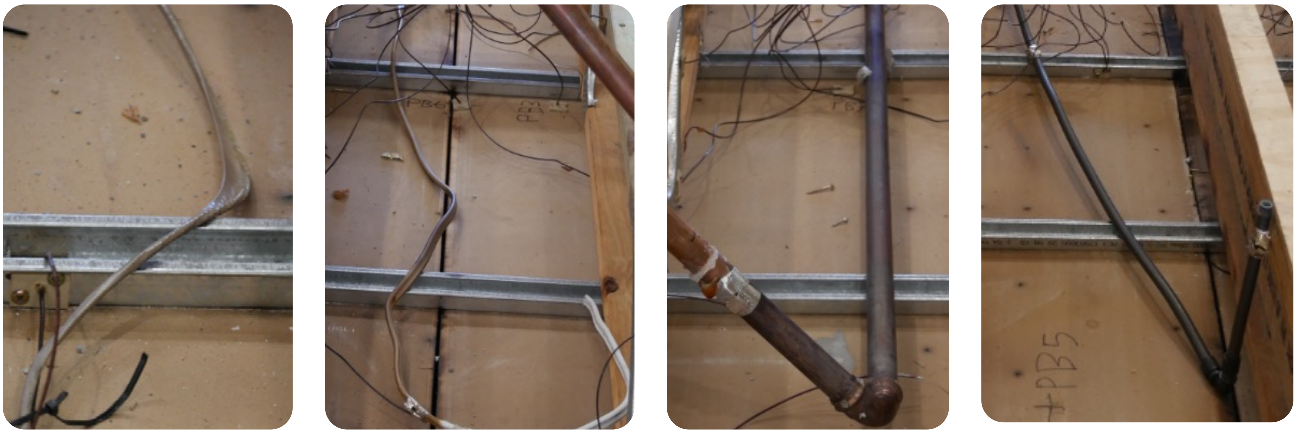


Figure 114: Services after test showing softening of communication cables and discolouration of other services.

C7.3 Test F3 high performance timber frame wall system

At the time of undertaking this test, there was some uncertainty in relation to the practical limits for the fire resistance performance of lightweight timber-frame construction protected by fire-protective grade plasterboard.

A loadbearing timber-frame wall system was designed utilising three layers of fire-protective grade plasterboard 16 mm thick applied to each face of 140 mm x 45 mm studs with cavities filled with non-combustible stone wool.

Key features of the design were:

- The installation of the stone wool insulation in lamella form to provide a practical means of reliably installing the insulation in intimate contact with the timber studs with a controlled level of compression. The high temperature specification and compression was intended to maintain 1-directional heating of the timber studs by avoiding heat transfer through the cavity.
- The installation of the outer layer of board with fixings approximately 38 mm from board edges and at enhanced centres to extend the time before the outer layer falls away.

Figure 115: Internal structure and non-fire side of high-performance timber-frame wall system.

The target FRL of 180/180/180 and Resistance to the Incipient Spread of Fire rating of 120 min was achieved with significant margins of safety. The full test load was applied until 198 min and then progressively reduced until heating was terminated after 227 min due to the risk of damage to the loading equipment with no failures under the criteria for insulation and integrity. The Resistance to the Incipient Spread of Fire criteria was exceeded after 135 min.

The specimen was then removed from the furnace after 227 min exposure and monitored for a further 30 min before water was applied to the wall system to suppress any residual combustion.

The field of application for the wall system was assessed by the Accredited Testing Laboratory with Evidence of Suitability being provided by the following reports for various applications.

- WF 55945800.2A.[218] The fire resistance performance of timber-framed walls lined with three layers of 16 mm fire-protective grade plasterboard if tested in accordance with AS 1530.4-2014 for 120 min.
- WF 55945800.1B[219] The fire resistance performance of timber-framed walls lined with three layers of 16 mm fire-protective grade plasterboard if tested in accordance with AS 1530.4-2014 for 180 min.
- WF 55945800.1C[220] The fire resistance performance of timber-framed walls lined with three layers of 16 mm fire-protective grade plasterboard if tested in accordance with AS 1530.4-2014 for 240 min.

Substantial supplementary data was recorded, and a brief overview follows.

Measurements included interface temperatures of each plasterboard layer using thermocouples soldered to copper discs at the centre and centre of each quarter section of the wall. Thermocouples were also fitted at approximately these locations on the inner surface of the base plasterboard layer on the fire-exposed side of the specimen to determine the RISF performance.

The RISF results are plotted in Figure 116 and the temperature of the RISF thermocouples after 120 min of the test was approximately 130°C before exceeding the 250°C limit after 136 min.

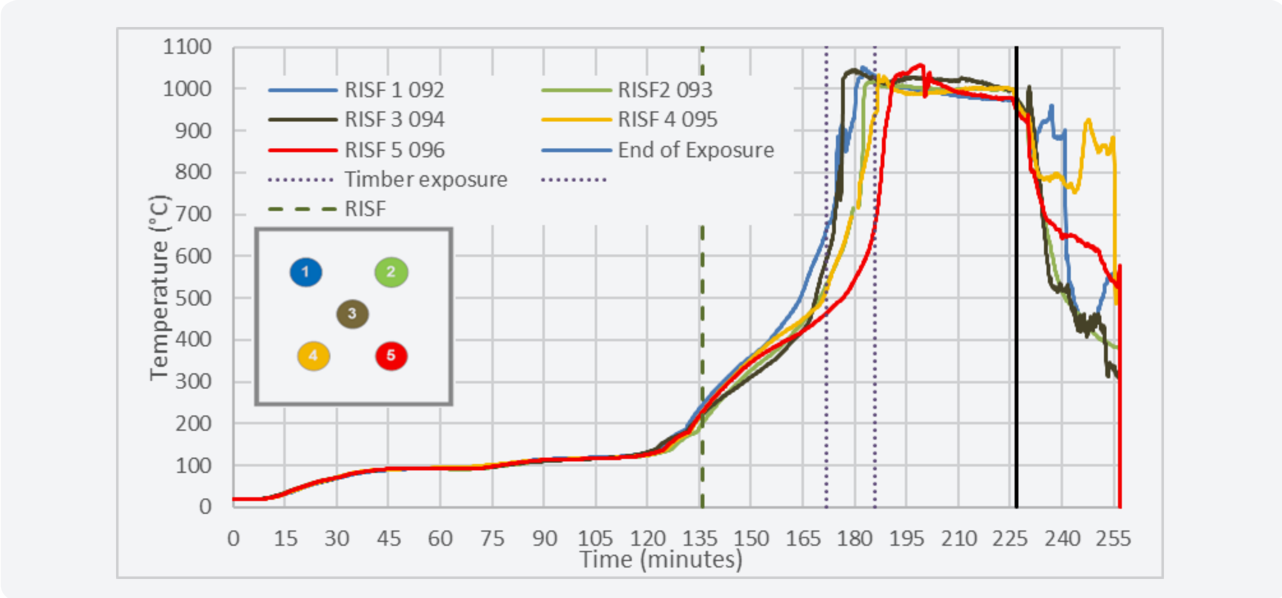


Figure 116: Resistance to the Incipient Spread of Fire temperature data and estimated time of direct exposure of the timber frame to furnace heating.

The results for the other interface temperatures are plotted in Figure 117 with a key identifying the group locations and dotted lines for the interface between the outer layer and middle layer, dashed lines for the interface between the middle and inner layer and solid lines for the interface of the plasterboard and stone wool infill. It was difficult to visually observe the general behaviour of the fire-exposed face, but reasonable estimates can be obtained from the temperature and furnace gas flow data.

The temperature data indicated that a plasterboard layer would tend to fall away after the interface temperature at the unexposed face of the board exceeded 600°C. It is difficult to provide a more precise estimate since the fall-off time depends on crack formation within the board and may be best described as a transition over several minutes rather than a single event as reflected by the variability of the data shown in Figure 117 but the following estimates are considered reasonable.

- Face layer ≈ 110 min
- Int. layer 150-165 min
- Base layer 172-186 min.

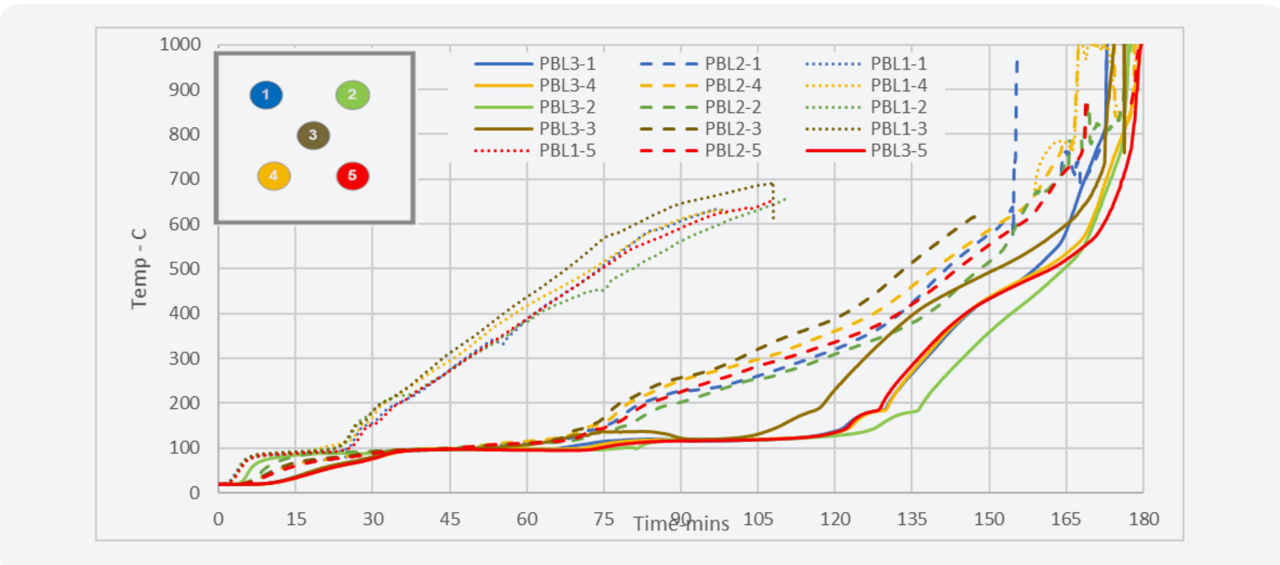


Figure 117: Plasterboard interface temperatures.

Note: Temperature data deleted after thermocouples developed faults to improve clarity.

Assuming charring occurs at the 300°C isotherm, the char rate can be estimated from temperature data obtained from three noggings which are plotted against time in Figure 118 and char rates calculated in Table 81. Char rates can be expressed as an instantaneous rate or rate averaged from commencement of charring which is the method nominated in Appendix A of AS/NZS 1720.4:2019[19]. Results obtained from both methods are included in Table 81 to demonstrate the variability as the timber studs are exposed and provide data consistent with the method nominated in AS/NZS 1720.4.

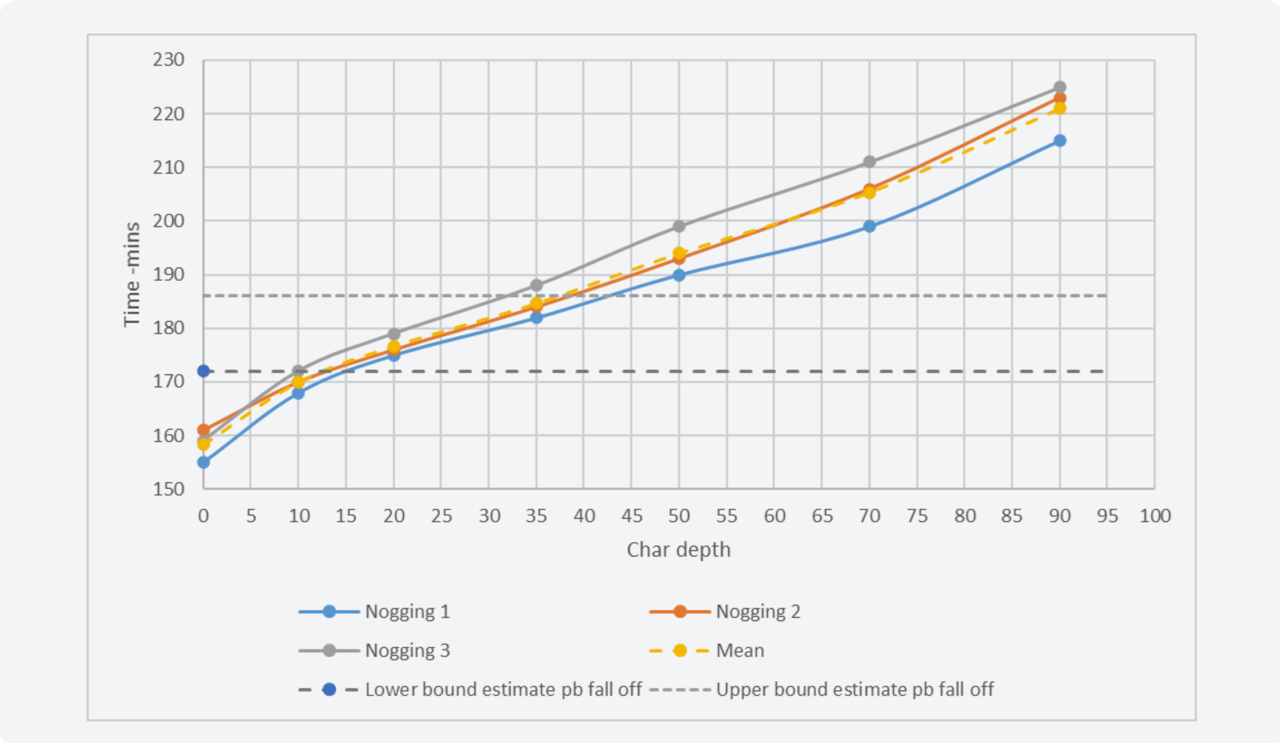


Figure 118: Char depth v time along centre line of noggings.

Table 81: Calculation of char rates.

Depth	Time/temperature exceeded 300°C (min)				Char rate (mm/min)	
	Nogging 1	Nogging 2	Nogging 3	Mean	Rate over time interval	Rate from char commencement
0	155	161	159	158	0	0
10	168	170	172	170	0.83	0.83
20	175	176	179	177	1.43	1.05
35	182	184	188	185	1.88	1.30
50	190	193	199	194	1.67	1.39
70	199	206	211	205	1.82	1.49
90	215	223	225	221	1.25	1.43

The average char rate from commencement of charring to a char depth of 90 mm was 1.43 mm/min. While the inner fire protective layer of plasterboard was substantially in place, the char rate was 0.86 mm/min.

The above char rates are substantially higher than those recommended in Eurocode 5 EN 1995-1-2:2004 and AS 1720.4:2006[21]. For example, the notional char rate in accordance with AS 1720.4 assuming a nominal density of 550 kg/m^3 would be 0.66 mm/min which for protected systems is increased by a factor of 1.1 yielding an increased char rate of approximately 0.73 mm/min.

The higher char rates obtained during the test may be explained by the longer pre-heating period and higher heat fluxes due to the longer fire-resistance test period and highlight the need for an upper bound fire-resistance time to be specified for the notional char rates currently specified in design codes or additional char rates specified for long durations and different heating regimes.

Figure 119 shows the non-fire side 229 min after commencement of the test with no visible degradation and Figure 120 shows the fire-exposed face during a 30 min monitoring period after the fire test and prior to application of water to suppress the residual burning.

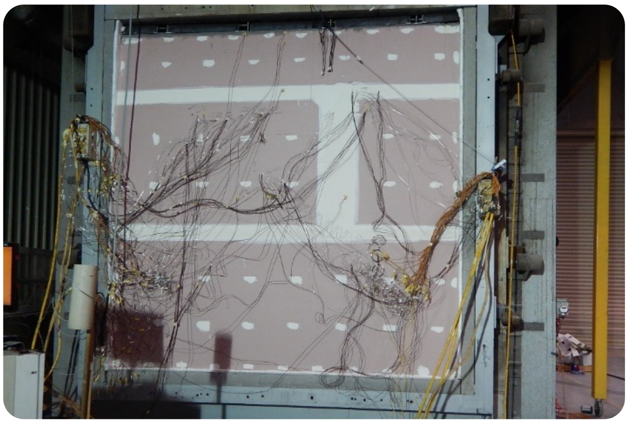


Figure 119: Non-fire side of specimen 229 min after commencement of test showing no visible degradation (heating terminated at 227 min).

Approximately 4 min after end of heating period.

Approximately 11 min after the end of the heating period.

Approximately 26 min after end of heating period.

Figure 120: View of exposed face of specimen after exposure to AS 1530.4 heating regime for 3h 47 min.

It can be observed that the flaming is localised, confirmed by the heat flux measurements taken 500 mm from the specimen from 8 minutes after termination of heating and removal of the specimen from the furnace, which indicate heat fluxes between 8 and 10 kW/m^2 except for isolated peaks less than 13 kW/m^2 (Refer Figure 121).

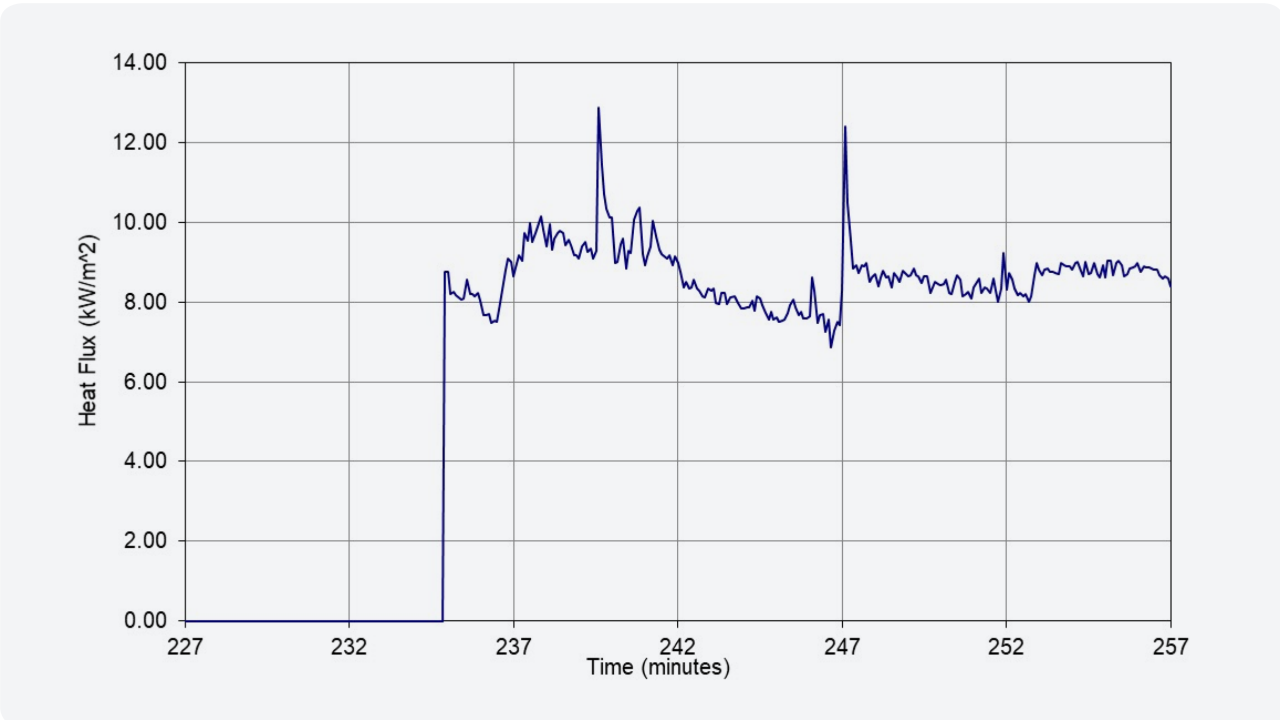


Figure 121: Heat flux measured 500 mm from the face of the specimen that was exposed to heating.

The glowing char at the stud and nogging locations indicate char oxidation. Ongoing combustion continued throughout the monitoring period and temperatures measured within the residual char were within the range of 500 to 600°C at the end of the 30 min monitoring period as shown in Figure 122.

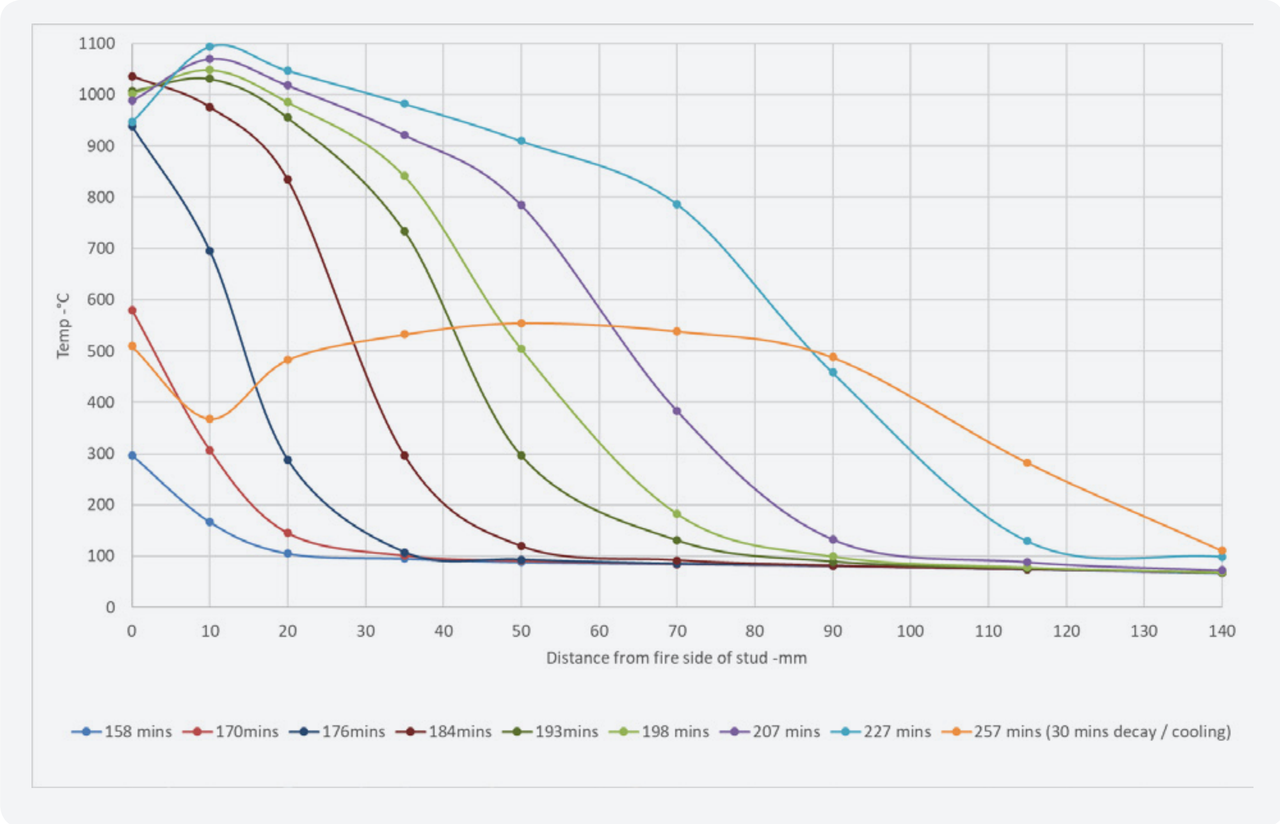


Figure 122: Mean cross-section temperatures at critical times.

From Figure 122 the char rate during the post-fire test monitoring period can be estimated assuming the char front corresponds to a temperature of approximately 300°C yielding a char rate of 13/30 =0.43 mm/min.

C7.4 Test F4 Lightweight engineered timber floor protected by two layers of 16 mm fire-protective grade plasterboard secured to steel furring channels when subjected to the hydrocarbon heating regime

To investigate the sensitivity of plasterboard ceilings to fires of greater severity than the AS 1530.4 standard heating regime, a full-scale test using the hydrocarbon heating regime was undertaken.

The specimen was similar to a floor system tested previously which is identified as test F1 in this Guide and summarised in the relevant preceding sub-section. The specimen was made up of the following lightweight engineered beams protected by a plasterboard ceiling system:

- I-section with OSB web
- Parallel chord steel web truss
- Parallel chord timber web truss
- I-section with steel web.

The ceiling system comprised two layers of fire-grade plasterboard (each 16 mm thick) fixed to furring channels which were supported from the beams by direct fixing brackets. The ceiling was constructed using normal industry installation methods.

Figure 123: Test assembly before fitting flooring.

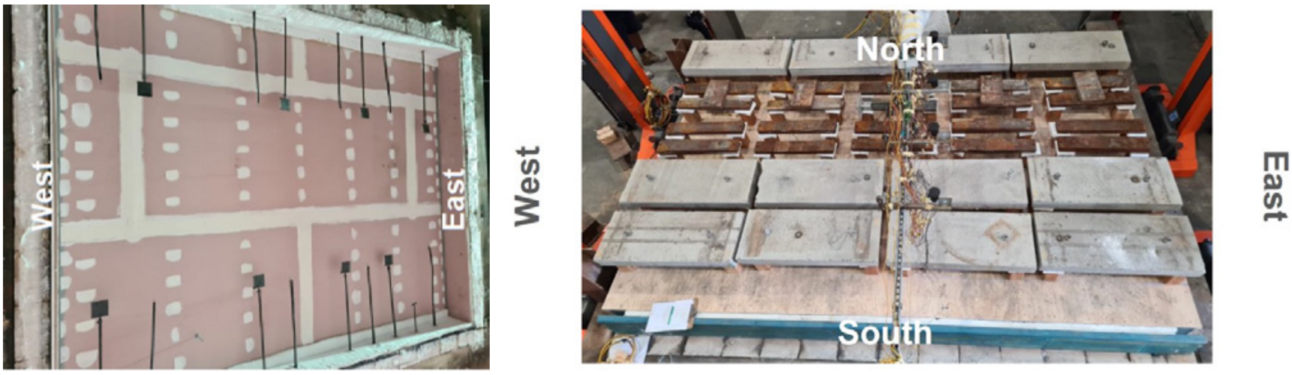


Figure 124: Test assembly prior to test.

The specimen achieved the following performance when exposed to the hydrocarbon heating regime for 57.5 min.

- Structural adequacy – no failure at 57 min
- Integrity – 57 min (flaming of flooring)
- Insulation – 57 min (failure deemed to occur at the time of integrity failure)
- RISF – 44 min.

Failure under the criteria of integrity occurred after 57 min due to localised burn-through of the floor system after which the test was terminated by the laboratory to manage the risk to equipment and staff. At that stage there was no failure under the criteria of structural adequacy.

The specimen continued to support the load until a total time of 66 min had elapsed from the start of the test, but the heating exposure after 57.5 min could not be recorded. At 66 min a localised failure of the flooring occurred close to the location of the integrity failure with a set of dead-weights falling through the floor/ceiling which is thought to have broken the bottom chords of two joists, but the remaining load was redistributed over the floor. The specimen was then lifted off the furnace and extinguished.

The RISF of the ceiling was 44 min. Only one of the five nominated thermocouples exceeded the 250°C limit prior to 45 min which was located close to the position of the subsequent failure of the flooring system.

The results are consistent with the following observations:

The face layer joint on grid D between grids Z1 and Z3, shown on Figure 125, began opening up at approximately 30 min with a section of board falling away to the east of grid D after approximately 33 min which led to a localised early increase in the upper surface temperature of the base plasterboard layer. The estimated extent of the loss of the face board at this stage is shaded light grey in Figure 125. The affected positions included the northeast quarter and central points (thermocouples PB-1 and PB-3) with the RISF criteria of 250°C being exceeded after 45 min and 44 min, respectively. This was approximately 5 min earlier than the other thermocouples used to determine the RISF performance which reached the limit after approximately 50 min of the test.

The rate of rise of the thermocouples fitted to the remainder of the ceiling began to accelerate after approximately 46 min of test when the majority of layer 2 (face layer) was observed to have fallen away.

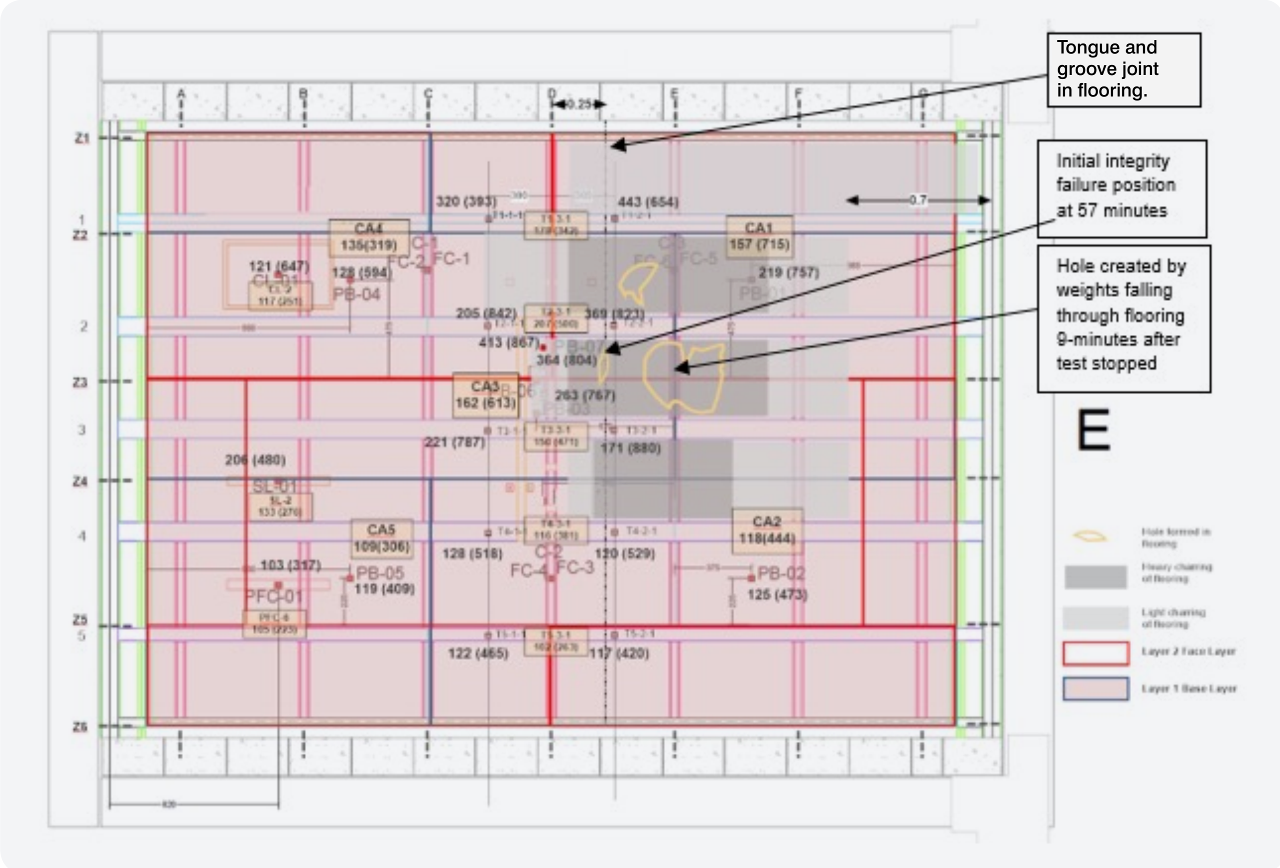


Figure 125: Location of critical events during the test.

A section of layer 1 (base layer) fell away locally opening up the ceiling cavity after approximately 53.5 min of the test between joists 2 and 3 to the east of the mid span position with cavity temperatures rapidly increasing to in excess of 800°C within the areas shaded in dark grey in Figure 125. The best estimate for the location of this localised failure of the plasterboard is the joint on grid line E which also coincides with the subsequent localised structural failure of the flooring.

Based on the observations, the performance of the ceiling was limited by the performance of the butt joints that occur over the furring channels due to the need for the screws to be located close to the plasterboard edges with very small tolerances. Better performance was obtained from the laminated joints in the face layer where the joint is located mid-way between the furring channels and laminating screws are used to secure the face layer to the base layer.

Where the laminated joint detail was located at each end of a 3 m long plasterboard sheet in the face layer, the RISF performance was improved considerably from 44 min to more than 50 min.

A localised area of the face layer of plasterboard fell away from a butt joint in the plasterboard located over a furring channel after 33 min; whereas the majority of the face layer, including at the positions of the laminated joints, fell away after 46 min.

It is therefore considered likely that the fire resistance performance of the floor/ceiling system would have been increased by at least 4 min (more likely 6-8 min) if all butt joints in the face layer at the ends of the plasterboard sheets had been fixed with laminating screws to the base plasterboard layer instead of fixing through the base layer to furring channels which required screws to be fitted close to the edge of the plasterboard.

Under these circumstances the premature failure of the face layer would be unlikely to occur, and the following performance could have been expected to be achieved when the specimen is exposed to the AS 1530.4 Appendix B Hydrocarbon Heating Regime:

- Resistance to the Incipient Spread of Fire greater than 45 min
- FRL greater than 60/60/60.

A method of transposing standard fire resistance times to an equivalent time when an element is exposed to an alternate heating regime using an equivalent temperature of a lumped thermal mass was adopted when undertaking an analysis to support the Proposal-for-change to allow Fire-protected Timber construction in mid-rise buildings in the NCC 2016. Further details can be found in the WoodSolutions Technical Design Guide 38 and Appendix G. The target thermal mass used was a steel element protected with 25 mm thick ceramic fibre which is shown as the thick solid brown line in Figure 126 together with the data points that were available at the time.

Based on the preceding analysis, there was also a premature loss of a localised part of the face layer of plasterboard which was identified to have initiated at a butt joint detail; which is very sensitive to installation methods and performance of the plasterboard sheets. It was estimated that if the premature failure had not occurred, the time to failure of the floor system could have been extended to approximately 66 min and the Resistance to the Incipient Spread of Fire performance would have been increased from 44 min to approximately 50 min. These ranges have been plotted as solid black vertical lines on Figure 126 and bracket the transposition plot.

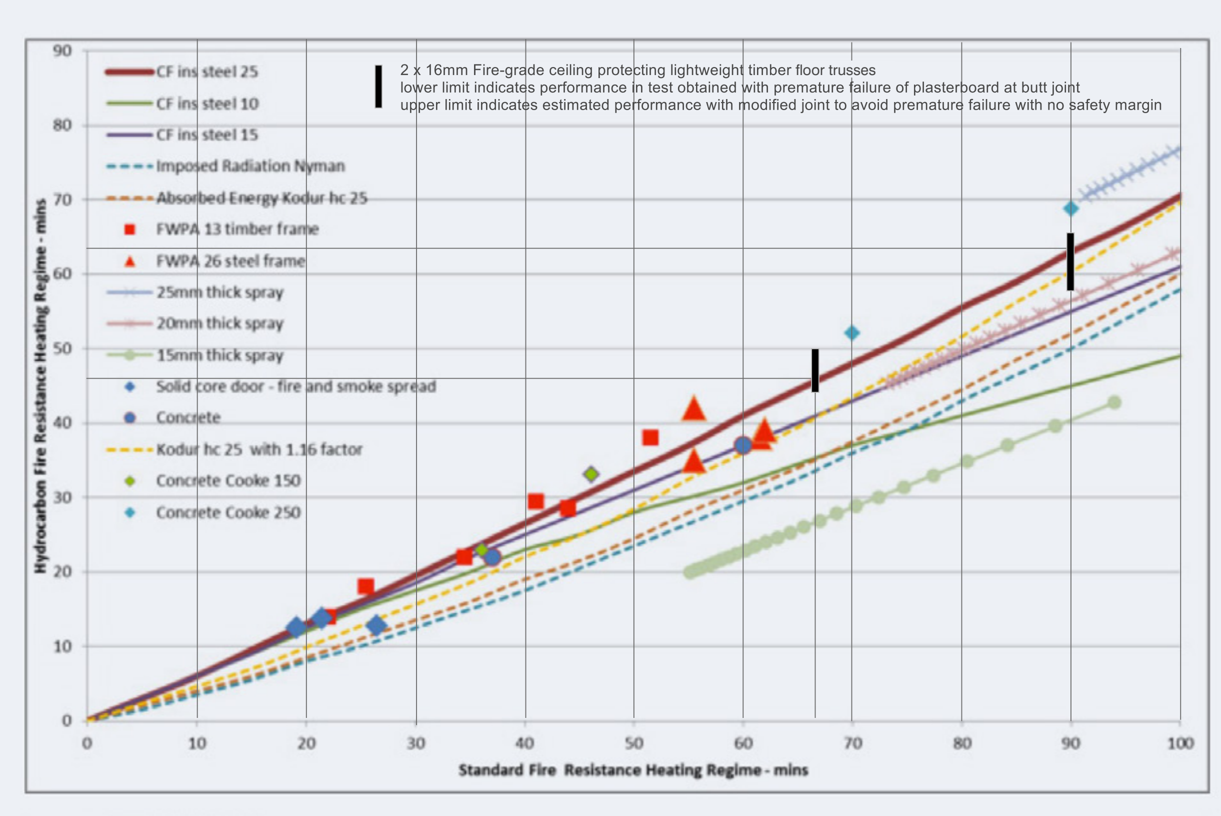


Figure 126: Calibration of transposition method for FRLs using data from hydrocarbon and standard heating regimes specified in AS 1530.4.

C8 Series G Comparative tests on intermediate scale plasterboard faced timber stud partitions exposed to hydrocarbon and standard heating regimes

This series was undertaken for the FWPA and was an extension of the work undertaken in Series B and D examining the impact of different heating regimes but with additional instrumentation provided and procedures to examine the behaviour of the partitions after the end of the heating period.

