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Timber Rivet Connection



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Introduction

1.1 Summary

The aim of this Design Guide is to provide an aid for engineers for designing timber rivet connections in structural seasoned wood products including seasoned sawn timber, glulam and laminated veneer lumber (LVL). This Guide includes the design checks for both wood and fastener load-carrying capacities under different loading directions; parallel and perpendicular to grain. By using the Design Guide, an efficient connection design can be made by decreasing the difference between the capacity of the wood and the rivets. It also allows the practitioners to predict the potential brittle (wood block tear-out/splitting), ductile (rivet yielding) and mixed failure modes of the connection.

Section 1 provides an introduction to timber rivets, along with the advantages and applications of timber rivet connections. It also includes characteristic stress tables for LVL, glulam and sawn timber. Flowcharts illustrating the key design steps in the design process are provided in Section 2. Section 3 covers the basic details for timber rivet connections, while Section 4 provides the design rules for rivet connections including rivet capacity, wood block tear-out and splitting capacity. To illustrate the design process, a series of examples are presented in Section 5. Finally, within the Appendices, reference capacity design tables and cost-efficiency analysis for rivets are provided to speed up the computation process.

1.2 Timber Rivets

Connections such as hinged and moment resisting connections are often the most critical parts of any type of structure. Evaluation of timber buildings damaged after extreme wind and earthquake events have shown that weak connections are one of the major causes of problem¹. As demonstrated over the decades, small-diameter fasteners have shown a significant advantage over large-diameter fasteners such as bolts, which cause large localized stresses and force brittle ruptures in timber. Of this family of fasteners, the timber rivet is a well-established example in timber connection technology². The development of a wood connection providing satisfactory load transfer, joint stiffness, easy manufacture, and good appearance led to the invention of the timber rivets³.

Timber rivets are hardened steel nails with a rectangular cross-section used in making connections with high load transfer capacity and high stiffness, as shown in Figure 1.1. Rivets are available in three standard lengths; 40, 65, and 90 mm (Figure 1.2). They are always used with a steel plate and the load transfer depends as much on the steel plate capacity as on the rivet connection capacity.

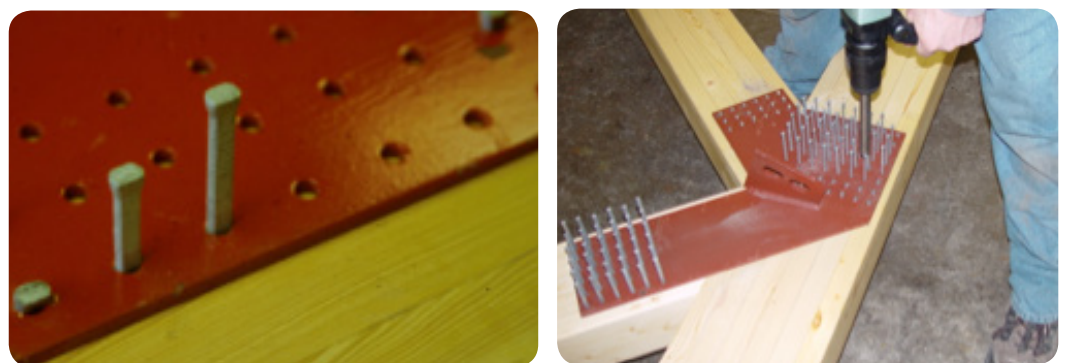


Figure 1.1: Timber rivet connections. Source: Buchanan, A., *Timber design guide* New Zealand Timber Industry Federation Inc. Wellington, New Zealand, 2007.



Figure 1.2: Timber rivets.

The rivets are driven through holes in the side plates by the use of either a standard hammer or a palm pneumatic hammer, until the conical heads are firmly seated with a maximum projection of 3.2 mm (half of the tip taper of 6.4 mm). When seated in this manner, the rivet head slightly deforms the steel side plate and wedges in place, creating a fixity that restricts the rivet head from rotating under load. This contributes to the overall stiffness of the connection.

Rivets should not be driven flush, as this will result in losing head fixity. Timber rivets are always driven with the major axis (long side of rectangular nail) parallel to the grain of the timber. They are installed in a spiral pattern from the outside of the group in towards the centre. This way, the pre-stressed fibres will minimise splitting from occurring⁴. Please refer to Section 3 for detailing of the rivets and rivet plates.

Timber Rivets are part of the Canadian CSA-O86⁵ and American NDS⁶ Wood Standards. However, these Standards have no closed form solution for the strength prediction of this type of connection under wood failure mechanisms. Also, these Standards restrict the use of rivets to specific configurations and for glulam and sawn timber of some limited species⁷.

1.2.1 Advantages for Designers

Timber rivet connections offer a number of benefits to designers:

- High load transfer capacity (see Table 1.1)
- Tight-fit dowel action providing stiff connections
- High ductility and the ability to dissipate dynamic loads if detailed to fail in a ductile fashion
- Low variability in strength and deflection properties
- No requirement for pre-drilling and no reduction of timber cross-section
- Ease of installation and inspection in the field
- A cost-effective alternative to other dowel-type fasteners.

Table 1.1: Rivet ultimate design capacity under ductile failure in a double-sided joint with an array of 8*8 i.e. 6 rows of nails with 8 nails in each row, in Radiata Pine LVL.

Rivet Length	40 mm	65 mm	90 mm
Parallel-to-grain loading	350 kN	495 kN	525 kN
Perpendicular-to-grain loading	345 kN	415 kN	440 kN

1.2.2 Applications

Timber rivet connections have been used successfully in Canada and the US for the past four decades in different types of structures (see Figure 1.3) including:

- Long span truss connections (see design example in Section 5.1)
- Long span beam splices
- Beam-to-column and column-to-foundation connections (see design example in Section 5.2)
- Couple moment connections (see design example in Section 5.3)
- Energy dissipating connections
- Shear wall hold-down anchorages (see design example in Section 5.5).

In large structures, where the ductile behaviour and energy dissipation of the connections can be desirable due to the applied wind and seismic loads, the use of rivet connections would assure more structural safety under these dynamic loads⁸. Their high load-transfer and high stiffness characteristics, ease of installation and flexibility in the field make them a highly effective and reliable connector choice.



Figure 1.3: Sample applications of timber rivet connections.

(Image credit: Specialized Timber Fasteners Ltd, Canada)



Figure 1.4: Riveted connections on the Carterton Event Centre, New Zealand.

(Image credit: McIntosh Timber Laminates Ltd)



Figure 1.5: Riveted connections of the Trimble building in Christchurch, New Zealand.

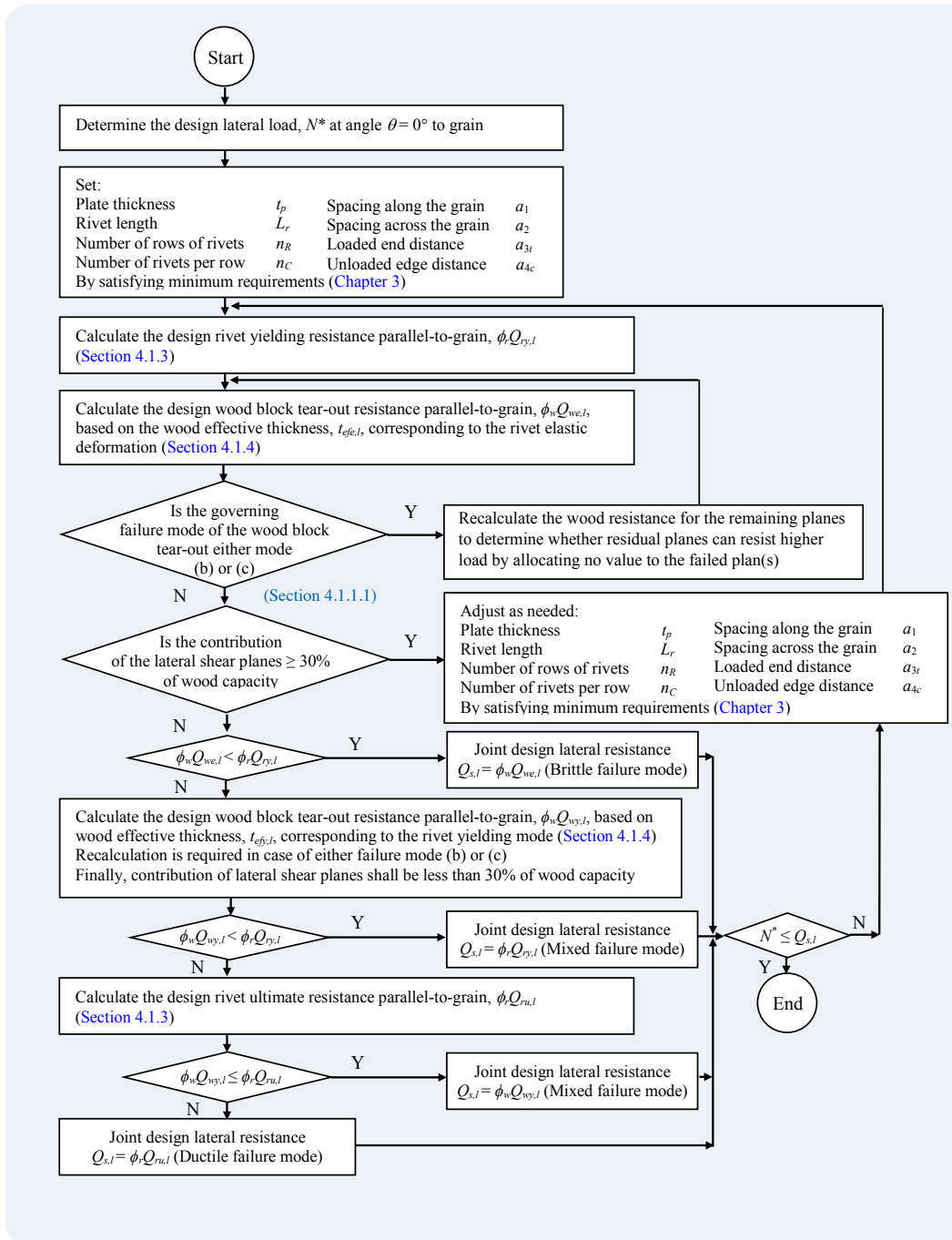
(Image credit: McIntosh Timber Laminates Ltd)

Timber Rivet Connection Design Process Flowcharts

The design process for timber rivet connections under different loading directions is illustrated through the following flowcharts. Mainly, two strength limit states are of interest: rivet resistance and wood resistance. Steel plate capacity is not covered in these flowcharts and should be checked using the appropriate steel design code.

2.1 Design Process Flowchart for Load Applied Parallel to Grain

The following flowchart describes the processes required to design a rivet connection.





```

graph TD
    Start((Start)) --> DetermineLoad[Determine the design lateral load,  $N^*$  at angle  $\theta = 90^\circ$  to grain]
    DetermineLoad --> SetParameters[Set:  
Plate thickness  $t_p$       Spacing across the grain  $a_2$   
Rivet length  $L_r$       Unloaded end distance  $a_{3c}$   
Number of rows of rivets  $n_R$       Loaded edge distance  $a_{4t}$   
Number of rivets per row  $n_C$       Unloaded edge distance  $a_{4c}$   
Spacing along the grain  $a_1$   
By satisfying minimum requirements (Chapter 3)]
    SetParameters --> CalculateRivetYield[Calculate the design rivet yield resistance perpendicular-to-grain,  $\phi_r Q_{r,p}$  (Section 4.1.3)]
    CalculateRivetYield --> CalculateWoodSplittingElastic[Calculate the design wood splitting resistance perpendicular-to-grain,  $\phi_w Q_{we,p}$ , based on the wood effective thickness,  $t_{eff,p}$ , corresponding to the rivet elastic deformation (Section 4.1.5)]
    CalculateWoodSplittingElastic --> Decision1{ $\phi_w Q_{we,p} < \phi_r Q_{r,p}$ }
    Decision1 -- Y --> JointResistance1[Joint design lateral resistance  
 $Q_{s,p} = \phi_w Q_{we,p}$  (Brittle failure mode)]
    Decision1 -- N --> CalculateWoodSplittingYield[Calculate the design wood splitting resistance perpendicular-to-grain,  $\phi_w Q_{wy,p}$ , based on the wood effective thickness,  $t_{eff,p}$ , corresponding to the rivet yielding mode (Section 4.1.5)]
    CalculateWoodSplittingYield --> Decision2{ $\phi_w Q_{wy,p} < \phi_r Q_{r,p}$ }
    Decision2 -- Y --> JointResistance2[Joint design lateral resistance  
 $Q_{s,p} = \phi_r Q_{r,p}$  (Mixed failure mode)]
    Decision2 -- N --> CalculateRivetUltimate[Calculate the design rivet ultimate resistance perpendicular-to-grain,  $\phi_o Q_{ru,p}$  (Section 4.1.3)]
    CalculateRivetUltimate --> Decision3{ $\phi_w Q_{wy,p} \leq \phi_o Q_{ru,p}$ }
    Decision3 -- Y --> JointResistance3[Joint design lateral resistance  
 $Q_{s,p} = \phi_w Q_{wy,p}$  (Mixed failure mode)]
    Decision3 -- N --> JointResistance4[Joint design lateral resistance  
 $Q_{s,p} = \phi_o Q_{ru,p}$  (Ductile failure mode)]
    JointResistance1 --> Decision4{ $N^* \leq Q_{s,p}$ }
    JointResistance2 --> Decision4
    JointResistance3 --> Decision4
    JointResistance4 --> Decision4
    Decision4 -- Y --> End((End))
    Decision4 -- N --> SetParameters
  
```



2.3 Design Process Flowchart for Load Applied at an Angle θ to Grain

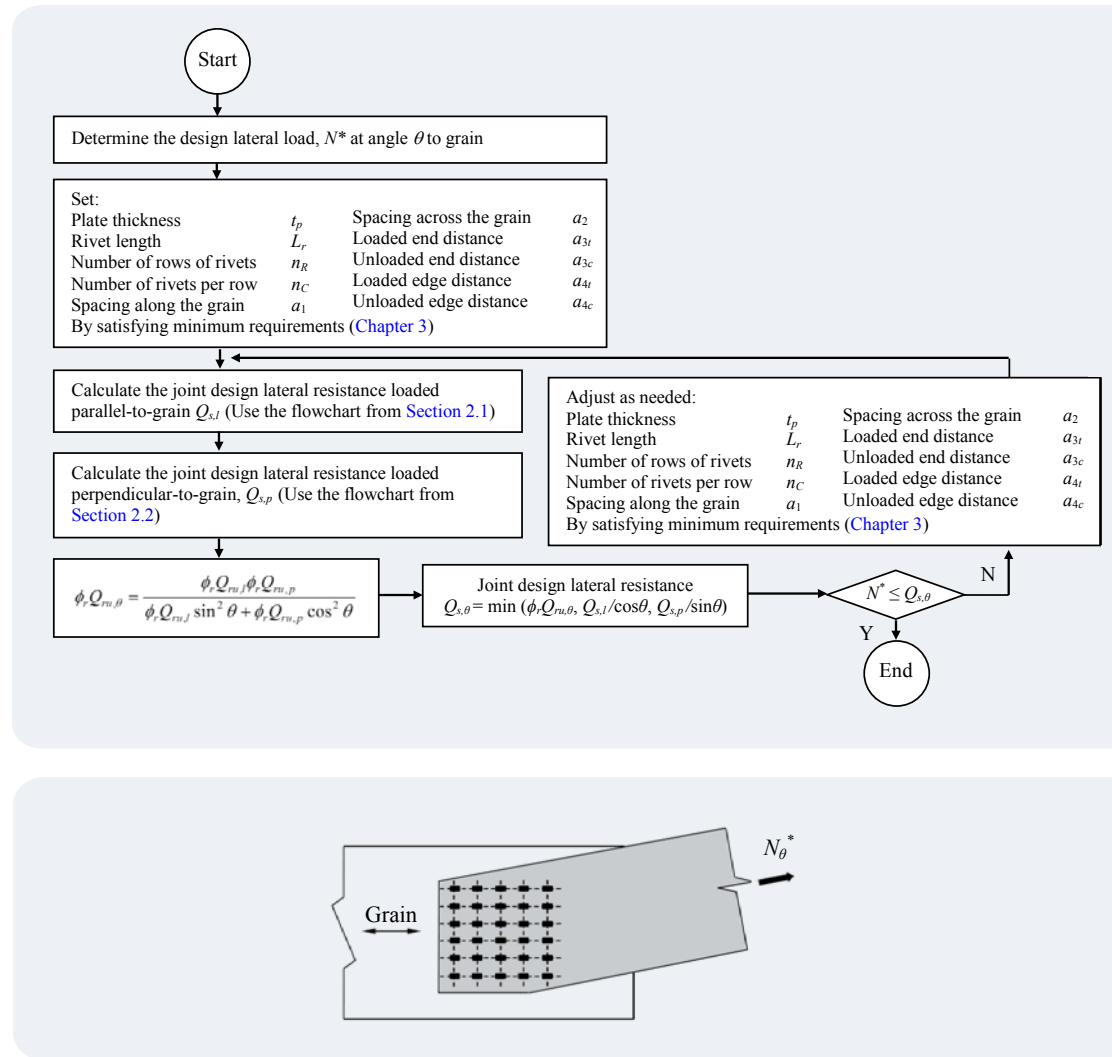


Figure 2.3: Loading at an angle.

Detailing of Rivets and Rivet Plates (General Notes and Requirements)

3.1 General Specifications

The design methods specified in Section 4 are for timber rivets that meet the following criteria:

1. Ultimate tensile strength: 1000 MPa, minimum
2. Hardness: Rockwell (C32-39)
3. Finish: hot-dip galvanized
4. Have dimensions as shown in Figure 3.1.

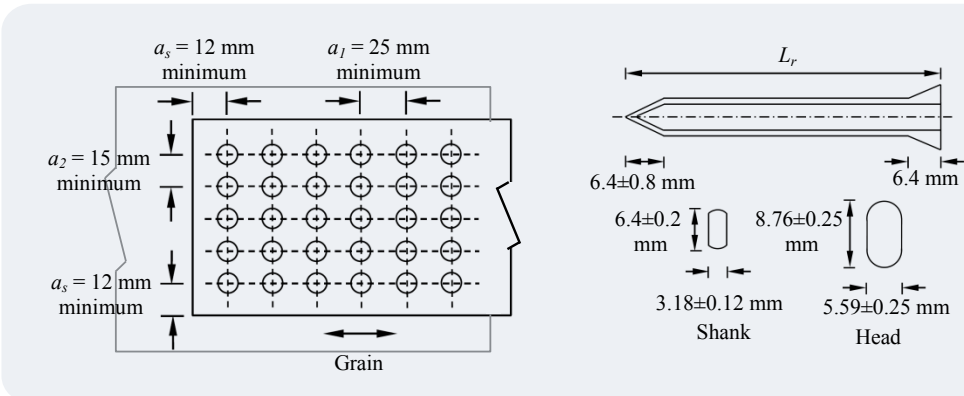


Figure 3.1: Timber rivet joint: rivet details (left); and typical steel plate configuration (right).

Notes:

1. Hole diameter: $6.9 \pm 0.1 \text{ mm}$
2. Tolerance in location of holes: 3 mm maximum in any direction.
3. Wide face of rivets parallel to grain, regardless of plate orientation.
4. All dimensions are prior to galvanizing.

3.2 Cross-Sectional Requirements

Side plates should have a cross-section adequate for resisting tension, compression and shear forces, but should be not less than 3.2 mm thick. (Minimum thickness is metrication of original research work.) For wet service conditions, side plates should be hot-dip galvanized. Particular attention should be paid to the possible interaction between any timber treatment chemical and the side plate material and protection. Refer to the WoodSolutions Design Guide #5: *Timber service life design* for further information on durability and fastener corrosion protection.

3.3 Placement Requirements

Each rivet should be placed with its major cross-sectional dimension aligned parallel to the grain for the timber element they penetrate. For connectors in trusses, this will generally mean alignment to the element in the joint. The design criteria in Section 4 are based on rivets driven through holes in the side plates until the conical heads are firmly seated with maximum projection of 3.2 mm. Rivets should not be driven flush.

To reduce timber splitting, it is important that timber rivets at the perimeter of the group should be driven first. Successive timber rivets should be driven in a spiral pattern from the outside to the centre of the group.

3.4 Spacing Requirements

The minimum rivet spacing should be:

- perpendicular to grain (a_2) = 15 mm
- parallel to grain (a_1) = 25 mm.

These minimum dimension become the starting of the layout. For C, the maximum penetration of the rivet should be 70% of the thickness of the wood member, as shown in Figure 3.2. For joints with rivets driven from opposite faces of a wood member, the rivet length should be such that the points do not overlap (Figure 3.3).



Figure 3.2: One-sided timber rivet connection.

3.5 End and Edge Distances Requirements

Based on research, the minimum end and edge distances are given in Tables 3.1 and 3.2

where

n_R = number of rows of rivets parallel to load

n_C = number of rivets per row

3.5.1 Parallel-to-Grain Loading

For parallel-to-grain loading:

1. Unloaded edge distance, a_{4c} : 25 mm
2. Loaded end distances, a_{3t} , for parallel-to-grain loading are tabulated in Table 3.1.

Table 3.1: Loaded end distance, a_{3t} , for parallel-to-grain loading.

Number of rivets per row n_C	Loaded end distance a_{3t} [mm]
1–6	75
7–10	100
11–12	125
13–14	150
15–16	175
≥ 17	200

3.5.2 Perpendicular-to-Grain Loading

For parallel-to-grain loading:

1. Unloaded edge distance, a_{4c} : 25 mm
2. Loaded end distances, a_{3t} , for parallel-to-grain loading are tabulated in Table 3.1.

Table 3.2: Unloaded end distance a_{3c} for perpendicular-to-grain loading.

Number of rows n_R	Unloaded end distance a_{3t} [mm]
1–6	75
7–10	100
11–12	125
13–14	150
15–16	175
≥ 17	200

3.5.3 Steel Side Plates

In the steel side plates (Figure 3.3):

1. Edge distance to rivet centres, both ways, as: 12 mm
2. Spacing along grain, a_1 : 25 mm
3. Spacing across grain, a_2 : 15 mm

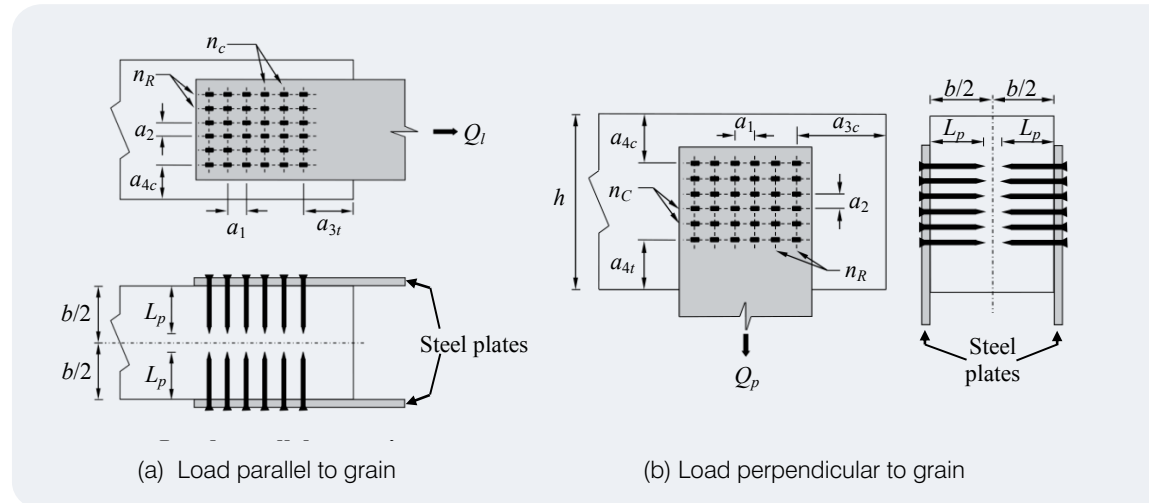


Figure 3.3: Geometry variables for timber rivet joints.

4

Structural Design Approach

4.1 Lateral Resistance

4.1.1 Failure Mechanism

There are three mechanisms of failure for riveted connections: the brittle tear-out of a plug of wood defined by the rivet's perimeter; the ductile yielding of rivets with localised wood crushing; and the mixed failure mode, which is a brittle failure of the wood with some deflection of the rivets before the rivets reach complete yielding.

The occurrence zone of these potential failure modes is illustrated on a typical load–deflection curve of a timber rivet joint (Figure 4.1). The failures can either be ductile (Figure 4.5); brittle (Figure 4.7a) or mixed (Figure 4.7b). The block tear-out in parallel-to-grain loading (Figure 4.6) and splitting in perpendicular-to-grain loading (Figure 4.10) are the possible wood failures.

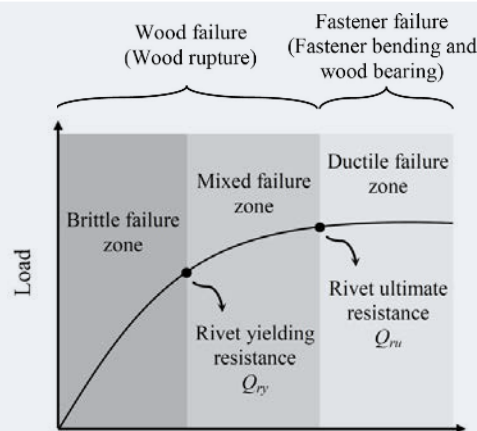


Figure 4.1: Occurrence zone of potential failure modes of timber rivet joints.

4.1.1.1 Brittle failure of wood

In the brittle zone (Figure 4.1), the fasteners deflection is in the elastic range, therefore, the effective wood thickness for the joint corresponds to the elastic deformation of the fasteners, $t_{el,ef}$, as shown in Figure 4.7a. In this failure zone, the wood capacity of the connection, $P_{w,tefe}$, is less than the fastener yielding resistance, $P_{r,yld}$. It should be noted that the $P_{r,yld}$ is not an ultimate failure but constitutes a boundary.

For parallel-to-grain loading, a brittle failure mode occurs when a block of wood bounded by the rivet cluster perimeter is pulled away from the member. As shown in Figure 4.2, the applied load transfers from the wood member to the resisting planes and involves both the tensile and shear capacities of the wood^{10,11,12}.

Due to the fact that rivets are small in diameter and installed in small spacing, they do not exhibit row shear or splitting failure modes under parallel-to-grain loading which can occur for larger dowel-type fasteners such as bolts.

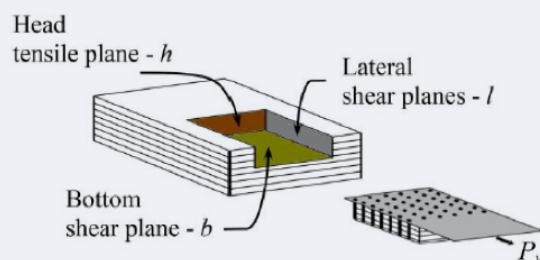


Figure 4.2: Brittle wood block tear-out failure – parallel to grain. Source: Zamani, P., Load-carrying capacity and failure mode analysis of timber rivet connections. 2013, ResearchSpace@ Auckland.

As shown in Figure 4.3, when the joint is subjected to transverse loading, a brittle failure mode can happen where the wood splits along the row of rivets next to the unloaded edge and the crack propagates towards the timber member ends till reaching the unstable zone^{12,13}.

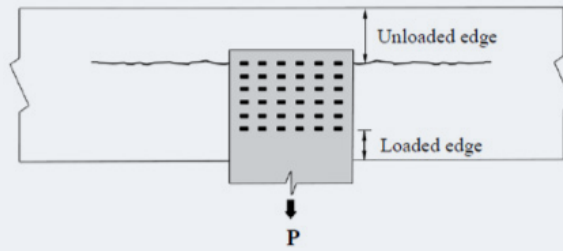


Figure 4.3: Crack growth on either side of the joint along the row of rivets next to the unloaded edge. Source: Zamani, P., Load-carrying capacity and failure mode analysis of timber rivet connections. 2013, ResearchSpace@ Auckland.

4.1.1.2 Mixed Failure

A mixed failure mode (a mixture of brittle and ductile behaviour) is also possible. In mixed failure mode, the wood fails following some deflection of the rivets but before they reach complete yielding. In this failure mode, the thickness of the failed block is significantly smaller than the one associated with the brittle failure mode. As shown in Figure 4.4, the wood effective thickness, t_{ef} , depends on the governing yielding mode of the fastener.

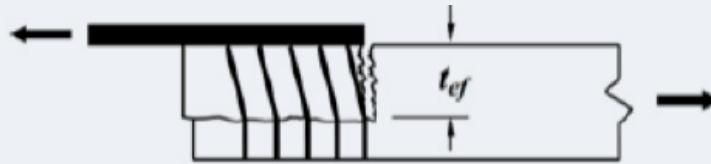


Figure 4.4: Effective wood thickness corresponding to rivet governing yielding mode – mixed failure mode.

As the yield point is reached, the effective wood thickness reduces if the yield mode is not Mode I. This reduction in effective wood thickness, $t_{ef,y}$, leads to the generation of a new connection failure mode (Figure 4.7b). If the wood capacity of the new connection, $P_{w,t_{ef,y}}$, cannot resist the fastener yielding load ($P_{w,t_{ef,y}} < P_{r,yld}$), a sudden wood failure with slight deflection on the fasteners which is called mixed failure mode occurs. Even if $P_{w,t_{ef,y}} > P_{r,yld}$, the mixed failure mode can happen as the deflection of the connection progresses if $P_{w,t_{ef,y}}$ is lower than the connection ultimate ductile strength, $P_{r,ult}$.

4.1.1.3 Ductile failure of rivet

If the wood strength based on effective wood thickness, $t_{ef,y}$ is greater than $P_{r,ult}$, the ductile failure governs and there is no wood rupture (Figure 4.1).

In ductile failure mode, either rivets are loaded longitudinally or transversely, and the rivet compresses the wood up to yielding which results in localised wood crushing. Since rivets are always used in single shear and the rivet head can be considered to be rotationally fixed as it is wedged into the steel plate's hole^{15,16}, only two yield modes can be possible (Figure 4.5)¹⁷.

The strength of the rivet under different ductile failure modes depends on the embedment resistance of the wood and the bending resistance of the rivet.

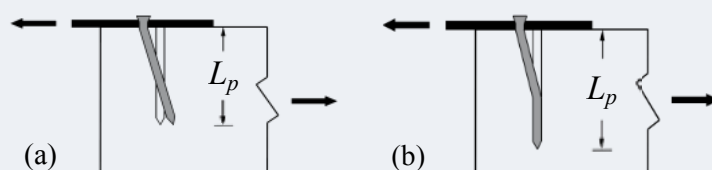


Figure 4.5: Different possible ductile failure modes of rivets: (a) one plastic hinge formation; (b) two plastic hinges

4.1.2 Design Requirement

Using the Load and Resistance Factor Design (LRFD) philosophy, a designer can evaluate the reliability of a structure with regard to its ultimate behaviour under extreme loads (e.g. wind) with significant displacements, where knowledge about the connection capacity beyond the yielding load is critical. In recognition of this fact, the design procedure presented enables a designer to determine the wood and fastener capacities in different possible connection failure modes under ultimate design.

If a designer wants to rely only on the yield limit state as the connection maximum capacity, therefore, the following design procedure can become briefer using:

$$Q_s = \min(\phi_w Q_{we}, \phi_r Q_{ry})$$

where

Q_s = joint design lateral resistance, kN, which should be derived as following the method given in this section.

Joints should be designed in accordance with the following requirement:

$$N^* \leq Q_s \quad (4.1)$$

where

N^* = design lateral load effects on joint due to factored load, kN

4.1.2.1 For joints loaded parallel to grain

By following the described mechanism for the potential failure modes, the joint ultimate capacity parallel to grain, $P_{c,ult}$, can be predicted as follows:

$$Q_s = Q_{s,l}$$

where

$$\begin{aligned} & \phi_w Q_{we,l} \text{ if } \phi_w Q_{we,l} < \phi_r Q_{ry,l} \quad (\text{Brittle mode}) \\ & \phi_r Q_{ry,l} \text{ if } \phi_w Q_{wy,l} < \phi_r Q_{ry,l} \leq \phi_w Q_{we,l} \quad (\text{Mixed mode, small slip}) \\ & \phi_w Q_{wy,l} \text{ if } \phi_r Q_{ry,l} \leq \phi_w Q_{wy,l} < \phi_r Q_{ru,l} \quad (\text{Mixed mode, large slip}) \\ & \phi_r Q_{ru,l} \text{ if } \phi_r Q_{ru,l} < \phi_w Q_{wy,l} \quad (\text{Ductile mode}) \end{aligned} \quad (4.2)$$

$\phi_w Q_{we,l}$: Design wood block tear-out resistance, parallel to grain, corresponding to rivet elastic deformation, kN (Section 4.1.4)

$\phi_r Q_{ry,l}$: Design rivet yielding resistance, parallel to grain, kN (Section 4.1.3-i)

$\phi_w Q_{wy,l}$: Design wood block tear-out resistance, parallel to grain, corresponding to rivet yielding mode, kN (Section 4.1.4)

$\phi_r Q_{ru,l}$: design rivet ultimate resistance, parallel to grain, kN (Section 4.1.3-i)

The flow charts of the design for rivets loaded parallel, perpendicular and at angle to the grain are given in Section 2.