The specimens comprised intermediate scale (1.2 m x 1.2 m) timber frame/plasterboard partitions with 90 mm x 45 mm Radiata Pine framing and two layers of 13 mm thick fire-protective grade plasterboard applied to each side of the framing. Half the specimen was provided with non-combustible glass fibre (GF) cavity insulation and the other half was not provided with cavity insulation. Timber stud temperatures were measured to provide comparative data to compare the performance when exposed to different heating regimes. Additional instrumentation was provided to record the temperature distribution across the studs and determine the RISF performance. An extract of this data is provided in Table 82 and Table 83.

Table 82: Time to 300°C at various depths from fire side of central timber studs from tests 55676500 and 55676600 at ¾ height position.

a) Comparison of char rates for 7.5 mm char depth.

Test	Heating Regime	Time to 300°C at depth of 7.5mm			Time (min) timber stud interface exceeds 300°C			Estimated char rate mm /min		
		GF edge	centre	cavity edge	GF edge	centre	cavity edge	GF edge	centre	cavity edge
55676500	Standard	72.5	77	80.5	60	64.5	65	0.6	0.6	0.49
55676600	Hydrocarbon	50.5	54	54.5	39.5	44	43	0.68	0.75	0.65

b) Char depth and char rate estimates at end of 90 min test with standard exposure

Test	Heating Regime	Temp (°C) at depth of 7.5mm after 90 min			Temp (°C) at depth of 15mm after 90 min			Estimated char depth and rate after 90 min		
		GF edge	centre	cavity edge	GF edge	centre	cavity edge	GF edge	centre	cavity edge
55676500	Standard	433	354	335	339	277	277	19.0	13.0	12.5
				Estimated char rate mm/min				0.63	0.51	0.50

c) Time to char depths of 15 mm and 25 mm and char rate to depth of 15mm with exposure to the hydrocarbon regime

Test	Heating Regime	Time to 300°C at depth of 15 mm			Time to 300°C at depth of 25 mm			Estimated char rate for 15 mm char depth		
		GF edge	centre	cavity edge	GF edge	centre	cavity edge	GF edge	centre	cavity edge
55676600	Hydrocarbon	60	64	65	73	79[1]	81[2]	0.73	0.75	0.68

Notes:

1 Heating terminated at 75 min with temperature at 255°C.

2 Heating terminated at 75 min with temperature at 238°C.

d) Char depth and char rate estimates after 60 min of hydrocarbon test exposure

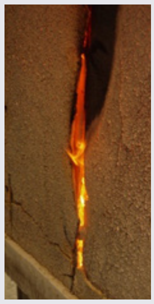
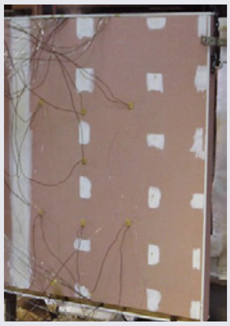
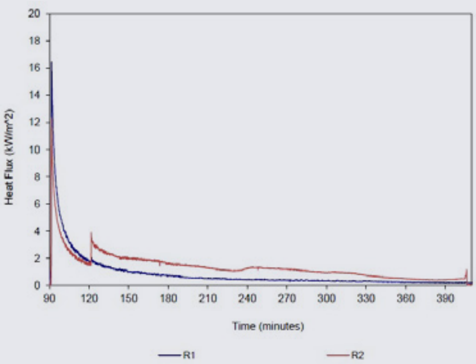
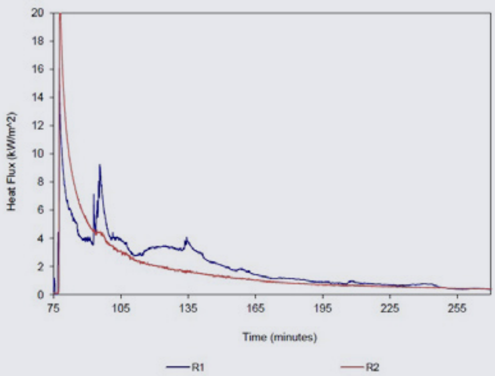
Test	Heating Regime	Temp (°C) at depth of 7.5 mm after 60 min			Temp (°C) at depth of 15 mm after 60 min			Estimated char depth and rate after 60 min		
		GF edge	centre	cavity edge	GF edge	centre	cavity edge	GF edge	centre	cavity edge
55676600	Hydrocarbon	459	379	362	300	255	247	15.0	12.0	11.5
				Estimated char rate mm/min				0.73	0.75	0.68

Table 83: RISF results for standard and hydrocarbon heating regimes for intermediate scale partitions protected by two layers of fire-protective grade plasterboard,13mm thick.

Test	Heating Regime	RISF (min) Non-combustible GF Insulation	RISF (min) No Insulation
55676500	Standard	48	54
55676600	Hydrocarbon	30	33

A review of the above results indicates that the extent of charring in the standard heating regime test after 90 min was roughly comparable to the hydrocarbon heating regime after 60 min. After completion of the heating period, each specimen was removed from the furnace and exposed to a residual heat flux from the furnace walls in free air conditions to approximate to the decay stage of a fire when the element could be exposed to an atmosphere with a sufficient oxygen content to readily support combustion. Some observations from the test are shown in Table 84.

Table 84: Post-heating phase behaviour of timber framed partitions that exceeded the Resistance to the Incipient Spread of Fire criteria during the heating phase.

Test 55676500 Standard heating regime	**Test 55676500 Hydrocarbon Heating Regime**
Heating terminated after 90 min	***Heating terminated after 75 min***
 Fire-exposed face after removal from the furnace – 90 min	 Fire-exposed face after removal from the furnace – at 75 min
 122 min after start of test large area of board fallen away exposing central joint. Flames released from central joint approximately 300 mm above base. Heavy charring and glowing/flaming combustion of char visible through opened up joint.	 Flames released from central joint 82-86 min before stopping  Intermittent flame from central crack and flaming within cavity after part of plasterboard outer facing falls away at 91 min
 Fire-exposed face after monitoring period (410 min). No external flaming but glowing/flaming combustion visible within cavity through open joint	 Exposed side fire protective boards removed between 94-96 initiating flaming combustions
 Non-fire exposed face at end of 410 min monitoring period	 Exposed face after 240 min  Non-fire exposed face after 240 min
 Heat flux measurements R1 from furnace, R2 from specimen	 Heat flux measurements R2 from furnace, R1 from specimen

The results indicated that, once ignited, if there is an air supply with an adequate oxygen content to support combustion, glowing/flaming combustion of the timber framing is likely to continue until manual suppression is undertaken. However, the heat flux measurements indicate that the heat release rate during the decay period was relatively minor and comparable to that from the non-combustible furnace linings.

C9 Series H FWPA Intermediate-scale Massive Timber Test Program

Overview

This program was developed to:

- Investigate the use of Massive Timber at high Fire Resistance Levels (up to four hours) with varying protection levels and provide data for char rates for fire-resistance periods beyond 90 min.
- Demonstrate the behaviour of exposed and Fire-protected Timber under different fire exposures to provide additional confidence in its performance under more severe exposure conditions.
- Include instrumentation to provide additional data relating to fire exposure to support fire safety engineering analyses and provide data for the validation of models.
- Characterise the protection provided by fire-protective grade plasterboard to timber including:
  - the delay in the time to commencement of charring based on the 300°C isotherm
  - indicative fall-off times for plasterboard facings
  - char rates while the plasterboard protection is in place
  - char rates after fall-off of plasterboard.
- Generate useful data to optimise configurations prior to undertaking full-scale fire tests on proprietary systems to achieve the most cost effective and practical combination of fire-protective coverings for massive timber and to provide supporting data that can be used to assess minor changes from tested prototypes.
- Examine the influence of various jointing techniques on the performance of panels.
- Obtain data on the potential behaviour of the systems during simulated decay phases and cooling phases relating to self-extinguishment behaviour of Fire-protected Timber after the interface temperatures have exceeded 300°C.

Nine intermediate-scale tests were conducted. Each specimen included a joint between the panels with various joint treatments. The tests were performed in the horizontal orientation with an area 1.2 m x 1.2 m exposed to the furnace heating conditions. An Australian proprietary fire-protective grade plasterboard (FPGPB) was used as required by the program. Table 85 summarises details of the tests and key events.

In most cases specimens were also monitored beyond the heating period to investigate:

- charring and combustion during the decay period with an abundant oxygen supply
- potential for self-extinguish during the decay period
- increasing cross-sectional temperatures after termination of heating due to the thermal inertia of the fire protection and timber elements and smouldering combustion.

Table 85: Summary of intermediate scale Massive Timber program.

Test ref	CLT depth	FPGPB facings	Heating regime	Heating period (h:min)	PB Fall-off (min)
H1-49385200[207]	225 mm	NA	Standard	2:31	NA
H2-49385300[208]	225 mm	1 x 16 mm	Standard	2:51	115
H3-49385400[209]	225 mm	2 x 16 mm	Standard	3:11	Face layer 92-110 Base layer 145
H4-49385500[210]	225 mm	3 x 16 mm	Standard	4:00	Face layer 110-128 Intermediate layer 150-156 Base layer 179
H5-49385600[211]	225 mm	2 x 16 mm	Hydrocarbon	2:33	Face layer 56-65 Base Layer 102
H6-49385700[212]	105 mm	1 x 16 mm	Standard	0:45	No fall-off
H7-54455300[213]	225 mm	NA	Hydrocarbon	1:49	NA
H8-54455500[214]	105 mm	1 x 16 mm	Standard	1:00	No fall-off
H9-54455301[215]	225 mm	1 x 16 mm	Hydrocarbon	2.00	69

Materials and methods

CLT Panels

All the specimens included a nominal 50 mm half-lap joint and were assembled from two CLT panels forming a specimen nominally 1760 mm x 1760 mm. The test specimen depth varied depending on the CLT thickness and level of plasterboard protection. The central area of the specimen (1200 mm x 1200 mm) was exposed to the furnace heating conditions and the sides of the panels were covered with a single layer of plasterboard to reduce the risk of flame spread around the perimeter of the specimens during the post furnace exposure monitoring period.

For tests 1 to 5, 7 and 9, 225 mm thick CLT panels, comprising five 45 mm thick Radiata Pine lamella bonded together with Purbond HS Polyurethane adhesive, were used. Only the faces of the lamella were bonded, not the edges. Each specimen included a half-lap joint secured with countersunk head HSB 8 mm diameter x 200 mm long wood screws at 300 mm centres. Typical details are shown in Figure 127 and Figure 128.

Figure 127: Edge of 225 mm thick CLT panel showing edge joints without adhesive between sides of timber sections forming the CLT panel.

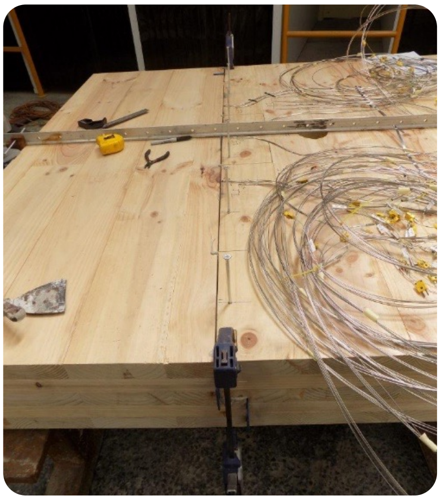


Figure 128: Construction of a typical lap joint with 200 mm long screws at 300 mm centres before fixing.

In tests 1 and 7, three half-lap joint treatments were evaluated:

- Joint 1 (Unprotected)
- Joint 2 (joint sealed with two beads of sealant between the bearing surfaces)
- Joint 3 (plasterboard cover on the fire-exposed side).

In tests 2 to 5 two half-lap joint treatments were evaluated.

- Joint 1 (plasterboard cover on the fire-exposed side)
- Joint 2 (joint sealed with two beads of sealant between the bearing surfaces).

In test 9 one half-lap joint treatment was evaluated. The joint was sealed with two beads of sealant (fire resistant mastic) between the bearing surface.

In all cases the half-lap bearing surfaces were in contact and a 3 mm gap was provided between the ends of the joint to represent typical site installations where the joints are not tight fitting. A mastic bead was applied to separate each joint detail to minimise the risk of interactions and a double bead applied to the right-hand joint as shown in Figure 129 and Figure 131.

Figure 129: Fire-resistant mastic applied to specimen 1 during construction.

Cross-sections through each of the joint types are shown in Figure 130 to Figure 132.

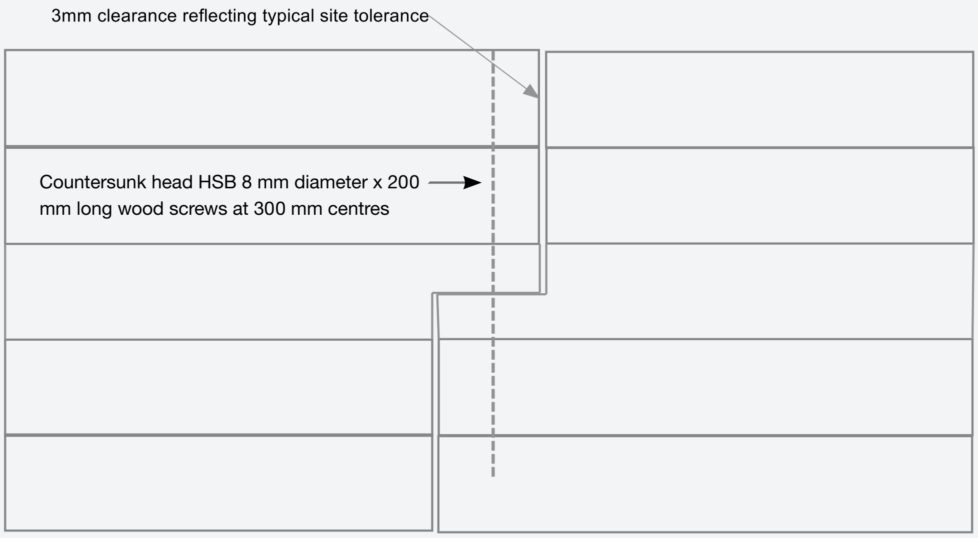


Figure 130: Unprotected joint detail.

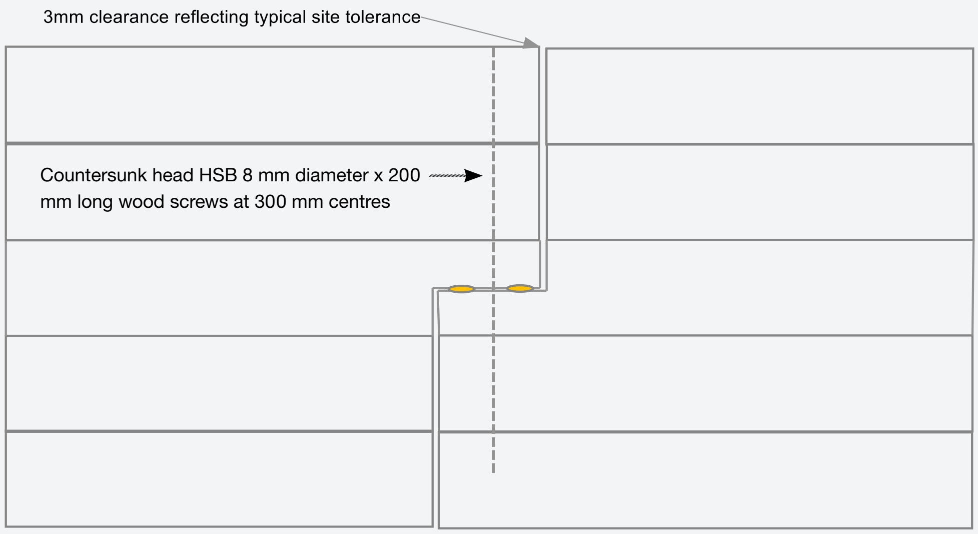


Figure 131: Joint protected by two fire-resistant mastic beads.

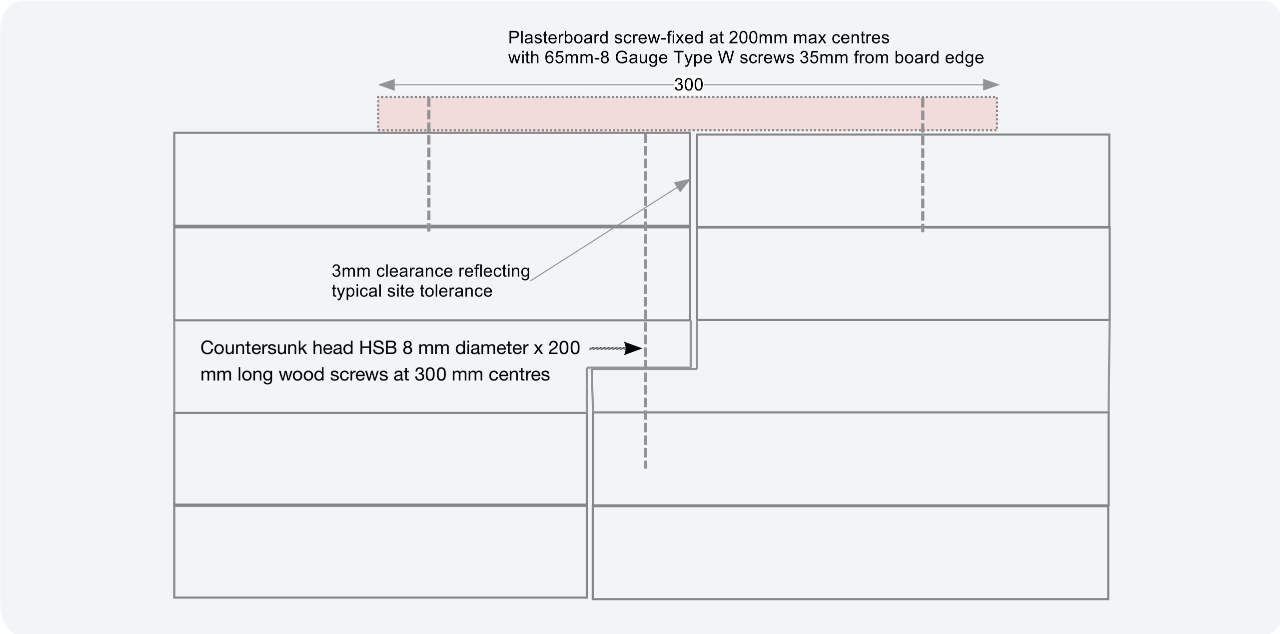


Figure 132: Joint protected by plasterboard cover.

For tests 6 and 8 CLT panels, 105 mm thick, comprising three Radiata Pine 35 mm thick lamella bonded together with Purbond HS Polyurethane adhesive were used. Only the faces of the lamella were bonded not the edges of the timber lamella. The specimen included a half-lap joint secured with countersunk head HSB 8 mm diameter x 100 mm long wood screws at 300 mm centres.

Typical details are shown in Figure 133 and Figure 134.

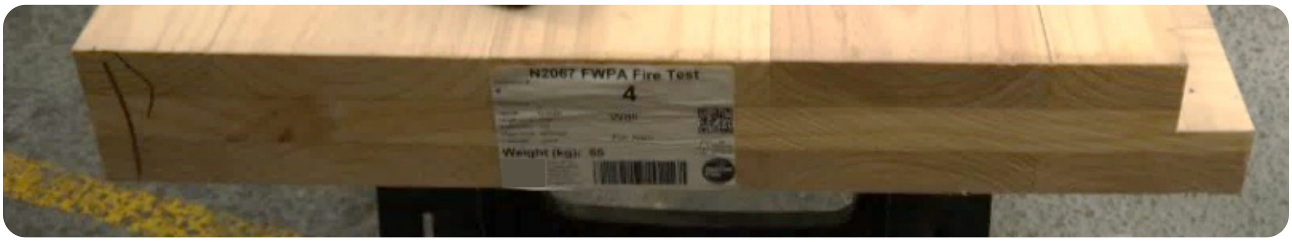


Figure 133: Edge of 105 mm deep panel showing edge rebate.

Two half-lap joint treatments were evaluated.

- Joint 1 (joint sealed with two beads of sealant between the bearing surfaces)
- Joint 2 (plasterboard cover on the non-fire exposed side).

The half-lap bearing surfaces were in contact and a 3 mm gap was provided between the ends of the joint to represent typical site installations where the joints are not tight fitting. A fire resistant mastic bead was applied to separate each joint detail to minimise the risk of interactions. These details were similar to the 225 mm thick specimens.

Note: To measure the heat flux level with the initial underside of the CLT panels, a heat flux meter was mounted in a 55 mm outside diameter stainless steel tube that penetrated a 92 mm diameter hole drilled through the CLT panel. The nominally 19 mm wide annular opening around the pipe was sealed with a ceramic fibre wrapping to the full depth of the CLT panel forming a service penetration.

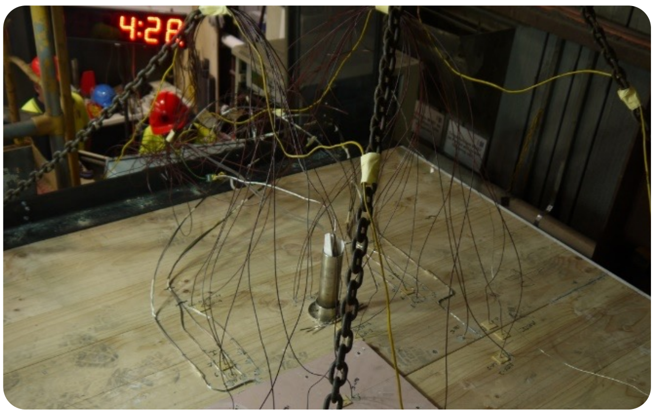


Figure 134: Non-fire side showing joint and heat flux meter service penetration.

Fire-protective grade plasterboard

All boards were fitted with a similar fixing system. The fire-protective grade plasterboard used for the test series was a typical proprietary board, 16 mm thick.

For a single layer application, the plasterboard was installed using bugle head needle point Type W 8 g x 65 mm screws at 200 mm centres around the board perimeter and 300 mm in the field. The minimum screw fixing distance from the edge of the board was 38 mm.

For a two-layer application, both layers of plasterboard were installed using bugle head needle point Type W 8 g x 65 mm screws at 200 mm centres around the board perimeter and 300 mm in the field. The minimum screw fixing distance from the edge of the board was 38 mm.

For a three-layer application, both inner layers of plasterboard were installed using bugle head needle point Type W 8 g x 65 mm screws at 200 mm centres around the board perimeter and 300 mm in the field. The minimum screw fixing distance from the edge of the board was 38 mm.

The outer face board was secured to the two inner layers using bugle head needle point Type G 10 g x 50 mm screws at 200 mm centres around the board perimeter and 300 mm in the field. The minimum screw fixing distance from the edge of the board was 38 mm.

In all cases, the outer-layer plasterboard joint was taped and sealed, and screw heads were also sealed. Joints in the lower layers of plasterboard were unfilled, following typical industry practice.

These fixing arrangements were selected to provide a practical means to reduce the risk of fixing failures at the perimeter of the board due to pull out or tearing of the plasterboard and to reduce the risk of failure of the board spanning between fixings.

Furnace

The tests were performed at the Warringtonfire test facility in Melbourne using an LPG-fired furnace, nominally 1.2 m x 1.2 m x 1.2 m internal dimensions (Figure 135). The furnace was lined with ceramic fibre and calcium silicate board fitted over a refractory lining. The burners were mounted in the lower part the side walls and the furnace exhaust in the upper part of the righthand wall (Figure 135). The gas air mixture was pre-mixed and the air/gas proportion at different flow rates characterised prior to the test series. Furnace pressure was controlled by a damper in the exhaust duct in conjunction with an exhaust fan.

Figure 135: Test furnace with front demountable panel removed to show the interior.

General Instrumentation

In all tests the furnace temperature was measured by four mineral insulated metal sheathed Type K thermocouples with wire diameters less than 1 mm and overall diameter 3 mm with the measuring junction insulated from the sheath. The thermocouples protruded a minimum of 25 mm from the steel supporting tubes. The furnace was controlled to follow the standard AS 1530.4:2014[18] heating regime except for tests EWF 5-49885600 and EWF 7-54455300 and EWF 9- 54455301 where the hydrocarbon heating regime specified in Appendix B of AS 1530.4 was followed.

The thermocouples were mounted through a supporting frame such that when the specimen was lifted from the furnace after the fire test for a monitoring period the distance of the furnace thermocouples from the specimen was maintained constant.

Figure 136: Typical underside of specimen before test showing furnace thermocouples and heat flux meter.

The furnace pressure was measured at a probe located 100 mm below the soffit of the test specimen and maintained at approximately 20 Pa above the laboratory atmosphere during the heating phase.

The following additional instrumentation was included in the program to provide further details on the fire exposure during the tests.

- plate thermocouples
- heat flux measurements
- air and gas flows to the furnace burners
- furnace oxygen concentration measurements
- additional furnace temperature measurements closer to the specimen.

Specimen temperature Instrumentation

Modified Resistance to the Incipient Spread of Fire (300°C isotherm)/encapsulation:

The 300°C isotherm/encapsulation times of the protected CLT panels was determined from measurements taken using Type K thermocouples with wire diameters less than 0.5 mm soldered to copper discs approximately 0.2 mm thick with a 12 mm diameter located at the interface with the CLT.

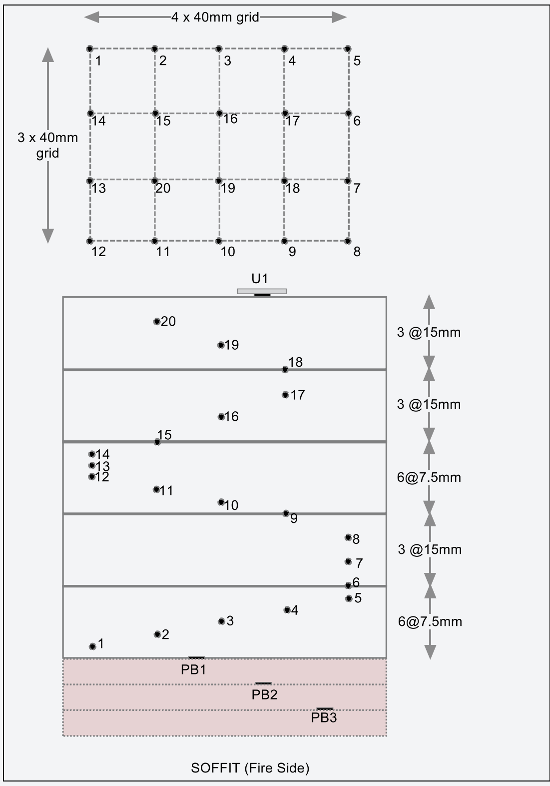
The Modified Resistance to the Incipient Spread of Fire performance/encapsulation times at the location of a stainless-steel tube penetration for the protected CLT panels was determined from temperature measurements taken using Type K thermocouples with wire diameters less than 0.5 mm soldered to copper discs 0.2 mm thick with a 12 mm diameter located at the interface with the CLT in some tests.

Other interface temperatures:

Interface temperatures between plasterboard layers were also measured to, among other things, determine the time of board fall-off. Type K thermocouples with wire diameters less than 0.5mm soldered to copper discs less than 0.5 mm thick having a diameter of 12 mm located at the interface with the CLT were used for this purpose.

CLT panel temperature:

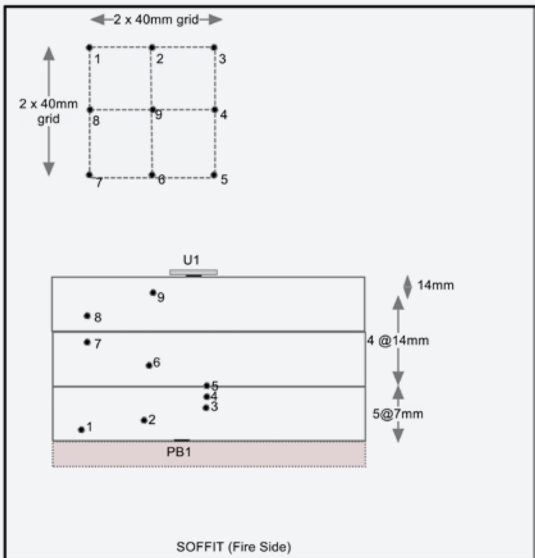
Internal temperatures were measured in two arrays using mineral insulated metal sheathed Type K thermocouples with an overall diameter of 1.5 mm with the measuring junction insulated from the sheath. A typical array for the 225 mm CLT panel is shown in Figure 137 and for the 105 mm CLT panel in Figure 138. Internal temperatures were not measured in Test 9.



Array	T/C Ref	Type	Position
I1	I1-1	Internal	7.5mm above CLT soffit
	I1-2	Internal	15mm above CLT soffit
	I1-3	Internal	22.5mm above CLT soffit
	I1-4	Internal	30mm above CLT soffit
	I1-5	Internal	37.5mm above CLT soffit
	I1-6	Internal	45mm above CLT soffit
	I1-7	Internal	60mm above CLT soffit
	I1-8	Internal	75mm above CLT soffit
	I1-9	Internal	90mm above CLT soffit
	I1-10	Internal	97.5mm above CLT soffit
	I1-11	Internal	105mm above CLT soffit
	I1-12	Internal	112.5mm above CLT soffit
	I1-13	Internal	120mm above CLT soffit
	I1-14	Internal	127.5mm above CLT soffit
	I1-15	Internal	135mm above CLT soffit
	I1-16	Internal	150mm above CLT soffit
	I1-17	Internal	165mm above CLT soffit
	I1-18	Internal	180mm above CLT soffit
	I1-19	Internal	195mm above CLT soffit
	I1-20	Internal	210mm above CLT soffit
	I1-U1	Unexposed	225mm above CLT Soffit -unexposed face
	I1-PB1	Disc	interface between CLT and PB
	I1-PB2	Disc	Interface between PB1 & PB2 -16mm
	I1-PB3	Disc	Interface between PB12&PB3 -32mm

Array I2 adopts the same numbering scheme and thermocouple positions

Figure 137: Typical thermocouple array for a 225 mm thick CLT panel.



Array	T/C Ref	Type	Position
I1	I1-1	Internal	7mm above CLT soffit
	I1-2	Internal	14mm above CLT soffit
	I1-3	Internal	21mm above CLT soffit
	I1-4	Internal	28mm above CLT soffit
	I1-5	Internal	35mm above CLT soffit
	I1-6	Internal	49mm above CLT soffit
	I1-7	Internal	63mm above CLT soffit
	I1-8	Internal	77mm above CLT soffit
	I1-9	Internal	91mm above CLT soffit
	I1-U1	Unexposed	105mm above CLT Soffit -unexposed face
	I1-PB1	Disc	interface between CLT and PB

Array I2 adopts the same numbering scheme and thermocouple positions

Figure 138: Typical thermocouple array for a 105 mm CLT panel.

CLT Joint Temperatures:

The temperatures at the joint positions were measured across the section to quantify any acceleration of charring at the joint positions due to leakage of hot gases. This was achieved by rebating mineral insulated metal sheathed Type K thermocouples with an overall diameter of 1.5 mm into the edge of the timber and running the thermocouple along the expected isotherms to reduce measuring errors (Figure 139 and Figure 140).

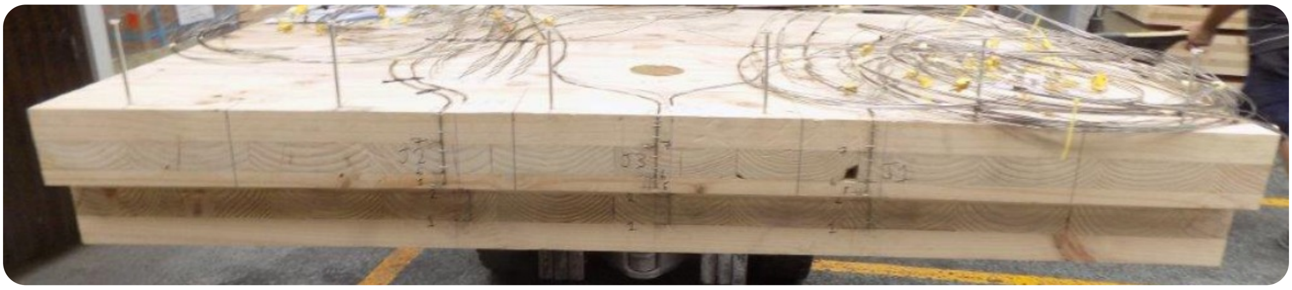


Figure 139: Typical thermocouple array for a 225 mm thick CLT panel.

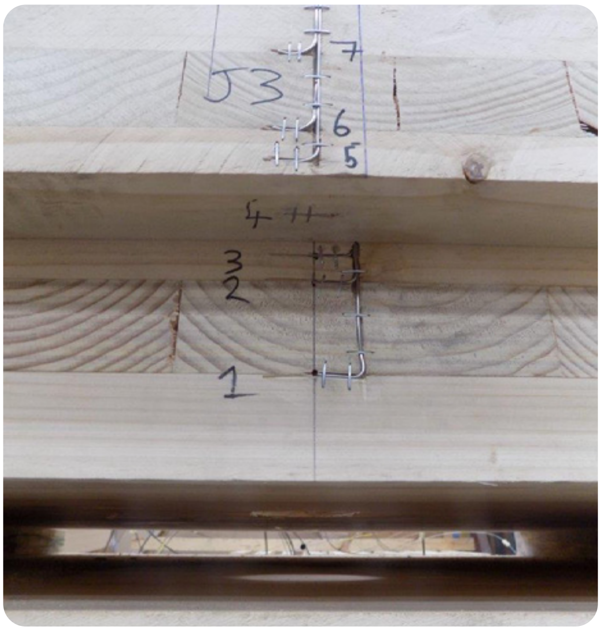


Figure 140: Close up of Joint 3 temperature measurement points from Test 1.

Figure 141 to Figure 143 show typical sections providing details of the positions of the thermocouples for each of the joint configurations. Temperatures were not measured at the joint position in test 9.

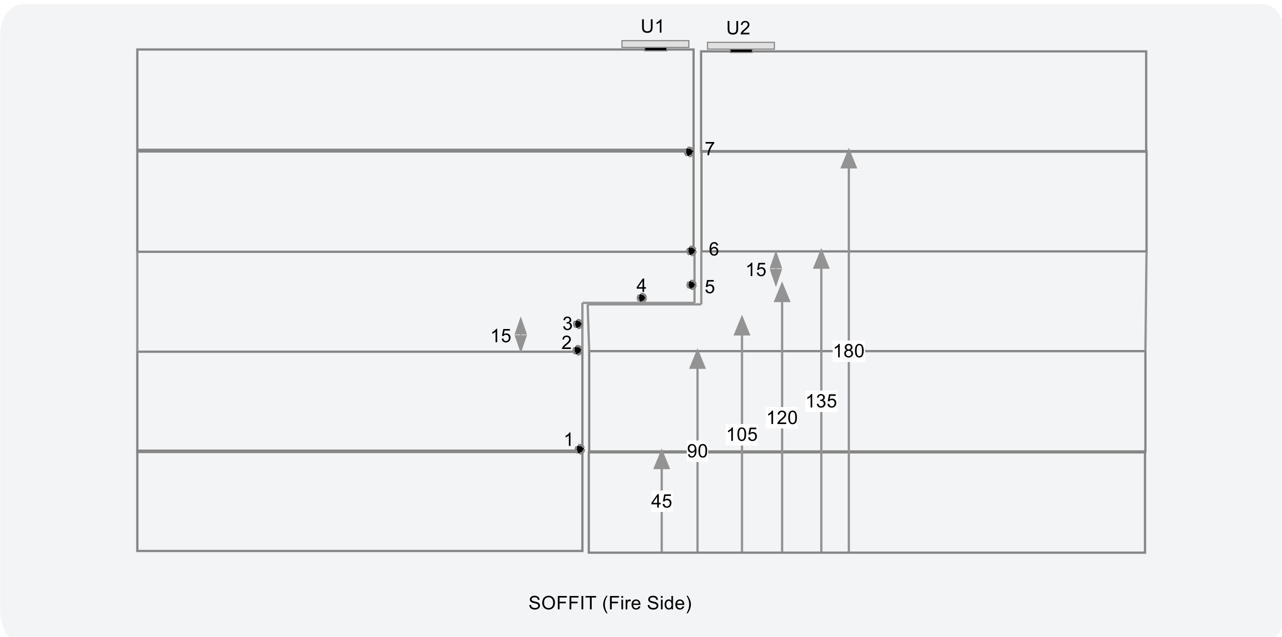


Figure 141: Instrumentation for unprotected joint detail.

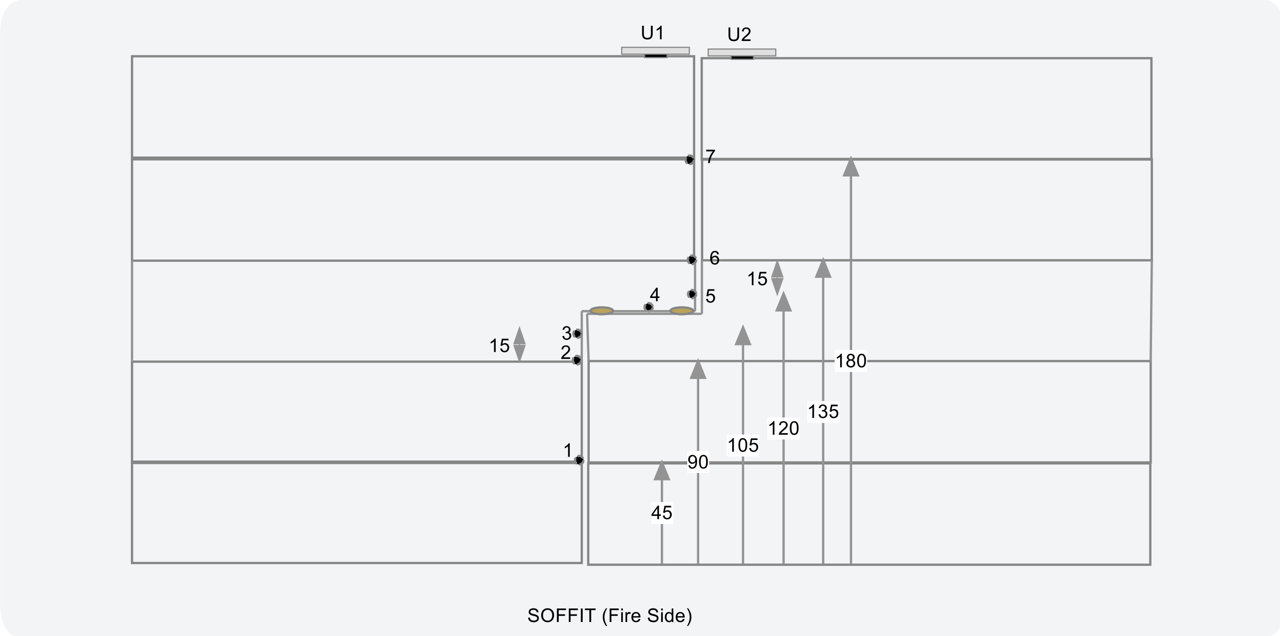


Figure 142: Instrumentation for Joint protected by beads of sealant.

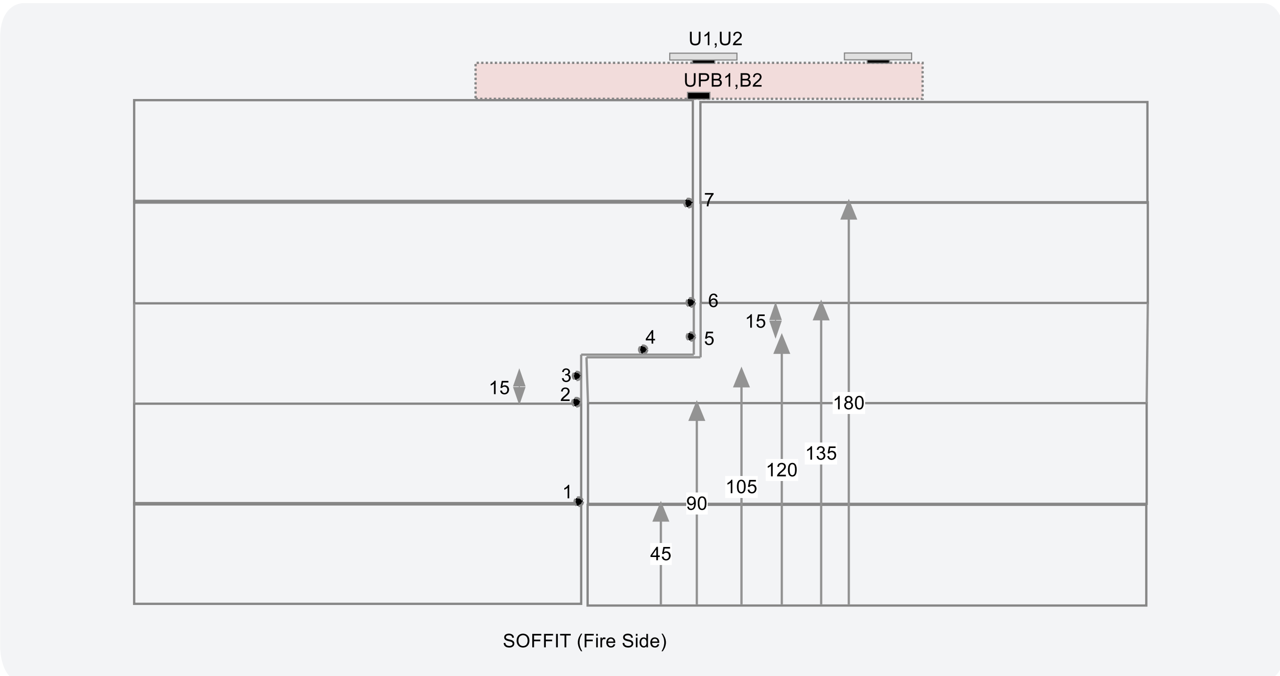


Figure 143: Instrumentation for joint protected by plasterboard covering on the non-fire side.

Insulation performance of system:

Non-fire side temperatures were measured using Type K thermocouples with wire diameters less than 0.5 mm soldered to a 12 mm diam. x 0.2 mm thick copper disk covered by 30 mm x 30 mm x 2.0 mm inorganic insulating pads. These were positioned to ascertain the insulation performance of the floor system and other details such as joint configurations and the stainless-steel pipe penetration used to mount the heat flux meter.

Post-fire test heat flux measurements

Except for test 9, after the heating period the specimen was raised above the furnace to provide free access to air while continuing to be exposed to an imposed heat flux from the cooling furnace, which was monitored by the heat flux meter fitted level with the initial underside of the specimen.

An additional heat flux meter was inserted approximately 410 mm below the specimen directed at the underside of the specimen to provide an indication of the radiant heat released from the test specimen. Figure 144 shows the post-test arrangement.

At the end of test 9 the specimen was quickly hosed down to enable char rates to be determined because internal measurements of the CLT panel were not taken. Therefore, no post-fire test monitoring was undertaken after test 9.

Figure 144: Post-fire test monitoring arrangement showing insulated tube mounting a heat flux meter monitoring the underside of the specimen and furnace thermocouples.

Additional fire test exposure measurements

Background

Furnace temperatures in all tests were additionally measured by two plate thermometers (PTs). Beyer[68] indicated PTs tend to provide more repeatable exposures between furnaces, and the measured temperatures are more independent of the thermal properties of the test specimen, and were therefore recommended when undertaking fire-resistance tests for performance-based fire design of buildings.

Wickstrom[230] indicated that the PT approximately measures adiabatic surface temperature. Therefore, furnace temperature as measured with the PTs can be used directly to calculate the heat transfer to a specimen and thereby its temperature. This simplifies finite element modelling of heat transfer at the boundary of the specimen and the data obtained may be very useful for validation of modelling approaches.

The incident heat flux was also measured in most tests at the level of the initial underside of the specimen throughout the tests using a Medtherm Heat Flux Gauge.

The furnace gas flow and the air flow to the furnace were measured with gas flow meters. Furnace oxygen content was measured using a gas analyser with a sampling point 295 mm below the soffit of the specimen in Tests 1-6. The oxygen content within the furnace represents an important component of the fire exposure when evaluating combustible materials and should be representative of the fire conditions under consideration when undertaking performance-based designs. For ventilation-controlled fires, low oxygen concentrations (below 10%) are appropriate.

The furnace temperature was also measured between 10 and 100 mm below the initial soffit in Tests 7 to 9 to investigate the temperature profiles below an exposed timber element and an element protected with plasterboard, as shown in Figure 145, using mineral-insulated metal sheathed Type K thermocouples with wire diameters less than 1 mm and overall diameters of 3 mm with the measuring junction insulated from the sheath.

Test 7-54455300

Test 8-54455500

Figure 145: Underside of specimens 7-54455300 and 8-54455500 before test showing furnace thermocouples, plate thermometers and heat flux gauges.

Plate thermometers

Two PTs were included in the furnace to provide additional data to quantify the exposure of the specimen (Figure 145). The plate thermometers were 100 mm x 100 mm x 0.7 mm with mineral-insulated metal sheathed Type K thermocouples having an overall diameter of 1 mm with the measuring junction insulated from the sheath. The 0.7 mm plate was insulated on one face with 10 mm inorganic insulating pads.

Under the standard heating regime of AS 1530.4, the PT indicated a higher or similar temperature to the Mineral Insulated Metal Sheathed (MIMS) furnace thermocouples prescribed by AS 1530.4 after approximately 20 min of the tests (Figure 146 to Figure 149).

During the first 20 min of the test, the PT generally indicated a lower temperature than the MIMs furnace thermocouples prescribed by AS 1530.4. This is expected to be due to the slower thermal response of the PT and lower proportion of radiant heat exposure.

Therefore, if during the test series, PTs had been used for control of the furnace, the specimens may have been exposed to slightly more severe heating conditions during the first 15-20 min of the test and for the remainder of the test similar or less severe conditions.

Generally, the variations between the two measurement methods are substantially less than the furnace temperature tolerances within the standard and therefore the differences will tend be critical only when undertaking verification work of models under carefully controlled conditions or considering Evidence of Suitability for marginal cases with respect to prescribed FRL periods and/or heating tolerances.

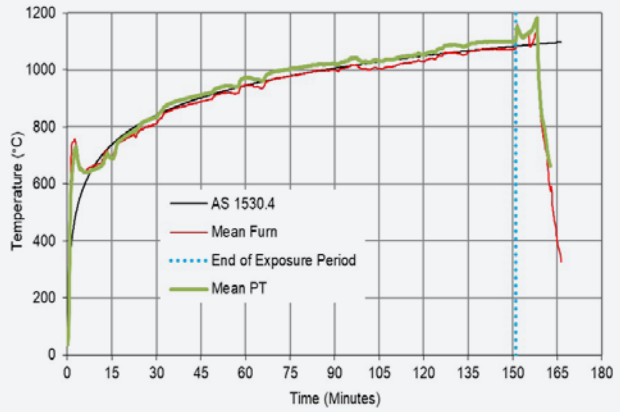


Figure 146: Test 1 Plate Thermometer and AS 1530.4 thermocouple furnace temperatures – unprotected CLT.

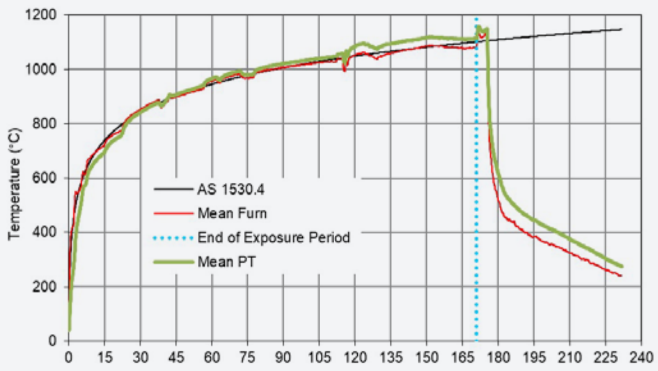


Figure 147: Test 2 Plate Thermometer and AS 1530.4 thermocouple furnace temperatures – CLT protected by 1 x 16 mm plasterboard.

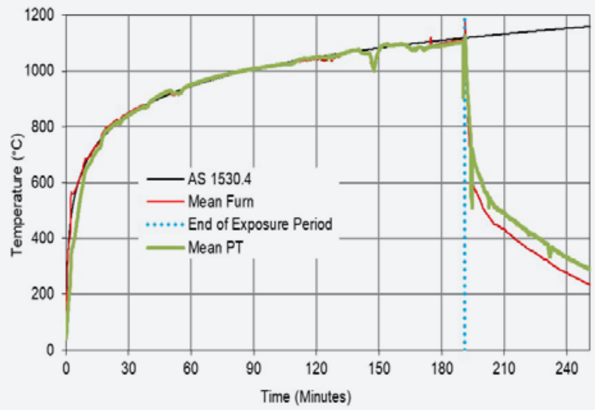


Figure 148: Test 3 Plate Thermometer and AS 1530.4 thermocouple furnace temperatures – CLT protected by 2 x 16 mm plasterboard.

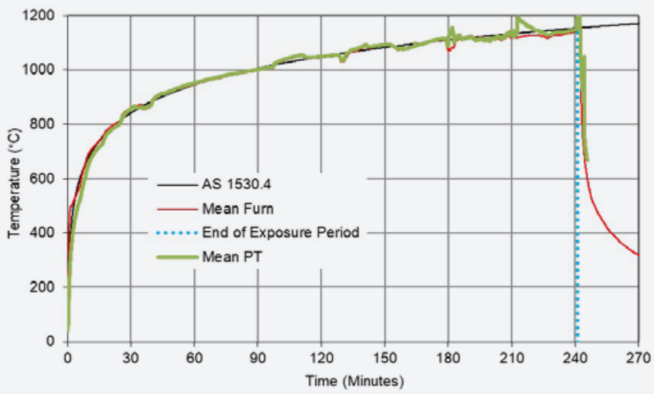


Figure 149: Test 4 Plate Thermometer and AS 1530.4 thermocouple furnace temperatures – CLT protected by 3 x 16 mm plasterboard.

Similar trends were visible during the tests performed to the hydrocarbon heating regime, as shown in Figure 150 to Figure 152, except that due to the rapid temperature gradients in the early part of the test, the period where PT recorded significantly lower temperatures compared to the standard AS 1530.4 furnace thermocouples was substantially reduced.

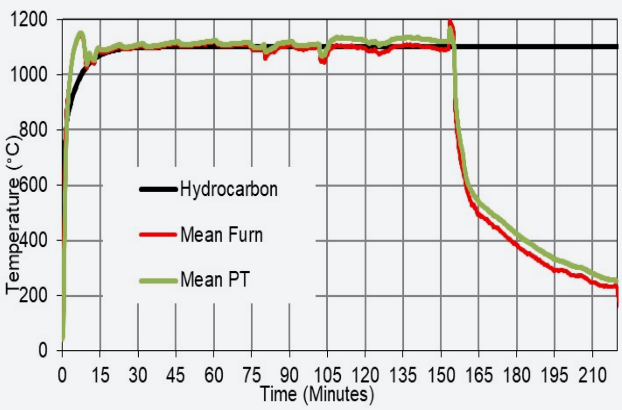


Figure 150: Test 5 plate thermometer and AS 1530.4 thermocouple furnace temperatures – CLT protected by 2 x 16 mm plasterboard with hydrocarbon heating regime.

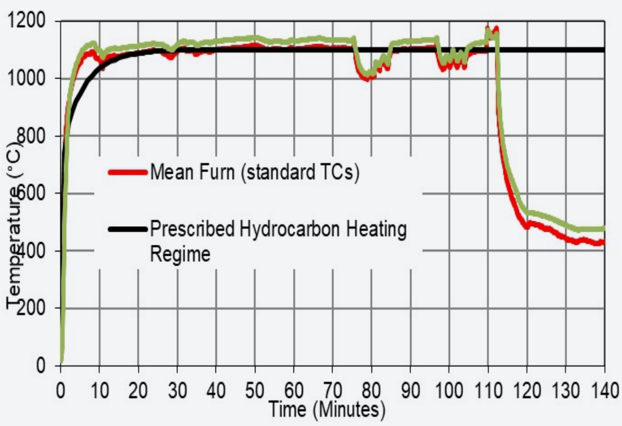


Figure 151: Test 7 plate thermometer and AS 1530.4 thermocouple furnace temperatures – unprotected CLT with hydrocarbon heating regime.

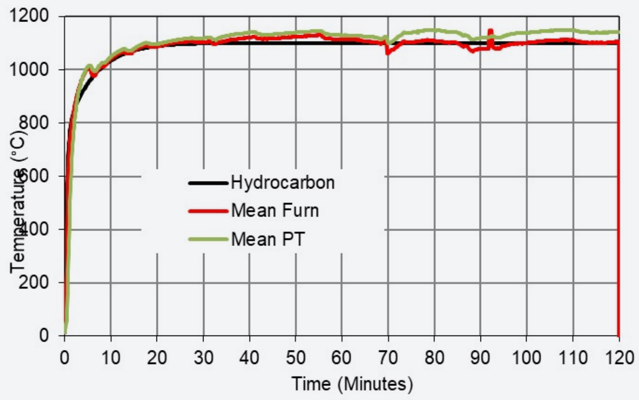


Figure 152: Test 9 plate thermometer and AS 1530.4 thermocouple furnace temperatures – CLT protected by 1 x 16 mm plasterboard with hydrocarbon heating regime.

Heat flux

The incident total heat flux at the initial soffit location of the specimen was measured using Medtherm Heat Flux Gauges. Significant work has been undertaken examining char rates when timber specimens are exposed to different heat fluxes; although the data tends to be limited to exposures less than 100 kW/m^2. The measured radiant heat flux may help explain the significantly higher char rates measured in the longer duration tests and tests adopting the hydrocarbon heating regime.

Incident heat flux was measured in the plane of the initial underside of the specimen by a water-cooled heat flux meter mounted in a steel tube. The heat flux measured during the long duration tests with CLT specimens subjected to the standard AS 1530.4 heating regime are plotted against time in Figure 153. There were transient drops in the measured heat flux from approximately 40 to 60 min during Test 2 that have been assumed to be intermittent connection faults. This data is circled in Figure 153.

The calculated radiant heat flux emitted from an assumed black body source at the prescribed furnace temperature is also plotted. The calculated heat flux does not account for variations from black body behaviour or convective heat transfer to the heat flux gauge. It does, however, provide a useful datum to compare measured heat flux with furnace temperatures.

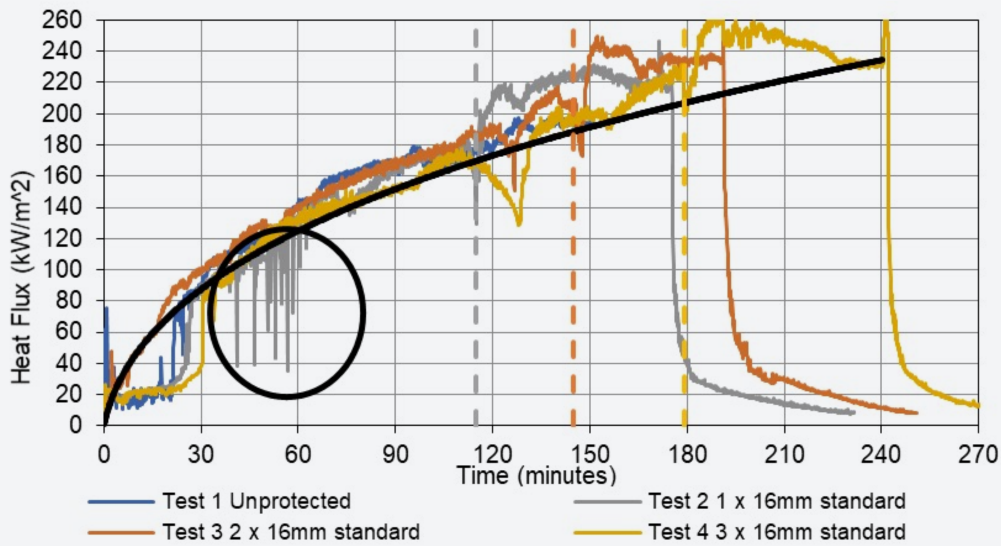


Figure 153: Heat flux at underside of specimens exposed to the AS 1530.4 Standard heating regime compared to the calculated radiant heat emitted from an assumed black body source at the prescribed furnace temperature.

In three of the four tests, exposed to the standard heating regime during the first 30 min, the measured heat flux varied markedly from the calculated black body radiant heat flux based on the measured furnace temperatures 100 mm from the specimen. This can be explained to some extent by the observation that during the early stages of the fire tests the predominant heat transfer is via convection. The impact of this is further increased if there is a temperature gradient close to the soffit of the specimen since furnace temperatures are measured 100 mm below the specimen. This theory was investigated further later in the test series.

In Test 8, for example, additional furnace thermocouples were fitted below the soffit of the specimen to measure the temperature profile between 10 mm to 100 mm below the soffit of a CLT panel protected by one layer of 16 mm plasterboard when subjected to the standard heating regime for 60 min. These results are plotted in Figure 154.

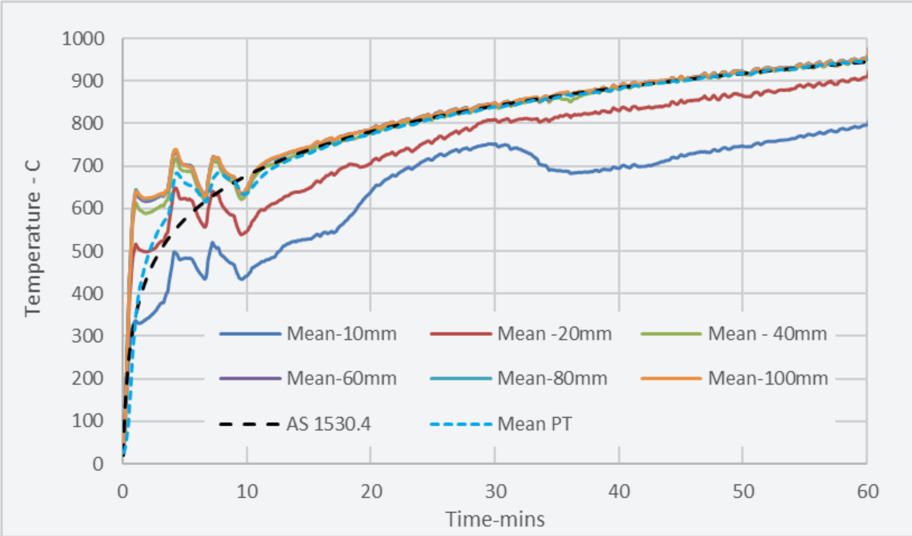


Figure 154: Furnace temperature profile at various distances below the soffit of a CLT panel protected by one layer of 16 mm fire-protective grade plasterboard subjected to the standard heating regimes (Test H8).

Typically, during the first 15 min of the test, a 200°C (approx) temperature gradient was measured between 10 mm and 40 mm below the soffit of the specimen with no significant gradient between 40 mm and 100 mm. It was impractical to run the thermocouples along isotherms and heat losses to the specimen would be greater for thermocouples closer to the specimen soffit, but the impact would be expected to be relatively small compared to the 200°C differential.

This data is consistent with the relatively low heat flux measurements at the soffit of the specimen until heat transfer is dominated by radiant heat and impacts on both combustible and non-combustible specimens.

There were also transient variations in the furnace temperature and heat flux measurements that coincided with fall-off of layers of plasterboard. Ignoring these transient variations, the measured heat flux exposure throughout the unprotected CLT panel tests and while plasterboard facings were in place in the remaining tests tracked slightly above the black body datum. When the last layer of plasterboard fell away exposing the CLT, there was an increase (of the order of 20 kW/m^2) in the measured heat flux relative to black body datum based on the furnace thermocouple data. As the test continued, the measured heat flux trended back towards the black body datum so that the difference between the measured heat flux and blackbody datum was similar to that before exposure of the CLT.

Figure 155 shows relevant results for CLT protected by two layers of fire-protective grade plasterboard when exposed to the standard and hydrocarbon heating regimes.

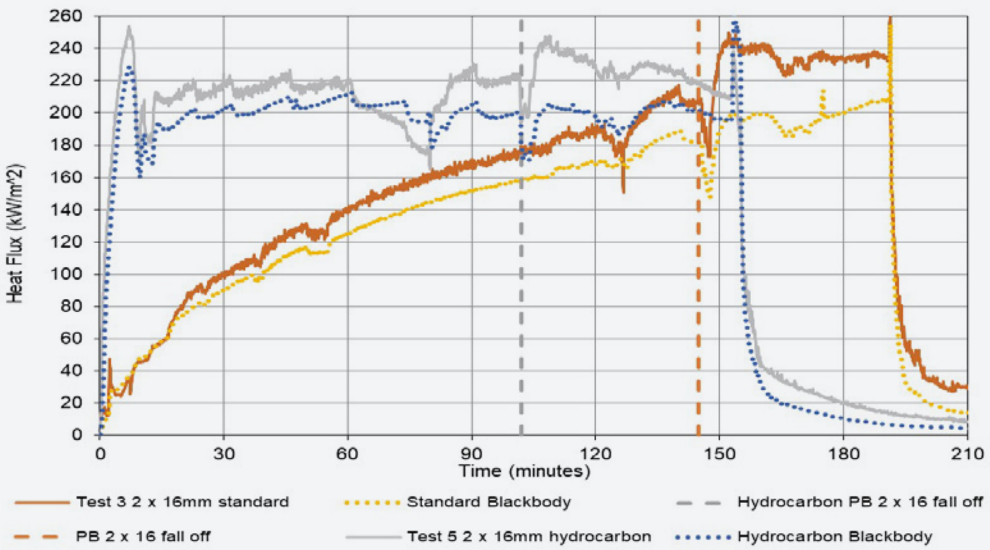


Figure 155: Heat flux at underside of specimens protected by two layers of 16 mm thick plasterboard exposed to the AS 1530.4 standard and hydrocarbon heating regime compared to the calculated radiant heat emitted from an assumed black body source at the measured mean furnace temperature.

In these plots, the black body heat fluxes were calculated using the mean furnace temperatures, which shows the immediate transient reduction in both measured temperatures and measured heat flux as the plasterboard layers fall away followed by a substantial increase in the measured heat flux after the CLT is exposed that is not reflected to the same extent in the calculated black body radiation levels. These are potentially significant findings in that they show the furnace thermocouples below the specimen are not recording a temperature rise commensurate with the increased heat flux at the surface of the CLT.

As the boards fell away, exposing the CLT, a significant increase in the pyrolysis rate from the freshly exposed CLT would be expected, which would progressively reduce as the char layer developed until the conditions would approximate to steady state. Under natural fire conditions, if the fire was initially ventilation controlled, the impact of the additional volatiles would be to reduce the heat release rate within the enclosure and lower the enclosure temperatures as observed by Hakkarainen[57]. In furnace tests, if the burners use pre-mixed gas and air (the most common approach) and depending on the initial oxygen content within the furnace, the gas/air supply may need to be increased or decreased to maintain the nominated heating regime. With the test configurations and furnace designs used for this program, additional heat was required and the gas/air supply was increased. Further information is provided in the following section regarding gas/air flows.

To further investigate these results, in Test 9, heat flux was measured 100 mm below the soffit of the specimen in addition to in the plane of the soffit of the specimen. The total incident heat flux was calculated based on the mean of the plate thermometer temperatures using the following relationship proposed by Wickstrom[230]:

$$\dot{q}''_{\mathrm{inc}} = \sigma T_{PT}^4 - h_{PT}(T_g - T_{PT}) / \varepsilon_{PT}$$

where:

$\dot{q}''_{\text{inc rad}}$	incident radiant heat flux (W/m²)
σ	Stefan-Boltzmann constant (W/m²K⁴)
ε_{PT}	emissivity
T_{PT}	plate thermometer temperature (K)
T_g	gas temperature (K)
h_{PT}	heat transfer coefficient (W/m²K)
T_f	furnace temperature (K)

Wickstrom suggested that the last term in the above equation is relatively small, especially when the enclosure is close to a constant temperature, and it is reasonable to ignore the term, enabling the incident radiant heat flux to be estimated using the following relationship:

$$\dot{q}''_{\text{inc rad}} = \sigma T^4_{PT}$$

The convective heat transfer to the heat flux meter 100 mm below the soffit was estimated based on the difference between the temperature of the nearest sheathed furnace thermocouple and the measured temperature of the heat flux gauge assuming a heat transfer coefficient of 25 W/m²K.

$$\dot{q}''_{\text{inc conv}} = h\,(T_g - T_f)$$

The results, shown in Figure 156, are consistent with minimal convective heat transfer to the heat flux meter flush with the soffit of the specimen, but a significant convective component measured by the heat flux meter 100 mm below the soffit. Further investigations are required to confirm these findings.

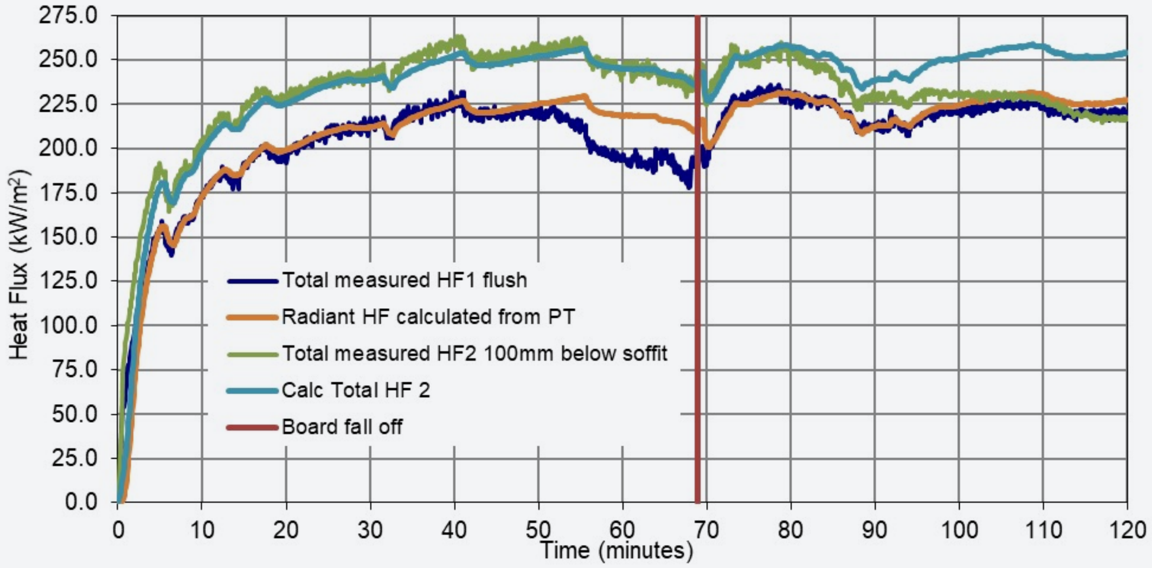
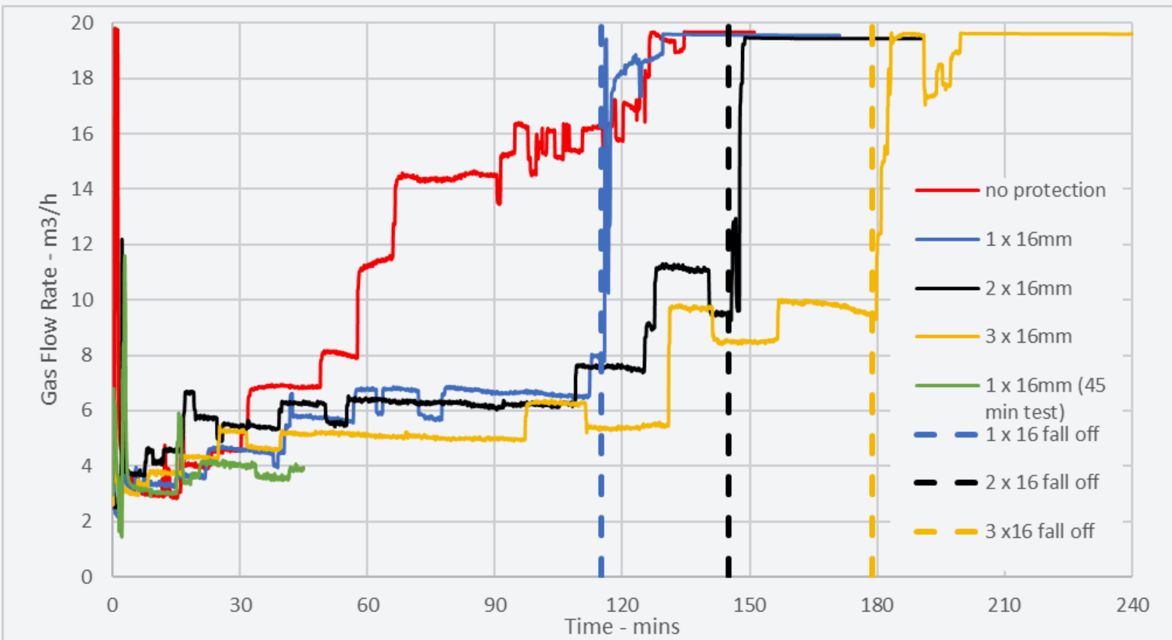


Figure 156: Heat flux measurements from test 9 CLT protected by one layer of 16 mm thick plasterboard exposed to the hydrocarbon heating regime compared to the calculated incident radiant heat flux and calculated convective heat flux.

Gas flow and furnace oxygen concentration

Supply LPG flow rates were measured to provide an indication of the timing of changes in the combustion processes within the furnace that could result from changes in the rate of release of volatiles into the furnace environment from pyrolysis of timber. The LPG gas is premixed with air in a fixed proportion and pre-test calibration runs were undertaken by the laboratory to determine the air flow to the furnace relative to the gas flow rate. In addition, oxygen concentration measurements were taken within the furnace 295 mm below the soffit of the specimen.

The supply LPG gas flow measurements show a rapid change coincident with the fall-off time of the fire-protective coverings exposing the CLT panels directly to the furnace (Figure 157).



Note: Max limit for gas flow measurement was approximately 20 m³/h.

Figure 157: Furnace LPG gas supply flow rate for specimens subjected to the standard heating regime.

The red plot shows the gas flow for the unprotected timber was substantially higher than the Fire-protected Timber elements. This may be considered counter intuitive because the volatiles produced by the timber could contribute to furnace heating if there is adequate oxygen. However, as there were low oxygen concentrations (typical of ventilation-controlled fires and fire-resistance test furnaces) it is more likely that significant energy is absorbed during pyrolysis in low oxygen environments compared to plasterboard once the moisture has been driven off from the surface. As the AS 1530.4 test methods require a prescribed time-temperature regime to be followed, the gas flow and corresponding air flow needs to be increased to increase the burner output. This effect can be viewed as analogous to a heavy steel or concrete member absorbing heat compared with an insulated member.

A significant increase in gas demand occurred following plasterboard coverings falling off and exposing the CLT surface. The increase in demand could have been required to compensate for boards falling on the furnace floor, reducing the radiant heat component received by the specimen from the floor of the furnace or due to the exposed CLT releasing excess volatiles and impacting on the convective heat transfer component. It is more likely both may have contributed to the increased demand.

There was little change during the tests in the percentage of oxygen within the furnace, measured 290 mm below the specimen soffit although measurements could only be taken intermittently due to the need to clean filters to obtain reliable readings. An oxygen concentration of approximately 6-7% was maintained through the test series despite substantial changes occurring in the supply LPG flow rates and corresponding increases in the supply air flow rate.

Results and analysis

Performance of Massive Timber exposed to high fire-resistance test exposure periods

A series of four fire-resistance tests were performed on 225 mm thick CLT panels comprising five 45 mm lamella. The specimens were tested in the horizontal orientation with an area of the underside approximately 1.2 m x 1.2 m exposed to the standard heating regime of AS 1530.4:2014.

The specimens were not full size or loaded and therefore full-scale loaded tests will be required to provide Evidence of Suitability in accordance with the National Construction Code[1] Deemed-to-Satisfy requirements.

The tests provided data to demonstrate the likely viability of the use of Massive Timber at high Fire Resistance Levels (up to four hours) with varying protection levels and to support suppliers developing these systems.

The following relevant data has been extracted and presented in Table 86.

- the time for the interface of the CLT and fire-protective coverings to exceed 300°C
- the time at which the fire-protective coverings fell away exposing the CLT directly to the furnace
- the time to exceed 300°C at selected depths (assumed char boundary).

Table 86: Summary of comparative data from long duration fire-resistance tests exposed to the AS1530.4 standard heating regime.

Test	FPGPB facings	Duration of heating (min)	MRISF (min)	PB. Fall-off (min)	Array	Time to 300°C (min)			
						Char depth (mm)			
						22.5	45	90	112.5
H1-49385200	Exposed CLT	151	NA	NA	1	40	61	89	106
					2	35.5	59	94	125.5
					Mean	38	60	92	110
H2-49385300	1 x 16 mm	171	32	Face Layer 115	1	118	121	132	171
					2	115	132	138	166
					Mean	117	127	136	169
H3-49385400	2 x 16 mm	191	85	Face layer 92-110 Base layer 145	1	153	170	191	-
					2	150	165	186	-
					Mean	152	168	189	-
H4-49385500	3 x 16 mm	240	144	Face layer 110-128 Inter. layer 150-156 Base layer 179	1	185	197	224	228
					2	184	201	217	265
					Mean	185	199	221	246

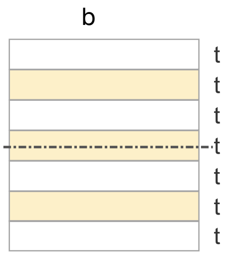
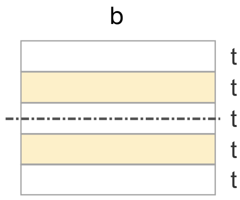
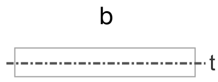
Delamination of the CLT panel at the glue lines was observed during the fire test and the post-test monitoring period; which is expected from panels bonded with the type of adhesive used. Improved performance would be expected from adhesives with better performance at elevated temperatures.

The fall-off times should be considered upper bounds since the specimens are intermediate scale and an optimised fixing system was used maintaining edge distances of at least 38 mm to reduce the risk of tearing/pull-out at edge fixing positions and the fixing spacing reduces sagging between fixings.

The CLT elements tested for high fire ratings were 225 mm thick comprising five lamella face bonded with a polyurethane adhesive. Common configurations include panels with three, five or seven lamella. Unless a full encapsulation system is adopted for longer FRLs, significant charring is likely to occur, removing any significant contribution from the outer lamella. The cross lamella will only make a small contribution to the loadbearing capacity if its grain runs perpendicular to the main span direction and its contribution can be conservatively ignored. This effectively means that the two bottom lamella may not make significant contribution to the loadbearing capacity for longer fire exposure periods.

A simple analysis of the section moduli for various CLT configurations has been undertaken to obtain an understanding of the potential impact on the moment capacity under fire limit state conditions of the loss of the lower lamellae (Table 87).

Table 87: Section moduli analysis for CLT panel configurations.