4.1.2.2 For joints loaded perpendicular to grain

By following the described mechanism for the potential failure modes, the joint ultimate capacity perpendicular to grain, $P_{c,ult}$, can be predicted as follows:

$$Q_s = Q_{s,p}$$

where

$$Q_{s,p} = \begin{cases} \phi_w Q_{we,p} & \text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p} \quad (\text{Brittle mode}) \\ \phi_r Q_{ry,p} & \text{if } \phi_w Q_{wy,p} < \phi_r Q_{ry,p} \leq \phi_w Q_{we,p} \quad (\text{Mixed mode}) \\ \phi_w Q_{wy,p} & \text{if } \phi_r Q_{ry,p} \leq \phi_w Q_{wy,p} < \phi_r Q_{ru,p} \quad (\text{Mixed mode}) \\ \phi_r Q_{ru,p} & \text{if } \phi_r Q_{ru,p} < \phi_w Q_{wy,p} \quad (\text{Ductile mode}) \end{cases} \quad (4.3)$$

4.1.2.3 For joints loaded at an angle, θ , to the grain

$$Q_s = Q_{s,\xi}$$

where

$$Q_{s,\xi} = \min(\phi_r Q_{ru,\theta}, Q_{s,l} / \cos \theta, Q_{s,p} / \sin \theta) \quad (4.4)$$

where

$$\phi_r Q_{ru,\theta} = \frac{\phi_r Q_{ru,l} \phi_r Q_{ru,p}}{\phi_r Q_{ru,l} \sin^2 \theta + \phi_r Q_{ru,p} \cos^2 \theta} \quad (4.5)$$

4.1.3 Rivet Resistance under Ductile Failure

The analysis and design formulae for the rivet resistance in the following sections are based on two possible ductile failure modes (Figure 4.5).

The design resistance of rivets should be calculated as follows:

4.1.3.1 For parallel-to-grain loading

(i) **Rivet yielding resistance:**

$$\phi_r Q_{ry,l} = \phi_r Q_{r,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hy,0} \text{ and } M_{ry,l}, \text{ respectively}$$

where

$f_{h,0}$ = embedment strength for rivet bearing, parallel to grain, MPa (Section 4.1.3.3-i)

$f_{hy,0}$ = yielding embedment strength for rivet bearing, parallel to grain, MPa

$M_{r,l}$ = parallel-to-grain moment capacity of the rivet (Section 4.1.3.4-i)

$M_{ry,l}$ = parallel-to-grain yielding moment capacity of the rivet

(ii) **Rivet ultimate resistance:**

$$\phi_r Q_{ru,l} = \phi_r Q_{r,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

where

$f_{hu,0}$ = ultimate embedment strength for rivet bearing, parallel to grain, MPa

$M_{ru,l}$ = parallel-to-grain ultimate moment capacity of the rivet

$$\phi_r Q_{r,l} = \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \quad (4.6)$$

where

$P_{rp,a}$ = characteristic strength, perpendicular to grain, for rivet failure mode (a), kN (Section 4.1.3.2-i)

$P_{rp,b}$ = characteristic strength, perpendicular to grain, for rivet failure mode (b), kN (Section 4.1.3.2.ii)

4.1.3.3 Parallel-to-grain rivet characteristic strength

The parallel-to-grain rivet characteristic strength can be calculated as:

(i) **For rivet ductile failure mode (a):**

$$P_{rl,a} = X_r \left[J_p f_{h,0} L_p d_l \left(\left(\sqrt{2 + \frac{4M_{r,l}}{f_{h,0} d_l L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3} \quad (4.8)$$

where

X_r = adjustment factor for characteristic resistance (see Appendix A3 for details)

= 0.93 for LVL

= 0.87 for glulam

= 0.84 for sawn timber

J_p = side plate factor

= 1.0 for a side plate thickness, $6.3 \text{ mm} \leq t_p$

= 0.9 for a side plate thickness, $4.7 \leq t_p < 6.3 \text{ mm}$

= 0.8 for a side plate thickness, $3.2 \leq t_p < 4.7 \text{ mm}$

$f_{h,0}$ = embedment strength for rivet bearing parallel to grain, MPa (Section 4.1.3.3-i)

L_p = rivet penetration length, mm

= $L_r - t_p - 3.2$

where

L_r = rivet length, mm

t_p = side plate thickness, mm

d_l = rivet cross-section dimension bearing on the wood, parallel to grain,

= 3.2 mm

$M_{r,l}$ = parallel-to-grain moment capacity of the rivet (Section 4.1.3.4-i)

f_{ax} = withdrawal resistance per millimetre of penetration, N/mm (Section 4.2)

(ii) **For rivet ductile failure mode (b):**

$$P_{rl,b} = X_r \left[2J_p \sqrt{M_{r,l} f_{h,0} d_l} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3} \quad (4.9)$$

The variables are as specified above.

4.1.3.4 Perpendicular-to-grain rivet characteristic strength

The perpendicular-to-grain rivet characteristic strength can be calculated as:

(i) **For rivet ductile failure mode (a):**

$$P_{rp,a} = X_r \left[J_p f_{h,90} L_p d_p \left(\left(\sqrt{2 + \frac{4M_{r,p}}{f_{h,90} d_p L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3} \quad (4.10)$$

where

$f_{h,90}$ = embedment strength for rivet bearing, perpendicular to grain, MPa (Section 4.1.3.3-i)

d_p = rivet cross-section dimension bearing on the wood, perpendicular to grain,

= 3.2 mm

$M_{r,p}$ = perpendicular-to-grain moment capacity of the rivet (Section 4.1.3.4-i)

The other variables are as specified in Section 4.1.3.1.

(ii) For rivet ductile failure mode (b):

$$P_{rp,b} = X_r \left[2J_p \sqrt{M_{r,p} f_{h,90} d_p} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3} \quad (4.11)$$

The variables are as specified above.

4.1.3.5 Wood embedment strength

The embedment strength of wood for rivets, MPa, should be calculated as follows:

(i) For parallel-to-grain loading

- Yielding embedment strength:

$$\begin{aligned} f_{hy,0} &= 75.1 \rho (1 - 0.0037 d_l) 10^{-3} \text{ for LVL} \\ &= 71.9 \rho (1 - 0.0024 d_l) 10^{-3} \end{aligned}$$

for glulam and sawn timber

where

ρ = wood design density at 12% moisture content, kg/m³ (from Table H2.3 AS 1720)

d_l = rivet cross-section dimension bearing on the wood, parallel to grain

- Ultimate embedment strength:

$$\begin{aligned} f_{hu,0} &= 90.4 \rho (1 - 0.0037 d_l) 10^{-3} \text{ for LVL} \\ &= 86.7 \rho (1 - 0.0024 d_l) 10^{-3} \text{ for glulam and sawn timber} \end{aligned}$$

(ii) For perpendicular-to-grain loading

- Yielding embedment strength:

$$\begin{aligned} f_{hy,90} &= 49.9 \rho (1 - 0.0037 d_p) 10^{-3} \text{ for LVL} \\ &= 35.9 \rho (1 - 0.0024 d_p) 10^{-3} \text{ for glulam and sawn timber} \end{aligned}$$

- Ultimate embedment strength:

$$\begin{aligned} f_{hu,90} &= 60.2 \rho (1 - 0.0037 d_p) 10^{-3} \text{ for LVL} \\ &= 43.3 \rho (1 - 0.0024 d_p) 10^{-3} \text{ for glulam and sawn timber} \end{aligned}$$

The variables are as specified above.

4.1.3.6 Rivet moment capacity

The moment capacity of rivets should be taken as follows:

(i) For parallel-to-grain loading

- Yielding moment capacity:

$$M_{ry,l} = 24,900 \text{ Nmm}$$

- Ultimate moment capacity:

$$M_{ru,l} = 30,000 \text{ Nmm}$$

(ii) For perpendicular-to-grain loading

- Yielding moment capacity:

$$M_{ry,p} = 12,450 \text{ Nmm}$$

- Ultimate moment capacity:

$$M_{ru,p} = 15,000 \text{ Nmm}$$

4.1.4 Wood Resistance: Parallel-to-Grain Wood Block Tear-Out

The analysis and design formulae for wood block tear-out strength in the following sections are based on a linearly elastic spring system, in which the applied load transfers from the main loaded wood block to the contact planes in conformity with the relative stiffness ratio of the wood block adjacent to each of the resisting planes.

The wood capacity is the sum of the load resisted by each plane when failure of one of these planes triggers failure of the joint. The analysis is based on three possible failure modes of wood block tear-out, as shown in Figure 4.6.

The design wood block tear-out depends upon rivet behaviour. The design block tear-out resistance of the wood is calculated as follows:

(i) $c, Q_{we,l}$

$$\phi_w Q_{we,l} = \phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efe,l}$$

(ii) *Corresponding to the rivet yielding mode, $Q_{wy,l}$*

$$\phi_w Q_{wy,l} = \phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efy,l}$$

where

$$\phi_w Q_{w,l} = \phi_w k_f k_r n_p \min (P_{w,h}, P_{w,b}, P_{w,l}) \quad (4.12)$$

where

ϕ_w = strength reduction factor for wood failure
= 0.7

k_f = load duration factor (AS1720.1)

k_r = modification factor for joint position effect

= 0.9 for joint on edge grain of LVL

= 1.0 for joint on face grain of LVL or on edge/face grain of glulam and sawn timber

n_p = number of plates

= 1 for one-sided joint

= 2 for double-sided joint

$P_{w,h}$ = characteristic resistance for failure of head tensile plane, kN
(Section 4.1.4.1)-wood block tear-out failure mode (a)

$P_{w,b}$ = characteristic resistance for failure of bottom shear plane, kN
(Section 4.1.4.2)- wood block tear-out failure mode (b)

$P_{w,l}$ = characteristic resistance for failure of side lateral shear planes, kN
(Section 4.1.4.3)- wood block tear-out failure mode (c)

The resistance calculation may necessitate iteration if failure mode (b) or (c) governs the wood strength. Thus, Equation (4.12) for $\phi_w Q_{w,l}$ should be recalculated for the remaining planes (a second recalculation is required if one of these failure modes [failure mode (b) or (c)] occurs again) to determine whether the residual planes can resist higher load by defining no value for the terms related to the failed planes as follows:

(i) If failure mode (b) governs, use λ_2 and $\lambda_3 = 0$ in Sections 4.1.4.1 and 4.1.4.2 and do not consider Section 4.1.4.3

(ii) If failure mode (c) governs, use λ_1 and $\lambda_3 - 1 = 0$ in Sections 4.1.4.1 and 4.1.4.3 and do not consider Section 4.1.4.2.

The contribution of the side lateral shear planes to the total wood load-carrying capacity of the joint should be less than 30% of the total joint capacity, to limit splitting on these resisting planes before reaching the joint ultimate capacity. The maximum contribution of the side lateral shear planes is given by:

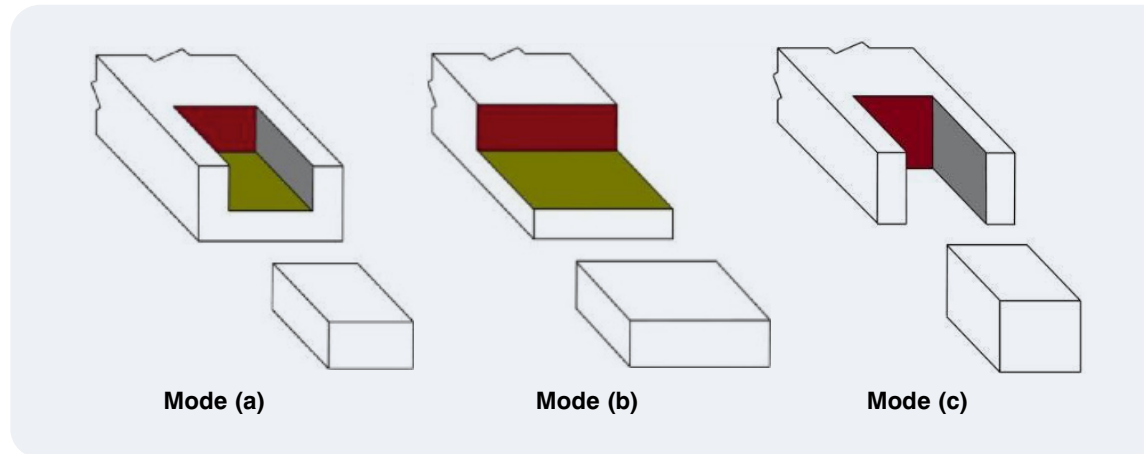


Figure 4.6: Different possible failure modes of wood block tear-out.

- (i) If the wood capacity governed when all resisting planes contributed: $(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$
- (ii) If the wood capacity governed when the head and lateral resisting planes contributed: $(1 + \lambda_2^{-1})^{-1} < 0.3$

4.1.4.1 Joint resistance governed by the head tensile plane failure – wood block tear-out failure mode (a)

The characteristic resistance for the failure of the joint triggered by the failure of the head tensile plane, $P_{w,h}$ kN, is given by:

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}, \text{ mode (a)} \quad (4.13)$$

where

X_t = adjustment factor for tension strength parallel to grain (see Appendix A3 for details)
= 1.06 for LVL
= 1.19 for glulam
= 1.29 for sawn timber

f_t = member characteristic strength in tension parallel to grain, MPa

$A_{t,b}$ = area of head plane subjected to tensile stress, mm²

$$= t_{ef,l} w_c$$

where

$t_{ef,l}$ = effective wood thickness parallel to grain (Section 4.1.4.4)

$$w_c = a_2 (n_R - 1)$$

where

a_2 = spacing across the grain, mm

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_2 = 0.25 \psi L_c (1 - F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

where

E = wood modulus of elasticity parallel to grain, MPa (from tables in Section 1.3)

G = wood modulus of rigidity parallel to grain, MPa

$$L_c = a_2 (n_c - 1)$$

where

a_1 = spacing along the grain, mm

$A_{s,b}$ = area of bottom plane subjected to shear stress, mm²

$$= w_c (L_c + a_{3t})$$

where

a_{3t} = loaded end distance, mm

$A_{s,l}$ = areas of side lateral planes subjected to shear stress, mm²

$$2t_{ef,l} = (L_c + a_{3t})$$

$$H = \begin{cases} 0, & \text{If } a_{4c} \geq 1.25w_c \\ 0.16(2.5 - 2a_{4c}/w_c)^2, & \text{If } a_{4c} \leq 1.25w_c \end{cases}$$

where

d_z = bottom distance, mm

$$= b/2 - t_{ef,l} \text{ for } n_p = 2$$

$$= b - t_{ef,l} \text{ for } n_p = 1$$

where b = member thickness, mm

$$H = \begin{cases} 0, & \text{If } a_{4c} \geq 1.25w_c \\ 0.16(2.5 - 2a_{4c}/w_c)^2, & \text{If } a_{4c} \leq 1.25w_c \end{cases}$$

A_{4c} = unloaded edge distance, mm

4.1.4.2 Joint resistance governed by the bottom shear plane failure – wood block tear-out failure mode (c)

The characteristic resistance for the failure of the joint triggered by the failure of the bottom shear plane or by the failure in tension of the wood block adjacent to the bottom shear plane, $P_{w,b}$, kN, is given by:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, & \text{Mode (a)} \\ X_t f_t w_c d_z, & \text{Mode (c)} \end{cases} \quad (4.14)$$

where

X_s = adjustment factor for longitudinal shear strength (see Appendix A3 for details)

= 1.02 for LVL

= 0.96 for glulam

= 0.93 for sawn timber

f_s = member characteristic longitudinal shear strength, MPa,

$$\lambda_3 = \frac{t_{ef,l}(1-F)}{w_c(1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

$$C_b = \frac{a_1(n_c(n_c+1)/2-1) + a_{3t}}{n_c(L_c + a_{3t})}$$

The other variables are as specified in Section 4.1.4.1.