Description	7 lamella panel	5 lamella panel	3 lamella panel	1 lamella panel
Configuration				
2nd moment of Area – Ix	Ix = 2(1/12 bt3+t2bt) + 2(1/12 bt3+(3t)2 bt) =20.33bt3	Ix = 1/12 bt3 + 2(1/12 bt3+(2t)2 bt) =8.25bt3	Ix = 2(1/12 bt3+t2bt) = 2.167 bt3	Ix = 1/12 bt3 =0.0833 bt3
Section Modulus Zx	Zx = Ix/3.5 t =5.81 bt2	Zx = Ix/2.5 t =3.3 bt2	Zx = Ix/ 1.5 t =1.44 bt2	Zx = Ix/ 0.5 t =0.167 bt2
Section modulus ratio for n/(n-2) lamella	=3.3/5.81 ≈ 0.57	=1.44/3.3 ≈ 0.43	=0.167/1.44 ≈ 0.11	

The ratio for n/(n-2) approximates to the ratio of the load capacity under Design Fire conditions to the design capacity under ambient conditions (LR_{fb}) if the lower layer is consumed and the cross layer provides no contribution to strength; which should exceed a load ratio of 0.5 to address load combinations applied by AS /NZS 1170.0 and the load duration factor required by AS/NZS 1720.1.

However, this simple preliminary analysis does not account for the inherent safety margin associated with the characteristic bending stress, which is based on the 5-percentile value assuming a log-normal distribution based on Boughton and Crews[231]. This implies there will be a probability of approximately 0.95 that the characteristic value will be exceeded. Assuming a coefficient of variance of 15% and the properties of XLG1 timber are similar to F7 graded timber as suggested by Navaratnam[232] with a characteristic bending stress of 18 MPa, the distribution shown in Figure 158 can be generated with a mean value of approximately 23 MPa. This is comparable with the results determined experimentally by Navaratnam[232] from 3-lamella and 5-lamella CLT panels tested to failure (summarised in Table 88).

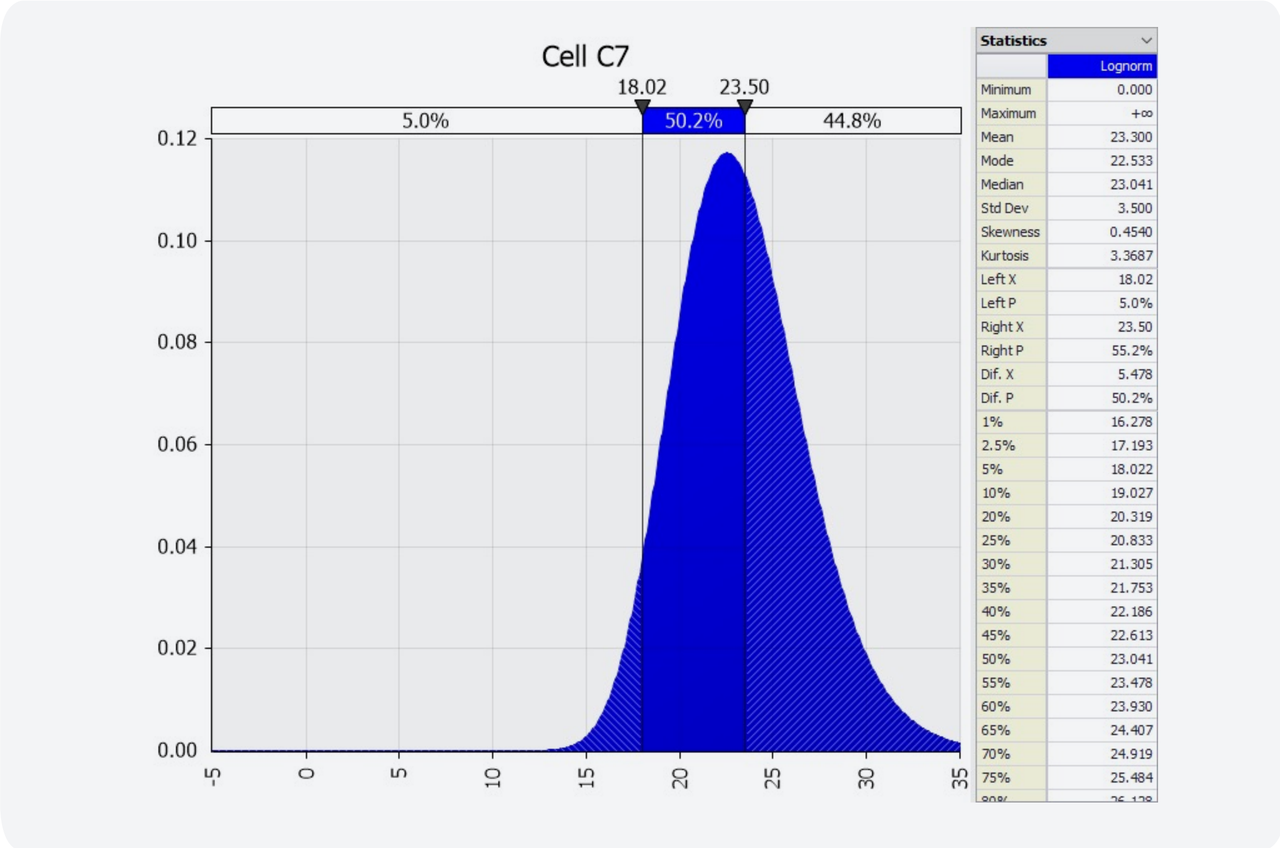


Figure 158: Lognormal distribution with a mean value of 18 and standard deviation of 3.5 indicative of assumed characteristic bending stress distribution for F7 graded timber.

Table 88: Structural test results for CLT panels derived from Navaratnam et al[232].

Value	3 x 35 mm – 2.1 m span	3 x 35 mm – 2.94 m span	5 x 35 mm – 2.9 m span	5 x 35 mm – 4.02 m span
Mean	26.61	23.41	28.67	26.84
Std. Dev	4.02	1.67	4.01	5.16
COV	0.15	0.07	0.14	0.19

In many applications, the ultimate loadbearing capacity does not control the selection of a structural element with criteria such as deflection of floors or acoustic performance of walls being more critical. In these circumstances, the load under fire limit state may be low enabling, for example, loss of the load-carrying capacity of the outer lamella, the non-load carrying intermediate layer and part or the central lamella of the five-lamella deep section without structural failure.

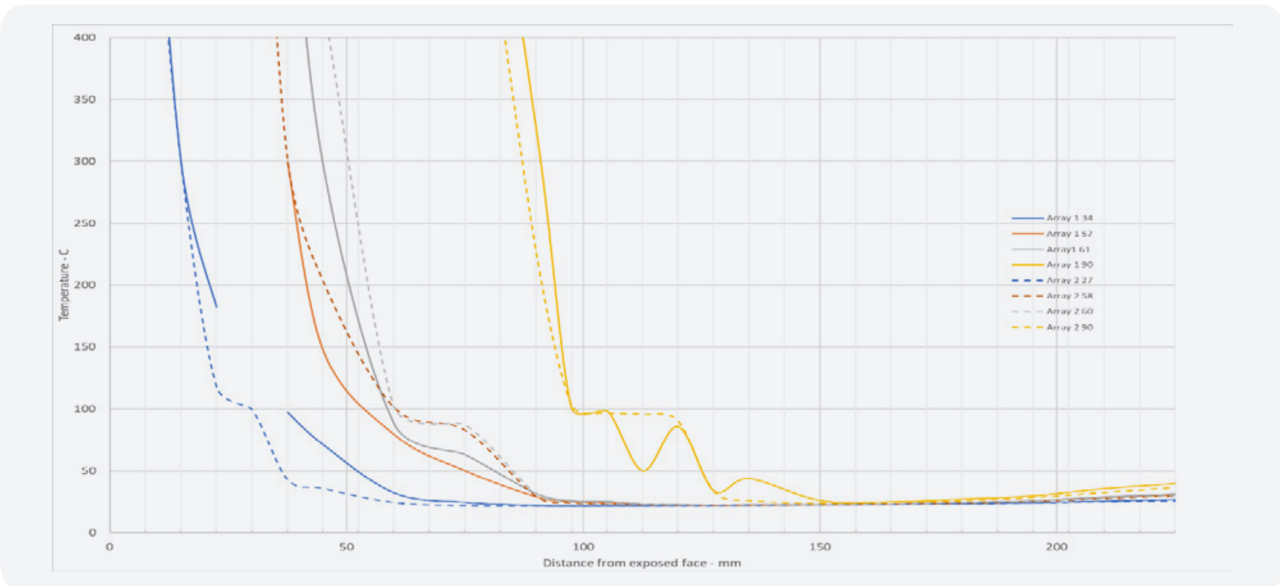


Figure 159: Temperature contours relative to the fire-exposed face for unprotected CLT exposed to standard AS 1530.4 at various time intervals.

From a review of Figure 159, after 60 min of test there was no significant increase in temperature of the middle lamella (90 mm to 135 mm from the fire-exposed face), but after 90 min the char interface would be close to 90 mm and some loss of strength and stiffness would occur across the central lamella.

This implies that a 60-90 min structural adequacy level can be expected and, at reduced load levels, a 120 min structural adequacy level may be viable for floors with no protection to the underside and with at least five 45 mm lamella.

Similarly, from an examination of Figure 160 and Figure 161, structural adequacy may be able to be maintained for 120 min with one layer of 16 mm fire-protective grade plasterboard and 180 min with three layers of 16 mm fire-protective grade plasterboard, but these estimates would need to be confirmed by full-scale testing. If load ratios are reduced, further increases in fire resistance performance may be obtained.

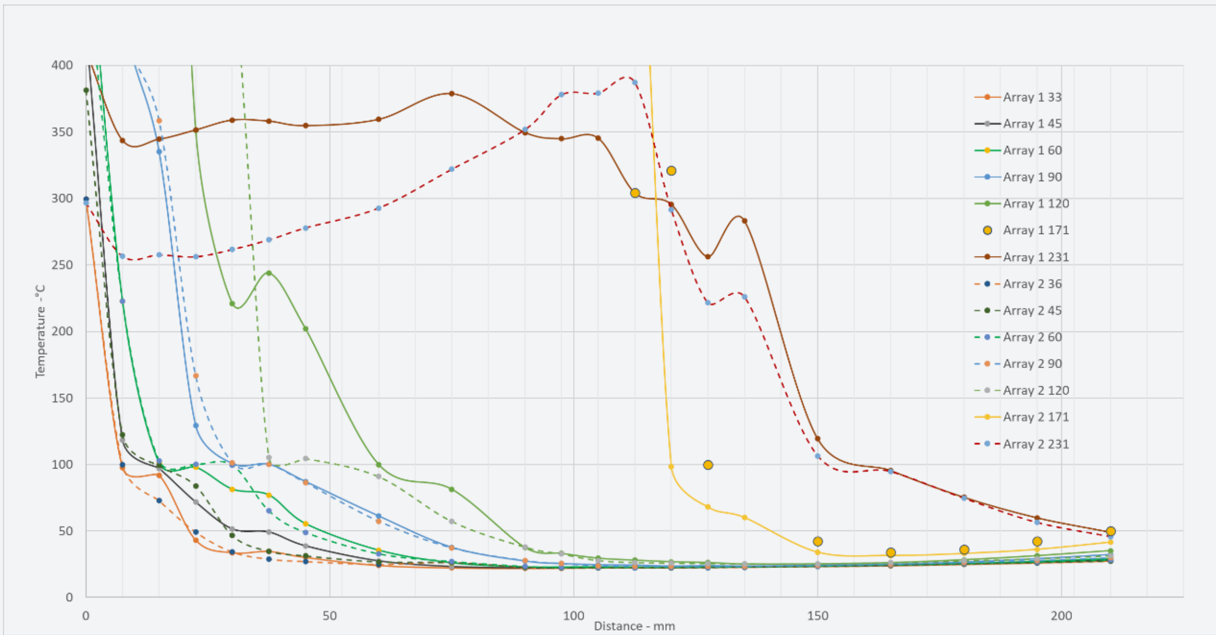


Figure 160: Temperature contours relative to the fire-exposed face for CLT protected by one layer of 16 mm fire-protective grade plasterboard exposed to standard AS 1530.4 heating regime at various time intervals.

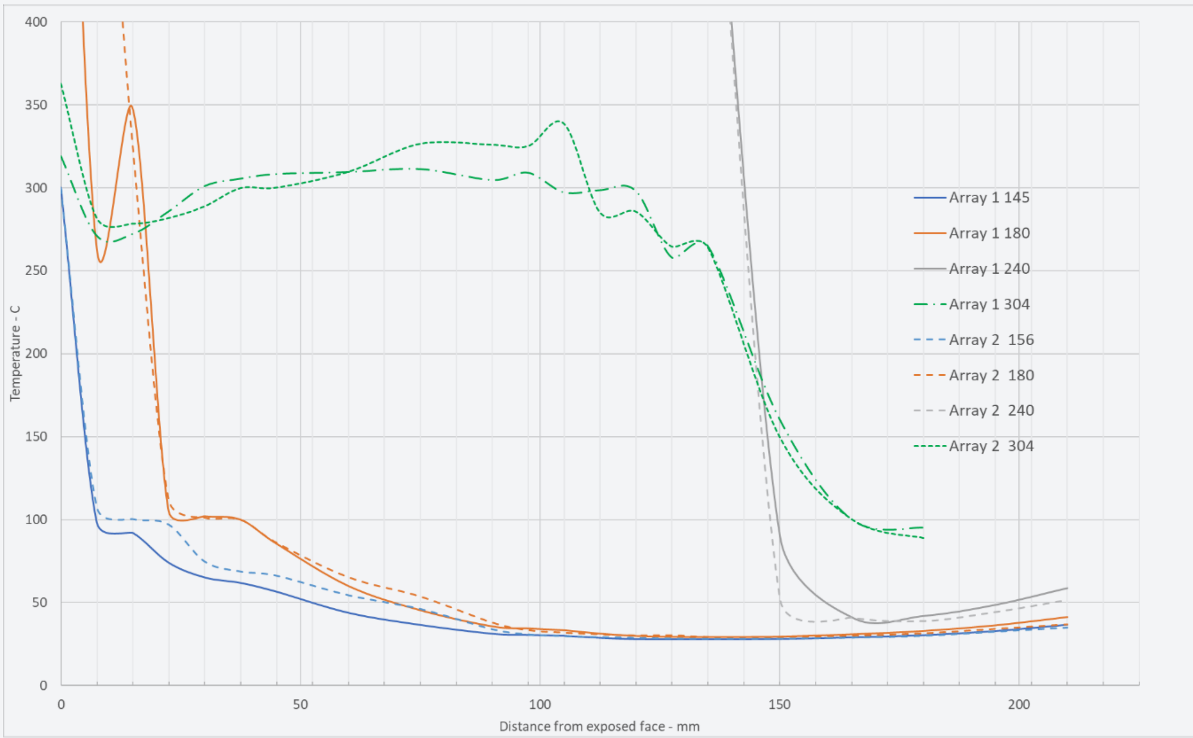


Figure 161: Temperature contours relative to the fire-exposed face for CLT protected by three layers of 16 mm fire-protective grade plasterboard exposed to standard AS 1530.4 heating regime at various time intervals.

Performance of joint details

Each specimen included a 50 mm half-lap joint with the bearing surfaces in contact and a 3 mm clearance at the ends (shoulder position) as shown in Figure 162 to represent typical tolerances.

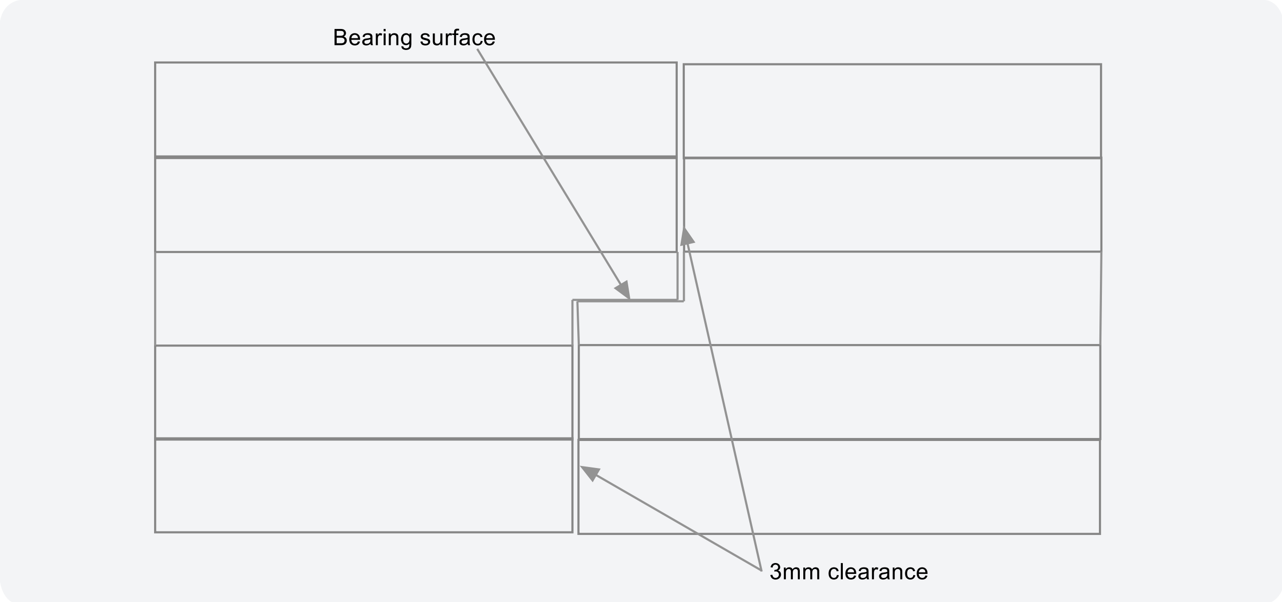


Figure 162: Half-lap joint configuration.

In Test 1 three details were evaluated with no protective coverings applied to the fire-exposed face. The following results were achieved with respect to the AS 1530.4 integrity criterion.

Table 89: Test 1 half-lap joint results – No fire-protective coverings applied to fire side.

Joint ref	Joint treatment	Joint Integrity (min)	Panel Integrity (min)
1	Unprotected	94	No failure at 151 (min)
2	Two beads of mastic applied to bearing surfaces	131	
3	Plasterboard cover on the unexposed side	143	

The results indicate that the joint detail tends to be the limiting criteria with respect to integrity unless adequately protected.

An understanding of the failure modes can be obtained from examination of the temperature data plotted in Figure 163. The CLT temperatures measured at the joint at distances from the fire-exposed face of 90 mm, 112.5 mm (on half-lap bearing surfaces) and 135 mm have been compared with data measured at distances of 90 mm and 112.5 mm from the fire-exposed face in the body of the CLT (array 1).

The char rate was accelerated at all the joint positions and integrity failure of the unprotected joint detail occurred substantially before the char depth in the body of the CLT panels had reached mid-depth. The performance of the joints was improved using a fire-resistant sealant applied to the bearing surfaces or the application of plasterboard over the joint on the non-fire side. The plasterboard cover was initially screw fixed without sealing around its perimeter allowing substantial leakage through the joint which would be expected to degrade the performance compared to a sealed plasterboard cover.

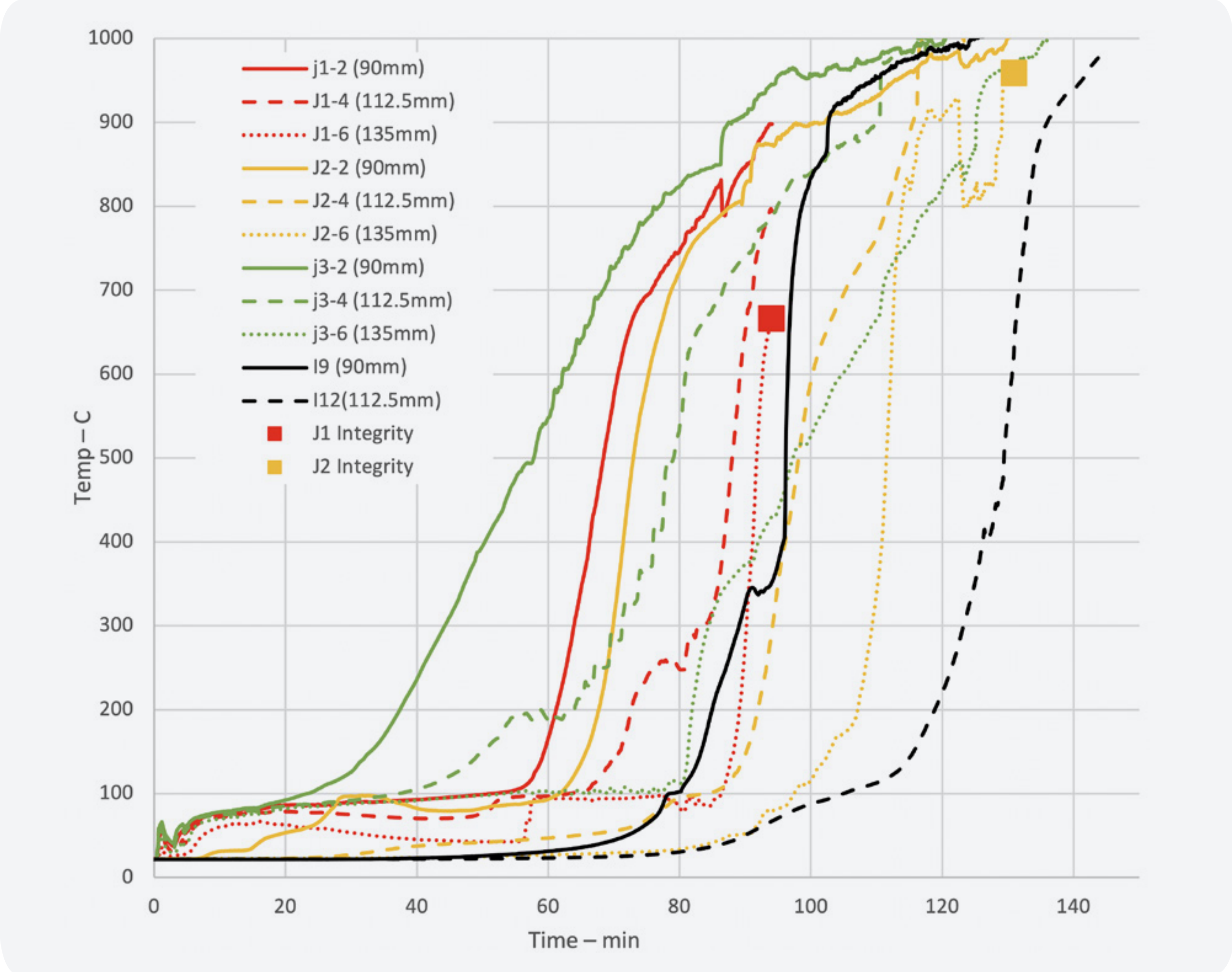


Figure 163: Half-lap joint temperature analysis from Test 1 – no fire-protective coverings to fire-exposed face.

Note: J1 Unprotected, J2 Mastic applied to bearing surfaces, J3 Plasterboard cover to non-fire side. I9 and I12 temperatures measured within CLT away from the joint.

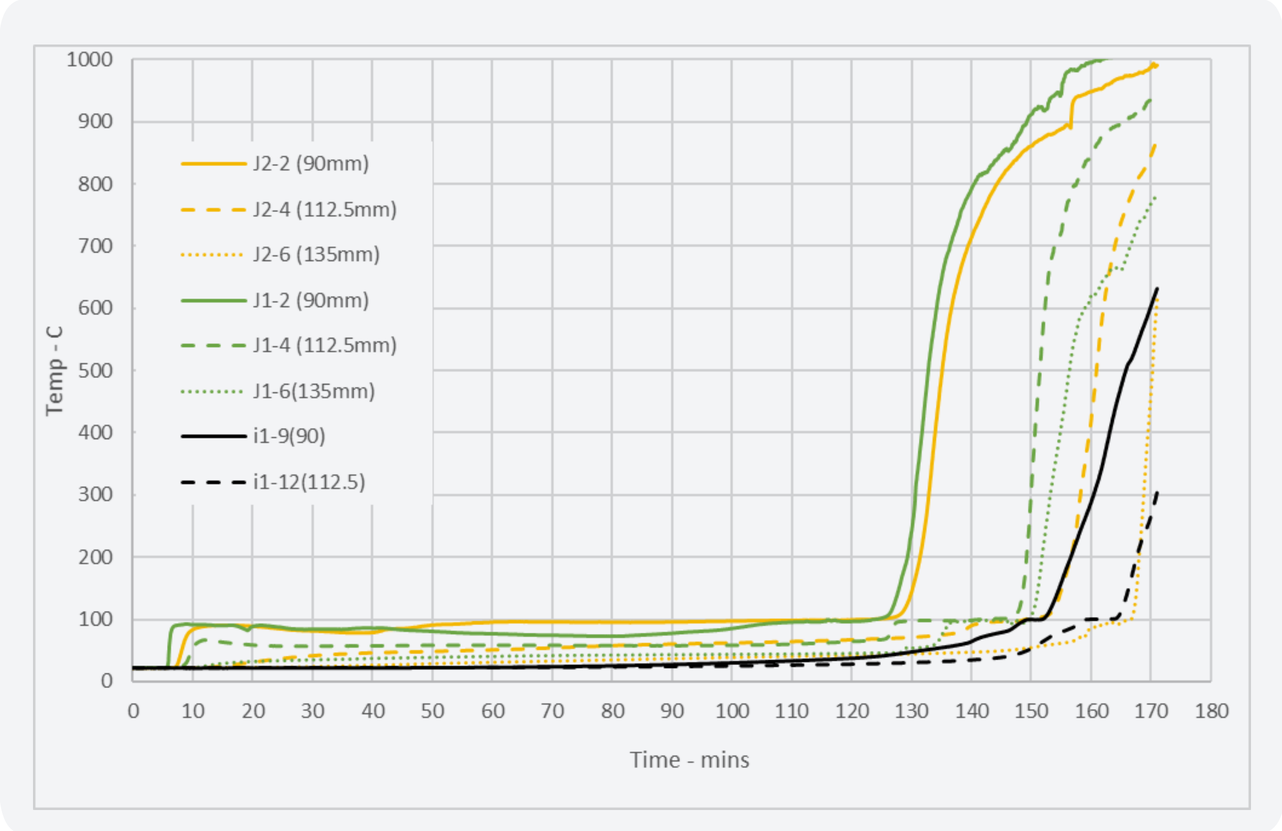
Similar behaviour was demonstrated with a similar specimen exposed to the more severe hydrocarbon regime. Relevant results are summarised in Table 90.

Table 90: Test 7 Half-lap joint performance when exposed to the hydrocarbon heating regime – no fire-protective coverings applied to fire side.

Joint ref	Joint treatment	Joint Integrity (min)	Panel Integrity (min)
1	Unprotected	68	No failure at 109
2	Two beads of mastic applied to bearing surfaces	75	
3	Plasterboard cover on the unexposed side	No failure at 109	

In the tests performed with fire-protective grade plasterboard, the perimeter of the plasterboard joint cover on the non-fire side was sealed to simulate a continuous face applied sheet. In these tests, failure did not occur at the joint positions during the heating period. The accelerated charring of the CLT at the joint was still greater than the body of the CLT. Data from Test 2 in Figure 164 shows that an integrity failure at the joint position had not occurred prior to the char depth in the body of the CLT reaching mid-depth, although the temperature trends indicate that failure could have been imminent for the mastic-only seal.

Based on the above discussion, joints should be incorporated in full-scale fire tests with representative sealing details. If the inherent fire resistance of the CLT as a fire-separating element is to be fully realised, careful detailing of joint treatments will be required.



Note: J1 Plasterboard cover to non-fire side, J2 Mastic applied to bearing surfaces, I9 and I12 temperatures measured within CLT away from the joint.

Figure 164: Half lap joint temperature analysis from Test 2 – one layer of 16 mm fire-grade plasterboard applied to fire-exposed face.

Impact of different heating regimes

Comparative test program

Alternative heating regimes are included in Appendix B of AS 1530.4:2014[18.] The Standard notes that, "Many modern fully developed fires in buildings and industrial applications are characterised by a very rapid growth to temperatures significantly higher than those specified in the standard fire resistance test", and that, "The hydrocarbon heating curve has been included to provide a means for the evaluation of elements of construction under more rapid heating conditions". The hydrocarbon heating regime was therefore adopted to obtain data for comparison with specimens exposed to the standard heating regime.

The hydrocarbon and standard heating regimes of AS 1530.4 are compared in Figure 165, together with data from enclosure tests reported by McGregor[58] that included fire-protected CLT and exposed CLT elements with a typical residential fuel load. Also included is a plot of the EN 1991-1-2:2002 parametric heating curve derived for the protected enclosure. If the slower pre-flashover growth phases of the experimental results are ignored, the hydrocarbon and standard regime will tend to bound the experimental results and the calculated parametric curve until the decay phase.

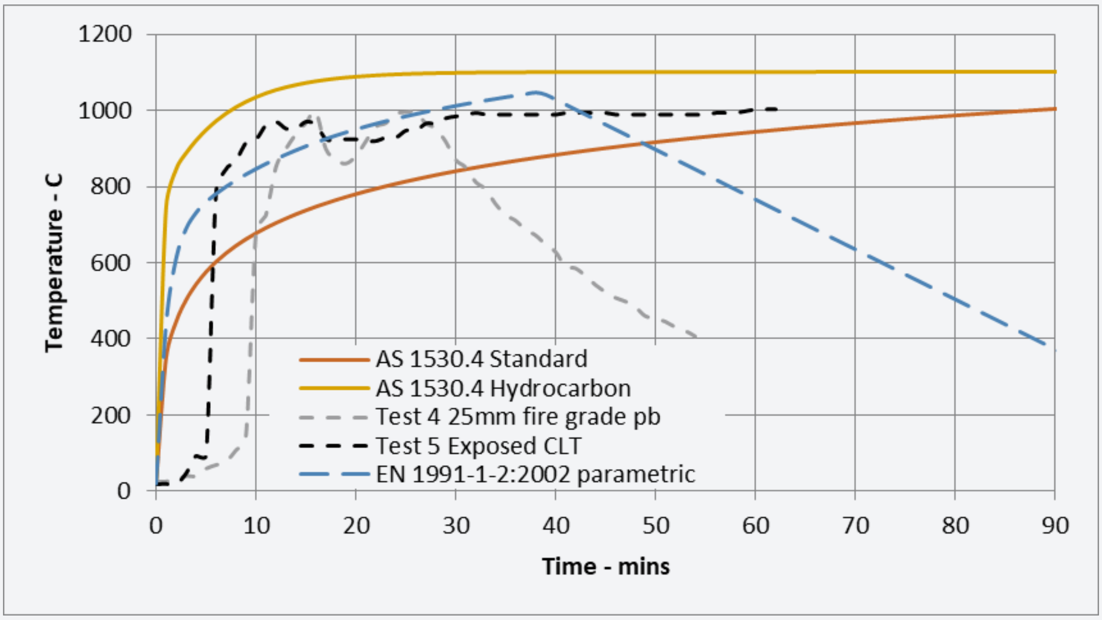


Figure 165: Comparison of AS 1530.4 standard and hydrocarbon heating regimes with experimental results from McGregor[58].

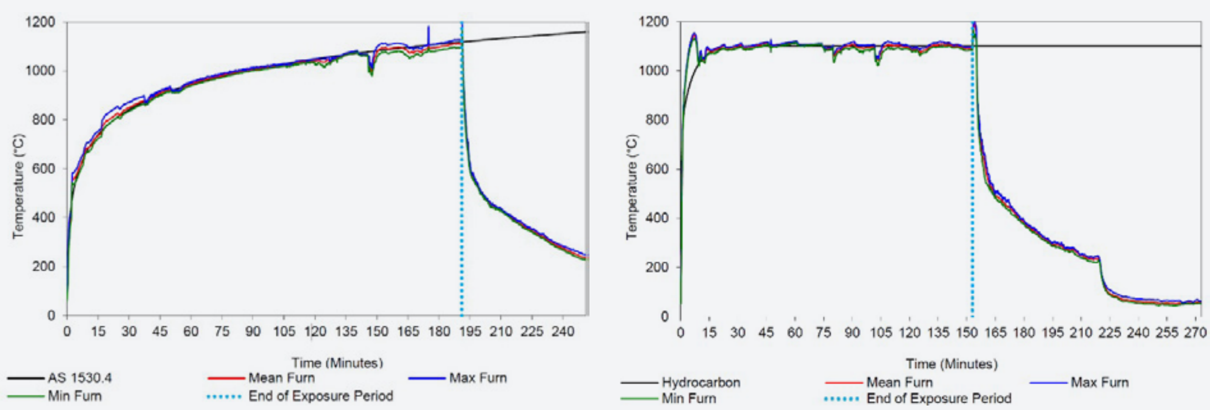
The direct comparative tests undertaken in the test series are summarised in Table 91.

Table 91: Summary of comparative tests undertaken.

Test configuration	Standard heating regime	Hydrocarbon heating regime
Exposed CLT	Test 1	Test 7
CLT protected by 2 x 16 mm PB	Test 3	Test 5
CLT protected by 1 x 16 mm PB	Test 2	Test 9

CLT protected by 2 x 16 mm thick fire-protective grade plasterboard

The furnace temperatures measured by the thermocouples prescribed in AS 1530.4 during test 3 (standard heating regime) and test 5 (hydrocarbon heating regime) are plotted in Figure 166. Both tests were performed on 225 mm thick CLT panels protected by two layers of 16 mm thick fire-protective grade plasterboard.



Test 3 Standard Heating Regime *Test 5 Hydrocarbon Heating Regime*

Figure 166: Actual furnace temperature conditions for fire tests on CLT protected by two layers of 16 mm fire-protective grade plasterboard.

The performance of the fire-protective coverings in Tests 3 and 5 are compared in Table 92.

Table 92: Comparison of CLT panels protected by two layers of 16 mm thick fire-protective grade plasterboard exposed to standard and hydrocarbon heating regimes.

Test	Heating regime	Test duration (h:min)	PB-CLT interface t_{ch}=300°C	PB. Fall-off (min)	Instantaneous char rates (mm/min)	
					Protected	Exposed
3-49385400	Standard	3:11	85	L1≈92-110 L2=145	0.28	1.68
5-49385600	Hydrocarbon	2:33	60	L1≈56-65 L2=102	0.56	1.71

The greater exposure during the early stages of the hydrocarbon heating regime had the following impacts:

- time for plasterboard CLT interface to reach 300°C reduced from 85 to 60 min
- fall-off time for fire-protective coverings reduced from 145 to 102 min
- instantaneous char rate with protective coverings in place increased from 0.28 to 0.56 mm/min (i.e. doubled).

The char rates after the fire-protective coverings fell away were similar for both regimes 1.68-1.71 mm/min. This can be explained by examination of the furnace temperatures when the fire-protective coverings fell away:

- hydrocarbon – prescribed temperature had plateaued at approximately 1100°C when fall-off occurred after 102 min
- standard –prescribed temp. 1077°C after 145 min increasing to 1110°C after 180 min.

Therefore, at the time when the CLT panels were directly exposed to the furnace, the furnace temperature would have been expected to be similar in both tests. The similarity of the heating conditions after board fall-off is demonstrated further by heat flux measurements (Figure 167) in which the standard heating regime is offset to align fall off times in the right-hand plot.

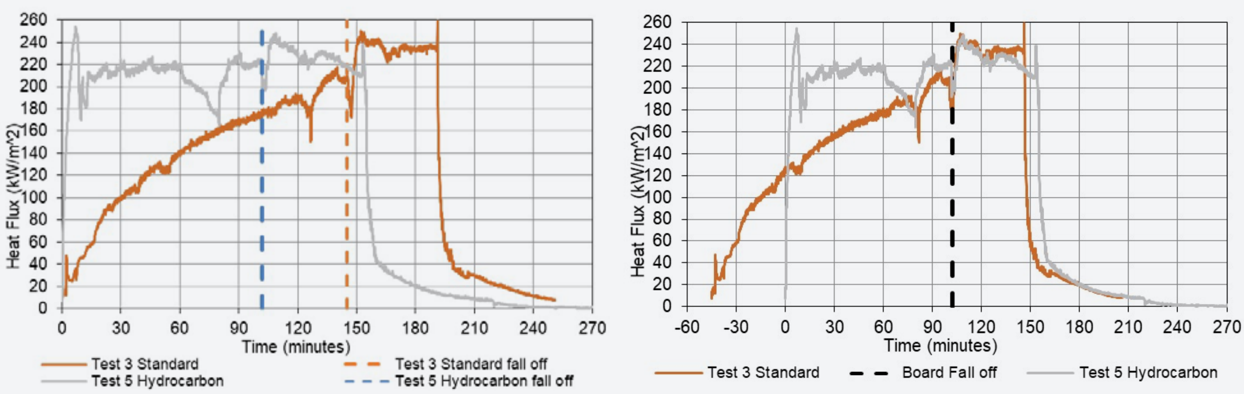
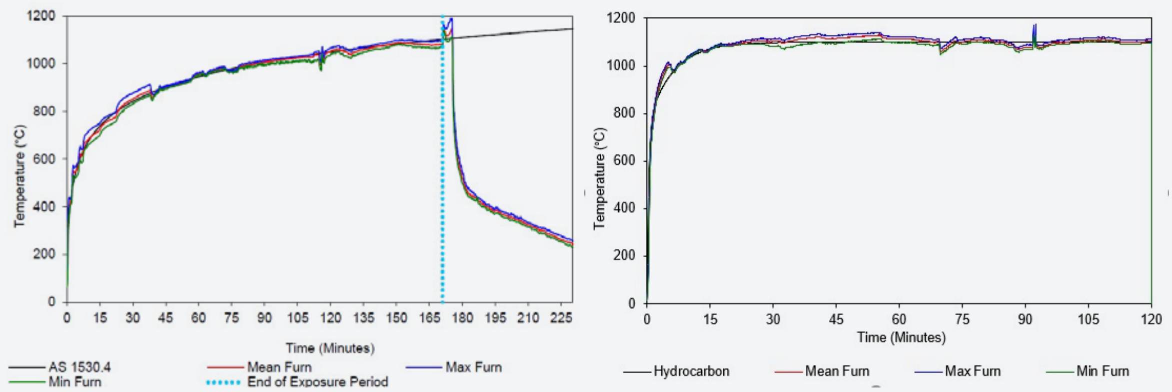


Figure 167: Heat flux measured at soffit of specimens with 2 x 16 mm fire-protective coverings.