4.1.4.3 Joint resistance by the side lateral shear planes failure – wood block tear-out failure mode (c)

The characteristic resistance for the failure of the joint triggered by the failure of the lateral shear planes or by the failure in tension of the wood blocks adjacent to the lateral shear planes, $P_{w,l}$, kN, is given:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases} \quad (4.15)$$

where

$$C_l = k_e C_b$$

where

$$k_e = \begin{cases} 1, & \text{If } a_{4c} \geq 1.25w_c \\ 0.8, & \text{If } a_{4c} < 1.25w_c \end{cases}$$

The other variables are as specified in Sections 4.1.4.1 and 4.1.4.2.

4.1.4.4 Parallel-to-grain wood effective thickness

The parallel-to-grain wood effective thickness is determined in accordance to rivet deformation as follows:

(i) Corresponding to the rivet elastic deformation (Figure 4.7a):

$$t_{efe,l} = C_{t,l} J_p L_p$$

where

$$\begin{aligned} C_{t,l} &= 0.90, \text{ for } L_p = 28.5 \text{ mm} \\ &= 0.85, \text{ for } L_p = 53.5 \text{ mm} \\ &= 0.80, \text{ for } L_p = 78.5 \text{ mm} \end{aligned}$$

For intermediate values of rivet penetration, L_p , use a linear interpolation to determine the value of the factor $C_{t,l}$.

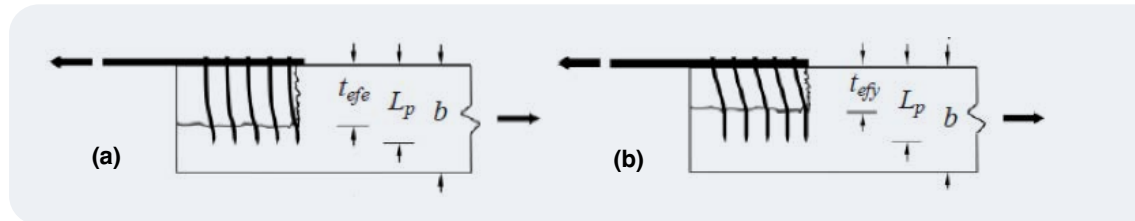


Figure 4.7: Effective wood thickness: (a) corresponding to rivet elastic deformation-brittle failure; (b) corresponding to rivet governing yielding mode-mixed failure.

(i) Corresponding to the rivet yielding mode (Figure 4.7b):

$$t_{efy,l} = \begin{cases} J_p \sqrt{\frac{M_{ry,l}}{f_{hy,0} d_l} + \frac{L_p^2}{2}}, \text{ Rivet yielding mode (a)} \\ 2J_p \sqrt{\frac{M_{ry,l}}{f_{hy,0} d_l}}, \text{ Rivet yielding mode (b)} \end{cases} \quad (4.16)$$

The other variables are as specified in Section 4.1.3.1.

4.1.4.5 Multiple joints in tension parallel to grain

In the case where there is more than one joint acting in tension parallel to grain, such as in Figure 4.8, the wood block tear-out resistance of each joint can be derived by considering the edge distance as:

$$a_{4c} = \min(a_{4c,a}, a_{4c,b})$$

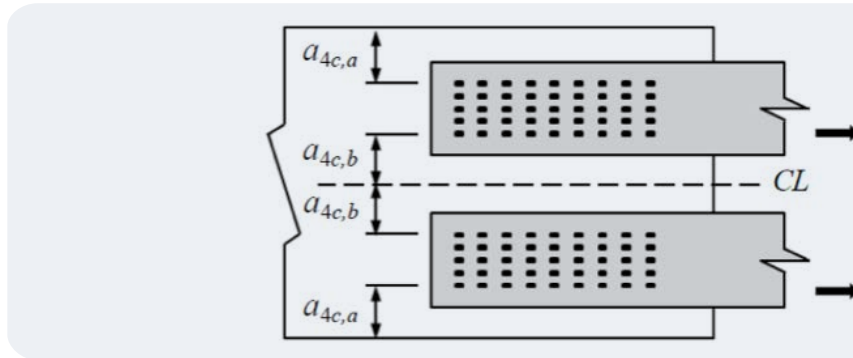


Figure 4.8: Multiple joints acting in tension parallel to grain.

4.1.4.6 Joints in both face and edge grains

If the rivets are required to be driven in both face and edge grains of the wood member, the following requirements should be satisfied to allow the top and side joints to work independently (Figure 4.9).

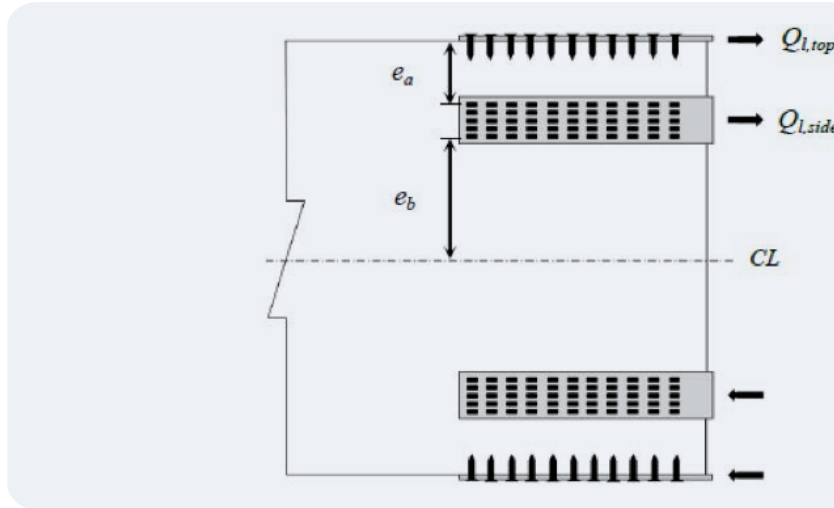


Figure 4.7: Effective wood thickness: (a) corresponding to rivet elastic deformation-brittle failure; (b) corresponding to rivet governing yielding mode-mixed failure.

(i) Minimum distance between the top of the member and the first rivet row of the side joint, e_a ; 3 times the $t_{efy,l}$ of the top joint.

(ii) To determine the wood capacity of the side joint, the edge distance should be considered as;

$$a_{4c} = \min(e_a - 3t_{efy,l}, e_b)$$

where

e_b is distance between last rivet row of the side joint to centreline.

(iii) To determine the wood block tear-out capacity of the top joint. The bottom distance should be considered as;

$$d_z = 2 t_{ef,e,l}$$

4.1.5 Wood Resistance: Perpendicular-to-Grain Wood Splitting

The analysis and design formulae for wood splitting strength in the following sections are based on two possible splitting failure modes: with crack width in member cross-section equal to (a) member thickness; or equal to (b) wood effective thickness on each side of the member (Figure 4.10). The wood capacity is the lesser of the resistance in these two possible splitting failure modes.

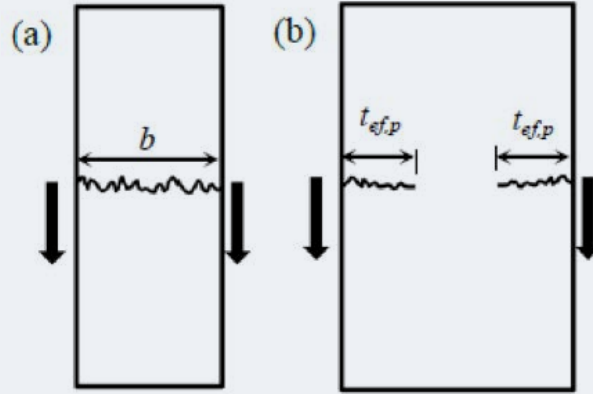


Figure 4 10: Crack width in member cross-section in different splitting failure modes: (a) entire member thickness; (b) $t_{ef,p}$ on each side

The design splitting resistance of the wood is calculated as follows:

(i) Corresponding to the rivet elastic deformation, $\Phi_w Q_{we,p}$;

$$\Phi_w Q_{we,p} = \Phi_w Q_{w,p} \text{ in which } t_{ef,p} \text{ equals to } t_{efe,p}$$

(ii) Corresponding to the rivet yielding mode, $\Phi_w Q_{wy,p}$;

$$\Phi_w Q_{wy,p} = \Phi_w Q_{w,p} \text{ in which } t_{ef,p} \text{ equals to } t_{efy,p}$$

where

$$\Phi_w Q_{w,p} = \Phi_w k_1 g_{42} k_f n_p \min (P_{s,a}, P_{s,b}) \quad (4.17)$$

where

Φ_w = strength reduction factor for wood failure
= 0.7

k_1 = load duration factor (as per AS 1720.1)

g_{42} = modification factor for interaction effect on a grid system specified in AS 1720.1
(see Section 4.1.5.3)

= 0.60 for multiple joints

= 1.0 for single joint

k_f = modification factor for joint position effect

= 0.55 for joint on edge grain of LVL

= 1.0 for joint on face grain of LVL or on edge/face grain of glulam and sawn timber

n_p = number of plates

= 1 for one-sided joint

= 2 for double-sided joint

$P_{s,a}$ = characteristic resistance for full width splitting – mode (a), (Section 4.1.5.1)

$P_{s,b}$ = characteristic resistance for partial width splitting – mode (b), (Section 4.1.5.2)

4.1.5.1 The characteristic full width splitting resistance – failure mode (a)

The characteristic resistance for the wood splitting failure of the whole member thickness, $P_{s,a}$, kN, is given by:

$$P_{s,a} = X_p \eta b C_{fp} \sqrt{\frac{h_e}{1 - \frac{h_e}{h}}} 10^{-3} \quad (4.18)$$

where

X_p = adjustment factor for tension perpendicular to grain (see Appendix A3 for details)
 = 1.23 for LVL
 = 1.28 for glulam
 = 1.31 for sawn timber

b = member thickness, mm

C_{fp} = member characteristic fracture parameter, N/mm^{1.5}, (from tables in Section 1.3)

$$\eta = \frac{\min(\gamma h_e, a_{3c,L}) + (\gamma h_e, a_{3c,R}) + w_{net}}{2\gamma h_e}$$

γ = effective crack length coefficient for splitting mode (a)
 = 4 for LVL
 = 2.7 for glulam and sawn timber

$a_{3c,L}$ = minimum of unloaded end distance and half of the distance to adjacent joint on the left side, mm (Figure 4 11)

$a_{3c,R}$ = minimum of unloaded end distance and half of the distance to adjacent joint on the right side, mm (Figure 4 11)

w_{net} = net section of joint width
 = $a_1 (n_R - 1) - 6.4 n_R$

h_e = effective member depth, mm
 = $h - a_{4c}$

where

h = member depth, mm

a = unloaded edge distance, mm

4.1.5.2 The characteristic partial width splitting resistance – failure mode (b)

The characteristic resistance for the wood splitting failure corresponding to $t_{ef,p}$ on each side of the member, $P_{s,b}$, kN, is given by:

$$P_{s,b} = X_p C_t f_{tp} t_{ef,p} [w_{net} + \min(\beta h_e, a_{3c,L}) + \min(\beta h_e, a_{3c,R})] 10^{-3} \quad (4.19)$$

where

$$C_t = \begin{cases} 1.264 \xi^{-0.37}, & \text{If } \xi < 1.9 \\ 1 & \text{If } \xi \geq 1.9 \end{cases}$$

where

$$\xi = \frac{a_{4c}}{a_2 (n_c - 1)}$$

f_{tp} = characteristic strength in tension perpendicular to grain, MPa (from tables in Section 1.3)

$t_{ef,p}$ = wood effective thickness perpendicular to grain, mm (Section 4.1.5.4)

β = effective crack length coefficient for splitting mode (b)
 = 2.4 for LVL
 = 1.6 for glulam and sawn timber

The variables are as specified above.

4.1.5.3 Multiple joints in tension perpendicular to grain

In the case where there is more than one joint acting in tension perpendicular to grain, such as in Figure 4.11, the estimated wood splitting capacity of each joint is reduced by 40% using the g42 factor to take the effect of interaction between joints into account.

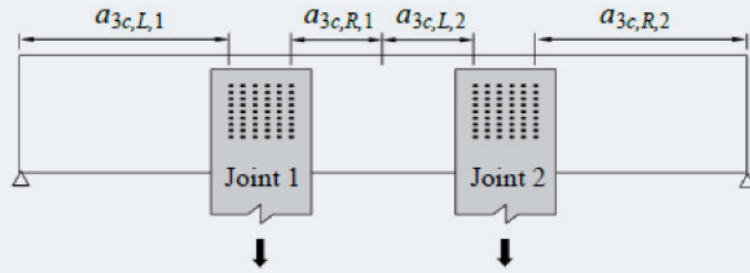


Figure 4.11: Multiple joints in tension perpendicular to grain.

4.1.5.4 Perpendicular-to-grain wood effective thickness

The perpendicular-to-grain wood effective thickness is determined as follows:

(i) *Corresponding to the rivet elastic deformation (Figure 4.7 a):*

$$t_{efe,p} = C_{r,p} J_p L_p$$

where

$$C_{r,p} = \begin{cases} 0.85, & \text{for } L_p = 28.5 \text{ mm} \\ 0.75, & \text{for } L_p = 53.5 \text{ mm} \\ 0.65, & \text{for } L_p = 78.5 \text{ mm} \end{cases}$$

For intermediate values of rivet penetration, L_p , use a linear interpolation to determine the value of factor $C_{r,p}$.

(ii) *Corresponding to the rivet yielding (Figure 4.7b):*

$$t_{efy,p} = \begin{cases} J_p \sqrt{\frac{M_{ry,p}}{f_{hy,90} d_p} + \frac{L_p^2}{2}} \\ 2J_p \sqrt{\frac{M_{ry,p}}{f_{hy,90} d_p}} \end{cases} \quad (4.20)$$

The other variables are as specified in Section 4.1.3.1.

4.2 Withdrawal Resistance

The design withdrawal resistance (kN) from the side grains of a timber rivet joint is taken as follows:

$$\Phi_{ax} F_{ax} = \Phi_{ax} k_f k_R n_C P_{ax} \quad (4.21)$$

where

$$\Phi_{ax} = \begin{cases} \text{strength reduction factor for withdrawal resistance} \\ 0.6 \end{cases}$$

$$k_f = \begin{cases} \text{modification factor for joint position effect} \\ 0.9 \text{ for joint on edge grain of LVL} \\ 1.0 \text{ for joint on face grain of LVL or on edge/face grain of glulam and sawn timber} \end{cases}$$

$$k_R = \begin{cases} \text{modification factor for joint position effect} \\ 0.9 \text{ for joint on edge grain of LVL} \\ 1.0 \text{ for joint on face grain of LVL or on edge/face grain of glulam and sawn timber} \end{cases}$$

$$P_{ax} = \begin{cases} \text{characteristic withdrawal resistance, kN} \\ X_{ax} L_p f_{ax} \end{cases}$$

$$P_{ax} = \begin{cases} \text{characteristic withdrawal resistance, kN} \\ X_{ax} L_p f_{ax} \end{cases}$$

$$P_{ax} = \begin{cases} \text{characteristic withdrawal resistance, kN} \\ X_{ax} L_p f_{ax} \end{cases}$$

where

- X_{ax} = adjustment factor for characteristic withdrawal resistance (see Appendix A3 for details)
 = 0.84 for LVL
 = 0.61 for glulam
 = 0.49 for sawn timber
- L_p = rivet penetration length, mm
- f_{ax} = withdrawal resistance per millimetre of penetration, N/mm
 = $15.9\rho d_p(1-0.0037d_p)10^{-3}$ for LVL
 = $11.5\rho d_p(1-0.0024d_p)10^{-3}$ for glulam and sawn timber

where

- ρ = wood design density at 12% moisture content, kg/m³ (from Table H2.3, AS 1720)
- d_p = rivet major cross-section dimension
 = 6.4 mm

4.3 Joint Deflection

The deflection of the joint due to rivet slip, y mm, can be determined by:

For parallel-to-grain loading:

$$\delta_l = 4 \left[1 - \sqrt{1 - \frac{N_l^*}{\phi_r Q_{ru,l}}} \right] \quad (4.22)$$

where

- N_l^* = serviceability design load, parallel to grain (kN), for deflection under (SLS)
 = ultimate design load, parallel to grain (kN), for deflection under (ULS)
- $\phi_r Q_{ru,l}$ = design rivet ultimate resistance, parallel to grain, kN (Section 3.1.3)

For perpendicular-to-grain loading:

$$\delta_p = 5.5 \left[1 - \sqrt{1 - 0.99 \frac{N_p^*}{\phi_r Q_{ru,p}}} \right] \quad (4.23)$$

where

- N_p^* = serviceability design load, perpendicular to grain (kN), for deflection under (SLS)
 = ultimate design load, perpendicular to grain (kN), for deflection under (ULS)
- $\phi_r Q_{ru,p}$ = design rivet ultimate resistance, perpendicular to grain, kN (Section 3.1.3)

For loading at angle θ to grain:

$$\delta_\theta = \sqrt{\delta_l^2 + \delta_p^2} \quad (4.24)$$

Design Examples

This section provides a series of examples to illustrate the design process. For the selection of an appropriate rivet layout and to help start the design, reference capacity tables for joint samples under parallel and perpendicular to grain loadings are provided in Appendix A1.