CLT protected by 1 x 16 mm thick fire-protective grade plasterboard

The furnace temperatures measured by the thermocouples prescribed in AS 1530.4 during test 2 (standard heating regime) and test 9 (hydrocarbon heating regime) are plotted in Figure 168. Both tests were performed on 225 mm thick CLT panels protected by one-layer of 16 mm thick fire-protective grade plasterboard.



Test 2: Standard Heating Regime

Test 9: Hydrocarbon Heating Regime

Figure 168: Actual furnace temperature conditions for fire tests on CLT protected by one layer of 16 mm fire-protective grade plasterboard.

The performance of the fire-protective coverings in tests 2 and 9 are compared in Table 93.

Table 93: Comparison of CLT panels protected by 1 x 16 mm thick fire-protective grade plasterboard exposed to standard and hydrocarbon heating regimes.

Test	Heating regime	Test duration (min)	PB-CLT interface t_{ch}=300°C	PB. Fall-off (min)	Est time to 125 mm char (min)
2-49385300	Standard	171	32	115	175[1]
9-54455301	Hydrocarbon	120	18	69	125[2]

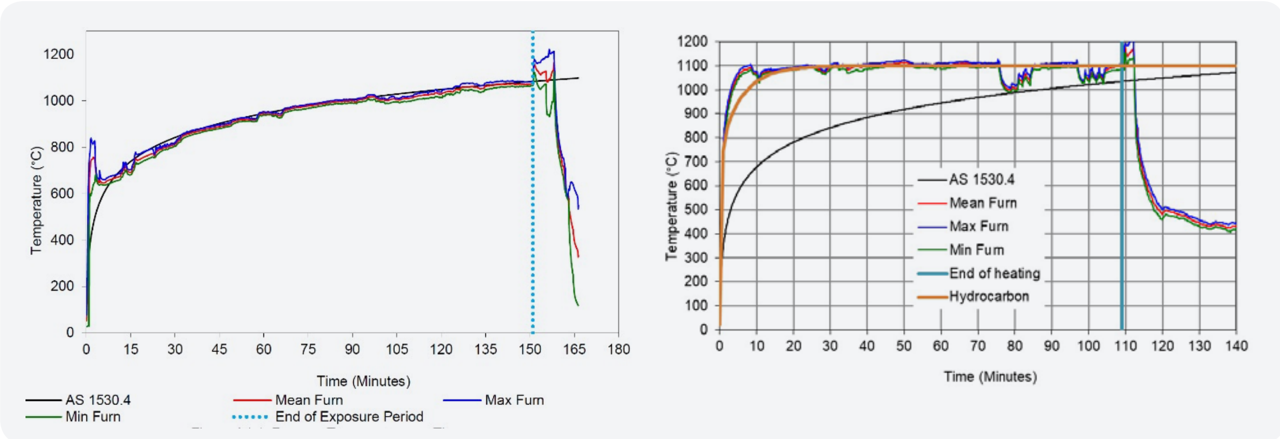
Notes

1. Extrapolated using correlation derived in Figure 177.

2. Char depth measured after test (reduced by 5 mm to allow for additional charring prior to suppression).

Exposed timber

Tests 1 and Test 7 were undertaken with unprotected CLT exposed to the standard and hydrocarbon heating regimes respectively. Furnace temperatures measured using thermocouples as prescribed in AS 1530.4 are shown in Figure 169. In both the hydrocarbon and standard tests there was an early peak above the prescribed heating conditions. These could have caused accelerated charring in the early stages of the tests.



Test 1 Standard Heating Regime *Test 7 Hydrocarbon Heating Regime*

Figure 169: Actual furnace temperature conditions for fire tests on unprotected CLT.

The time to reach nominated char depths was determined by measuring temperatures at various depths in the CLT panels and these are plotted against time in Figure 170.

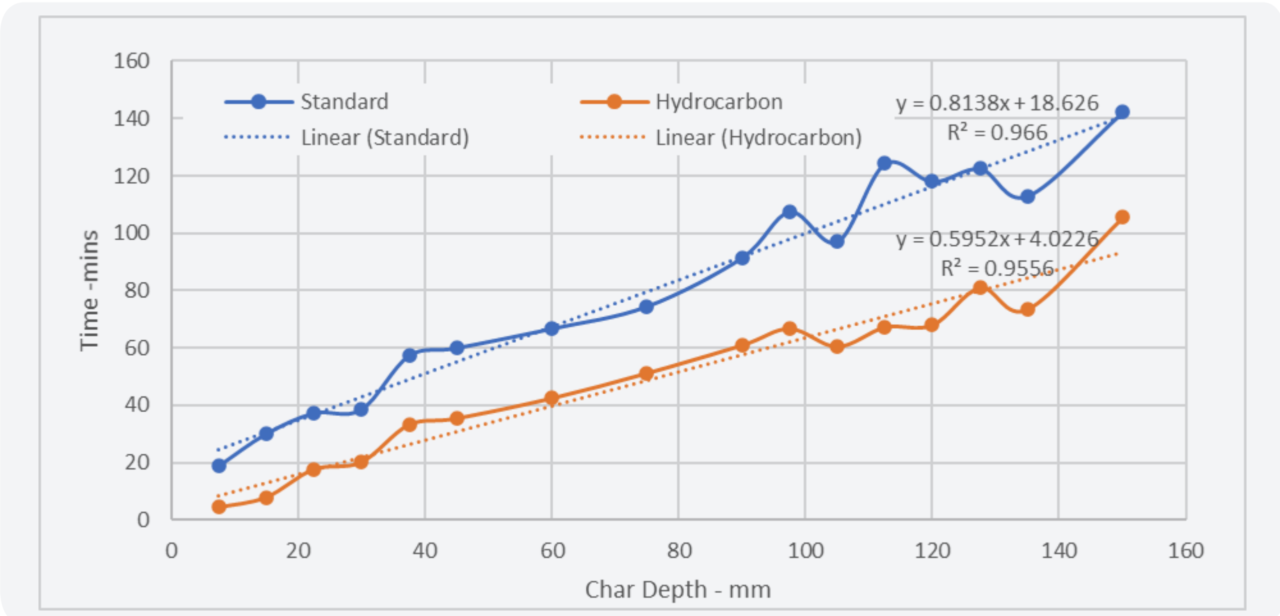


Figure 170: Comparison of char depths for unprotected CLT exposed to standard and hydrocarbon heating regimes.

Lines of best fit for char depths between 7.5 mm and 150 mm were plotted for comparison. Note that the final data point for the hydrocarbon heating regime occurred after the furnace temperature deviated from standard hydrocarbon heating conditions.

It is significant that, when exposed to the standard heating regime, the trend line intersects the time axis at 19 min whereas the trend line when exposed to the hydrocarbon heating regime intersects the time axis at 4 min. This outcome is consistent with heat flux measurements at the underside of the specimens that remained at approximately 20 kW/m^2 until approximately 21 min had elapsed when exposed to the standard heating regime whereas when exposed to the hydrocarbon heating regime the heat flux rapidly increased to 180 kW/m^2 after approximately 5 min as shown in Figure 171.

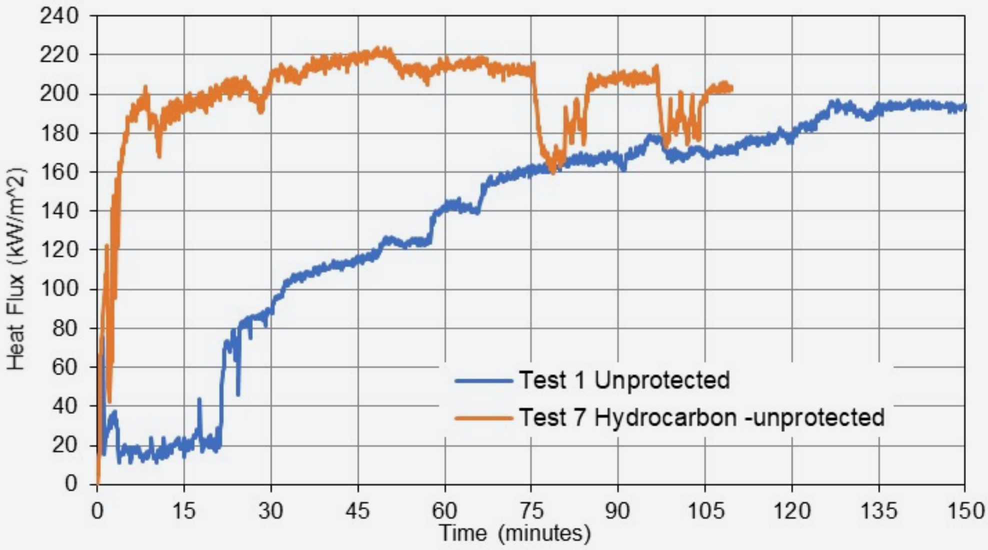


Figure 171: Comparison of heat flux at specimen soffit with CLT panels exposed to the standard and hydrocarbon heating regimes in Tests 1 and 7 respectively.

Similar early plateaus were recorded for specimens protected with one and three layers of plasterboard but were less pronounced when protected with two layers of plasterboard during tests performed using the standard heating regime.

During these early stages, the plate thermometers also recorded temperatures slightly below the sheathed thermocouples prescribed by AS 1530.4; which is consistent with a relatively low incident radiant heat flux component compared to convective heat flux and the slower time response of the PT.

To further explore these anomalies in Tests 7 and 8, additional instrumentation was provided to measure temperature contours close to the soffit of the specimens (Figure 172 and Figure 173). The thermocouples were mounted through the specimens but were not run along isotherms within the furnace because of the risk of providing additional support to sections of CLT or plasterboard therefore conduction through the sheathed cable could have had a minor impact on the measured temperatures.

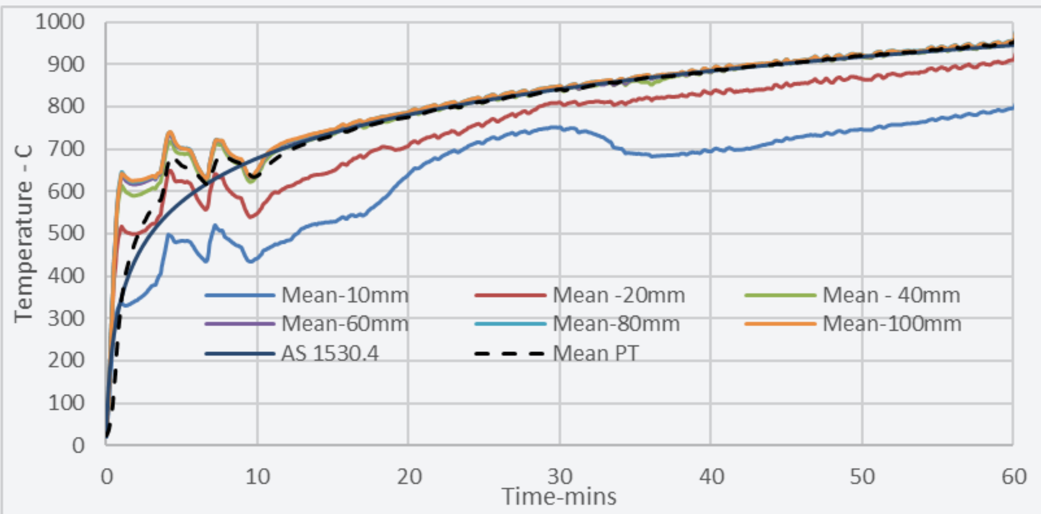


Figure 172: Temperature contours below soffit of Test 8 CLT protected by a single layer of 16 mm plasterboard exposed to the standard heating regime.

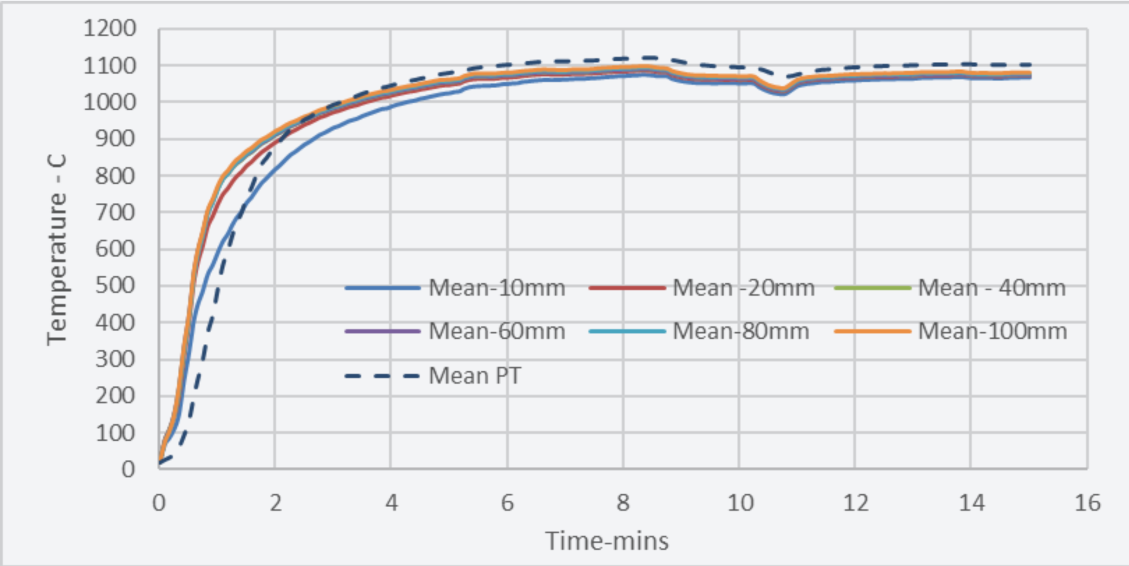


Figure 173: Temperature contours below soffit of Test 7 unprotected CLT exposed to the hydrocarbon heating regime during the early stages of the test

It can be observed from Figure 172 that when exposed to the standard heating regime the temperatures within 20 mm of the specimen were substantially less than those 100 mm from the soffit.

Performance of fire-protective grade plasterboard

Overview of plasterboard performance

Plasterboard is commonly used as a fire-protective covering for timber members and enhances the fire resistance by:

- delaying the onset of charring and strength reduction of the element
- limiting the charring rate while the protective covering remains intact
- limiting the rate of reduction in structural properties of the timber before and after the onset of charring
- delaying the contribution of volatiles released during pyrolysis to the combustion process within a fire enclosure
- restricting the supply of oxygen limiting char oxidation.

The performance of fire-protective grade plasterboard is influenced by fixing/installation methods; particularly when subjected to longer fire resistance exposure periods and the results are only applicable to the total system including fixings.

Onset of charring

The onset of charring is commonly assumed to commence when the interface with timber exceeds 300°C. The time for this to occur is summarised in Table 94 from tests performed under the standard and hydrocarbon heating regimes.

Table 94: Consolidation of time CLT-PB interface exceeds 300°C when exposed to the hydrocarbon and standard heating regimes.

Configuration	Time CLT-PB interface exceeds 300°C (t_{ch}) (min)		Test References	
	Standard regime	Hydrocarbon regime	Standard regime	Hydrocarbon regime
1 x 16 mm FPGPB	32 34 32	18	49385300 49385700 54455500	54455301
2 x 16 mm FPGPB	85	60	49385400	49385600
3 x 16 mm FPGPB	144	-	49385500	

The National Construction Code deems that one layer of 16 mm fire-protective grade plasterboard will prevent the interface temperature exceeding 300°C for 30 min when exposed to the standard heating regime. The test series described in this report confirmed the deemed value of 30 min.

Board fall-off times

The fall-off times for the plasterboard facings are summarised in Table 95. The fall-off times should be considered upper bounds because the specimens are intermediate scale and an optimum fixing system was used, maintaining edge distances of at least 38 mm to reduce the risk of tearing/pull-out at edge fixing positions and the fixing spacing reduces sagging between fixings.

Plasterboard fall-off times were estimated primarily based on interface temperatures measured between plasterboard sheets and between the plasterboard and CLT. As the boards fall away there is a rapid increase of the interface temperature to a value approximating to the furnace temperature.

Further confidence in the estimates of the time of exposure of the CLT is provided from reviewing gas flow and furnace conditions which vary as the combustion and/or heat transfer within the furnace is modified by exposure of the CLT.

The time between commencement of charring and fall-off of the board system, exposing the CLT, reduces as the number of layers of fire-protective grade plasterboard increases. This may not apply to other types of fire-protective covering that may retain their strength for longer periods than plasterboard.

Table 95: Critical times for board performance events.

Test ref	FPGPB facings	Heating regime	Time(min) CLT -PB interface > 300°C (t_{ch})	Time Timber exposed (min)	Time from t_{ch} to exposure (min)	PB fall-off (min)	Heating period (min)
H2	1 x 16 mm	Standard	32	115	83	Face Layer 115	171
H3	2 x 16 mm	Standard	85	145	60	Face layer 92-110 Base layer 145	191
H4	3 x 16 mm	Standard	144	179	35	Face layer 110-128 Intermediate layer 150-156 Base layer 179	240
H9	1 x 16 mm	Hydrocarbon	18	69	51	Face layer 69	120
H5	2 x 16 mm	Hydrocarbon	60	102	42	Face layer 56-65 Base Layer 102	153

Estimating the timing of a contribution from protected CLT to fire severity

The analysis (England[12]) undertaken in support of the Proposal-for-Change (PFC) to permit mid-rise Fire-protected Timber construction in the NCC 2016 and 2019 made conservative assumptions where data was limited. One of the more significant assumptions was that once the RISF or PB-CLT interface limits of 250°C or 300°C respectively were exceeded, the underlying timber would contribute to the fire severity within an enclosure immediately and continue burning until collapse or intervention. This assumption ignores the ability of fire-protective coverings to restrict the flow of volatiles and air once charring commences and for timber to self-extinguish and will therefore tend to overpredict the contribution from the timber structure to the fire severity.

If a fire is ventilation controlled, due to combustion of the moveable fire load, any additional volatiles will be unlikely to increase the enclosure temperatures but may increase the volatiles expelled through vents and, as a result, increase flame extension and the associated hazards as well as increasing the fire duration.

Based on these considerations, it is preferable for fire-protective coverings to remain in place even after interface temperatures exceed 300°C to continue to limit the exposure of CLT and facilitate fire brigade intervention.

Supply LPG flow rates were measured during the test series to provide an indication of the timing of changes in the combustion processes within the furnace that could result from the release of significant quantities of volatiles into the furnace environment from pyrolysis of timber.

The supply LPG flow measurements show a rapid change coincident with the fall-off time of the fire-protective coverings exposing the CLT panels directly to the furnace as shown in Figure 157. This effect continued after the fall-off event and the LPG flows were similar for the remainder of the test to that required for tests on exposed CLT.

These matters are addressed further below when the behaviour of the CLT floor sections is evaluated during a simulated decay and cooling phase.

Char rates

Char rate background

Generic char rates are specified in various design codes, standards and guidelines such as AS 1720.4[21] and Eurocode 5:Part 1-2: General – Structural fire design[42] and vary in complexity from specification of a single char rate for the whole duration of a fire-resistance test (AS 1720.4 approach) to methods that nominate char rates taking into account factors such as fall-off times for fire-protective coverings and exposure of uncharred timber surfaces after delamination of bonded timber lamella. These are often based on empirical approaches that have been validated for use with the standard fire-resistance heating regime for relatively short heating durations.

This series of tests, with longer durations and heating regimes bracketing a range of enclosure temperatures commonly experienced in fully developed fires, provides data to estimate char rates throughout the test period assuming charring commences at 300°C. Two thermocouple arrays were fitted in the body of a CLT panel in addition to thermocouples measuring the performance of joints and other features

Unprotected CLT

The results for an unprotected CLT specimen exposed to the standard heating regime of AS 1530.4 are shown in Figure 174.

Reasonably consistent results were obtained to a char depth of 90 mm corresponding to an exposure period of approximately 90 min and two distinct zones could be identified for layers 1 and 2. Some acceleration of charring occurred as the char depth exceeded 37.5 mm. At this stage, the glueline at a depth of 45 mm could be expected to have started deteriorating and delamination is considered the most likely cause of the acceleration in char rate. As the char depth increased further, the variability of the data increased, which may be attributed to the variability of the delamination process and fissuring of timber causing uneven heating at various depths.

A line of best fit using the least squares method was derived for each of the lower three lamellae and the char rate can be obtained from the reciprocal of the gradient yielding the instantaneous char rates presented in Table 96. The line of best fit has not been forced to pass through the origin and therefore the regression values are only valid within the stated range of char depths.

The average char rate was also calculated from the commencement of heating as specified in AS/NZS 1720.4:2019[19], to the time for the char layer to reach layer interfaces at depths of 45 mm and 90 mm and at a depth of 127.5 mm and the results included in Table 96.

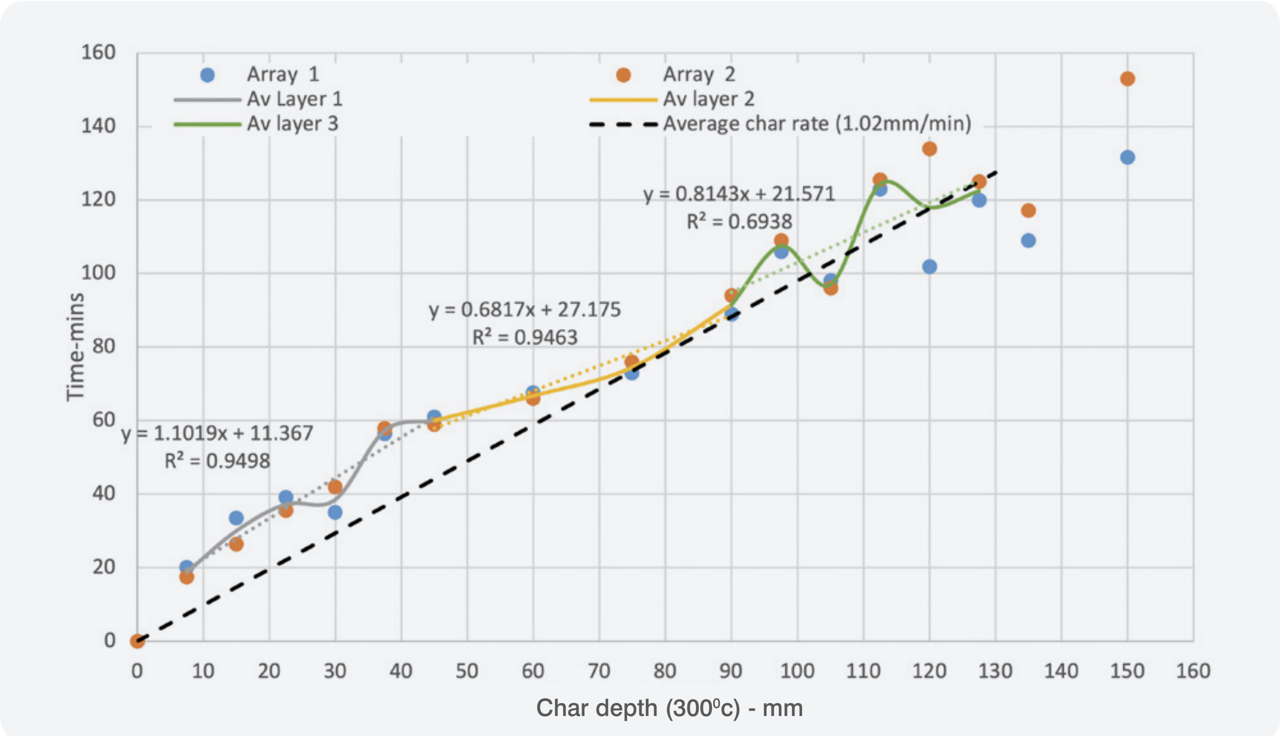


Figure 174: Exposure time v char depth for unprotected CLT panel exposed to AS 1530.4 standard heating regime.

Table 96: Calculated char rates for exposed CLT – exposed to standard heating regime.

Layer	Max Depth from soffit (mm)	Char rates mm/min	
		Lamella	Average from t = 0
1	45	0.91	0.74
2	90	1.47	1.02
3	127.5	1.23	1.02

AS/NZS 1720.4 determines the notional charring rate using the following relationship:

$$c = 0.4 + \left(\frac{280}{\delta}\right)^2$$

c = notional charring rate, in mm/min

δ = timber density at a moisture content of 12% in kg/m^3

The measured density at 9% moisture content was approximately 500 kg/m^3. Since the moisture content at the time of testing was 9%, for comparison with the test data, a density of 500 kg/m^3 was used for the value of δ without adjustment for a moisture content of 12%, yielding a notional char rate of 0.7 mm/min. This value is similar to the average charring rate from commencement of heating to a depth of 45 mm (i.e. before a significant impact from delamination) but is significantly less than the average charring rate of 1.02 mm/min that occurred once delamination started to occur. The current field of application of AS/NZS 1720.1 excludes CLT. Based on the findings from these tests this exclusion is appropriate and the performance of CLT systems should be determined based on full-scale fire tests. However, it would be reasonable to use char calculations for interpolation purposes when assessing the impact of variations from tested prototypes using char data from the prototype tests. Figure 174 shows that the adoption of an average char value of 1.02 mm/min will tend to overpredict the actual char rates prior to delamination during the early stages of a fire-resistance test.

The results for unprotected CLT specimen exposed to the hydrocarbon heating regime are shown in Figure 175. A burner malfunction caused inconsistent heating and furnace conditions after approximately 76 min. The furnace heating regime for this test is shown in Figure 176.

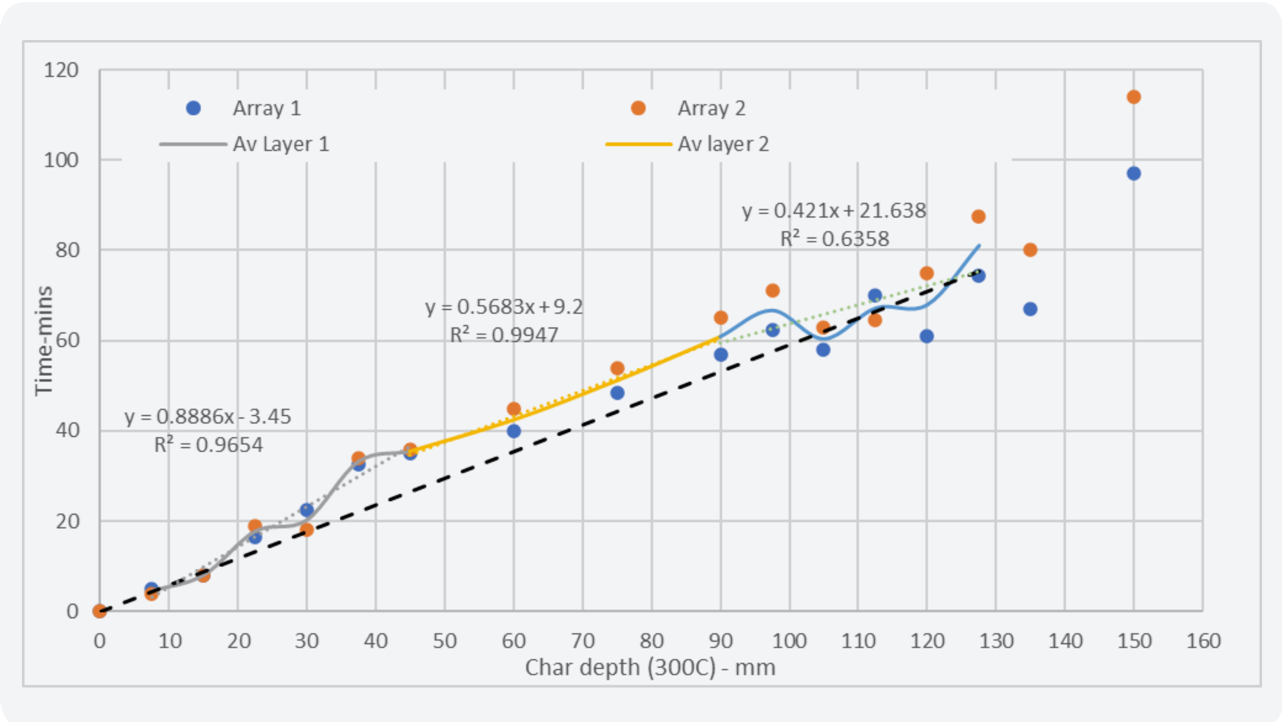


Figure 175: Exposure time v char depth for unprotected CLT panel exposed to hydrocarbon heating regime.

Reasonably consistent results were obtained to a char depth of 97.5 mm, corresponding to an exposure period of approximately 65 min and two distinct zones could be identified for layers 1 and 2. Some acceleration of charring occurred as the char depth exceeded 30 mm. At this time the glue line at a depth of 45 mm could be expected to have started deteriorating and delamination is considered the most likely cause of the acceleration in char rate. As the char depth increased further, the variability of the data increased, which may be attributed to the variability of the delamination process and fissuring of timber causing uneven heating at various depths. The furnace heating variability after 76 min would also have contributed to the variability of the results.

A line of best fit using the least squares method was derived for each of the lower three lamella and the instantaneous char rates calculated from the reciprocal of the gradient are given in Table 97.The line of best fit has not been forced to pass through the origin and therefore the regression values are only valid within the stated range of char depths.

The average char rate was also calculated from the commencement of heating to the time for the char layer to reach layer interfaces at depths of 45 mm and 90 mm and at a depth of 127.5 mm (Table 97).

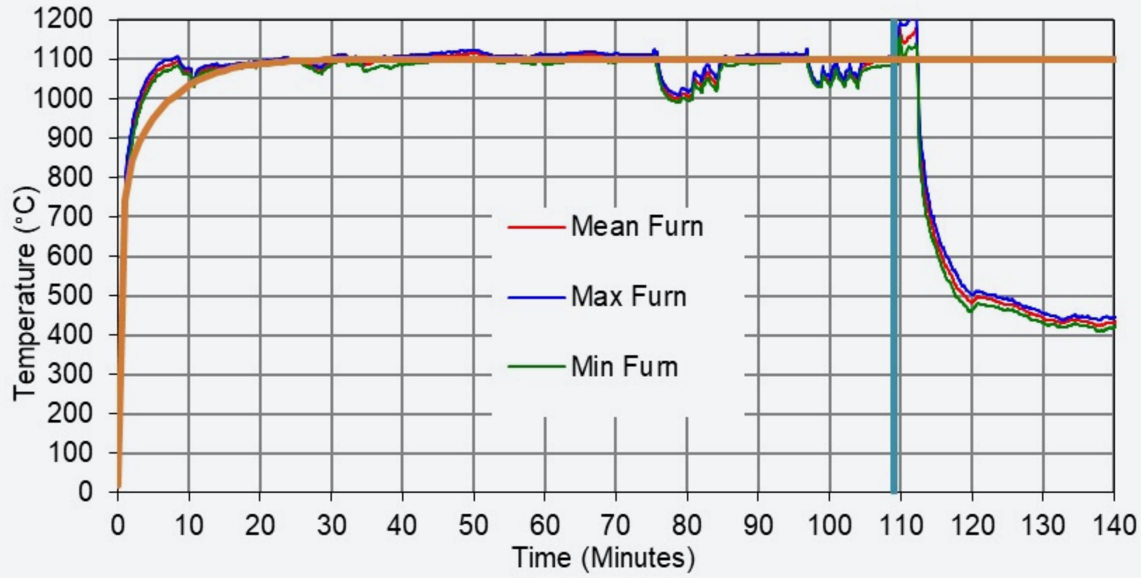


Figure 176: Test 7 furnace temperature compared to the hydrocarbon heating regime.

Table 97: Calculated char rates for CLT exposed to the hydrocarbon heating regime.

Layer	Max depth from soffit -mm	Char rates mm/min	
		Instantaneous	Average from t = 0
1	45	1.13	1.23
2	90	1.77	1.49
3	127.5	2.38	1.69

As expected, the char rates are greater than those obtained with a similar CLT panel exposed to the standard heating regime. The higher values obtained with a hydrocarbon heating regime may be more appropriate for estimating the impact of modern enclosure fires with peak temperatures of 1100°C or greater.

Protected CLT

The results for the CLT panels protected by fire-protective grade plasterboard performed in the initial series of six tests are presented in Figure 177 to Figure 180.

Two distinct zones were identified. The first zone occurs from commencement of charring until the fire-protective grade plasterboard falls away exposing the CLT directly to the furnace. The second occurs after exposure of the CLT and terminates either at the end of exposure to the heating conditions or when the results became inconsistent.

There was little evidence of delamination at the first glue line compared to the unprotected CLT panel. This could be attributed, at least in part, to the mechanical fixing provided by the 65 mm screws fixing the first layer of plasterboard that would have penetrated the second timber lamella. This technique could be further developed and longer screws at reduced spacings used if necessary to mitigate the risk of delamination at the first glue line.

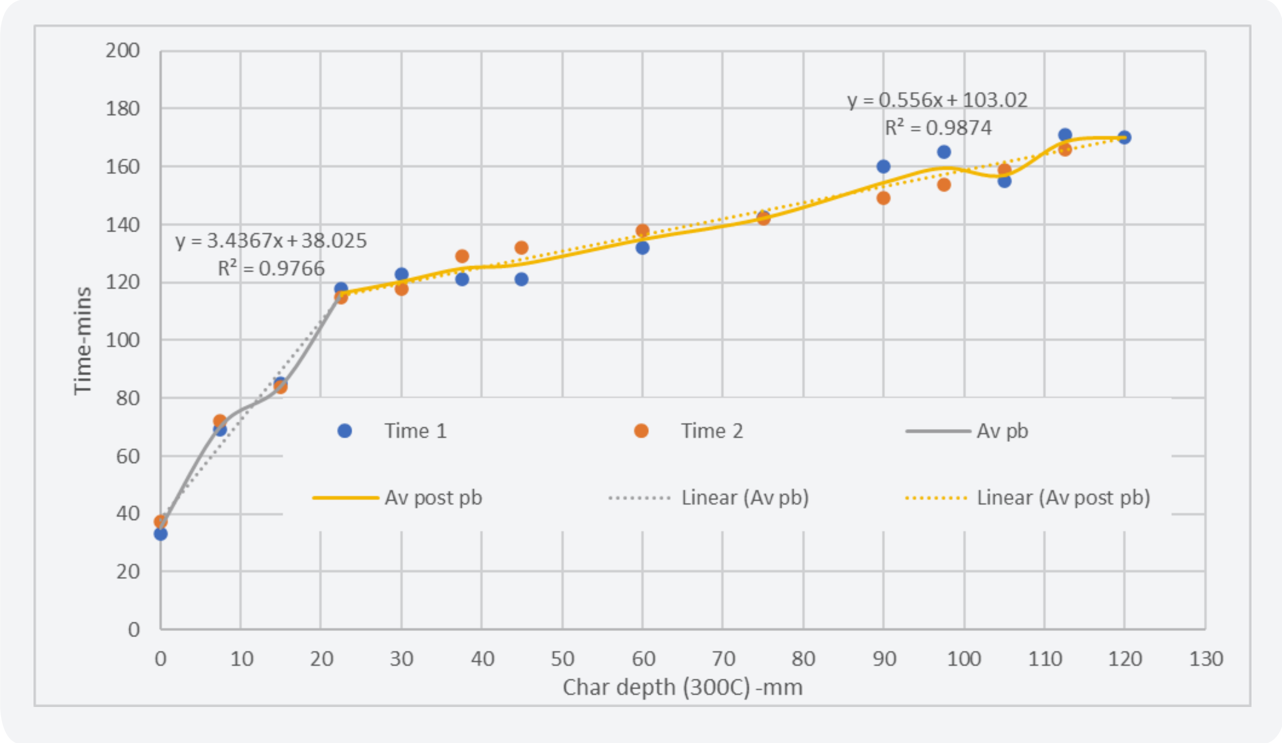


Figure 177: Exposure time v char depth for CLT panel protected by one layer of 16 mm thick, fire-protective grade plasterboard exposed to AS 1530.4 standard heating regime.

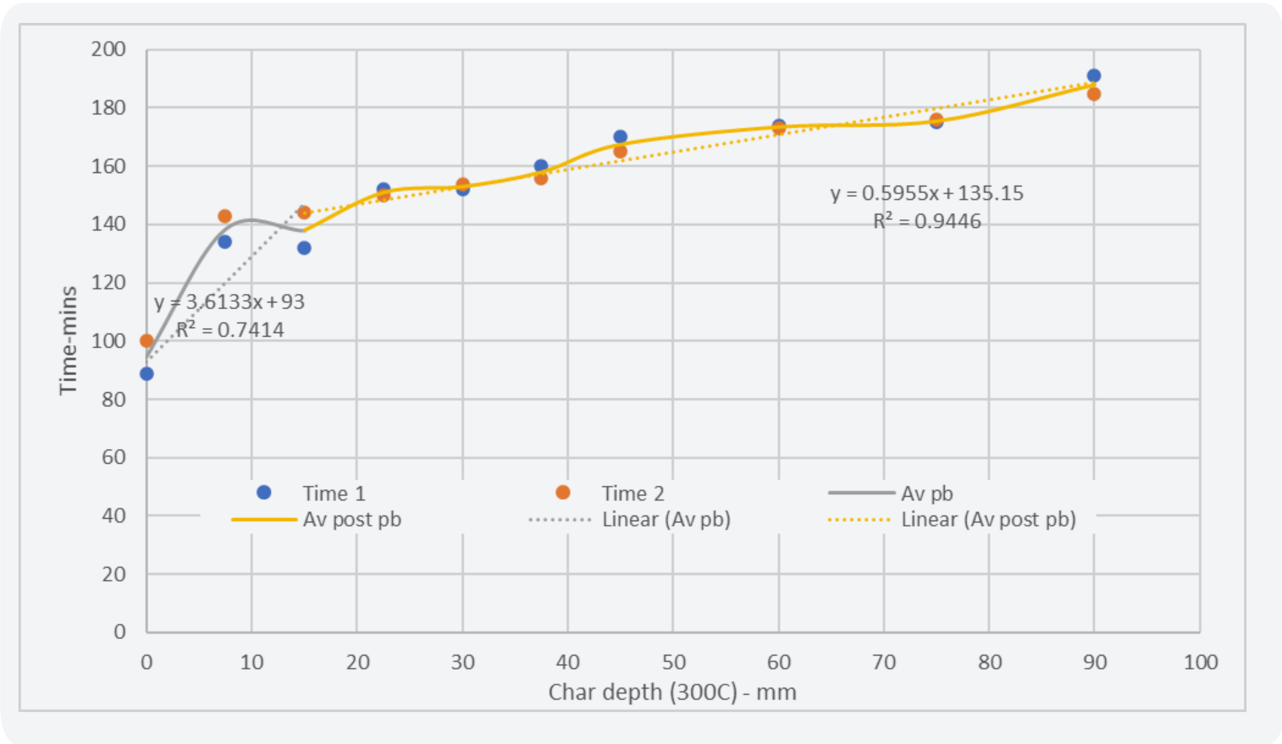


Figure 178: Exposure time v char depth for CLT panel protected by 2 layers of 16 mm thick, fire-protective grade plasterboard exposed to AS 1530.4 standard heating regime.

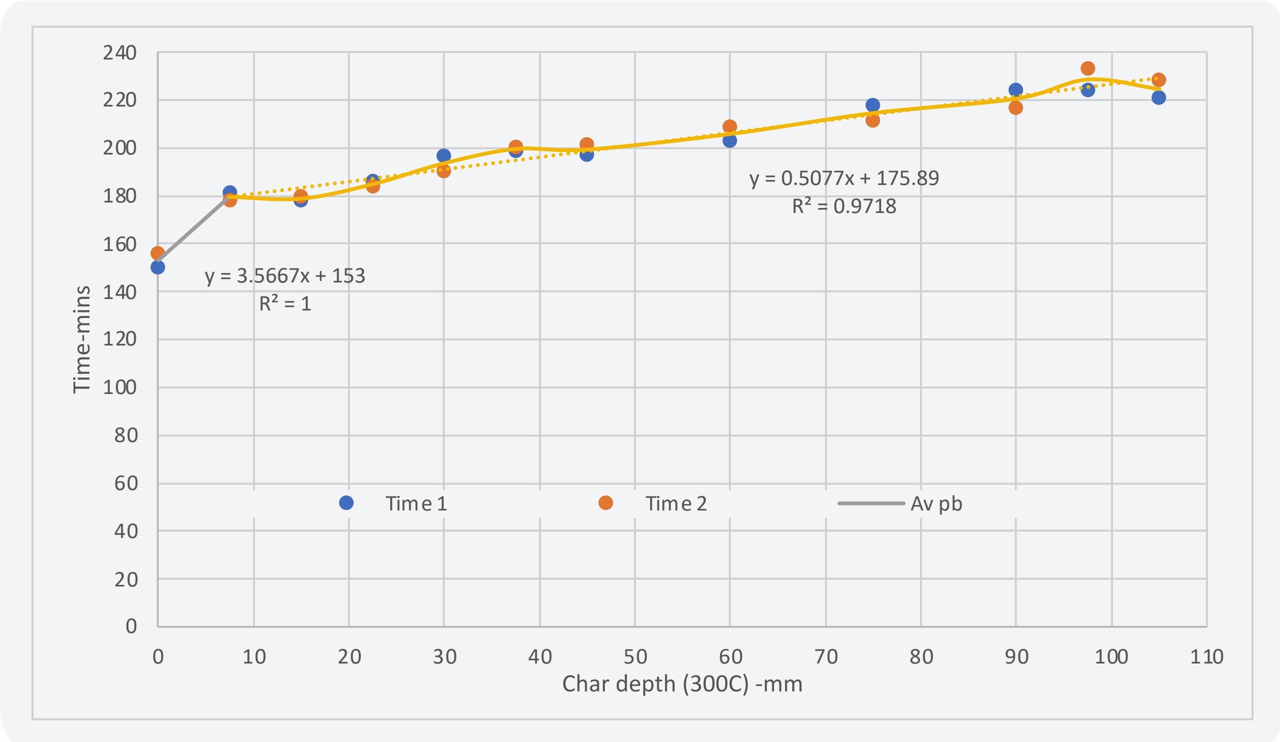


Figure 179 Exposure time v char depth for CLT panel protected by 3 layers of 16 mm thick, fire-protective grade plasterboard exposed to AS 1530.4 standard heating regime.

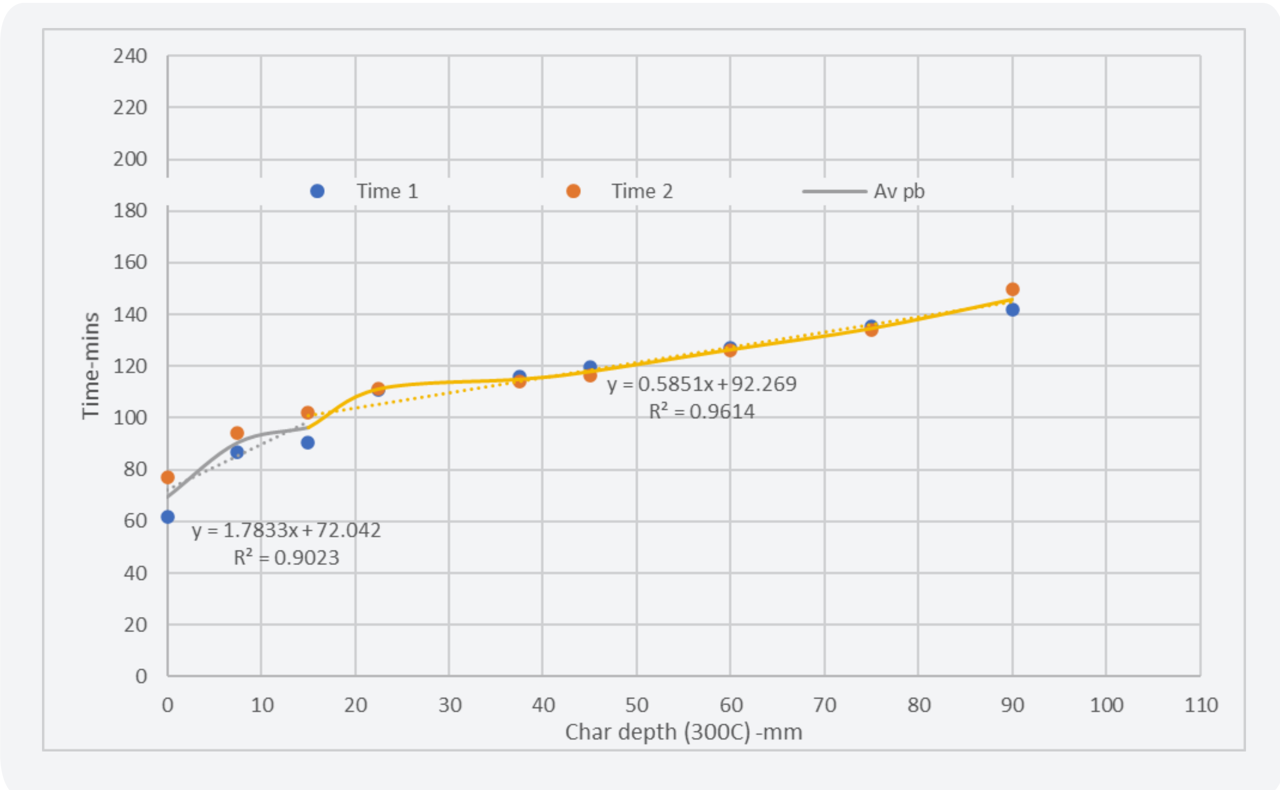


Figure 180: Exposure time v char depth for CLT panel protected by 2 layers of 16 mm thick, fire-protective grade plasterboard exposed to AS 1530.4 hydrocarbon heating regime .

The calculated char rates and performance of the fire-protective grade plasterboard are summarised in Table 98. The results are reasonably consistent for exposure to the standard heating regime with char rates varying between 0.28 mm/min and 0.29 mm/min while the board protection remains in place and 1.68 mm/min to 1.97 mm/min after board fall-off. These char rates do, however, vary considerably from the AS/NZS 1720.4 average notional rate of 0.71 mm/min that is required by the standard to be increased by a factor of 1.1 for protected timber, yielding an increased char rate of approximately 0.78 mm/min while the board is in place. If the board falls away before a char depth of 25 mm, a factor of 2 is applied until a char thickness of 25 mm is attained, yielding a char rate of 1.42 mm.

It is recommended that a cautious approach is adopted when considering the use of AS/NZS 1720.4 char rates for CLT members where the char depth approaches the first glueline and for protected timber members. This is consistent with the NCC mid-rise timber provisions that require Evidence of Suitability in the form of full-scale fire-resistance tests.

Table 98: Fire-protective grade plasterboard performance and char rates during long exposure fire-resistance test.

Test-ref	Protective covering	Heating regime	Time(min) CLT - PB interface > 300°C (t_{ch})	PB fall-off (min)	Instantaneous char rate (mm/min)	
					Protected	Exposed
2-49385300	1 x 16 mm	Standard	32.5	Face Layer 115	0.29	1.80
3-49385400	2 x 16 mm	Standard	85	Face layer ≈92-110 L2=145	0.28	1.68
4-49385500	3 x 16 mm	Standard	144	Face layer 110-128 Intermediate layer 150-156 Base layer 179	0.28	1.97
5 -49385600	2 x 16 mm	Hydrocarbon	60	Face layer ≈56-65 Base layer ≈ 102	0.56	1.71

An additional test was undertaken, designated Test 9 (54455301.1), which subjected a 225 mm thick CLT panel protected by a single layer of 16 mm plasterboard to the hydrocarbon heating regime for 120 min after which the specimen was removed from the furnace and extinguished. The char depth was found to average approximately 130 mm over the central 400 mm of the specimen. Figure 181 shows a representative cross-section after test.

Figure 181: Cross-section of CLT at end of 120 min hydrocarbon heating regime test.

Based on the results in Table 98, once the 300°C interface temperature limit had been exceeded, a char rate of approximately 0.56 mm/min would be expected until board fall-off after which the char rate would be expected to be greater than the 1.8 mm/min for the standard regime. Values of 1.77 and 2.38 mm/min have been assumed for the periods 69 to 90 min and 90 min to 120 min respectively based on the results for unprotected CLT exposed to the hydrocarbon regime from Table 97. In test 9 (54455301), the 300°C interface temperature limit was exceeded after 18 min when exposed to the hydrocarbon heating regime and board fall-off occurred after 69 min.

The char depth after 120 min exposure can be calculated as follows:

Time to char commencement (t_{ch}) = 18 min

Char while board in place (69-18) x 0.56 = 28 mm

Char after board fall-off to 90 min (90-69) x 1.77 = 37 mm

Char from 90 to 120 min after board fall-off (120-90) x 2.38 = 71 mm

Total calculated char depth = 136 mm

This calculation over-predicts the char rate by approximately 6 mm, which is to be expected because the impact of char fall-off tended to increase through the test duration for the unprotected CLT and the protection of the single layer of plasterboard potentially delayed the acceleration of the char rate.

Simulation of the decay and cooling fire phases/post fire test monitoring

Background

The experiments described in the previous sections have shown that there is unlikely to be a significant contribution to fire severity while the fire-protective coverings remain in place.

The concept of self-extinguishment of exposed timber has been investigated by several researchers.(e.g. Crielaard[95] and Emberley[233]). If self-extinguishment can also be demonstrated for Fire-protected Timber elements it would provide further confidence in the NCC changes relating to Fire-protected Timber.

When heating is terminated, temperatures over the cross-section of an element may continue to rise due to the thermal inertia of the element and heat exchange within an enclosure. The effect is commonly described as a thermal wave. Because the strength and stiffness of wood products can be reduced substantially as temperatures exceed 100°C, it can have a significant impact on structural performance.

Post-test monitoring was undertaken after all tests performed using fire-protected and exposed CLT for varying periods, except for Test 9. In addition, heating was terminated after 45 min of Test 6 and 60 min of Test 8 to specifically investigate self-extinguishment.

Self-extinguishment after shorter duration fire test

This part of the program included two intermediate-scale tests to investigate the self-extinguishment characteristics of Fire-protected Timber (Tests 6 and 8). The fire-protective boards will tend to reduce the exposure of the timber and oxygen supply, improving the potential for self-extinguishment and slowing the char rate; but the coverings may also reduce heat losses with the potential to sustain smouldering combustion.

Test 6 was performed on a 105 mm (3 x 35 mm) thick CLT panel protected by 1 x 16mm plasterboard when exposed to the standard heating regime of AS 1530.4 for a period of 45 min. The interface temperature exceeded 300°C after approximately 34.5 min and the test was continued for a further 10.5 min before the specimen was raised above the furnace and the conditions monitored for a further 15 hours; simulating a decay scenario at the end of the 45 min heating period, with a plentiful supply of oxygen while subjected to background heat flux broadly simulating the decay phase.

A second test on a similar configuration designated as Test 8 was undertaken with a heating duration of 60 min to determine if self-extinguishment occurred after 60 min exposure to the standard heating regime. The specimen did not include a heat flux gauge to monitor the heat flux exposure of the specimen, but additional thermocouples were included to measure furnace temperatures at depths of 10 mm to 100 mm below the specimen soffit.

The specified and measured furnace temperatures with both standard AS 1530.4 furnace thermocouples and plate thermometer (PTs) are plotted in Figure 182 for the 45 min heating period.

The specified and measured furnace temperatures with both standard AS 1530.4 furnace thermocouples and PTs are plotted in Figure 183 for the 60 min heating period adopted in Test 8. The area under the mean furnace temperature-time plot exceeded the prescribed standard heat regime plot by approximately 13.5% after the first 10 min of the test. For the remainder of the 60 min heating regime the mean furnace temperature closely followed the standard heating regime. After 60 min, the area under the mean furnace temperature-time plot exceeded the prescribed standard heating regime plot by approximately 1.5%.

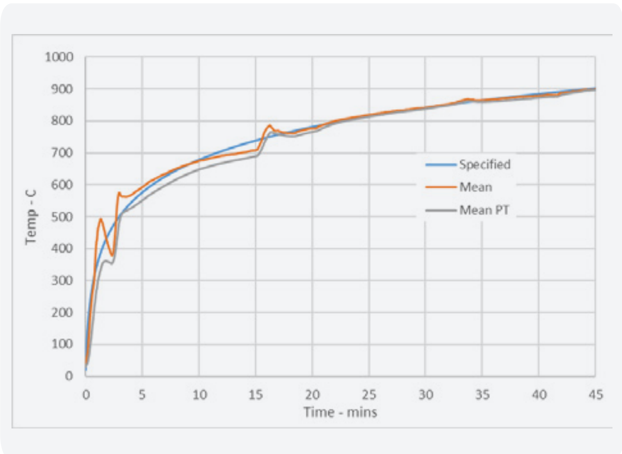


Figure 182: Test 6 furnace temperatures during 45 min heating period.

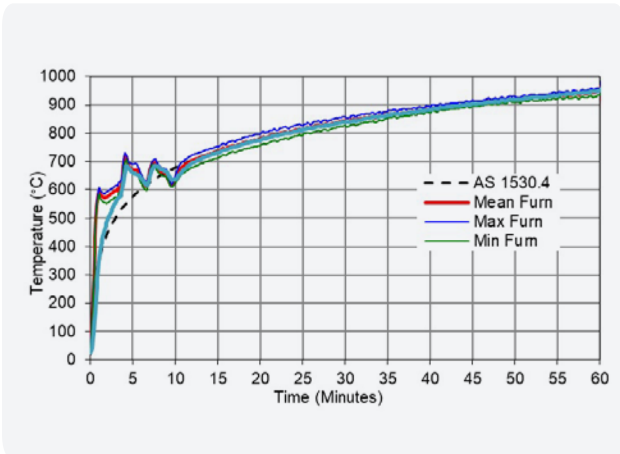


Figure 183: Test 8 furnace temperatures during 60 min heating period.

At the end of the heating periods, the specimens were raised approximately 320 mm above the furnace to allow natural airflow across their surface and data monitoring was continued for 15 hours for Test 6 and 23 hours for Test 8. The distances of the furnace thermocouples and PTs relative to the specimen were maintained throughout this period so that the decaying heat exposure from the furnace during this period was recorded.

The furnace thermocouple data is presented for the first 45 min of the monitoring period for Test 6 in Figure 184 and for the first 60 min of the monitoring period for Test 8 in Figure 185. During this period, the temperatures measured by the furnace thermocouples reduced to approximately 100°C.

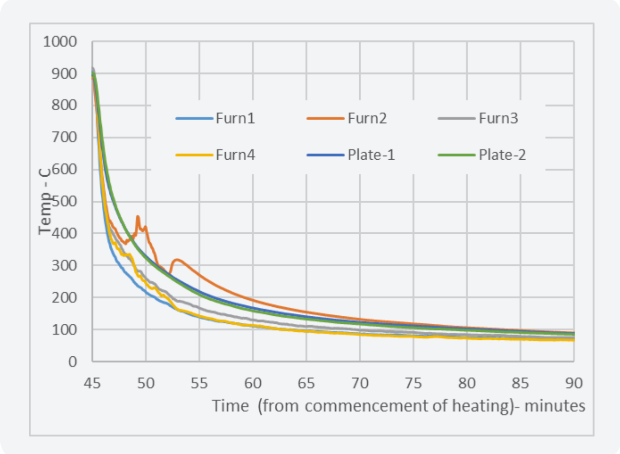


Figure 184: Temperatures recorded by furnace thermocouples during the first 45 min of the monitoring period – Test 6.

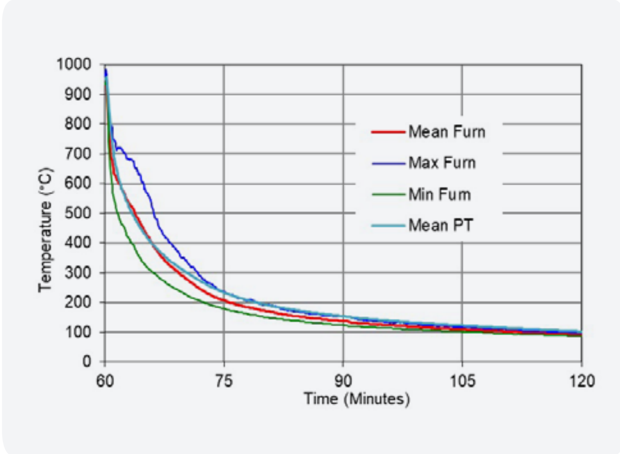


Figure 185: Temperatures recorded by furnace thermocouples during the first 60 min of the monitoring period – Test 8.

The furnace thermocouple data is presented for the 15-hour monitoring period for Test 6 in Figure 186 and for the 23-hour monitoring period for Test 8 in Figure 186. During this period, the temperatures had effectively reduced to ambient temperatures with no evidence of continuing smouldering combustion.

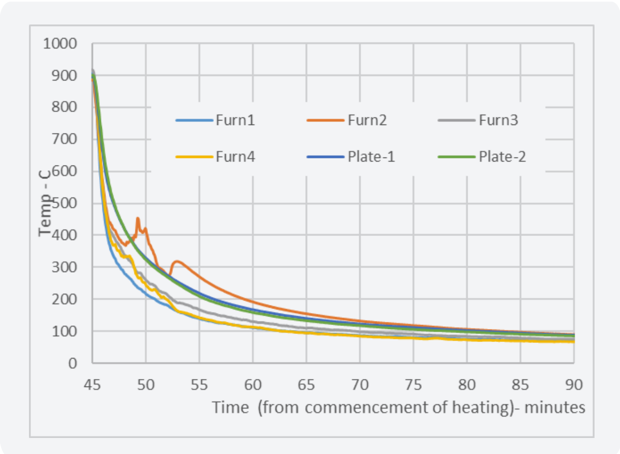


Figure 186: Temperatures recorded by furnace thermocouples throughout the 15-hour monitoring period – Test 6.

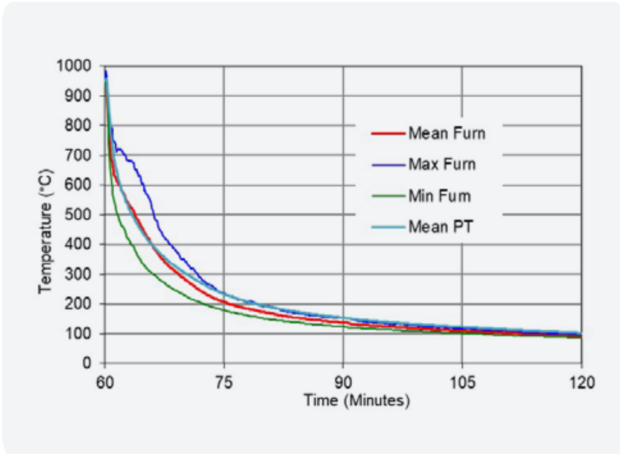


Figure 187: Temperatures recorded by furnace thermocouples throughout the 23-hour monitoring period – Test 8.

Additional mineral insulated metal sheathed Type K thermocouples with wire diameters not greater than 1 mm and overall diameters of 3 mm were included in two positions in Test 8 at depths of 10 mm, 20 mm, 40 mm, 60 mm, 80 mm and 100 mm below the underside of the specimen. Data from these thermocouples are shown for the fire test period and first three hours of the monitoring period in Figure 188. During the furnace heating period the temperatures closest to the specimen were lower but during the cooling period they were higher. Beyond a distance of 40 mm, the variation in temperature with distance from the specimen soffit were relatively minor.

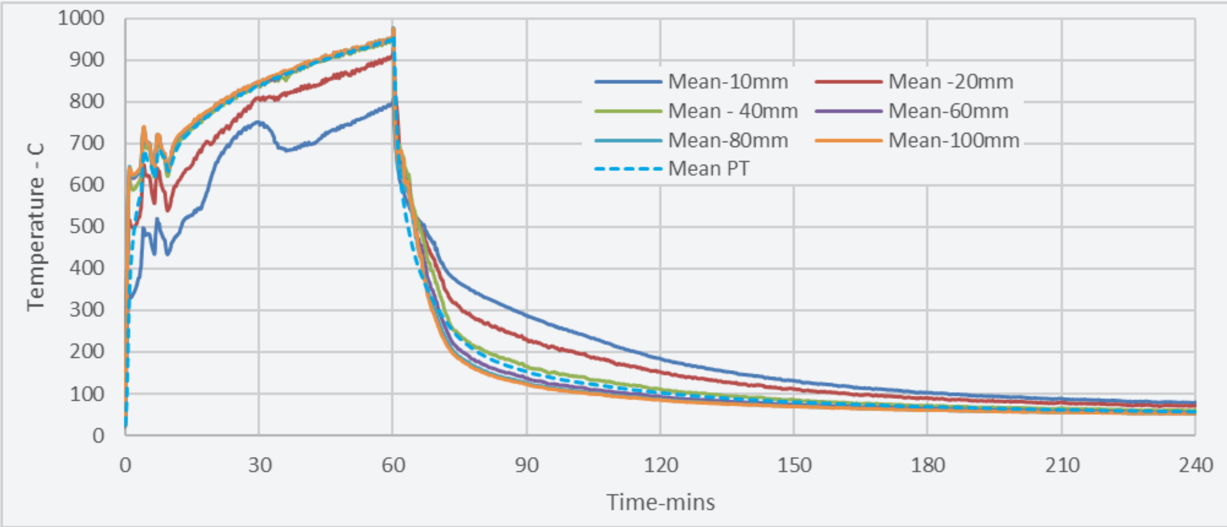


Figure 188: Temperatures recorded by additional furnace thermocouples during the 60 min fire test and first 180 min of the monitoring period – Test 8.

The heat flux at the soffit of the specimen was recorded throughout Test 6 and the monitoring period. The measured heat flux throughout the heating period and first 15 min of the monitoring period is plotted against time in Figure 189.

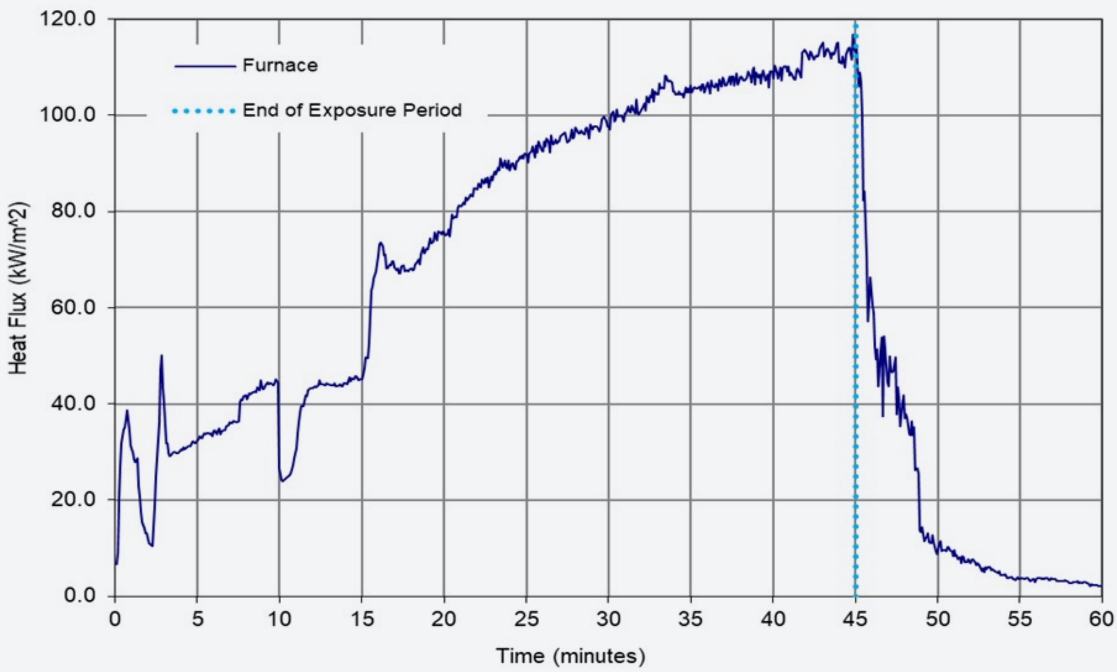


Figure 189: Heat flux at soffit of specimen during the 45 min heating period and first 15 min of the monitoring period – Test 6.

After completion of the heating period, the specimens were raised approximately 220 to 320 mm above the furnace to allow free access to air while exposed to radiant and convective heat from the furnace walls and floor. A heat flux meter was inserted to measure heat flux from the specimen 420 mm below the specimen soffit.

Five minutes after completion of heating during Test 6 the measured heat fluxes had reduced to approximately 10 kW/m^2 and 10 min after completion of heating the heat fluxes had reduced to approximately 4 kW/m^2 (Figure 190).

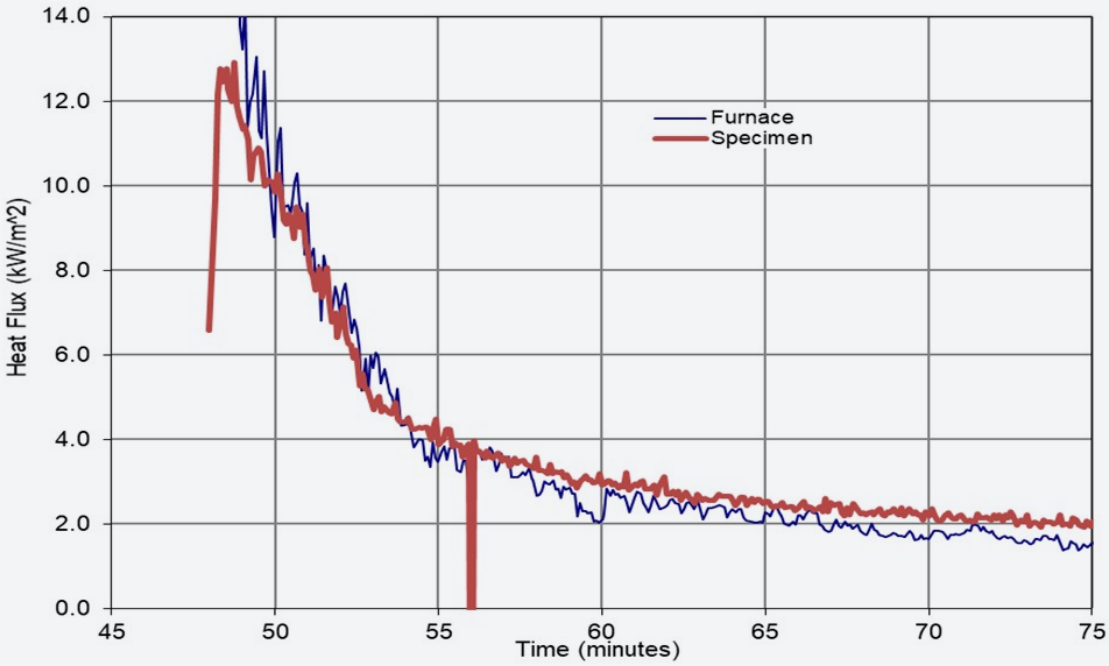


Figure 190: Heat flux from furnace and from specimen for 15 min after heating – Test 6.

In Test 8 the incident heat flux the underside of the specimen was exposed to is plotted for the first three hours of the monitoring period in Figure 191. Approximately 11 min after completion of heating the measured heat flux had reduced to approximately 10 kW/m^2; 42 min after completion of heating the heat flux had reduced to approximately 4 kW/m^2; and 108 min after completion of heating the measured heat flux had reduced to approximately 2 kW/m^2.

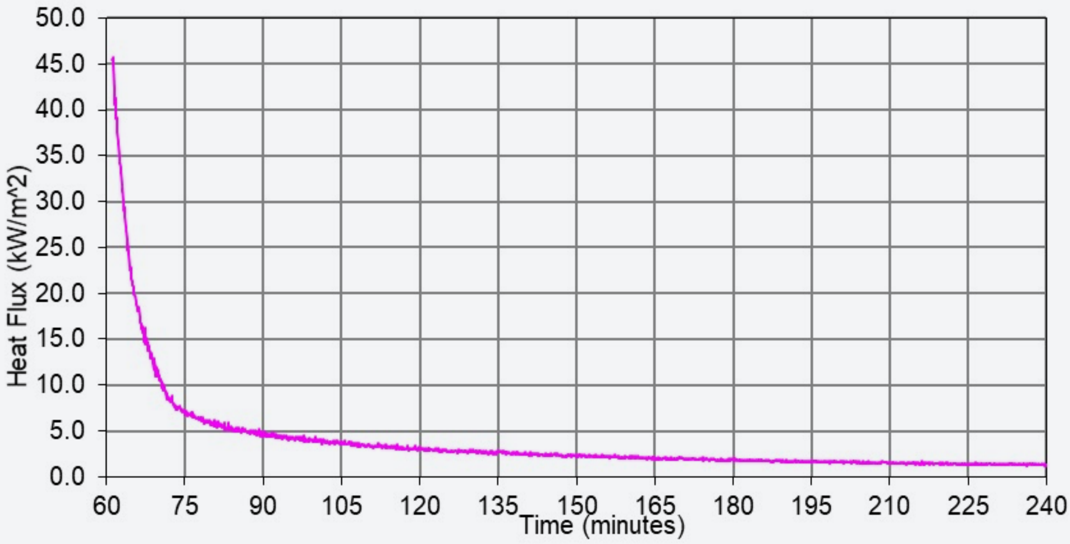


Figure 191: Heat flux from furnace and from specimen for 15 min after heating – Test 8.

The slower reduction in heat flux for Test 8 relative to Test 6 can be explained by the additional heat absorbed into the furnace during the heating phase that is released as the furnace cools in a similar manner to cooling after a natural enclosure fire.

Test 6 Observations: After removal from the furnace at the end of the Test 6 heating period, there was some flaming from the joint and around the penetration for the heat flux meter, which progressively reduced until flaming combustion ceased approximately 7.5 min after the end of the heating period, as shown in the series of photographs in Table 99.

The external flaming occurred due to the venting of volatiles that mixed with the unconstrained air supply as the specimen was raised from the furnace, although the impact was localised as demonstrated by the minor influence on the measured heat fluxes. No-recurrence of flaming combustion was observed after 7.5 min.

Internal temperatures were monitored for 15 hours to identify any residual smouldering combustion. The data recorded by these thermocouples is presented in Figure 192 to Figure 194. Temperatures on the non-fire side of the specimen peaked below 45°C except at the heat flux meter service penetration where a peak of 79°C was recorded.

The interface temperatures between the plasterboard and CLT peaked below 450°C. The temperatures within the CLT at a depth of 7 mm from the fire-exposed face peaked below 250°C and the temperatures measured within the joints at a depth of 14 mm from the fire-exposed face also peaked below 250°C.

In all cases the internal thermocouples cooled exponentially towards ambient conditions, confirming no ongoing smouldering combustion was occurring.

Table 99: Observations during the monitoring period from Test 6.

1 min after end of 45 min heating period

6 min after end of 45 min heating period

7 min after heating period

7.5 min after heating period – self extinguishment of flaming combustion

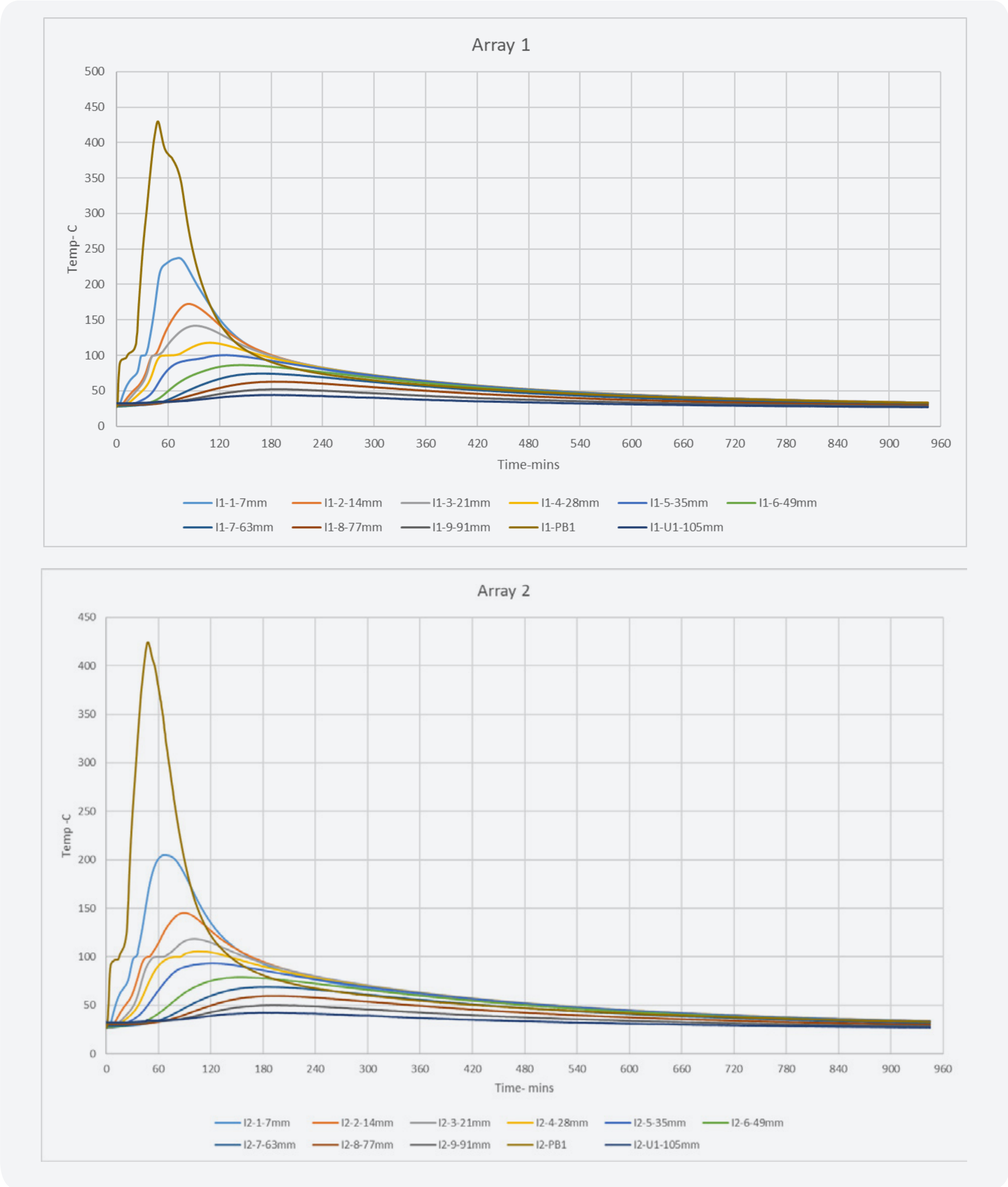


Figure 192: Thermocouple array temperatures in body of the CLT panels – Test 6.

Figure 193: Thermocouple temperatures at joint positions – Test 6.