Truss connection

The example outlines the design of an LVL truss connection that connects the bottom chord, post and strut (see Section 5.1). Each joint is designed separately and resists a load acting parallel to grain (Figure 5.1).

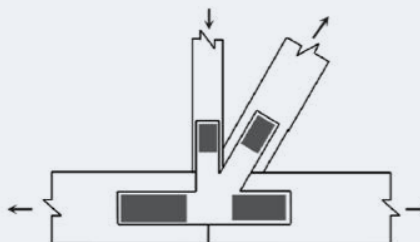


Figure 5.1: Truss connection.

Base connection

The example outlines the design of a base joint that connects a glulam column to the foundation (see Section 5.2). The joint resists load acting at an angle to grain, therefore requires calculation of the capacity for both parallel-to-grain and perpendicular-to-grain loads (Figure 5.2).

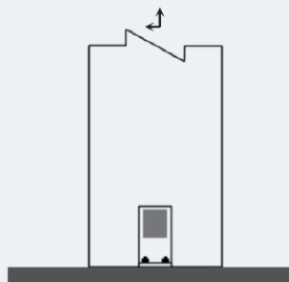


Figure 5.2: Base connection.

Moment connection

The example outlines the design of a connection that transfers moment between two LVL members in a beam (see Section 5.3). Each joint is identical and resists a parallel-to-grain load (Figure 5.3).

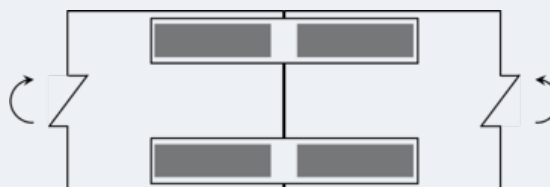


Figure 5.3: Moment connection.

AS 1170.1, Structural design actions, in Permanent, imposed and other actions. 2002, Australian Standard™.

AS 1720.1, Timber structures, in Part 1: Design methods. 2010, Standards Australia: Australia.

Buchanan, A., Timber design guide New Zealand Timber Industry Federation Inc. Wellington, New Zealand, 2007.

Hanger connection

The example outlines the design of a hanger joint that connects a glulam secondary beam to the primary beam (see Section 5.4). The connection acts as two identical joints resisting a load acting perpendicular to grain (Figure 5.4).

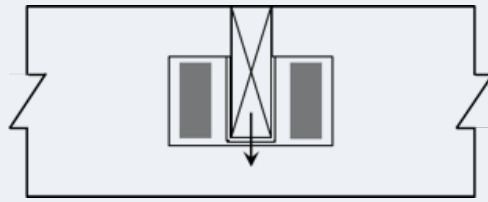


Figure 5.4: Hanger connection.

Shear wall connections

The example outlines the design of the connections in an LVL shear wall, including a hold-down and a floor– wall connection (see Section 5.5). Each joint in the hold-down connection is identical and resists a load acting parallel to grain. The two arrays of rivets in the floor– wall connection act as one joint and resist a load perpendicular to grain (Figure 5.5).

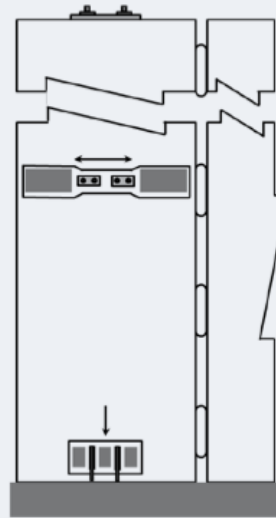


Figure 5.5: Shear wall connections.

5.1 Truss Connection

For a truss node to connect the bottom chord, post, and strut together, the rivet connection is arranged as shown in Figure 5.6. The rivet plates are installed on opposing faces of the dry wood members, which are of grade 11 Radiata Pine LVL.

5.1.1 Design Actions

It is assumed that after taking the effect of the load duration factor (k_t) into account, the critical load combination for the connection design is [1.2G, 1.5Q], as per AS 1170. The design loads acting on the joint are shown in Figure 5.6. Two strength limit states are of interest: rivet strength and wood strength. An efficient connection design can be achieved by decreasing the difference between the capacity of the wood and the rivets.

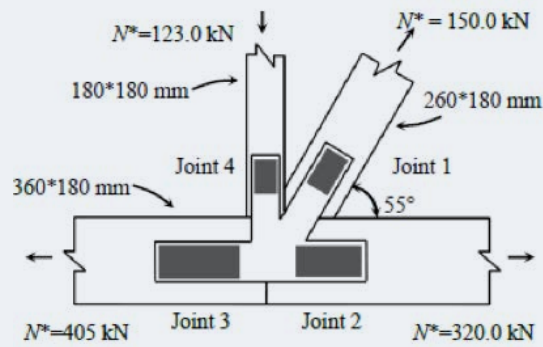


Figure 5.6: Design actions.

This example assumes that four standard 45 mm thicknesses of LVL have been laminated together in a factory with full indoor quality control of the secondary fabrication process. LVL of 45 mm thickness has sufficient over thickness tolerance to enable planning of the surface to glue and deliver a 180mm section. LVL of 90 mm thickness is typically produced with a 'minus' tolerance to fit inside framing so cannot be glued to make 180 mm.

5.1.2 Connection Geometry

Try 65 mm long rivets with the following configuration for each joint:

Side plate thickness: $t_p = 10$ mm

Note that the steel side plates need to be checked to verify that they have cross-section adequate for resisting tension and compression forces.

5.1.2.1 Joint-1

$N^* = 150.0$ kN

Number of rows of rivets parallel to direction of load: $n_R = 5$

Number of rivets per row: $n_C = 6$

Spacing along the grain: $a_1 = 25$ mm

Spacing across the grain: $a_2 = 25$ mm

End distance: $a_{3t} = 100$ mm

Edge distance: $a_{4c} = 80$ mm (based on member width)

5.1.2.2 Joint-2

$N^* = 320.0$ kN

Number of rows of rivets parallel to direction of load: $n_R = 7$

Number of rivets per row: $n_C = 8$

Spacing along the grain: $a_1 = 25$ mm

Spacing across the grain: $a_2 = 25$ mm

End distance: $a_{3t} = 120$ mm

Edge distance: $a_{4c} = 105$ mm (based on member width)

5.1.2.3 Joint-3

$N^* = 405.0$ kN

Number of rows of rivets parallel to direction of load: $n_R = 8$

Number of rivets per row: $n_C = 9$

Spacing along the grain: $a_1 = 25$ mm

Spacing across the grain: $a_2 = 25$ mm

End distance: $a_{3t} = 120$ mm

Edge distance: $a_{4c} = 93$ mm (based on member width)

5.1.2.4 Joint-4

$$N^* = 123.0 \text{ kN}$$

Number of rows of rivets parallel to direction of load: $n_R = 5$

Number of rivets per row: $n_C = 5$

Spacing along the grain: $a_1 = 25 \text{ mm}$

Spacing across the grain: $a_2 = 25 \text{ mm}$

End distance: $a_{3t} = 75 \text{ mm}$

Edge distance: $a_{4c} = 40 \text{ mm}$ (based on member width)

5.1.3 Connection Lateral Resistance

$$Q_s = Q_{s,l}$$

$$Q_{s,l} = \begin{cases} \phi_w Q_{we,l} & \text{if } \phi_w Q_{we,l} < \phi_r Q_{ry,l} \text{ (Brittle mode)} \\ \phi_r Q_{ry,l} & \text{if } \phi_w Q_{wy,l} < \phi_r Q_{ry,l} \leq \phi_w Q_{we,l} \text{ (Mixed mode)} \\ \phi_w Q_{wy,l} & \text{if } \phi_r Q_{ry,l} \leq \phi_w Q_{wy,l} < \phi_r Q_{ru,l} \text{ (Mixed mode)} \\ \phi_r Q_{ru,l} & \text{if } \phi_r Q_{ru,l} < \phi_w Q_{wy,l} \text{ (Ductile mode)} \end{cases}$$

5.1.3.1 Joint-1

Check if $\phi_w Q_{we,l} < \phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

Step 1: Rivet capacity corresponding to yielding, parallel to grain, $\phi_r Q_{ry,l}$

$$\phi_r Q_{ry,l} = \phi_r Q_{ry,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hy,0} \text{ and } M_{ry,l}, \text{ respectively}$$

$$\phi_r Q_{ry,l} = \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for edge grain of glulam}$$

$$n_p = 2$$

$$n_R = 5$$

$$n_C = 6$$

Rivet failure – mode (a)

Determine $P_{rl,a}$ using Section 4.1.3.1(i):

$$P_{rl,a} = X_r \left[J_p f_{h,0} L_p d_l \left(\left(\sqrt{2 + \frac{4M_{r,l}}{f_{h,0} d_l L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.93 \text{ for LVL}$$

$$J_p = 1.0 \text{ (side plate factor)}$$

$$f_{h,0} = f_{hy,0}$$

$$= 75.1 \rho (1 - 0.0037d_l) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$\rho = 620 \text{ kg/m}^3 \text{ for grade 11 LVL}$$

$$f_{hy,0} = 46.0 \text{ MPa}$$

$$L_p = L_r - t_p - 3.2$$

$$L_r = 65 \text{ mm}$$

$$t_p = 10 \text{ mm}$$

$$L_p = 51.8 \text{ mm}$$

$$d_l = 3.2 \text{ mm}$$

$$M_{r,p} = M_{ry,p}$$

$$= 24900 \text{ Nmm}$$

$$f_{ax} = 15.9 \rho d_p (1 - 0.0037d_p) 10^{-3}$$

$$d_p = 6.4$$

$$f_{ax} = 61.6 \text{ N/mm}$$

Calculate $P_{rl,a}$:

$$P_{rl,a} = 4.11 \text{ N}$$

Rivet failure – mode (b)**Determine $P_{rl,b}$ using Section 4.1.3.1(ii):**

$$P_{rl,b} = X_r \left[2J_p \sqrt{M_{r,l} f_{h,0} d_l} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$P_{rl,b} = 4.12 \text{ kN}$$

Therefore, the rivet yield capacity, parallel to grain,

$$\Phi_r Q_{ry,l} = \Phi_r k_1 k_f n_D n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$$\Phi_r Q_{ry,l} = 151.9 \text{ (Rivet Yielding mode: a)}$$

Step 2: Wood capacity, parallel to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$

$$\Phi_w Q_{we,l} = \Phi_w Q_{wl} \text{ in which } t_{ef,l} \text{ equals to } t_{efe,l}$$

$$= \Phi_w n_D k_1 k_f \min(P_{wh}, P_{wb}, P_{wl})$$

$$\Phi_w = 0.7$$

Wood failure – mode (a)**Determine P_{wh} using Section 4.1.4.1:**

$$P_{wh} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$$

$$X_t = 1.06 \text{ for LVL}$$

$$f_t = 30 \text{ MPa for grade 11 LVL}$$

$$A_{t,h} = t_{ef,l} w_c$$

$$t_{ef,l} = t_{efe,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)}$$

$$= 44.2 \text{ mm}$$

$$w_c = a_2 (n_R - 1) = 100 \text{ mm}$$

$$A_{t,h} = a_2 (n_R - 1) = 4420 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

$$G = 550 \text{ MPa for grade 11 LVL}$$

$$E = 11000 \text{ MPa for grade 11 LVL}$$

$$\gamma = 0.05$$

$$L_c = a_1 (n_c - 1) = 125 \text{ mm}$$

$$d_z = 45.8$$

$$H = 0.23$$

$$A_{s,b} = 22500 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_1 = 0.215$$

$$\lambda_2 = 0.25 \psi L_c (1 - F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_2 = 0.209$$

Calculate P_{wh} :

$$P_{wh} = 200.2 \text{ kN, mode (a)}$$

Wood failure – mode (b)**Determine $P_{w,b}$ using Section 4.1.4.2:**

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

$$X_s = 1.02 \text{ for LVL}$$

$$C_b = 0.44$$

$$f_s = 6 \text{ MPa for grade 11 LVL}$$

$$\lambda_3 = \frac{t_{ef,l}(1-F)}{w_c(1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

$$\lambda_3 = 0.974$$

Calculate $P_{w,b}$:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} 60588, \text{ Mode (a)} \\ 14544, \text{ Mode (c)} \end{cases}$$

$$P_{w,b} = 405.6 \text{ kN, mode (a)}$$

Wood failure – mode (c)**Determine $P_{w,l}$ using Section 4.1.4.3:**

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} 43821.6, \text{ Mode (a)} \\ 9855032.9, \text{ Mode (b)} \end{cases}$$

$$C_l = 0.36$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} 43821.6, \text{ Mode (a)} \\ 9855032.9, \text{ Mode (b)} \end{cases}$$

$$P_{w,l} = 294.3 \text{ kN, mode (a)}$$

Therefore, the wood capacity, parallel to grain, corresponding to rivet elastic deformation,

$$\phi_w Q_{we,l} :$$

$$\phi_w Q_{we,l} = \phi_w n_p k_1 k_f \min (P_{w,h}, P_{w,b}, P_{w,l})$$

$$\phi_w Q_{we,l} = \phi_w n_p k_1 k_f \min (P_{w,h}, P_{w,b}, P_{w,l})$$

$$= 341.7 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4). The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.147 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \phi_r Q_{ry,l}$ (brittle failure mode)

$$\text{If } \phi_w Q_{wy,l} < \phi_w Q_{ry,l}$$

$$224.2 \geq 151.9 \text{ (unsatisfied)}$$

Thus, check if $\phi_w Q_{wy,l} < \phi_w Q_{ru,l}$. If so, then $Q_{s,l} = \phi_w Q_{wy,l}$ (mixed failure mode)

$$\phi_w Q_{wy,l} = \phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efy,l}$$

$$t_{ef,l} = t_{efy,l}$$

$$t_{ef,p} = J_p \sqrt{\frac{M_{ry,p}}{f_{hy,90} d_p} + \frac{L_p^2}{2}}, \text{ yielding mode (a)}$$

$$t_{ef} = 38.9 \text{ mm}$$

The recalculated wood capacity (by following the same design procedure as defined above):

$$\Phi_w Q_{wy,l} = 208.2 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Note that if the yielding mode (b) was governing then the reduction of wood strength would be much higher.

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4). The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.139 < 0.3$$

The connection does not need to be redesigned.

$$\text{Check if } Q_{s,l} = \Phi_w Q_{we,l} \text{ (brittle failure mode)}$$

$$\text{If } \Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$$

$$208.2 \geq 151.9 \quad (\text{unsatisfied})$$

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ru,l}$. If so, then $Q_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

Ultimate rivet capacity parallel to grain, $\Phi_r Q_{ru,l}$

$$\Phi_r Q_{ru,l} = \Phi_r Q_{r,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

$$f_{h,0} = f_{hu,0}$$

$$= 90.4 \rho (1 - 0.0037 d_l) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$= 55.4 \text{ MPa}$$

$$M_{r,l} = M_{ru,l}$$

$$= 30,000 \text{ Nmm}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\Phi_r Q_{ru,l} = \Phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$$= 178.5 \text{ kN (Rivet failure mode: a)}$$

Check if $Q_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

$$\text{If } \Phi_w Q_{wy,l} \leq \Phi_r Q_{ru,l}$$

$$208.2 > 178.5 \text{ (unsatisfied)}$$

Thus, $Q_{s,l} = \Phi_r Q_{ru,l}$ (ductile failure mode)

$$Q_{s,l} = 178.5 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N^* = 150.0 \text{ kN}$$

$$Q_s = Q_{s,l}$$

$$= 178.5 \text{ kN}$$

$$150.0 \leq 178.5, \text{ OK (Joint mode of failure: ductile)}$$

Adopt 65 mm long rivets with an array of 5 rows by 6 columns, spacing 25 mm by 25 mm along and across the grain, and 100 mm end distance (see Figure 5.7).