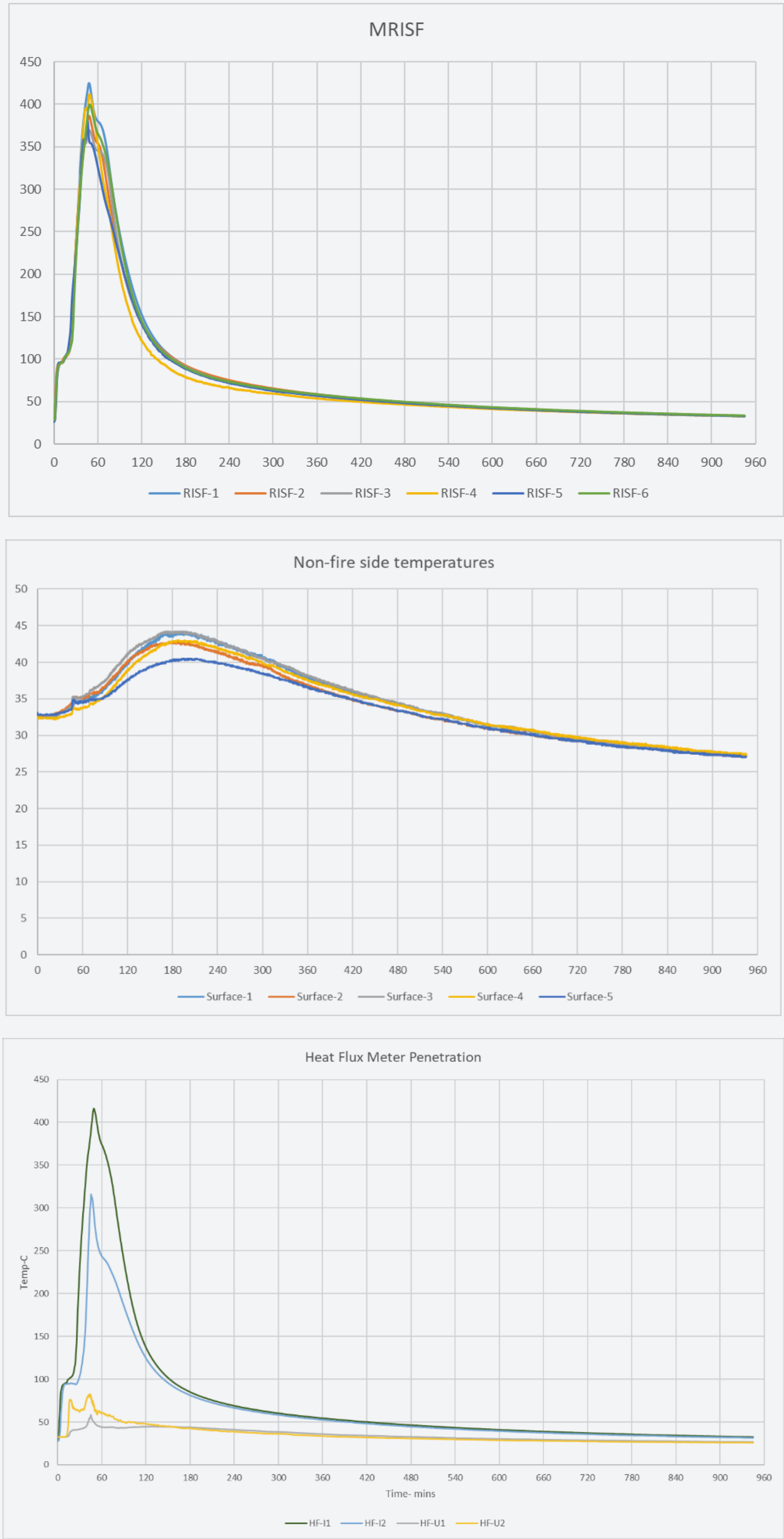


Figure 194: Modified Resistance to the Incipient Spread of Fire, non-fire side and heat flux meter service penetration thermocouple data – Test 6.

The specimen from Test 6 two hours after completion of the heating period is shown in Figure 195.

Fire-exposed face

Non-fire side

Figure 195: Specimen two hours after completion of 45 min fire-resistance test – Test 6.

Figure 196 and Figure 197 show the specimen after completion of the monitoring period and removal of the fire-protective covering to expose the charred CLT, which confirmed that the charring was superficial and did not extend significantly beyond the 1.2 m x 1.2 m heated area.

Figure 196: Fire-exposed face after completion of 15-hour monitoring period with plasterboard face removed – Test 6.

Figure 197: Sections through 105 mm CLT panel after test – Test 6.

Visual observations from Test 8 (60 min heating period and 23-h monitoring period) are provided in Table 100.

Table 100: Visual observations from Test 8.

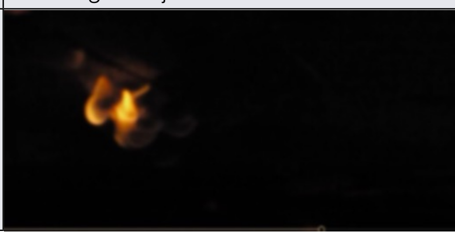
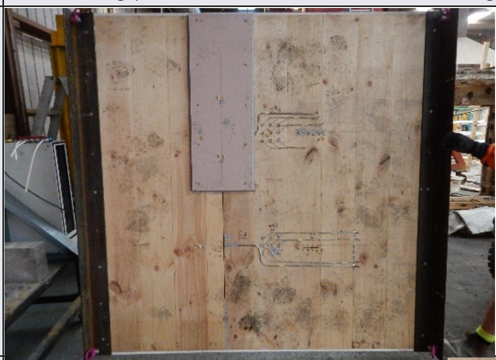
Time h:mm:ss	Observation test started	Comments
Pre-test		Fire-exposed face before test
0:58:00		Non-fire side showing no visible degradation or smoke release through specimen
1:00:00	Heating terminated	
1:00:30		Fire-exposed face showing flaming from joint and additional furnace thermocouple penetrations
1:01:30		Fire-exposed face showing flaming from joint and additional furnace thermocouple penetrations
1:03:30		Fire-exposed face showing flaming from joint
1:04:30		Fire-exposed face showing flaming from joint
1:07:00		Fire-exposed face showing flaming from joint
1:09:30	Flaming from joint intermittent	
1:10:40		Intermittent flaming from joint continuing

Table 100: Visual observations from Test 8.

Time h:mm:ss	Observation test started	Comments
1:11:30	Intermittent flaming stopped – no further flaming combustion	
1:13:00		Fire-exposed face – no flaming
1:36:00		Fire-exposed face – no flaming
24:00:00	Monitoring period ended – no evidence of ongoing combustion	
Post test		Non-fire side showing no evidence of degradation
Post test	 	Fire-exposed face with plasterboard removed showing charred zone. No significant delamination but the timber strips making up the lower lamella had shrunk opening up the joints between lower lamella boards which were not glued on the side faces.

The external flaming occurred due to the venting of volatiles that mixed with the unconstrained air supply as the specimen was raised from the furnace, although the impact was localised, as demonstrated by the minor influence on the measured heat fluxes and temperatures.

No recurrence of flaming combustion was observed after 11.5 min following completion of the heating period.

Internal temperatures were monitored for 23 hours to identify any residual smouldering combustion. The data recorded by these thermocouples is presented in Figure 198 through Figure 200. Temperatures on the non-fire side of the specimen peaked below 35°C. The interface temperatures between the plasterboard and CLT peaked at approximately 500°C with the highest measured peak of 520°C. The temperatures within the CLT at a depth of 7 mm from the fire-exposed face peaked below 280°C but the temperatures measured within the joints at a depth of 14 mm from the fire-exposed face peaked at approximately 330°C for joint 1 (sealant applied to single rebate) and 430°C for joint 2 (plasterboard applied to non-fire side of joint). This indicates that joint details will provide a potential for premature fire spread unless adequate protection is provided.

In all cases the internal thermocouples cooled exponentially towards ambient conditions, confirming no ongoing smouldering combustion was occurring.

The two tests of 45 min and 60 min heating duration demonstrated that, under the specific configurations and exposure conditions, the fire protected Massive Timber elements can self-extinguish if exposed to the standard heating regime of AS 1530.4 for periods greater than the estimated time to commencement of charring.

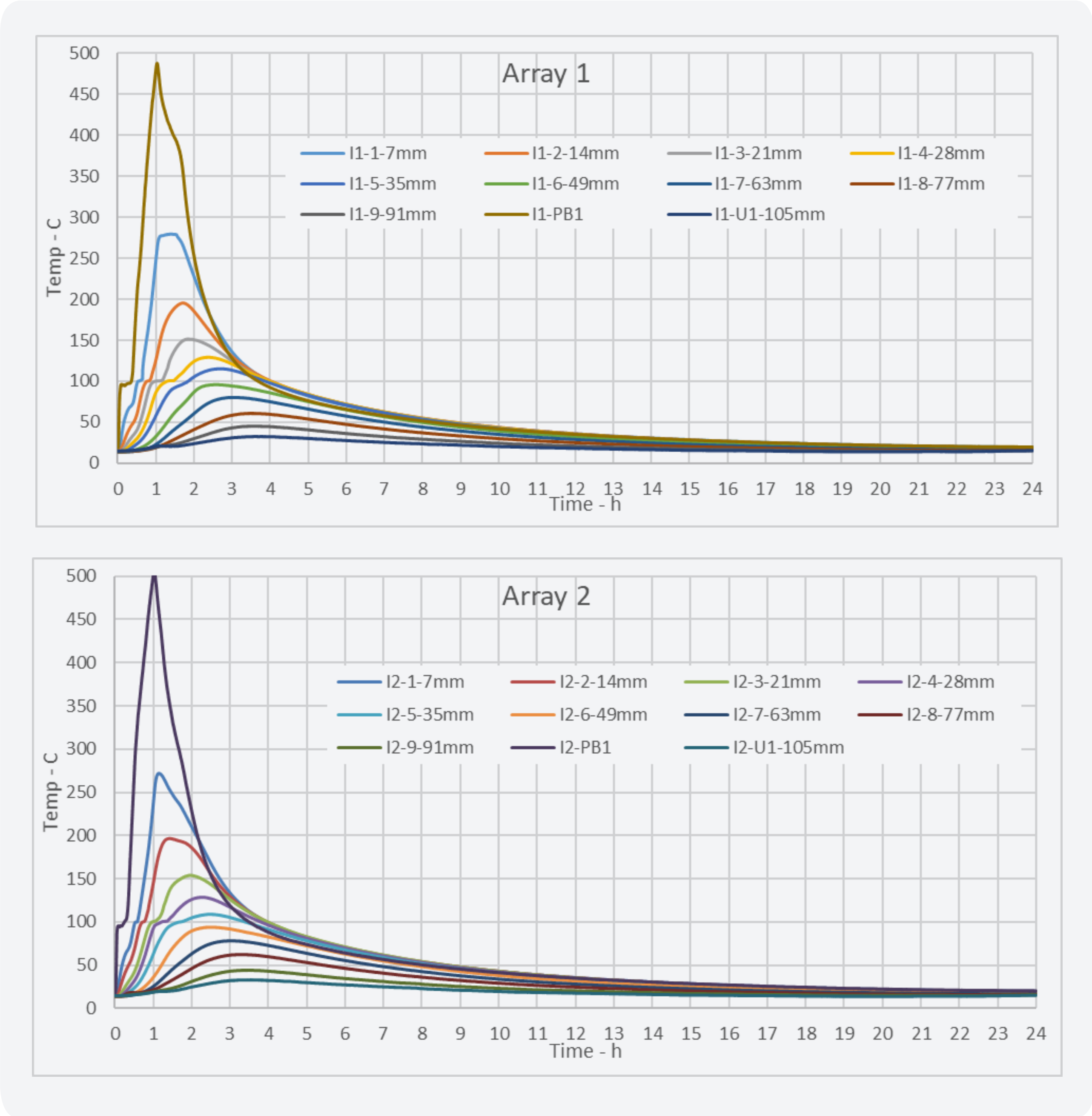


Figure 198: Thermocouple array temperatures in body of the CLT panels – Test 8.

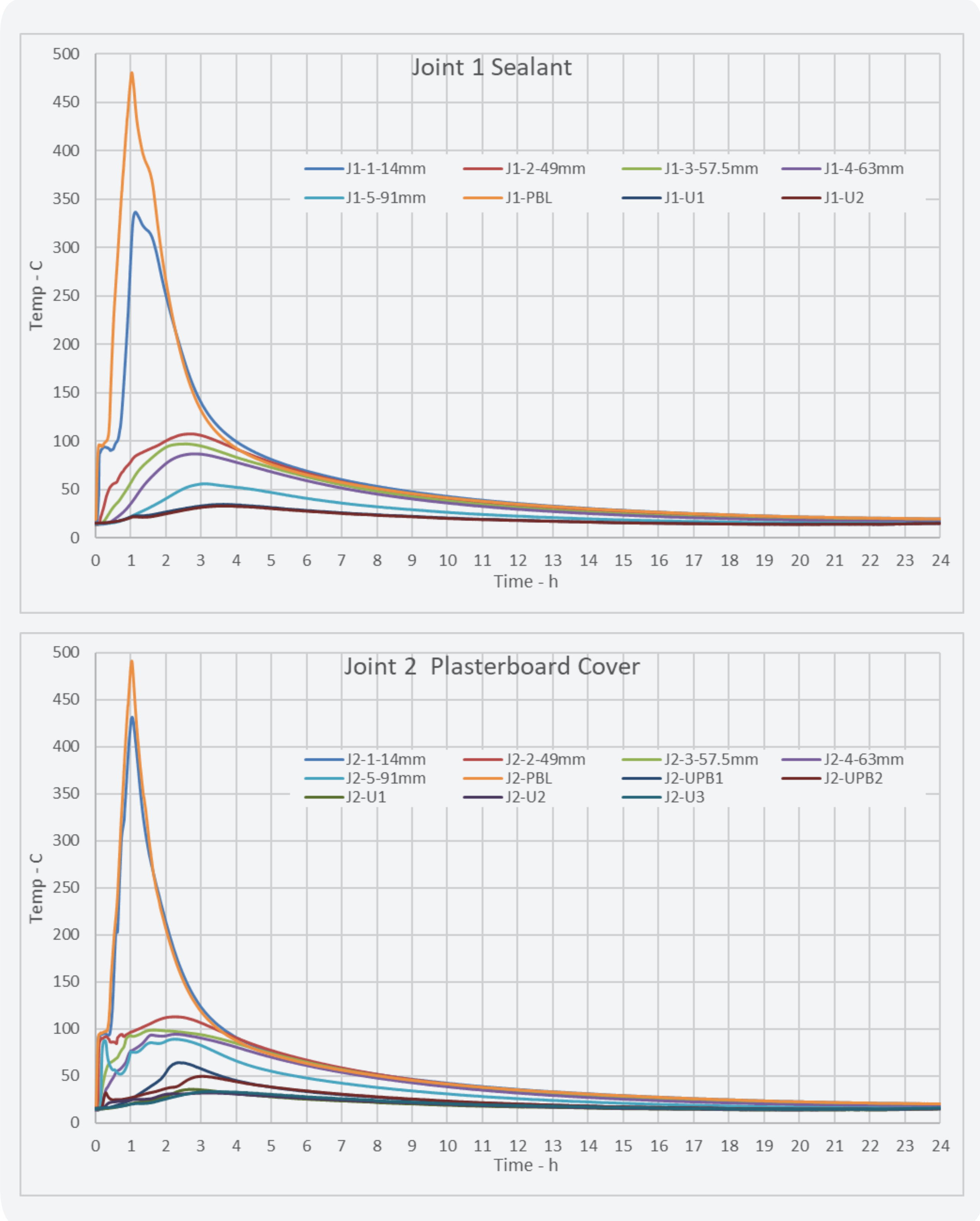


Figure 199: Thermocouple temperatures at joint positions – Test 8.

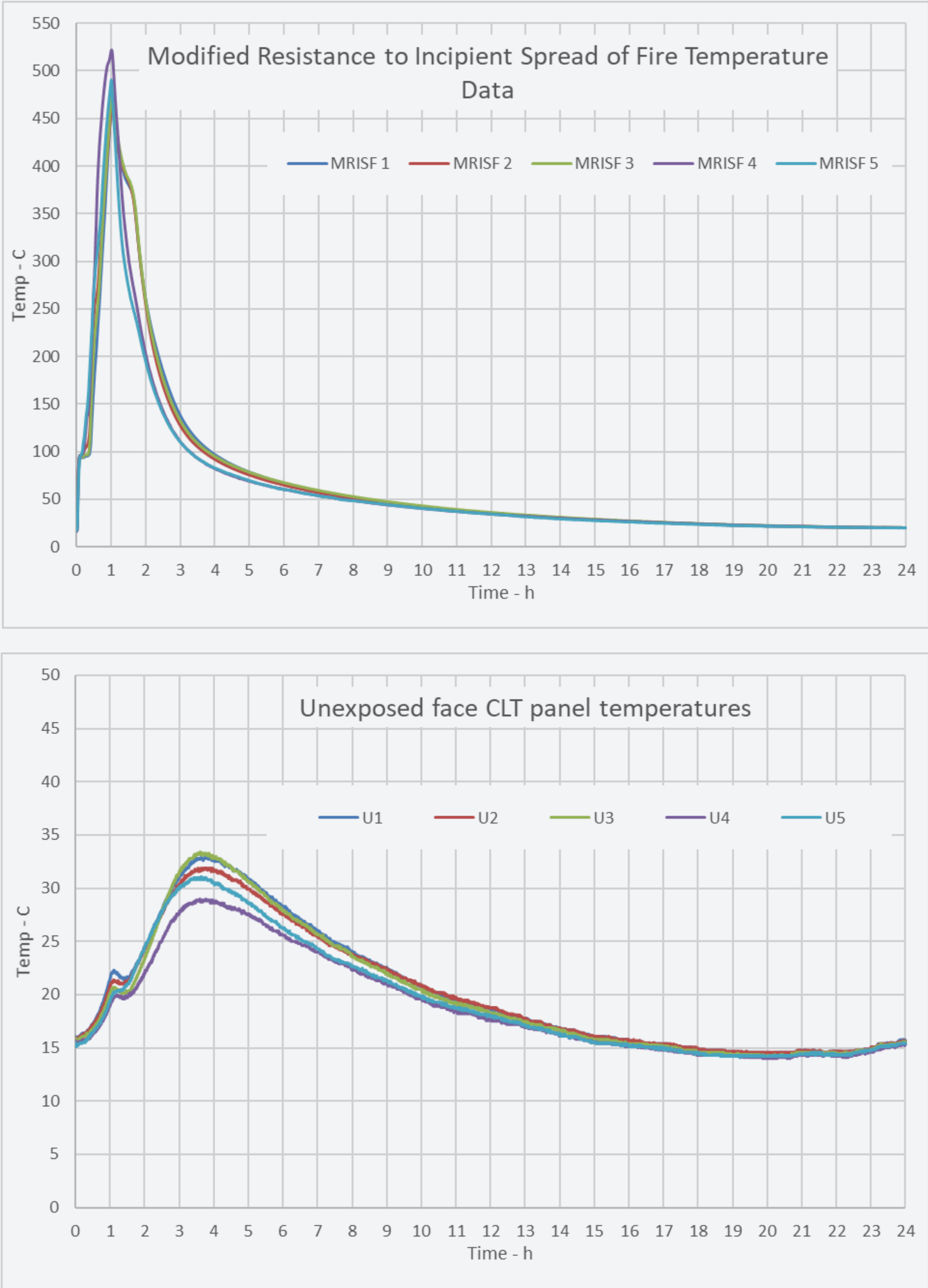


Figure 200: Modified Resistance to the Incipient Spread of Fire and non-fire side thermocouple data – Test 8.

Decay after longer duration fire tests

The behaviour of the Massive Timber elements after the longer duration fire tests was also monitored. The most relevant comparison with the shorter duration tests was Test 2; a 225 mm thick CLT panel protected by a single layer of 16 mm fire-protective grade plasterboard subjected to the standard heating regime. The conditions were monitored for a relatively short 59 min because the element continued to show evidence of continuing char oxidation albeit at a reduced rate.

A comparison of the tests is provided in Table 101.

Table 101: Comparison of tests with single layer of 16 mm plasterboard protection.

Test	CLT depth (mm)	Furnace heating (h:min)	Monitoring period (h:min)	Time (min) CLT - PB interface > 300°C (t_{ch})	PB fall-off (min)
6-49385700	105mm	0:45	15:00	34	No fall-off
8-54455500	105mm	1:00	23:00	32	No fall-off
2-49385300	225mm	2:51	0:59	32	115

The heating period for Test 2 was terminated after approximately 171 min when failure at the joint positions was considered imminent. Subsequently, failures under the criterion of insulation occurred for Joint 1, Joint 2 and in the body of a CLT panel 5, 22 and 29 min after termination of heating respectively.

The furnace temperature plotted against time during Test 2 in Figure 147 for the heating and subsequent monitoring period. As expected, the reduction in furnace temperature after the heating period is much slower compared to the shorter test due to the additional heat absorbed by the furnace linings and test specimens during longer tests.

This trend is also reflected in the heat flux measurements from Test 2 (Figure 201). Despite evidence of some ongoing combustion, the decay of radiant heat from the specimen reduced to approximately 11 kW/m² after 60 min.

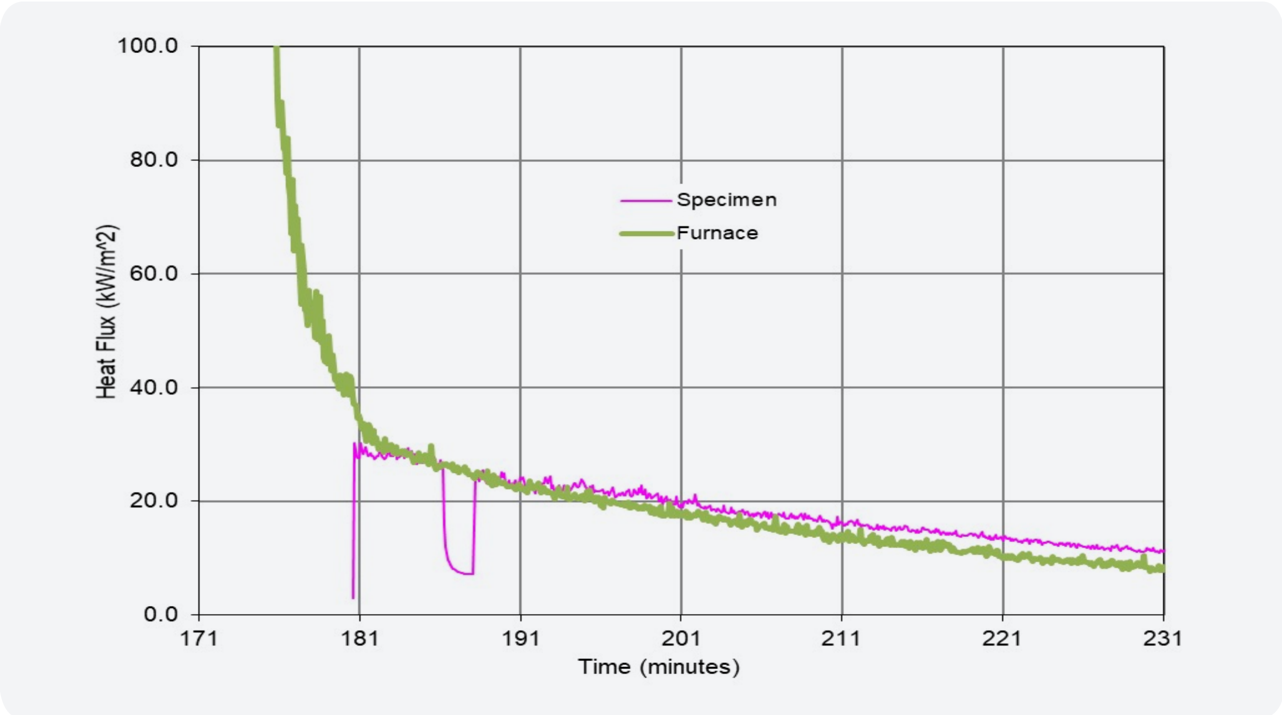


Figure 201: Heat flux from furnace and from specimen for 60 min after heating – Test 2.

There was little visible evidence of damage to the non-fire side of the specimen at the end of exposure to the 171 min fire test, except for localised damage at the joint positions (Figure 202).

Figure 202: Non-fire side 2 min after completion of 171 min heating period.

However, there was ongoing deterioration around the joint positions (Figure 203 shows the non-fire side with the plasterboard covering removed 60 min after the end of the heating period).

Figure 203: Non-fire side after monitoring period with plasterboard cover removed.

Figure 204 to Figure 207 show the fire-exposed face after 6, 10, 18 and 60 min of the post-heating monitoring period. A substantial reduction in the combustion rate is visible confirming the thermal data, however combustion was ongoing at the joint positions and the exposed perimeter of the specimen at the end of the 60 min monitoring period.

Significant delamination occurred such that 90 mm or more of the specimen face had been lost over the heated area, creating a detail at the perimeter where a horizontal face meets a vertical face of timber facilitating radiative feedback. These observations indicate that as heat penetration into timber elements increases, intersections and joint details will become more critical if self-extinguishment is an objective. It may also be important to maintain fire-protective coverings in place if used to reduce radiant heat interchanges at intersections of elements.

Figure 204: Fire side 6 min after completion of heating period.

Figure 205: Fire side 10 min after completion of heating period.

Figure 206: Fire side 18 min after completion of heating period.

Figure 207: Fire side after monitoring period (approximately 6 min after completion of heating period).

The temperatures measured by two arrays of thermocouples in the body of the CLT panels are plotted against time in Figure 208. As the test progressed, many initially embedded thermocouples were exposed directly to the furnace and the rapid decay of these thermocouple temperatures reflected the general environmental changes. However, valid observations can be made from the thermocouples embedded in the two lamella furthest from the soffit. These thermocouples increased in temperature during the monitoring period but were beginning to plateau.

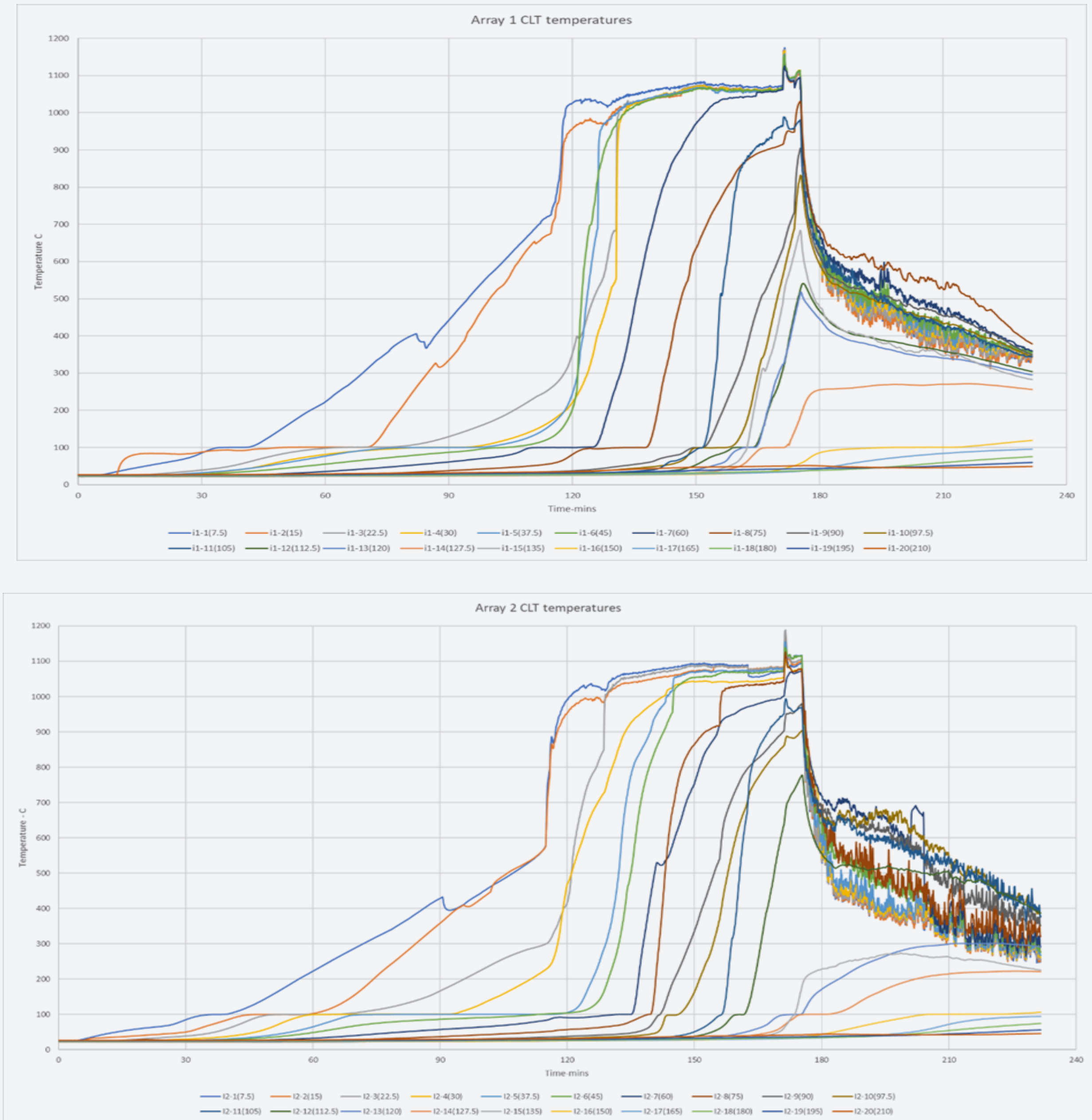


Figure 208: Thermocouple array temperatures in body of the CLT panels – Test 2.

Figure 209 presents temperature data measured at the joint positions and Figure 210 presents the temperatures measured on the non-fire side of the CLT. Some variability in the temperature data was observed, which can be expected if delamination occurs. The observed variability and delamination may also have been influenced by the method of bonding the CLT lamella (i.e. face bonding only was used with the edges unglued).

Figure 209: Thermocouple temperatures at joint positions – Test 2.

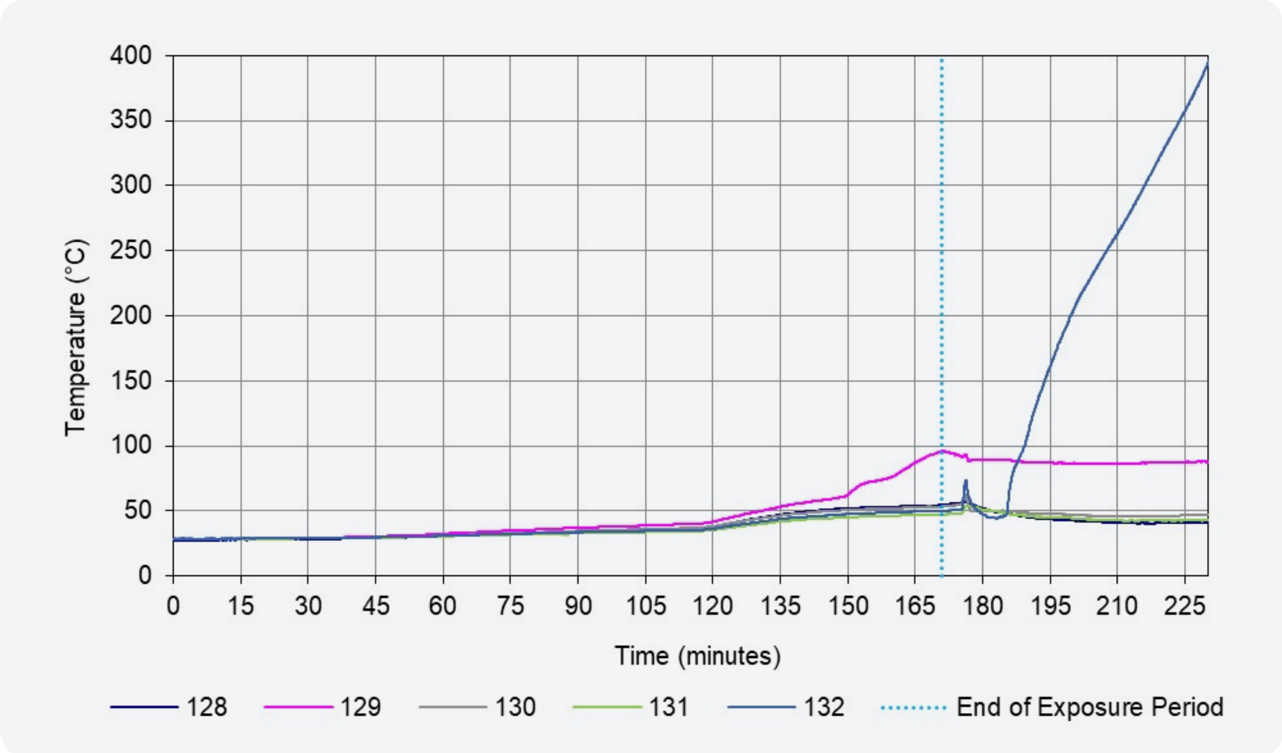


Figure 210: Unexposed face temperatures – Test 2.

The performance of the CLT element in Test 2, which was exposed to a long test with heating terminated close to failure under the insulation/integrity criteria of AS 1530.4, was similar to Tests 3 and 4. Under these circumstances, the fire-protective grade plasterboard facings are expected to have fallen away, delamination of the CLT is likely and full self-extinguishment of the CLT is unlikely; although it is noteworthy that if an external heat source is not maintained, the burning rate is likely to be substantially reduced except close to features that promote re-radiation, such as joints and element intersections.

The shorter tests (Tests 6 and 8) demonstrated that Fire-protected Timber can self-extinguish, even if the CLT-plasterboard interface temperatures substantially exceeded 300°C.

The tests can be regarded as bracketing the extremes of behaviour and have demonstrated repeatable self-extinguishment behaviour with 45 and 60 min exposures to the standard heating regimes. Comparison of the results from the three tests suggests that there is significant potential to explore the concept of self-extinguishment of fire-protected Massive Timber with exposures equivalent to a 60 min fire-resistance test.

Conclusions

A series of nine intermediate-scale tests was conducted on Massive Timber elements instrumented to measure char rates and other key parameters. Each element included a joint between the panels with various joint treatments. The tests were performed in the horizontal orientation with an area 1.2 m x 1.2 m exposed to the furnace heating conditions. A proprietary fire-protective grade plasterboard was used.

All tests were performed at an intermediate scale and the CLT specimens were not subjected to loading. Events such as plasterboard fall-off and delamination may be sensitive to specimen size, orientation and applied loads. While the intermediate tests provide useful comparative data, there may be some reduction in the times of these events when full-scale specimens are tested.

Notwithstanding these limitations, the research program demonstrated that:

- Fire protected Massive Timber elements have the potential to achieve FRLs up to 240/240/240 subject to careful detailing of joints, connections, and fire protection systems.
- Data from additional instrumentation can provide insights into the behaviour of Massive Timber maximising the value of ‘standard’ fire tests by:
  - confirming estimates of timing of a contribution to fire severity from fire protected timber
  - providing accurate estimation of fall-off times of plasterboard coverings
  - providing char rates throughout the various stages of a test
  - providing insights into the difference in cross-sectional temperatures at joint positions
  - providing insights into the timing of reductions and termination of combustion within the CLT elements.

- The behaviours of three joint configurations were investigated and it was concluded that special treatments need to be applied to joints to prevent the joints limiting the FRL performance of a specimen.
- Self-extinguishment of CLT panels protected by a single layer of 16 mm fire-protective grade plasterboard when exposed to standard fire-resistance test exposures of 45 and 60 min was demonstrated. These results indicate there may be a significant margin of safety if it is assumed that once the timber interface temperature of fire protected Massive Timber exceeds 300°C and pyrolysis of the timber substrate occurs the timber will ignite and continue to burn until totally consumed if there was no intervention. While self-extinguishment was demonstrated, further work is required to define the boundaries and explore interactions at vulnerable locations such as joints and connections in further detail.
- The impact of different heating regimes on unprotected CLT exposed to long duration fires was demonstrated and data obtained to facilitate correlations for increased char rates for elements exposed to heating regimes more severe than the standard heating regime.
- Char rates were substantially reduced by the presence of the plasterboard until exposure of the CLT panels after the plasterboard fell away. Once the CLT was exposed, accelerated char rates were measured in line with expectations. Higher char rates were measured for the long duration fires.

A potential inconsistency between heat flux measurements and furnace temperatures was identified during the early stages of the fire tests following the standard heating regime that was independent of the involvement of timber and may be due to the dominance of convective heat transfer in the early stages of the test until radiant heat transfer becomes dominant as the test progresses. Tests that adopted the hydrocarbon regime were not as sensitive to this effect due to the substantially greater heating rate, which considerably reduces the period that convective heat transfer is dominant. Transient inconsistencies also occurred at the time of exposure of the CLT after the plasterboard coverings fell away, which may have resulted from changes in boundary conditions and/or a sudden increase in pyrolysis rate of exposed CLT.

D Appendix D - Wall and Ceiling Lining Tests

D1 Fire Hazard Properties - Australian Research Fire Spread in Corridors (Gardener and Whitlock)

Between 1989 and 1993, Gardner and Whitlock[234] examined flame spread in corridors. The initial report was provided in 1994 and updated in 1998 to include information on the solid-core timber doors and development of the moveable shutter. The revised report was externally reviewed as a prerequisite for publication and amended to meet the reviewers' recommendations. The conclusions and recommendations were unchanged in intent from the 1993 to the 1998 reports and are identical for the 1998 report and the 2005 publication.

Gardner and Whitlock concluded that: The research demonstrated that the current test (AS 1530.3) prescribed in Specification C1.10 of the Building Code of Australia (BCA) to regulate the use in public corridors of lining materials according to their flame spread and smoke release properties was not a reliable indicator and it recommended that additional or alternative test methods be specified in the BCA.

It was also recommended that Specification C1.10 of the BCA be amended for public corridors to allow:

a) The use of fire-retardant coatings to achieve required flame spread properties for lining materials. The report also noted that it may be appropriate to require compliance with a code of practice that covers application and maintenance of fire-retardant coatings.

b) The use of lining materials with higher flame spread properties on the lower parts of walls.

c) Lining materials with higher flame spread properties when sprinklers are installed.

Following further work by the Fire Code Reform Centre, the BCA (now known as the NCC) was modified, changing the classification system for lining materials and allowing the use of lining materials with higher flame spread properties when sprinklers are installed. To date, no changes have been made to the DTS requirements to permit the use of fire-retardant coatings applied to lining materials or application of lining materials with higher flame spread properties to the lower parts of walls.

In the absence of any facilitating DTS Provisions, the Performance Solution Pathway will have to be followed if fire-retardant coatings are applied to improve the reaction-to-fire performance as well as the use of wood products on the lower parts of walls requiring lining materials that achieve the Group1 or Group 2 classification. The following is a review of the most relevant results from the Flame Spread in Corridors Study addressing the lower parts of walls.

The study identified that the repeatability of the solid core door performance was poor, and this had affected the results of the corridor tests. A procedure was developed with an openable damper in lieu of a door to provide repeatable exposure conditions to the corridor linings. Only comparative results from tests with an openable damper simulating a failing door in a repeatable manner will be discussed further in this review. The test configuration is shown in Figure 211 and Table 102 summarises results for the time to untenable conditions and for flame spread beyond the corridor for this data set.

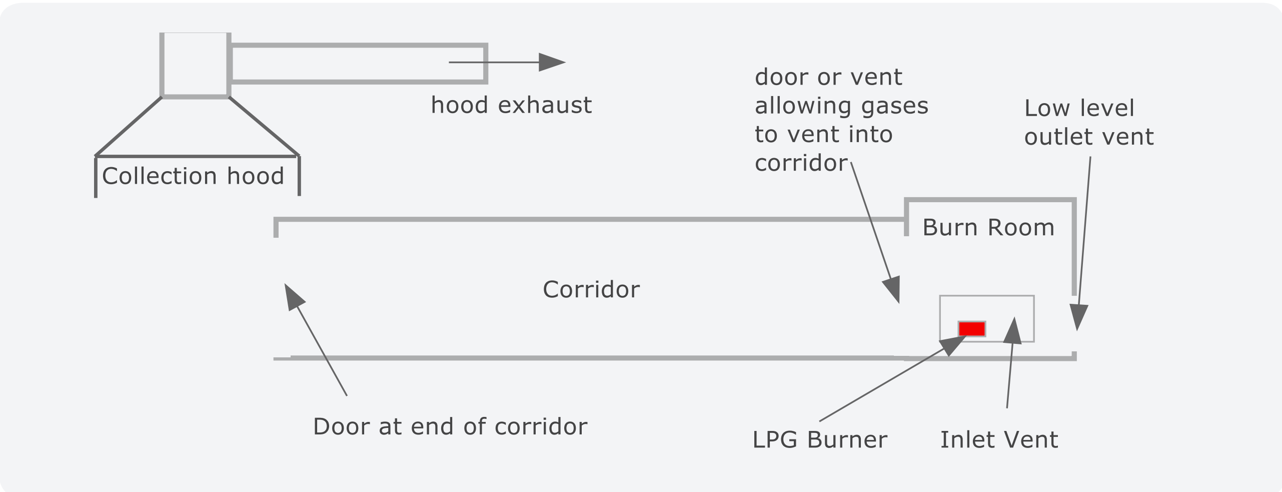


Figure 211: Schematic of test configuration used by Gardner and Whitlock.

Table 102: Comparison of relevant results for Gardner and Whitlock[234] flame spread to corridors study.

Test	Lining board/material			Time (s)			Mean Optical Density last 10 readings	Max HRR (kW)
	Wall	Ceiling	Floor	untenable conditions	flame spread to exit end	to ignition		
1	GPB	GPB	Concrete	Not achieved	Not reached	Not reported	0.041	430
2	GPB	GPB	Concrete	Not achieved	Not reached	Not reported	0.019	490
3	GPB	GPB	Concrete	Not achieved	Not reached	Not reported	1.033	440
4	Particle B.	GPB	Concrete	540	510	355	0.573	1090
5	Particle B.	GPB	Concrete	630	560	400	1.56	1140
6	Particle B.	GPB	Concrete	610	570	390	0.339	1100
7	Wool/Nyl. Carpet	GPB	Concrete	440	425	280	0.479	No data
8	Wool/Nyl. Carpet	GPB	Concrete	440	440	290	Missing data	No data
9	Wool/Nyl. Carpet	GPB	Concrete	440	400	285	0.271	No data
10	Sheet Vinyl	GPB	Concrete	Not achieved	Not reached	345	0.267	680
11	Polystyrene	GPB	Concrete	570	480	380	0.128	1210
12	Western Red Cedar	GPB	Concrete	560	510	325	0.759	No Data
13	Polyester/nylon textile	GPB	Concrete	Not achieved	Not reached	400	0.205	760
14	Fire-retard. Particle B.	GPB	Concrete	Not achieved	Not reached	485	0.027	710
15	1/2 Particle B	GPB	Concrete	Not achieved	No ignition	No ignition	0.011	500
16*	Particle B	GPB	Concrete	Not achieved	No ignition	No ignition	Missing data	40
17	GPB	Particle	Concrete	Not achieved	810	375	0.719	890
18	GPB	GPB	Particle B	Not achieved	No ignition	No ignition	0.040	580
19	Particle B	GPB	Particle B	610	550	320	0.297	1720
20	Particle B	Particle	Particle B	580	480	310	-0.646	No data
21	GPB	GPB	Wool/Nyl Carpet	Not achieved	No ignition	No ignition	0.081	760
22	GPB	GPB	Concrete	Not achieved	Not reached	Not observed	Not measured	Not measured
23	Particle B	GPB	Wool/Nyl Carpet	680	605	400	0.935	

*Notes: * operational automatic fire sprinkler system intervention in test 16.*
GPB: plasterboard. Particle B: particle board

The first nine results included three replicates of three configurations.

Tests 1 to 3 comprised a corridor with plasterboard walls and ceilings and a concrete floor. The defined tenability and flame spread criteria were not reached during the tests indicating that the configuration represented a low flame spread option (least hazardous).

Tests 7 to 9 comprised a corridor with wool/nylon carpeting fitted to the walls, a plasterboard ceiling and concrete floor. The defined tenability and flame spread criteria were both exceeded between 400 and 440 s of the test. These were the smallest times to exceed the limits and represented a high spread option (most hazardous).

Tests 4 to 6 comprised a corridor with untreated particleboard walls, plasterboard ceiling and concrete floor. The defined tenability criterion was exceeded between 540 and 630 s during the three tests and the flame spread criterion between 510 and 570 s indicating that the performance of the untreated particleboard represented an intermediate level of performance.

The results indicated reasonable repeatability for similar configurations and that the flame spread criterion was more reliable than the tenability criterion for comparing different configurations.

Test 12 indicated that the performance of Western Red Cedar was comparable with the particleboard, but insufficient replicates were undertaken to clearly rank the performance of the chipboard and Western Red Cedar.

Test 14 demonstrated the large improvement in performance that can be obtained by applying a fire-retardant coating to the particleboard.

Test 15 demonstrated that the application of particleboard sheets to the lower 1.2 m of the wall did not facilitate fire spread or lead to untenable conditions. The report observed that the low-level boards were not ignited, demonstrating that for this configuration the use of timber dado panels and rails up to a height of 1.2 m does not significantly increase the hazards of fire spread.

Test 16 demonstrated the capability of an operational automatic fire sprinkler system to mitigate the risk of fire spread associated with the particleboard lining for the test scenario.

Test 17 indicated that a particleboard ceiling presented a lower hazard than particleboard wall linings for the test scenario.

Tests 18 and 19 indicated that there was no appreciable increase in the rate of flame spread with particleboard flooring compared to the concrete flooring for the test scenario.

In Test 20 with particleboard floor, wall and ceiling linings, the flame spread time was slightly reduced compared to the cases with particleboard linings applied only to the walls.

Replicate tests (1-3 and 4-6) show reasonable repeatability of results obtained from the test procedure.

The wall and ceiling linings used for Tests 1 to 3 achieve Group 1 performance when evaluated in accordance with the current requirements of NCC 2019 Specification C1.10 and the wall and ceiling linings in Test 20 would achieve Group 3 performance close to the transition to Group 4.

Comparing the results from Tests 1 to 3 and Test 20 demonstrates the ability of the test procedure to differentiate the performance of different types of lining systems.

Test 15 shows that the 1.2 m high dado walls in conjunction with Group 1 linings applied to the remainder of the walls and ceiling achieved similar performance to the full Group 1 lining configuration, while Tests 4-6 demonstrated that full height wood product wall linings yield results close to that achieved with complete wall and ceiling wood product linings.

The combination of wood product linings applied to walls to a maximum height of 1.2 m in combination with non-combustible or plasterboard linings to the remainder of the walls and ceilings were shown to behave in a similar manner to Group 1 wall and ceiling linings when exposed the corridor fire scenario developed by Gardner and Whitlock.

D2 FCRC Fire performance of wall and ceiling lining materials Project 2

Details of the project are consolidated in the Final Report and Supplement[97] and the primary outcomes were revised Deemed-to-Satisfy requirements for the NCC for internal linings based on Group numbers consistent with the recommendations of Gardner and Whitlock[234].

Data and conclusions from the final report, Research Paper 5[235], Research Paper 7 and Dowling[236] are summarised below.

Table 103 shows results extracted from the above reports for wall only, ceiling only and wall and ceiling plywood linings with plasterboard applied to the remaining wall and ceiling surfaces.

Table 103: Comparative data for wall only timber linings and ceiling only timber lining ISO 9705 tests.

Material	Thickness (mm)	Configuration	Time (s)		
			to ignition	from ignition to FO	Total to FO
Plasterboard	16	Walls & ceiling	-	No FO	No FO
Hoop Pine FR Plywood	4	Walls & ceiling	30	160	190
Hoop Pine FR Plywood	4	Walls	22	238	260
Hoop Pine FR Plywood	4	Ceiling	290	245	535
Lauan Plywood (mean results of 2 tests)	4	Walls	20	143	163
Lauan Plywood	4	Ceiling	240	160	400
Lauan Plywood	4	Walls & ceiling	30	95	125

The time to flashover for the wood product ceiling lining with plasterboard wall linings is significantly longer than the wood product wall linings with plasterboard ceiling configuration. This finding is consistent with the results for particleboard linings in corridors reported by Gardner and Whitlock[234]. However, the time to flashover was less than 600 s and therefore the performance of the wall only or ceiling only linings was equivalent to a Group 3 material applied to walls and ceilings despite the large increase in time to flashover for the ceiling-only configuration.

The improvement in performance for the fire-retardant treated plywood was relatively modest. Details of the level of fire-retardant treatment were not provided in the referenced reports but the results are consistent with a low level of impregnation or a treatment with limited efficacy.

The FCRC project also undertook a series of corridor tests with a similar configuration, but modified fire source (1 MW), and made the following observations: "Gardner and Whitlock (1998) compared one material – particleboard – as a wall lining and as a ceiling lining. They found that the particleboard wall linings produced untenable conditions more rapidly and spread fire more rapidly than particleboard ceiling linings.This finding agrees with the findings of the CSIRO Project 2 corridor experiments, and shows that in narrow corridors, untreated timber products used as wall linings can produce untenable conditions and spread flame more rapidly than untreated timber products used as ceiling linings.

Gardner and Whitlock also looked at the effect of lining only the lower half of walls in corridors with a combustible material, in this case particleboard. They found that when particleboard was used to line only the lower half of the walls, ignition did not occur. This demonstrates that in corridors, the lower half of the wall does not play as large a part in fire growth and spread as the upper half."

D3 Data from EUREFIC Project and subsequent European studies

The EUREFIC Project generated a database of ISO 9705 test results, among other things. Table 104 summaries results relevant to this guide derived from Söderblom[109]. All products were fixed to a lightweight, aerated concrete substrate (density approximately 500 kg/m^2).

Table 104: ISO 9705 data from Urefic study.

Description	Coating	Thickness (mm)	Density (kg/m^2)	Time (s)		Peak HRR (kW) after m:s	Max Heat Flux at floor (kW/m^2)
				FO	Flames from door		
Painted plasterboard	PVA 100 g/m^2	12		DNO	DNO	426 (10:25)	9
Ordinary Plywood		12	600	2:30	2:22	-	15
FR Particleboard B1		16	630	10:30	12:10	-	22
FR Particleboard		12	750	DNO	DNO	747(18:05)	18

Note: DNO=Did not occur

These results are consistent with Group 1 performance expected from plasterboard without excessive overpainting, Group 3 performance for untreated timber products, and Group 1 or 2 performance for timber products treated with fire retardants; with products tested in the standard ISO room configuration and walls and the ceiling lined with the subject material under test. Further testing was reported by Sundstrom[237], with the most relevant results consolidated in Table 105.

Table 105: European ISO 9705 results from Sundstrom[237].

Ref	Description	Thickness (mm)	Density (kg/m^2)	Time (m:s) to FO	Peak HRR -kW (m:s)
E1	Painted plasterboard	12		DNO	426 (10:25)
E2	Ordinary plywood	12	600	2:30	-
E6	FR Particleboard B1	16	630	10:30	-
E8	FR Particleboard	12	750	DNO	747(18:05)
M01	Plasterboard	13	716	DNO	94(10:26)
M05	Varnished Pine	9	459	1:46	-
M06	FR chipboard	12	785	DNO	423(20:00)
M08	Painted plasterboard	13	727	DNO	71(10:25)
M09	Paper covering on plasterboard	13 + 0.4	719	DNO	394 (10:40)
M12	Spruce unvarnished	9	439	2:50	-
M15	Intumescent coated particleboard	13 + 0.4	723	11:40	-
M16	Melamine faced MDF	12 + 0.1	768	2:30	-
M20	Melamine faced particleboard	12 + 0.1	695	2:45	-
M22	Ordinary particleboard	12	713	2:35	-
M23	Ordinary plywood	12	718	2:40	-
M24	Paper covering on particleboard	13 + 0.4	694	2:45	-
M25	MDF	12	846	3:10	-
M26	Low density fibreboard	12	294	0:58	-

Note: DNO=Did not occur

Again, these results are consistent with Group 1 performance expected from plasterboard without excessive overpainting, Group 3 performance for untreated timber products and Group 1 or 2 performance for timber products treated with fire retardants with products tested in the standard ISO room configuration with walls and the ceiling lined with the subject material under test.

D4 BRANZ Study Report No. 160 Fire properties of wall and ceiling linings

Collier[238] reported the findings of a project undertaken to demonstrate the effectiveness of the ISO 9705 room corner test method and cone calorimeter test methods prior to the methods being adopted by the New Zealand Building Code. A series of eight ISO 9705 ISO room tests were undertaken and the results from three tests relevant to wood products are summarised in Table 106.

Table 106: Selected ISO 9705 results from Study Report SR 160.

Ref	Description	Thickness (mm)	Density (kg/m^2)	Time (m:s) to FO	Peak HRR -kW (m:s)
SR160-2	Plywood	9	513	3:45	-
SR160-3	Plywood plus two coats of intumescent paint	9	510	15:51	-
SR160-4	Glazed fibre cement sheet	6	1378	DNO	191(>10:00)

During the test series, additional instrumentation was provided to estimate flame spread over the linings. At flashover flame spread had occurred over approximately 40% of the wall lining surfaces and 100% of the ceiling linings in tests SR 160-2 and SR 160-3. This provides useful preliminary indicative data on the area of linings required for flashover to occur. The extent of flame spread over the walls at flashover shows no direct involvement of the plywood below 1.2 m except in the immediate vicinity of the burner, providing further data showing no significant contribution is likely from dado paneling below 1.2 m.

D5 Experiments with rooms partially lined with timber – (Harriet Peel et al)

The results of a series of seven ISO 9705 room tests investigating the effect of partial timber linings were reported by Peel[239]. Table 107 summarises the tests and the results.

Table 107: Results from partially lined enclosures.

Experiment	1	2	3	4	5	6	7
Timber wall linings	Full	Upper half	Lower half	None	1.2 m each side of burner	2.4 m each side of burner	3.6 m each side of burner
Timber ceiling linings	Yes	None	None	Yes	Yes	None	None
Total area of timber (m^2)	31.7	8.64	8.64	8.64	14.4	11.5	17.3
Area of timber above 1.2 m (m^2)	20.16	8.64	0	8.64	14.4	5.76	8.64
% room timber lined	85	23	23	23	38	30	46
Ply specification	7 mm thick untreated D-grade 3-ply pinus radiata plywood panels (540 kg/m^3)						
Calcium silicate	15 mm thick calcium silicate board panels (975 kg/m^3)						
Time to FO (s)	174	No FO	No FO	No FO	366	630	414
Peak RHR (kW)	-	941	600	809	-	-	-
Time to peak RHR (s)	-	486	1200	723	-	-	-
% lining charred	66	100	56	100	99	100	90
% room charred	58	23	13	23	38	30	42

Relevant observations:

Experiment 1: The performance of the fully lined (3 walls plus ceiling) standard ISO 9705 configuration with 7 mm ply achieved consistent results with other ISO room burn data achieving Group 3 performance under the NCC Classification System. There was minimal involvement of the timber lining below 1.2 m except near the burner.

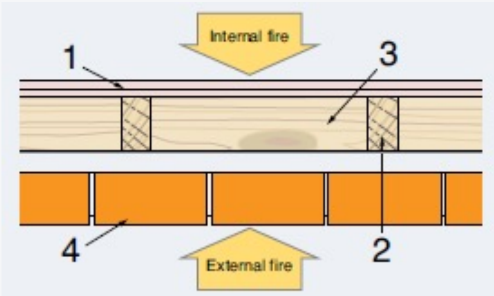
The flashover criteria of 1 MW HRR was not reached in experiments 2, 3 and 4 all of which included 23% timber linings. In experiment 3 (timber applied to the lower half of the walls) there was little involvement of the timber except for an area within approximately 1.5 m of the burner and this provides strong supporting evidence for the use of dado linings up to 1.2 m height.

Although flashover did not occur in Tests 2 and 4, flame spread across the entire timber surfaces and peak HRR of 951 and 809 kW occurred after 486 s and 723 s respectively indicating that the timber had been fully consumed and that flashover could occur with thicker boards. Also, data in Table 103 indicates that thinner boards may also flashover due to more rapid spread prior to consumption of the lining. Therefore, the configuration with fully timber lined ceilings and combustible walls is unlikely to provide equivalence to Group 1 performance over a broad range of sizes but equivalence to Group 2 may be able to be shown for specific applications using a Performance Solution pathway.

Tests 5, 6 and 7 provide useful information for comparison with projects examining the performance of Massive Timber enclosures with partially exposed walls and ceilings.

E Appendix E - Example Data Sheet Identifying Evidence of Suitability

External Brick Veneer Timber framed wall system



1 Fire protective grade plasterboard, 2 x 13 mm thick

2.Timber framing in accordance with Evidence of Suitability

3 Cavity. – Cavity insulation may be required to achieve sound ratings and R –value (insulation must be non-combustible)

4 Outer brick veneer 90 mm thick

Typical Performance

Fire-protected timber	FRL90/90/90: RISF45: NC
Sound transmission and insulation	R_w 50: R_w+C_{tr} 50
Thermal resistance	R Value 3.3 m^2K/W
Damp and weatherproofing	NCC performance requirement FP1.4
Structural tests	NCC specification C1.8 Clause 3.4

Evidence of Suitability

Fire-protected timber:	
Internal Fire Exposure	FRL Test or assessment report from an Accredited Testing Laboratory complying with NCC A5.4 – (Lab XYZ Report Ref 123) RISF – 45 (NCC Spec C1.13a DTS)
External Fire Exposure	FRL Test or assessment report from an Accredited Testing Laboratory complying with NCC A5.4 or design in accordance with AS 3700 RISF – 45 (AS 3700 design for insulation or test or assessment report from an Accredited Testing Laboratory)
Non-combustibility	Plasterboard NCC C1.9(e)(i) DTS Fire-protected timber NCC C1.13 Concession Cavity Insulation AS 1530.1 test Brickwork – NCC C1.9 / C2D10(4) n iii (planned introduction in 2022) DTS

Sound Transmission and Insulation No NCC requirement for external walls in NCC but commonly specified for inner city locations. Report from a laboratory or acoustics engineer stating performance achieved.

Thermal Resistance R-Value Report complying with NCC Clause A5.2

Weatherproofing Statement of compliance with relevant requirements of AS 3700 and report confirming applicability of AS 3700 – complying with NCC Clause A5.2.

Structural tests for lightweight construction Report complying with NCC Clause A5.2 expressing results of tests in accordance with NCC specification C1.8.

Primary Distributors Plasterboard Supplier xyz

Note: The above is an example of how summaries can be developed to identify necessary Evidence of Suitability for fire protected timber elements. A document similar to the above could be included in a product technical statement from a manufacturer. Selection of systems that are fit for purpose and the provision of Evidence of Suitability to the satisfaction of the Appropriate Authority is the responsibility of the designers and product suppliers. Forest and Wood Products Australia Limited (FWPA) and the authors of this Guide make no warranties or assurances with respect to the fitness for purpose of the systems described in this Guide.

F Appendix F - European Standard EN 1991-1-2: 2002 Annex A (Eurocode 1-1-2)

The Eurocode parametric heating curves for fully developed fires are referred to in various parts of this Guide. This Appendix describes the method for generating the parametric heating curves.

The 'standard heating regime' has changed little over the years. It was originally based on natural fire tests undertaken with cellulosic fire loads and enclosure boundaries having a high thermal inertia. Application of the standard heating regime to modern enclosures with fire loads that include large proportions of plastics and bounding construction with low thermal inertia have been questioned because significantly higher enclosure temperatures are generated for the same ventilation conditions. This limitation is well known and has been identified by numerous researchers[68,110]. This led to the inclusion of the more severe hydrocarbon heating regime as an alternative heating regime in the informative Appendix B to AS 1530.4 in the 2005 edition[240].

The impact of differing oxygen concentrations with furnace and enclosure fires has also been identified as a variable that may need to be taken into account[241] and a practical method of treating this in relation to wood products is to assume low oxygen concentrations (typically below 10%) for the fully developed fire stage consistent with a ventilation-controlled fire and the conditions within modern fire-resistance test furnaces using pre-mixed burners without secondary air supplies, and to assume plentiful supplies of oxygen (>15%) during the fire growth, decay and cooling phases. Oxygen concentrations within enclosure fires are discussed in more detail in the body of this Guide.

A common approach to characterise the fully developed stage of a fire is the adoption of parametric time-temperature curves that account for variations in fire loads, ventilation conditions and thermal properties of boundaries of an enclosure. A typical example is the method described in Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire 2002 Annex A[39].

F1 Limitations

a) EN 1991-1-2:2002 states the temperature-time curves are valid for fire compartments up to 500 m^2 of floor area, without openings in the roof and for a maximum compartment height of 4 m.

Note: This can present complications for timber construction if the fixed fire load is significant and some adjustment to the method may be required. Since a time/temperature history is derived, it is possible with additional analysis to determine scenario times to failure of elements of construction and to take account of interventions allowing the interactions between various parts of a fire safety strategy to be evaluated. Where quantitative risk assessments are undertaken, the frequency of scenarios where a fire burns out completely is likely to be extremely low in most cases, but it is still necessary to consider low probability high consequence events.

b) The method assumes that the specified fire load of the compartment is completely burnt out.

c) Annex E of EN 1991-1-2 must not be used for the determination of the fire load densities when using the Annex F method to determine the time equivalence when determining compliance with the NCC.

This restriction is applied because Annex E of EN 1991-1-2 includes a series of adjustments to account for the floor area, potential characteristics of the fire load, fire protection measures in place and fire brigade intervention. These matters should be addressed specifically as part of the fire engineering analysis process. The use of Annex E is not appropriate when using the NCC FSVM method or other methods to demonstrate compliance using the Performance Solution pathway.

d) The standard indicates that the method should be limited to fire compartments with mainly cellulosic type fire loads.

F2 Fire load

$q_{t,d}$ is the design value of the fire load density related to the total surface area (A_t) of the enclosure subject to:

$50 \leq q_{td} \leq 1\,000$ – MJ/m^2

$q_{t,d}$ can be derived from the more commonly used fire load density ($q_{f,d}$) related to the surface area of the floor (A_f) using:

$q_{t,d} = q_{f,d} \, . \, A_f/A_t$ – MJ/m^2

where A_t is the total area of enclosure (walls, ceiling and floor, including openings) – m^2

F3 Burning regime

Opening factor calculation:

$O = A_v (h_{eq})^{1/2}/A_t - m^{1/2}$ $\quad 0.02 \le O \le 0.20$

where:

A_v is the total area of vertical openings on all walls (m^2)

h_{eq} is the weighted average of window heights on all walls (m)

A_t is the total area of enclosure (walls, ceiling and floor, including openings) (m^2)

Determination of Burning Regime:

The fire is ventilation controlled if $[0.2\, q_{t,d}\, 10^{-3}/O] \ge t_{lim}$ otherwise the fire is treated as fuel controlled.

where:

t_{lim} expressed in hours is 0.417 for a slow growth rate, 0.333 for a medium growth rate and 0.25 for a fast growth rate.

F4 Thermal properties of boundaries

Thermal Inertia $\quad b = (\rho c \lambda)^{1/2}$ $\quad$ - $J/m^2s^{1/2}K$ $\quad 100 \le b \le 2200$

where:

ρ is density of bounding enclosure (kg/m^3)
c is specific heat of boundary enclosure (J/ kgK)
λ is thermal conductivity of boundary of enclosure (W/mK)

Calculation of thermal inertia for enclosure surfaces with different layers of material:

If $b_1 < b_2$, $b=b_1$

If $b_1 > b_2$, a limit thickness s_{lim} is calculated for the exposed material according to:

$s_{lim} = (3600\, t_{max}\, \lambda_i/c_i\rho_i)^{1/2}$

If $s_1 > s_{lim}$ then $b = b_1$

If $s_1 < s_{lim}$ then $b = s_1/s_{lim}\, b_1 + (1 - s_1/s_{lim})\, b_2$

Where the index, 1, represents the layer directly exposed to the fire, the index, 2, the next layer….and s_i is the thickness of layer i

$b_i = (\rho_i c_i \lambda_i)^{1/2}$
ρ_i is the density of the layer i
c_i is the specific heat of the layer i
λ_i is the thermal conductivity of the layer i

Calculation of thermal inertia for different b factors in walls ceilings and floors:

$b = (\sum(b_j A_j))/(A_t - A_v)$
where:
A_j is the area of enclosure surface j, openings not included
b_j is the thermal property of enclosure surface j

Typical material properties:

The material properties of the enclosure boundaries are generally based on the properties under ambient conditions, but the use of effective values may be more appropriate if justified and validated appropriately. The values listed in Table 108 have been assembled from various studies and other sources but the material properties to be used should be agreed during the PBDB process.

Table 108: Nominal material properties for enclosure boundaries for deriving EN 1991-1-2 parametric curves.

Material	Mat Code	Thermal Cond. (k) (W/mK)	Density (ρ) (kg/m3)	Specific Heat (c) (J/ kgK)	b=√(kρc) (J/m2s1/2 K)	Source
Normal Weight Concrete	NWC	1.8	2300	940	1973	England et al (b factor similar order to Buchanan and a b value of 1900)
Lightweight Concrete Blocks	LWC	0.42	1375	753	659	Kirby
Autoclaved Aerated Concrete	AAC	0.16	450	1505	329	Kirby
Fire Grade Plaster board	GBP	0.24	900	1250	520	Kirby
Ceramic Fibre	HDF	0.02	128	1130	54	Kirby
Wood	WOOD	0.14	470	1700	334	Hakkarainen
Mineral Wool Density 30 kg/m^2	LDF	0.03	30	1000	30	Hakkarainen
Autoclaved Aerated Concrete – 2	AAC-2	0.36	350	1000	355	McNamee et al
Calcium Silicate Board	CSB-2	0.212	900	1000	437	McNamee et al
Mineral Wool – 2	MF-2	0.05	96	1000	69	McNamee et al
Wood – 2	WOOD-2	0.12	450	1530	287	McNamee et al
Normal weight concrete – 2	NWC-2	1.33	2400	900	1695	McNamee et al
Wood – 3	WOOD-3	0.14	550	1700	362	Hakkarainen with adjusted density.
Wood – 4	WOOD-4	0.14	650	1700	393	Hakkarainen with adjusted density.
Wood Char @800°C	CHAR -1	0.35	143	1650	287	Eurocode 5 char values

F5 Modification factor, fictitious time and time to maximum temperature

Ventilation controlled fires:

If the fire is ventilation controlled, the modification factor Γ is calculated using the following equation:

$$\Gamma = (O/b)^2/(0.04/1160)^2$$
$$t^* = t\,\Gamma$$

and the maximum temperature θ_{max} occurs when $t^* = t^*_{max}$ where:

$$t^*_{max} = t_{max}\,\Gamma$$
$$\text{and } t_{max} = 0.2\, q_{t,d}\, 10^{-3}/O$$

Fuel-controlled fires:

If the fire is fuel controlled

$$\Gamma_{lim} = (O_{lim}/b)^2/(0.04/1160)^2$$
$$O_{lim} = 0.1\, q_{t,d}\, 10^{-3}/t_{lim}$$

If $O_{lim} > 0.04$, $q_{t,d} < 75$ and $b < 1160$; Γ_{lim} has to be multiplied by k where:

$$k = 1+((O-0.04)/0.04)\,((q_{t,d} - 75)/75)\,((1160 - b)/1160)$$
$$t^* = t\,\Gamma_{lim}$$

F6 Temperature – time curves

The temperature-time curves in the heating phase are given by:

$$\theta_g = 20 + 1325\,(1 - 0.324\, e^{-0.2t^*} - 0.204\, e^{-1.7t^*} - 0.472\, e^{-19t^*})$$

where:

θ_g is the enclosure gas temperature (°C)

t^* is a fictitious time given by $t^* = t\,\Gamma$ if ventilation controlled or $t^* = t\,\Gamma_{lim}$ if fuel controlled

t is time (h)

F7 Decay/cooling phase

During the decay/cooling phase, the temperature is assumed to decrease linearly at one of three rates specified below

$\theta_g = \theta_{max} - 625 (t^* - t^*_{max} X)$ for $t^*_{max} \leq 0.5$ hours

$\theta_g = \theta_{max} - 250 (3 - t^*_{max}) (t^* - t^*_{max} X)$ for $0.5 < t^*_{max} < 2$ hours

$\theta_g = \theta_{max} - 250 (t^* - t^*_{max} X)$ for $t^*_{max} \geq 2$ hours

$t^*_{max} = (0.2\ q_{t,d}\ 10\text{-}3/O)\ \Gamma$

$X = 1.0$ if $t_{max} > t_{lim}$, (ventilation-controlled case) or

$X = t_{lim}\ \Gamma/t^*_{max}$ if $t_{max} = t_{lim}$ (fuel-controlled case)

F8 Eurocode 5 EN 1995-1-2 charring rates under parametric heating and cooling curves

For unprotected softwood the relation between the charring rate β and time t shown in Figure A1 should be used. The charring rate β_{par} during the heating phase of a parametric fire curve is given by:

$$\beta_{par} = 1.5\ \beta_n \frac{0.2\sqrt{\Gamma} - 0.04}{0.16\sqrt{\Gamma} + 0.08}$$

$$t_o = 0.009 \frac{q_{t,d}}{O}$$

Where:

β_{par} is the charring rate during the heating phase of a parametric fire curve

O is the opening factor, in $m^{0.5}$

β_n is the notional design charring rate (mm/min)

Γ is the modification factor

$q_{t,d}$ is the design value of the fire load density related to the total surface area (A_t) of the enclosure

t_0 is the time period with a constant charring rate, in minutes (approximate duration of fully developed fire)

The charring rate then reduces to zero over a further time period of $2t_0$

During the $2t_0$ decay period the char depth (dchar) is given by the following equation

$d_{char} = \beta_{par} (1.5t_0 - t_2/4t_0 - t_0/4)$

At the end of the char period, the char depth will be $2\beta_{par}\ t_0$

The following constraints apply to the above methods:

$t_0 \leq 40$ min

$d_{char} \leq b/4$

$d_{char} \leq h/4$

where:

b is the width of the cross-section

h is the depth of the cross-section

Additionally, the above relationships assume that charring discontinues at the end of the $2t_0$ decay period, inferring that both flaming and smouldering combustion has ceased.

G Appendix G - Generic Model for Comparison of Fire Exposures

In most instances, the time to failure of an element of construction ascertained in a standard fire-resistance test will differ from the failure time if the element is exposed to a real or simulated fire scenario, such as a parametric heating curve based on the Annex A of EN 1991-1-2:2002[39] approach, because the time temperature histories differ.

If an element of construction comprises homogeneous materials with known thermal and mechanical properties at elevated temperatures, it is possible to determine the time to failure using simple correlations or more complex methods, such as finite element analysis. However, many fire-resistant elements or components are complex to model reliably, such as fire doors, penetration seals, composite systems, connections, board fixings, adhesion of sprayed materials, spalling of high-strength concrete, etc. A simple general method for conversion of fire-resistance times to scenario times may be adequate if used in conjunction with appropriate fire-resistance test data.

A method based on equal temperature of a protected thermal mass has been developed that can determine equivalent fire exposures estimates throughout a whole fire scenario.

A 'target element' is defined with appropriate thermal properties and the temperature at a critical point calculated when exposed to the fire scenarios and the standard heating regime. Equivalent exposure is deemed to have occurred when the critical part of the element reaches the same temperature under the different heating regimes. In this case, a lumped thermal mass approach was adopted with the mean temperature calculated using the following equation from Milke[242].

$$\Delta T_s = \frac{k_i}{h}\left[\frac{(T_f - T_s)}{c_s\left(W/D\right) + \frac{c_i \rho_i h}{2}}\right]\Delta t$$

Where:

T_s is the steel temperature (°C)

T_f is the enclosure temperature (°C)

k_i is the thermal conductivity of the insulation (W/m.K)

c_i is the heat capacity of the insulation (K/kg.K)

ρ_i is the density of the insulation (kg/m^3)

c_s is the heat capacity of steel (J/kg.K)

W/D is the mass per unit length divided by the heated perimeter (kg/m^2)

Δt is the time step (s)

h is the insulation thickness (m)

The process is shown in Figure 212. If it is required to determine the time to failure of an element that achieved an FRL of 63/-/- when exposed to the fire scenario (parametric curve) fire, the following approach is adopted:

- the target element attains a temperature of 454°C when exposed to the standard fire-resistance test for 63 min
- the target element would need to be exposed to the fire scenario for 45 min to attain the same temperature.

Therefore, the fire scenario failure time would be 45 min.

In this example, the target element would need to be exposed to the hydrocarbon heating regime for 45 min to attain 454°C as well.

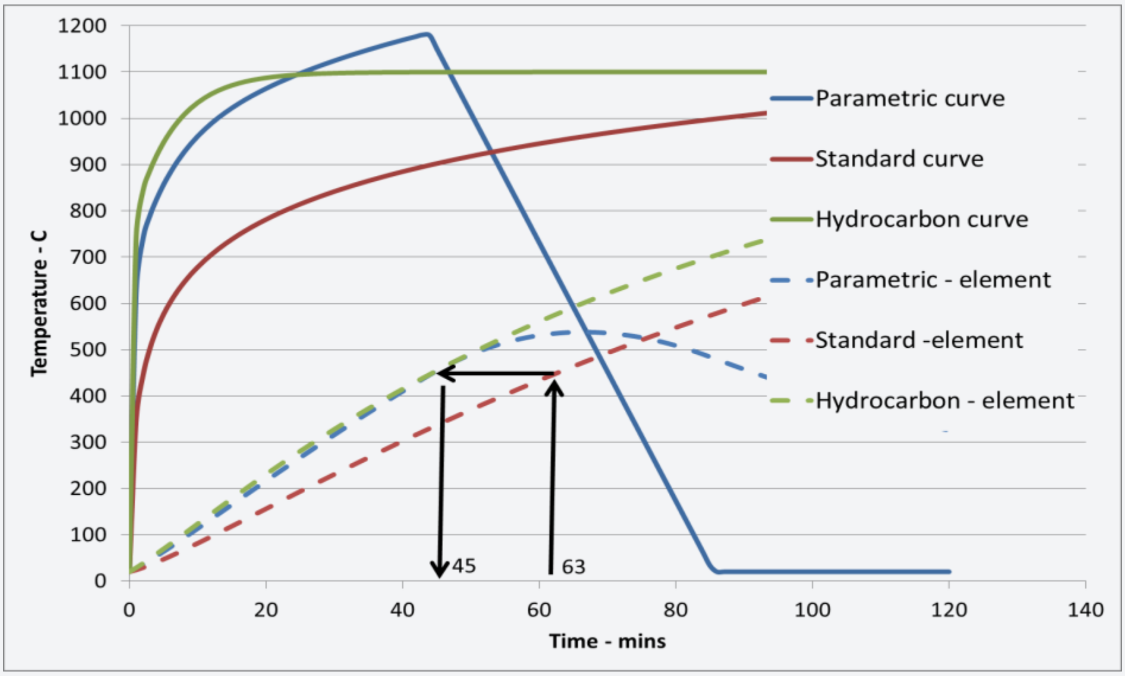


Figure 212: Conversion of fire resistance period to fire scenario time.

The process can be repeated in reverse. For example, if it was required to estimate the FRL capable of withstanding a parametric scenario, the peak temperature for the target element (thermal mass) is approximately 540°C for the parametric scenario. The target element would need to be exposed to the standard heating regime for approximately 80 min to attain 540°C. This is normally rounded up to the nearest 'standard FRL period' to specify a system, i.e. an FRL of 90/90/90 could be specified if the element is required to maintain fire compartmentation and structural adequacy throughout the parametric fire scenario.

The main limitation with the above method is that it considers thermal performance only.

Other factors (such as thermally induced deflections and or stresses, degradation of structural materials and materials used for protection such as spalling, shrinkage, thermal shock, smouldering combustion, and other chemical reactions) may need to be taken account of separately if they are not indirectly accounted for in the thermal analysis. Validation against a range of heating conditions can provide confidence in the application of a method to an element of construction and highlight sensitivities of the system to heating rates.

H Appendix H - References

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