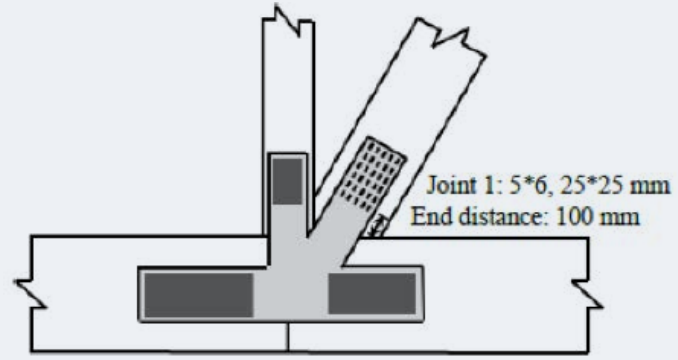


Figure 5.7: Connection configuration of joint 1.

5.1.3.2 Joint-2

Check if $\Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \Phi_w Q_{we,l}$ (brittle failure mode)

Rivet capacity corresponding to yielding parallel to grain, $\Phi_r Q_{ry,l}$

$\Phi_r Q_{ry,l} = \Phi_r Q_{ry,l}$ in which $f_{h,0}$ and $M_{r,l}$ equal to $f_{ry,0}$ and $M_{ry,b}$ respectively

$\Phi_r Q_{ry,l} = \Phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$

$P_{rl,a}, P_{rl,b}$ are calculated before.

$\Phi_r = 0.8$

$k_1 = 0.77$ for load combination [1.2G, 1.5Q]

$k_f = 1.0$ for edge grain of glulam

$n_p = 2$

$n_R = 7$

$n = 8$

$\Phi_r Q_{ry,l} = 0.8 \times 0.77 \times 1.0 \times 1.0 \times 2 \times 7 \times 8 \min(4.11, 4.12)$

$= 283.5 \text{ kN}$ (Yielding mode of failure: a)

Wood capacity parallel to grain corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$

$\Phi_w Q_{we,l} = \Phi_w Q_{w,l}$ in which $t_{ef,l}$ equals to $t_{efe,l}$

$= \Phi_w n_p k_1 k_f \min(P_{w,h}, P_{w,b}, P_{w,l})$

$\Phi_w = 0.7$

Wood failure – mode (a)

Determine $P_{w,h}$ using Section 4.1.4.1:

$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$

$X_t = 1.19$ for glulam

$F_t = 11 \text{ MPa}$ for grade GL10 glulam

$A_{t,h} = t_{ef,l} w_c$

$t_{ef,l} = t_{efe,l}$ (Corresponding to rivet elastic deformation, Section 4.1.4.4)

$= 44.2 \text{ mm}$

$w_c = a_2 (a_2 - 1) = 150 \text{ mm}$

$A_{t,h} = a_2 (a_2 - 1) = 6630 \text{ mm}^2$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

G = 670 MPa for grade GL10 glulam

E = 10,000 MPa for grade GL10 glulam

ψ = 0.067

L_c = $a_1 (n_c - 1) = 175$ mm

d_z = 45.8

H = 0.23

$A_{s,b}$ = 44250 mm²

$$\lambda_1 = 0.25\psi L_c (1-H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

λ_1 = 0.330

$$\lambda_2 = 0.25\psi L_c (1-F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

λ_2 = 0.173

Calculate $P_{w,h}$:

$P_{w,h}$ = 317.0 kN, mode (a)

Wood failure – mode (b)

Determine $P_{w,b}$ using Section 4.1.4.2:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

X_s = 1.02

X_t = 1.06

C_b = 0.42

f_s = 6 MPa

$$\lambda_3 = \frac{t_{ef,l} (1-F)}{w_c (1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

λ_3 = 0.524

Calculate $P_{w,b}$:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} 119347, \text{ Mode (a)} \\ 53374, \text{ Mode (c)} \end{cases}$$

$P_{w,b}$ = 519.6 kN, mode (a)

Wood failure – mode (c)

Determine $P_{w,l}$ using Section 4.1.4.3:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases}$$

$P_{w,l}$ = 467.4 kN, mode (a)

Therefore, the wood capacity parallel to grain corresponding to rivet elastic deformation,

$\Phi_w Q_{we,l}$:

$$\Phi_w Q_{we,l} = \Phi_w n_p k_1 k_f \min (P_{w,h}, P_{w,b}, P_{w,l})$$

= 341.7 kN (failure governed by head tensile plane, mode (a))

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4). The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.115 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

$$\text{If } \phi_w Q_{we,l} < \phi_r Q_{ry,l}$$

$$341.7 > 283.5 \text{ (unsatisfied)}$$

Thus, check if $\phi_w Q_{wy,l} < \phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \phi_r Q_{ry,l}$ (mixed failure mode)

Wood capacity parallel to grain corresponding to rivet yielding mode, $\phi_w Q_{wy,l}$

$$\phi_w Q_{wy,l} = \phi_w Q_{wy,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efy,l}$$

$$t_{ef,l} = t_{efy,l}$$

$$t_{ef,l} = 38.9 \text{ mm}$$

The recalculated wood capacity (by following the same design procedure as defined above):

$$\phi_w Q_{wy,l} = 327.5 \text{ kN}$$

Note that if the yielding mode (b) was governing then the reduction of wood strength would be much higher.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.106 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

$$\text{If } \phi_w Q_{we,l} < \phi_r Q_{ry,l}$$

$$327.5 \geq 283.6 \text{ (unsatisfied)}$$

Thus, check if $\phi_w Q_{wy,l} < \phi_r Q_{ru,l}$. If so, then $Q_{s,l} = \phi_r Q_{wy,l}$ (mixed failure mode)

Ultimate rivet capacity parallel to grain, $\phi_r Q_{ru,l}$

$$\phi_r Q_{ru,l} = \phi_r Q_{r,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\begin{aligned} \phi_r Q_{ru,l} &= \phi_r k_f k_t n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ &= 333.5 \text{ kN (Rivet failure mode: a)} \end{aligned}$$

Check if $\phi_{s,l} = \phi_w Q_{wy,l}$ (mixed failure mode)

$$\text{If } \phi_w Q_{wy,l} \leq \phi_r Q_{ru,l}$$

$$327.5 \leq 333.5 \text{ OK}$$

$$\begin{aligned} \phi_{s,l} &= \phi_w Q_{wy,l} \\ &= 327.5 \text{ kN} \end{aligned}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N^* = 320.0 \text{ kN}$$

$$\begin{aligned} Q_s &= Q_{s,l} \\ &= 327.5 \text{ kN} \end{aligned}$$

$$320.0 \leq 327.5, \text{ OK (Joint mode of failure: mixed)}$$

Adopt 65 mm long rivets with an array of 7 rows by 8 columns, spacing 25 mm by 25 mm along and across the grain, and 120 mm end distance (see Figure 5.8).

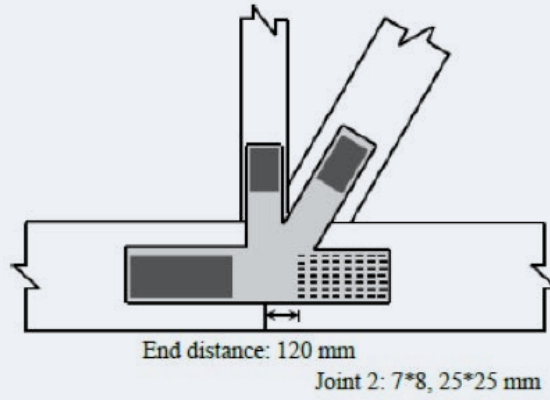


Figure 5.8: Connection configuration of Joint 2

5.1.3.3 Joint-3

Check if $\phi_w Q_{we,l} < \phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

Rivet capacity corresponding to yielding parallel to grain, $\phi_r Q_{ry,l}$

$\phi_r Q_{ry,l} = \phi_r Q_{ry,l}$ in which $f_{h,0}$ and $M_{r,l}$ equal to $f_{hy,0}$ and $M_{ry,b}$ respectively

$$\phi_r Q_{ry,l} = \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$P_{rl,a}, P_{rl,b}$ are calculated for previous joints.

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for edge grain of glulam}$$

$$n_p = 2$$

$$n_R = 8$$

$$n = 9$$

$$\begin{aligned} \phi_r Q_{ry,l} &= 0.8 \times 0.77 \times 1.0 \times 1.0 \times 2 \times 8 \times 9 \min(4.11, 4.12) \\ &= 364.6 \text{ kN (Yielding mode of failure: a)} \end{aligned}$$

Wood capacity parallel to grain corresponding to rivet elastic deformation, $\phi_w Q_{we,l}$

$$\phi_w Q_{we,l} = \phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efe,l}$$

$$= \phi_w n_p k_1 k_f \min(P_{w,h}, P_{w,b}, P_{w,l})$$

$$\phi_w = 0.7$$

Wood failure – mode (a)

Determine $P_{w,h}$ using Section 4.1.4.1:

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda^1 + \lambda^2) 10^{-3}$$

$$X_t = 1.19 \text{ for glulam}$$

$$F_t = 11 \text{ MPa for grade GL10 glulam}$$

$$A_{t,h} = t_{ef,l} w_c$$

$$t_{ef,l} = t_{efe,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)}$$

$$= 44.2 \text{ mm}$$

$$w_c = a_2 (n_R - 1) = 150 \text{ mm}$$

$$A_{t,h} = a_2 (n_R - 1) = 7735 \text{ mm}^2$$

$$\psi = 0.05$$

$$L_c = a_1 (n_C - 1) = 200 \text{ mm}$$

$$d_z = 23.3$$

$$L_c = a_1 (n_C - 1) = 200 \text{ mm}$$

$$H = 0.23$$

$$A_{s,b} = 56,000 \text{ mm}^2$$

$$\lambda_1 = 0.25\psi L_c(1-H) \left[\frac{A_{s,b}}{t_{ef,l}A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_1 = 0.391$$

$$\lambda_2 = 0.25\psi L_c(1-F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$A_{s,l} = 28,288 \text{ mm}^2$$

$$F = 0.33$$

$$\lambda_2 = 0.136$$

Calculate $P_{w,h}$:

$$P_{w,h} = 375.7 \text{ kN, mode (a)}$$

Wood failure –mode (b)

Determine $P_{w,b}$ using Section 4.1.4.2:

$$P_{w,b} = (1+\lambda_1^{-1}+\lambda_3)10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

$$X_s = 1.02$$

$$C_b = 0.42$$

$$f_s = 6 \text{ MPa}$$

$$\lambda_3 = \frac{t_{ef,l}(1-F)}{w_c(1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

$$\lambda_3 = 0.349$$

Calculate $P_{w,b}$:

$$P_{w,b} = (1+\lambda_1^{-1}+\lambda_3)10^{-3} \min = \begin{cases} 143942, \text{ Mode (a)} \\ 254877, \text{ Mode (c)} \end{cases}$$

$$P_{w,b} = 566.9 \text{ kN, mode (c)}$$

Wood failure – mode (c)

Determine $P_{w,l}$ using Section 4.1.4.3:

$$P_{w,l} = (1+\lambda_2^{-1}+\lambda_3^{-1})10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases}$$

$$C_l = 0.34$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1+\lambda_2^{-1}+\lambda_3^{-1})10^{-3} \min = \begin{cases} 58862, \text{ Mode (a)} \\ 261434, \text{ Mode (b)} \end{cases}$$

$$P_{w,l} = 657.2 \text{ kN, mode (a)}$$

Therefore, the wood capacity parallel to grain corresponding to rivet elastic deformation,

$\Phi_w Q_{we,l}$:

$$\Phi_w Q_{we,l} = \Phi_w n_p k_t k_f \min (P_{w,h}, P_{w,b}, P_{w,l})$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_t k_f \min (375.7, 566.9, 657.2)$$

$$= 405.0 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4).

The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1+\lambda_2^{-1}+\lambda_3^{-1})^{-1} < 0.3$$

$$0.089 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \Phi_w Q_{we,l}$ (brittle failure mode)

If $\Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$

405.0 > 364.6 (unsatisfied)

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \Phi_r Q_{ry,l}$ (mixed failure mode)

Wood capacity parallel to grain corresponding to rivet yielding mode, $\Phi_w Q_{wy,l}$

$\Phi_w Q_{wy,l} = \Phi_w Q_{w,l}$ in which $t_{ef,l}$ equals to $t_{efy,l}$

$$t_{ef,l} = t_{efy,l}$$

$$t_{ef,l} = 38.9 \text{ mm}$$

The recalculated wood capacity (by following the same design procedure as defined above):

$$\Phi_w Q_{wy,l} = 409.5 \text{ kN}$$

Note that if the yielding mode (b) was governing then the reduction of wood strength would be much higher.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.081 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \Phi_w Q_{we,l}$ (brittle failure mode)

If $\Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$

409.5 $\geq$ 364.6 (unsatisfied)

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ru,l}$. If so, then $Q_{s,l} = \Phi_r Q_{ru,l}$ (mixed failure mode)

Ultimate rivet capacity parallel to grain, $\Phi_r Q_{ru,l}$

$\Phi_r Q_{ru,l} = \Phi_r Q_{r,l}$ in which $f_{h,0}$ and $M_{r,l}$ equal to $f_{hu,0}$ and $M_{ru,l}$, respectively

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\begin{aligned} \Phi_r Q_{ru,l} &= \Phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ &= 428.8 \text{ kN (Rivet failure mode: a)} \end{aligned}$$

Check if $\Phi_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

If $\Phi_w Q_{wy,l} \leq \Phi_r Q_{ru,l}$

$$409.5 \leq 428.8 \text{ OK}$$

$$\begin{aligned} \Phi_{s,l} &= \Phi_w Q_{wy,l} \\ &= 409.5 \text{ kN} \end{aligned}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N^* = 405 \text{ kN}$$

$$\begin{aligned} Q_s &= Q_{s,l} \\ &= 409.5 \text{ kN} \end{aligned}$$

405 $\leq$ 409.5, OK (Joint mode of failure: mixed)

Adopt 65 mm long rivets with an array of 8 rows by 9 columns, spacing 25 mm by 25 mm along and across the grain, and 120 mm end distance (see Figure 5.9)

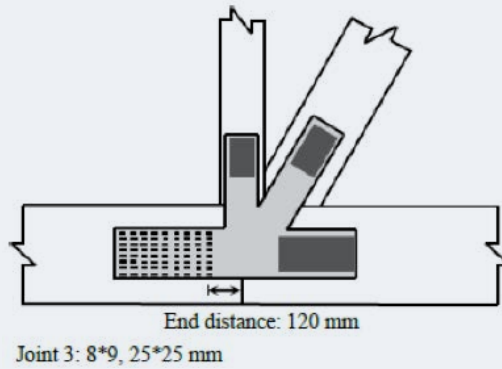


Figure 5.9: Connection configuration of Joint 3.

5.1.3.4 Joint-4

Note that the force is applied in such a way that the member is in compression, therefore, there is no need to check the wood block tear-out resistance.

Ultimate rivet capacity parallel to grain, $\Phi_r Q_{ru,l}$

$$\Phi_r Q_{ru,l} = \Phi_r Q_{ru,u,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

$$\begin{aligned} f_{h,0} &= f_{hu,0} \\ &= 90.4 \rho (1 - 0.0037d_l) 10^{-3} \text{ for LVL (Section 4.1.3.3)} \\ &= 55.4 \text{ MPa} \end{aligned}$$

$$\begin{aligned} M_{r,l} &= M_{ru,l} \\ &= 30,000 \text{ Nmm} \end{aligned}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\begin{aligned} \Phi_r Q_{ru,l} &= \Phi_r k_f k_t n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ n_p &= 2 \\ n_R &= 5 \\ n_C &= 5 \\ P_{rl,a} &= 4.83 \\ P_{rl,b} &= 4.84 \\ &= 0.8 \times 0.77 \times 1.0 \times 1.0 \times 2 \times 5 \times 5 \times \min(4.83, 4.84) \\ &= 148.9 \text{ kN (Rivet failure mode: a)} \end{aligned}$$

Check if $\Phi_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

$$\begin{aligned} \text{If } \Phi_w Q_{wy,l} &\leq \Phi_r Q_{ru,l} \\ 346.6 &> 269.8 \text{ (unsatisfied)} \end{aligned}$$

Thus, $\Phi_{s,l} = \Phi_r Q_{ru,l}$ (ductile failure mode)

$$\Phi_{s,l} = 269.8 \text{ kN}$$

Check joint ultimate lateral resistance:

$$\begin{aligned} N^* &\leq Q_s \\ N^* &= 123 \text{ kN} \\ Q_s &= Q_{s,l} \\ Q_s &= 148.9 \text{ kN} \\ 123 &< 148.9, \text{ OK (Joint mode of failure ductile)} \end{aligned}$$

Adopt 65 mm long rivets with an array of 5 rows by 5 columns, spacing 25 mm by 25 mm along and across the grain, and 75 mm end distance (see Figure 5.10)

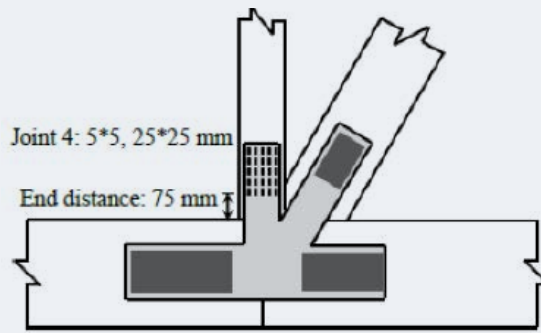


Figure 5.10: Connection configuration of Joint 4.

If ductile behaviour at the connection ultimate capacity is desirable, the failure mode of the connection can be improved from brittle/mixed to ductile by increasing the wood resistance with larger rivet spacing across and along the grain. Spreadsheets can be used to speed up computation and, once they are set up, adjustments in spacing, end and edge distances and capacities for a range of rivet lengths can be evaluated relatively quickly.

5.2 Base connection

For a base joint to connect the column to the foundation, the rivet connection is arranged as shown in Figure 5.11. The rivet plates are installed on opposing faces of the dry wood member, which is of GL10 Radiata Pine glulam.

5.2.1 Design Actions

It is assumed that after taking the effect of the load duration factor (k_t) into account, the critical load combination for the connection design is $[0.9G, W_{\text{d}}]$, as per AS 1170. The design loads acting on the joint are shown in Figure 5.11. Two strength limit states are of interest: rivet strength and wood strength. An efficient connection design can be made by decreasing the difference between the capacity of the wood and the rivets.

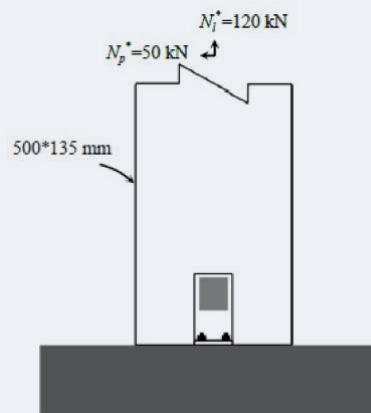


Figure 5.11: Design actions.

5.2.2 Connection Geometry

Try 65 mm long rivets with the following configuration:

Number of rows of rivets parallel to direction of load, $n_R = 8$ for tension force and $n_R = 9$ for shear force

Number of rivets per row, $n_C = 9$ for axial force and $n_C = 8$ for shear force

Spacing along the grain, $a_1 = 35$ mm Spacing across the grain, $a_2 = 25$ mm

End distance, a_{3t} (for tension force)/ $a_{3c,L}$ (for shear force) = 200 mm

Upper end distance, $a_{3c,R} = 2,520$ mm (based on a column free height of 3,000 mm)

Edge distance, $a_{4c} = 163$ mm (based on member width)

Side plate thickness, $t_p = 10$ mm

The steel side plates should be checked to have a cross-section adequate for resisting tension and shear forces.

5.2.3 Connection Lateral Resistance

$$\begin{aligned}
 Q_s &= Q_{s,\theta} \\
 &= \min(\phi_r Q_{ru,\theta}, Q_{s,l}/\cos \theta, Q_{s,p}/\sin \theta) \\
 \theta &= \tan^{-1}(N_p^*/N_l^*) \\
 N_p^* &= 50 \text{ kN} \\
 N_l^* &= 120 \text{ kN} \\
 \theta &= \tan^{-1}(50/120) = 22^\circ
 \end{aligned}$$

Joint design lateral resistance parallel to grain,

$$Q_{s,l} = \begin{cases} \phi_w Q_{we,l} & \text{if } \phi_w Q_{we,l} < \phi_r Q_{ry,l} \text{ (Brittle mode)} \\ \phi_r Q_{ry,l} & \text{if } \phi_w Q_{wy,l} < \phi_r Q_{ry,l} \leq \phi_w Q_{we,l} \text{ (Mixed mode)} \\ \phi_w Q_{wy,l} & \text{if } \phi_r Q_{ry,l} \leq \phi_w Q_{wy,l} < \phi_r Q_{ru,l} \text{ (Mixed mode)} \\ \phi_r Q_{ru,l} & \text{if } \phi_r Q_{ru,l} < \phi_w Q_{wy,l} \text{ (Ductile mode)} \end{cases}$$

Check if $\phi_w Q_{we,l} < \phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

Rivet capacity corresponding to yielding parallel to grain, $\phi_r Q_{ry,l}$

$$\begin{aligned}
 \phi_r Q_{ry,l} &= \phi_r Q_{ry,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hy,0} \text{ and } M_{ry,l}, \text{ respectively} \\
 &= \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})
 \end{aligned}$$

$$\phi_r = 0.8$$

$$k_1 = 1.14 \text{ for load combination [0.9G, Wu]}$$

$$k_f = 1.0 \text{ for edge grain of glulam}$$

$$n_p = 2$$

$$n_R = 8$$

$$n_C = 9$$

Rivet failure – mode (a)

Determine $P_{rl,a}$ using Section 4.1.3.1(i):

$$P_{rl,a} = X_r \left[J_p f_{h,0} L_p d_l \left(\left(\sqrt{2 + \frac{4M_{r,l}}{f_{h,0} d_l L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.87 \text{ for glulam}$$

$$J_p = 1.0 \text{ (side plate factor)}$$

$$\begin{aligned}
 f_{h,90} &= f_{hy,90} \\
 &= 71.9\rho (1-0.0024d_p) 10^{-3} \text{ for glulam (Section 4.1.3.3)}
 \end{aligned}$$

$$\rho = 470 \text{ kg/m}^3 \text{ for GL10 glulam}$$

$$d_l = 3.2 \text{ mm}$$

$$f_{hy,90} = 33.5 \text{ MPa}$$

$$\begin{aligned}
 M_{r,p} &= M_{ry,p} \\
 &= 24,900 \text{ Nmm}
 \end{aligned}$$

$$f_{ax} = 11.5\rho d_p (1-0.0024d_p) 10^{-3}$$

$$f_{ax} = 34.1 \text{ N/mm}$$

Calculate $P_{rl,a}$:

$$P_{rl,a} = 2.86 \text{ N}$$

Rivet failure – mode (b)**Determine $P_{rl,b}$ using Section 4.1.3.1(ii):**

$$P_{rl,b} = X_r \left[2J_p \sqrt{M_{r,l} f_{h,0} d_l} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$P_{rl,a} = 3.13 \text{ kN}$$

Therefore, the rivet yield capacity parallel to grain,

$$\Phi_r Q_{ry,l} = \Phi_r k_1 k_{12} k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$$\Phi_r Q_{ry,l} = 329.3 \text{ (Rivet yielding mode: a)}$$

Wood capacity parallel to grain corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$

$$\Phi_w Q_{we,l} = \Phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efe,l}$$

$$= \Phi_w n_p k_1 k_{12} k_f \min(P_{w,h}, P_{w,b}, P_{w,l})$$

$$\Phi_w = 0.7$$

Wood failure – mode (a)**Determine $P_{w,h}$ using Section 4.1.4.1:**

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$$

$$X_t = 1.19 \text{ for glulam}$$

$$f_t = 11 \text{ MPa for grade GL10 glulam}$$

$$A_{t,h} = t_{ef,l} w_c$$

$$t_{ef,l} = t_{efe,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)}$$

$$= 44.2 \text{ mm}$$

$$w_c = a_2 (n_R - 1) = 175 \text{ mm}$$

$$A_{t,h} = a_2 (n_R - 1) = 4420 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

$$\psi = 0.067$$

$$L_c = a_1 (n_C - 1) = 200 \text{ mm}$$

$$d_z = 23.3$$

$$L_c = a_1 (n_C - 1) = 280 \text{ mm}$$

$$H = 0.54$$

$$A_{s,b} = 84,000 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_1 = 0.573$$

$$\lambda_2 = 0.25 \psi L_c (1 - F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_2 = 0.368$$

Calculate $P_{w,h}$:

$$P_{w,h} = 196.5 \text{ kN, mode (a)}$$

Wood failure – mode (b)**Determine $P_{w,b}$ using Section 4.1.4.2:**

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

$$X_s = 0.96 \text{ for glulam}$$

$$C_b = 0.40$$

$$f_s = 3.7 \text{ MPa for grade GL10 glulam}$$

$$\lambda_3 = \frac{t_{ef,l}(1-F)}{w_c(1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

$$\lambda_3 = 0.642$$

Calculate $P_{w,b}$:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} 119347, \text{ Mode (a)} \\ 53374, \text{ Mode (c)} \end{cases}$$

$$P_{w,b} = 180.8 \text{ kN, mode (c)}$$

Wood failure – mode (c)**Determine $P_{w,l}$ using Section 4.1.4.3:**

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases}$$

$$C_l = 0.32$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} 48237, \text{ Mode (a)} \\ 188616, \text{ Mode (b)} \end{cases}$$

$$P_{w,l} = 256.2 \text{ kN, mode (a)}$$

Therefore, the parallel-to-grain wood capacity corresponding to rivet elastic deformation,

$$\Phi_w Q_{we,l} :$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_1 k_{12} k_f \min (P_{w,ht} P_{w,b} P_{w,l})$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_1 k_{12} k_f \min (P_{w,ht} P_{w,b} P_{w,l})$$

$$= 292.1 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4).

The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

Therefore, the parallel-to-grain wood capacity corresponding to rivet elastic deformation,

$$\Phi_w Q_{we,l} :$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_1 k_{12} k_f \min (P_{w,ht} P_{w,b} P_{w,l})$$

$$\Phi_w Q_{we,l} = 0.7 \times 2 \times 1.14 \times 1.0 \times 1.0 \times \min (196.5, 180.8, 256.2)$$

$$= 288.6 \text{ kN (failure governed by bottom shear plane, mode (c))}$$

Wood failure mode (c) governs failure, therefore the wood capacity, $\Phi_w Q_{we,l}$, should be recalculated from the remaining planes to determine whether the residual head tensile plane and lateral shear planes can resist higher load:

$$\lambda_1 = 0$$

$$\lambda_2 = 0.368$$

$$\lambda_3^{-1} = 0$$

Wood failure – mode (a)**Determine $P_{w,h}$ using Section 4.1.4.1:**

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$$

$$P_{w,h} = 1.19 \times 11 \times 7736 \times (1 + 0.0 + 0.368) \times 10^{-3}$$

$$= 138.5 \text{ kN, mode (a)}$$

$$X_t = 1.19$$

$$f_t = 11$$

$$A_{t,h} = t_{ef,l} w_c$$

$$t_{ef,l} = t_{efe,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)}$$

$$A_{t,h} = a_2 (n_R - 1) = 7736 \text{ mm}^2$$

Wood failure – mode (c)**Determine $P_{w,l}$ using Section 4.1.4.3:**

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2 X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases}$$

$$C_l = 0.32$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1 + 0.368^{-1} + 0) 10^{-3} \min = \begin{cases} 0.96 \times 0.32 \times 3.7 \times 42438 \\ 2 \times 1.19 \times 11 \times 44.2 \times 163 \end{cases}$$

$$P_{w,l} = (1 + 0.368^{-1} + 0) 10^{-3} \min = \begin{cases} 48237, \text{ mode (a)} \\ 188616, \text{ mode (b)} \end{cases}$$

$$P_{w,l} = 180.6 \text{ kN, mode (a)}$$

Therefore, the parallel-to-grain wood capacity corresponding to rivet elastic deformation,

$$\phi_w Q_{we,l} :$$

$$\phi_w Q_{we,l} = \phi_w n_p k_1 k_{12} k_f \min (P_{w,h}, P_{w,l})$$

$$\phi_w Q_{we,l} = 0.7 \times 2 \times 1.14 \times 1.0 \times 1.0 \times \min (138.5, 180.6)$$

$$= 220.6 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4). The residual head tensile plane and lateral shear planes resist lower load of 220.6 kN compared to wood capacity of 288.6 kN considering all resisting planes. Thus, $\phi_w Q_{we,l} = 288.6 \text{ kN}$.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.190 < 0.3$$

The connection does not need to be redesigned.

$$\text{Check if } Q_{s,l} = \phi_w Q_{we,l} \quad (\text{brittle failure mode})$$

$$\text{If } \phi_w Q_{we,l} < \phi_r Q_{ry,l}$$

$$253.2 < 329.3 \quad \text{OK}$$

$$Q_{s,l} = \phi_w Q_{we,l}$$

$$= 288.6 \text{ kN}$$

Joint design resistance, perpendicular to grain,

$$Q_s = Q_{s,p}$$

where

Check if $\phi_w Q_{we,p} < \phi_r Q_{ry,p}$.

If so, then $Q_{s,p} = \phi_w Q_{we,p}$ (brittle failure mode)

Rivet capacity corresponding to yielding, perpendicular to grain, $\phi_r Q_{ry,p}$

$$\begin{aligned}\phi_r Q_{ry,p} &= \phi_r Q_{ry,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } h_{y,90} \text{ and } M_{ry,p}, \text{ respectively} \\ &= \phi_r k_1 k_{12} k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b})\end{aligned}$$

Rivet failure – mode (a)

Determine $P_{rp,a}$ using Section 4.1.3.2(i):

$$Q_{s,p} = \begin{cases} \phi_w Q_{we,p} & \text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p} \text{ (Brittle mode)} \\ \phi_r Q_{ry,p} & \text{if } \phi_w Q_{wy,p} < \phi_r Q_{ry,p} \leq \phi_w Q_{we,p} \text{ (Mixed mode)} \\ \phi_w Q_{wy,p} & \text{if } \phi_r Q_{ry,p} \leq \phi_w Q_{wy,p} < \phi_r Q_{ru,p} \text{ (Mixed mode)} \\ \phi_r Q_{ru,p} & \text{if } \phi_r Q_{ru,p} < \phi_w Q_{wy,p} \text{ (Ductile mode)} \end{cases}$$

$$\begin{aligned}f_{h,90} &= f_{hy,90} \\ &= 35.9p (1-0.0024d_p) 10^{-3} \text{ for glulam (Section 4.1.3.3)}\end{aligned}$$

$$d_p = 6.4 \text{ mm}$$

$$f_{hy,90} = 16.6 \text{ MPa}$$

$$\begin{aligned}M_{r,p} &= M_{ry,p} \\ &= 12450 \text{ Nmm}\end{aligned}$$

Calculate $P_{rp,a}$:

$$P_{rp,a} = 2.56 \text{ kN}$$

Rivet failure – mode (b)

Determine $P_{rp,b}$ using Section 4.1.3.2(ii):

$$P_{rp,b} = 2.29 \text{ kN}$$

Rivet capacity corresponding to yielding, perpendicular to grain, $\phi_r Q_{ry,p}$

$$\begin{aligned}\phi_r Q_{ry,p} &= \phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b}) \\ &= 0.8 \times 1.14 \times 1.0 \times 2 \times 9 \times 8 \times \min(2.56, 2.29) \\ &= 300.7 \text{ kN (Yielding mode of failure: b)}\end{aligned}$$

Wood design splitting resistance capacity, perpendicular to grain, corresponding to rivet elastic deformation, $\phi_w Q_{we,p}$

$$\begin{aligned}\phi_w Q_{we,p} &= \phi_w Q_{w,p} \text{ in which } t_{el,p} \text{ equals to } t_{ele,p} \\ &= \phi_w k_1 g_{42} k_{12} k_f n_p \min(P_{s,a}, P_{s,b})\end{aligned}$$

$$\phi_w = 0.7$$

$$g_{42} = 1.0 \text{ for one joint}$$

Determine characteristic full width splitting resistance, failure mode (a), $P_{s,a}$ using Section 4.1.5.1:

$$P_{s,a} = X_p \eta b C_{fp} \sqrt{\frac{h_e}{1 - \frac{h_e}{h}}} 10^{-3}$$

$$X_p = 1.28 \text{ for glulam}$$

$$\gamma = 2.7 \text{ for glulam}$$

$$h_e = h - a_{4c}$$

$$h_e = 500 - 163 = 337 \text{ mm}$$

$$w_{net} = a_1 (n_R - 1) - 6.4 n_R$$

$$w_{net} = 222.4 \text{ mm}$$

$$a_{3c,L} = 200 \text{ mm}$$

$$a_{3c,R} = 2520 \text{ mm}$$

$$\eta = 0.732$$

$$b = 135 \text{ mm}$$

$$C_{fp} = 11.1 \text{ N/mm}^2 \text{ for GL10 Radiata Pine glulam}$$

$$P_{s,a} = 5.1 \text{ kN}$$

Determine characteristic partial width splitting resistance, failure mode (b), $P_{s,b}$ using Section 4.1.5.2:

$$P_{s,b} = X_p C_t f_{tp} t_{ef,p} [w_{net} + \min(\beta h_e, a_{3c,L}) + \min(\beta h_e, a_{3c,R})] 10^{-3}$$

$$\zeta = \frac{a_{4c}}{a_2 (n_c - 1)}$$

$$\zeta = 0.776$$

$$C_t = 1.388$$

$$f_{tp} = 1.19 \text{ MPa}$$

$$t_{ef,p} = t_{efe,p} \text{ (Corresponding to rivet elastic deformation, Section 4.1.5.4)}$$

$$= 39.2 \text{ mm}$$

$$\beta = 1.6 \text{ for glulam}$$

Calculate $P_{s,b}$

$$P_{s,b} = 79.7 \text{ kN}$$

Therefore, the wood design splitting resistance capacity, perpendicular to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,p}$:

$$\Phi_w Q_{we,p} = \Phi_w k_1 k_f g_{42} n_p \min(P_{s,a}, P_{s,b})$$

$$= 0.7 \times 1.14 \times 1.0 \times 1.0 \times 2 \times \min(45.1, 79.7)$$

$$= 72.0 \text{ kN (governing failure, splitting width equal to member width, mode (b))}$$

Check if $Q_{s,p} = \Phi_w Q_{we,p}$ (brittle failure mode)

$$\text{If } \Phi_w Q_{we,p} < \Phi_r Q_{ry,p}$$

$$72.0 < 300.7 \quad \text{OK}$$

$$Q_{s,p} = \Phi_w Q_{we,p}$$

$$= 72.0 \text{ kN}$$

Ultimate rivet capacity at angle, $\theta = 22^\circ$, to the grain, $\Phi_r Q_{ru,\theta}$

$$\phi_r Q_{ru,\theta} = \frac{\phi_r Q_{ru,l} \phi_r Q_{ru,p}}{\phi_r Q_{ru,l} \sin^2 \theta + \phi_r Q_{ru,p} \cos^2 \theta}$$

Ultimate rivet capacity, parallel to grain, $\phi_r Q_{ru,l}$

$$\phi_r Q_{ru,l} = \phi_r Q_{ru,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

$$\begin{aligned} f_{h,0} &= f_{hu,0} \\ &= 86.7 \rho (1 - 0.0024 d_l) 10^{-3} \text{ for glulam (Section 4.1.3.3)} \\ &= 40.4 \text{ MPa} \end{aligned}$$

$$\begin{aligned} M_{r,l} &= M_{ru,l} \\ &= 30,000 \text{ Nmm} \end{aligned}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\begin{aligned} \phi_r Q_{ru,l} &= \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ &= 444.9 \text{ kN (Rivet failure mode: a)} \end{aligned}$$

Ultimate rivet capacity, perpendicular to grain, $\phi_r Q_{ru,p}$

$$\phi_r Q_{ru,p} = \phi_r Q_{ru,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } f_{hu,90} \text{ and } M_{ru,p}, \text{ respectively}$$

$$\begin{aligned} f_{h,90} &= f_{hu,90} \\ &= 43.3 \rho (1 - 0.0024 d_p) 10^{-3} \text{ for glulam (Section 4.1.3.3)} \\ &= 20.0 \text{ MPa} \end{aligned}$$

$$\begin{aligned} M_{r,p} &= M_{ru,p} \\ &= 15,000 \text{ Nmm} \end{aligned}$$

The rivet ultimate capacity, perpendicular to grain (by following the same design procedure as defined above):

$$\phi_r Q_{ru,p} = \phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b})$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\phi_r Q_{ru,p} = 354.8 \text{ kN (Rivet failure mode: b)}$$

Therefore, ultimate rivet capacity at angle, $\theta = 22^\circ$, to the grain, $\phi_r Q_{ru,\theta}$:

$$\phi_r Q_{ru,\theta} = \frac{\phi_r Q_{ru,l} \phi_r Q_{ru,p}}{\phi_r Q_{ru,l} \sin^2 \theta + \phi_r Q_{ru,p} \cos^2 \theta}$$

$$\phi_r Q_{ru,\theta} = 429.7 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N_\theta^* = \sqrt{N_l^2 + N_p^2}$$

$$N_\theta^* = \sqrt{120^2 + 50^2}$$

$$N^* = 130.0 \text{ kN}$$

$$\begin{aligned} Q_s &= Q_{s,\theta} \\ &= \min(Q_{s,l}/\cos\theta, Q_{s,p}/\sin\theta, \phi_r Q_{ru,\theta}) \\ &= \min(288.6/\cos 22, 72.0/\sin 22, 429.7) \\ &= \min(311.3, 192.3, 429.7) = 192.3 \text{ kN} \end{aligned}$$

$130.0 \leq 192.3$, OK (Connection mode of failure: Brittle wood splitting – perpendicular to grain)

Adopt 65 mm long rivets with an array of 8 rows by 9 columns, spacing 35 mm by 25 mm along and across the grain, and 200 mm end distance (see Figure 5.12).

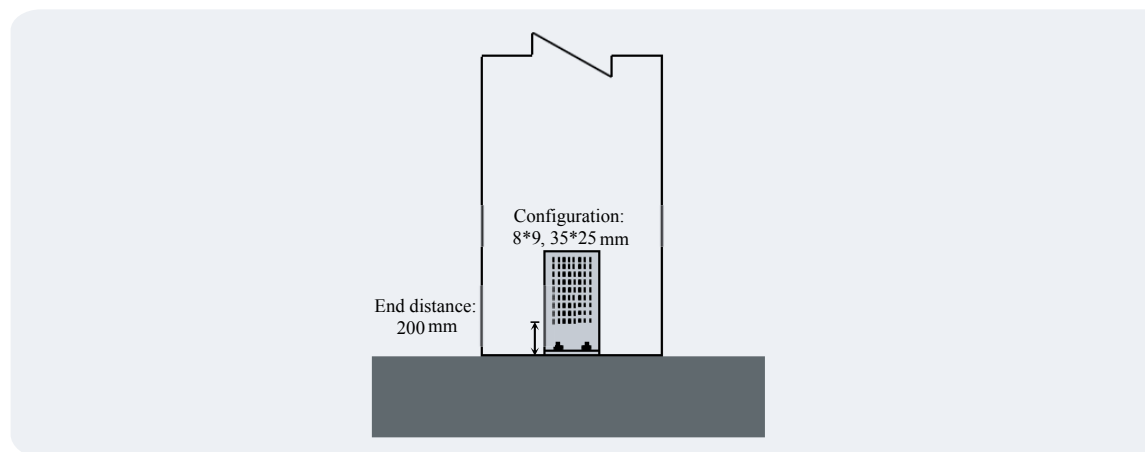


Figure 5.12: Connection configuration.

If ductile behaviour at the connection ultimate capacity is desirable, the failure mode of the connection can be improved from brittle/mixed to ductile by increasing the wood resistance with larger rivet spacing across and along the grain. Spreadsheets can be used to speed up the computation process, and once they are set up, adjustments in spacing, end and edge distances and capacities for a range of rivet lengths can be evaluated relatively quickly.

5.3 Moment Connection

To develop the moment in a beam splice, the rivet connection is arranged as shown in Figure 5.13. The rivet plates are installed on opposing faces of the dry wood member, which is of grade 11 Radiata Pine LVL. Shear is transferred by another scheme.

5.3.1 Design Actions

It is assumed that after taking the effect of the load duration factor (k_t) into account, the critical load combination for the connection design is $[1.2G, 1.5Q]$, as per AS 1170. The design loads acting on the joint are shown in Figure 5.13. Two strength limit states are of interest: rivet strength and wood strength. An efficient connection design can be made by decreasing the difference between the capacity of the wood and the rivets.

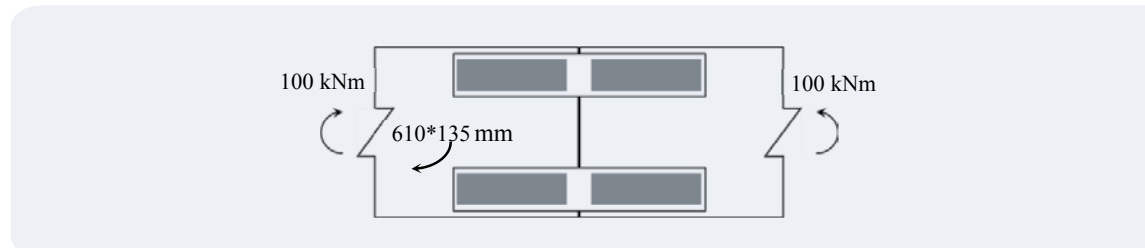


Figure 5.13: Connection configuration.

5.3.2 Connection Geometry

Number of rows of rivets parallel to direction of load: $N_R = 5$

Number of rivets per row: $n_c = 10$

Spacing along the grain: $a_1 = 30 \text{ mm}$

Spacing across the grain: $a_2 = 25 \text{ mm}$

End distance: $a_{gt} = 150 \text{ mm}$

Edge distance: $a_{ec} = 50 \text{ mm}$ (minimum of the edge distance and half the distance between adjacent joints)

Side plate thickness: $t_p = 10 \text{ mm}$

The steel side plates should be checked to have a cross-section adequate for resisting tension and shear forces.

5.3.3 Connection Lateral Resistance

$$Q_s = Q_{s,l}$$

$$Q_{s,l} = \begin{cases} \phi_w Q_{we,l} & \text{if } \phi_w Q_{we,l} < \phi_r Q_{ry,l} \text{ (Brittle mode)} \\ \phi_r Q_{ry,l} & \text{if } \phi_w Q_{wy,l} < \phi_r Q_{ry,l} \leq \phi_w Q_{we,l} \text{ (Mixed mode)} \\ \phi_w Q_{wy,l} & \text{if } \phi_r Q_{ry,l} \leq \phi_w Q_{wy,l} < \phi_r Q_{ru,l} \text{ (Mixed mode)} \\ \phi_r Q_{ru,l} & \text{if } \phi_r Q_{ru,l} < \phi_w Q_{wy,l} \text{ (Ductile mode)} \end{cases}$$

Check if $\phi_w Q_{we,l} < \phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \phi_w Q_{we,l}$ (brittle failure mode)

Rivet capacity corresponding to yielding – parallel to grain, $\phi_r Q_{ry,l}$.

$$\phi_r Q_{ry,l} = \phi_r Q_{ry,l} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hy,0} \text{ and } M_{ry,l}, \text{ respectively}$$

$$\phi_r Q_{ry,l} = \phi_r k_1 k_f n_p n_R n_C \min(P_{n,a}, P_{n,b})$$

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for face grain}$$

$$n_p = 2$$

$$n_R = 5$$

$$n_C = 10$$

Rivet failure – mode (a)

Determine $P_{n,a}$ using Section 4.1.3.1(i):

$$P_{n,a} = X_r \left[J_p f_{h,0} L_p d_l \left(\left(\sqrt{2 + \frac{4M_{r,l}}{f_{h,0} d_l L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.93 \text{ for LVL}$$

$$J_p = 1.0 \text{ (side plate factor)}$$

$$f_{h,0} = f_{hy,0}$$

$$= 75.1(1-0.003dl) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$\rho = 620 \text{ kg/m}^3 \text{ for grade 11 LVL}$$

$$dl = 3.2 \text{ mm}$$

$$f_{hy,0} = L_r t_p - 3.2 \text{ MPa}$$

$$L_p = 65 \text{ mm}$$

$$M_{r,l} = M_{ry,l}$$

$$= 24,900 \text{ Nmm}$$

$$f_{ax} = 15.9\rho d_p(1-0.0024d_p)10^{-3}$$

$$= 61.6 \text{ N/mm}$$

Calculate $P_{n,a}$:

$$P_{n,a} = 4.11 \text{ kN}$$

Rivet failure – mode (b)

Determine $P_{n,b}$ using Section 4.1.3.1(ii):

$$P_{n,b} = X_r \left[2J_p \sqrt{M_{r,l} f_{h,0} d_l} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$P_{n,a} = 4.12 \text{ kN}$$

Therefore, the rivet yield capacity parallel to grain,

$$\begin{aligned}\Phi_r Q_{ry,l} &= \Phi_r k_f k_t n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ &= 0.8 \times 0.77 \times 1.0 \times 2 \times 5 \times 10 \min(4.11, 4.12)\end{aligned}$$

$$\Phi_r Q_{ry,l} = 253.0 \text{ (Rivet Yielding mode: a)}$$

Wood capacity, parallel to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$

$$\begin{aligned}\Phi_w Q_{we,l} &= \Phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efe,l} \\ &= \Phi_w n_p k_f k_t \min(P_{w,h}, P_{w,b}, P_{w,l})\end{aligned}$$

$$\Phi_w = 0.7$$

Wood failure – mode (a)

Determine $P_{w,h}$ using Section 4.1.4.1:

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$$

$$X_t = 1.06 \text{ for LVL}$$

$$f_t = 30 \text{ MPa for grade 11 LVL}$$

$$A_{t,h} = t_{ef,l} w_c$$

$$\begin{aligned}t_{ef,l} &= t_{efe,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)} \\ &= 44.2 \text{ mm}\end{aligned}$$

$$w_c = a_2 (n_R - 1) = 100 \text{ mm}$$

$$A_{t,h} = a_2 (n_R - 1) = 4420 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

$$G = 550 \text{ MPa for grade 11 LVL}$$

$$E = 11,000 \text{ MPa for grade 11 LVL}$$

$$\psi = 0.067$$

$$L_c = a_1 (n_c - 1) = 270 \text{ mm}$$

$$d_z = 23.3$$

$$H = 0.54$$

$$A_{s,b} = 42,000 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_1 = 0.378$$

$$\lambda_2 = 0.25 \psi L_c (1 - F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_2 = 0.427$$

$$A_{s,l} = 2 t_{ef,l} (L_c + a_{3l})$$

$$A_{s,l} = 37,133 \text{ mm}^2$$

$$F = 0.36$$

Calculate $P_{w,b}$:

$$P_{w,h} = 253.7 \text{ kN, mode (a)}$$

Wood failure – mode (b)**Determine $P_{w,b}$ using Section 4.1.4.2:**

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

$$X_s = 1.02 \text{ for LVL}$$

$$C_b = 0.421$$

$$f_s = 6 \text{ MPa for grade 11 LVL}$$

$$\lambda_3 = \frac{t_{ef,l}(1-F)}{w_c(1-H)} \left[\frac{5\psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5\psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]$$

$$\lambda_3 = 1.130$$

Calculate $P_{w,b}$:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} 108214, \text{ Mode (a)} \\ 74094, \text{ Mode (c)} \end{cases}$$

$$P_{w,b} = 354.0 \text{ kN, mode (c)}$$

Wood failure – mode (a)**Determine $P_{w,l}$ using Section 4.1.4.3:**

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} X_s C_l f_s A_{s,l}, \text{ Mode (a)} \\ 2X_t f_t t_{ef,l} a_{4c}, \text{ Mode (b)} \end{cases}$$

$$C_l = 0.337$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} 76585, \text{ Mode (a)} \\ 140556, \text{ Mode (b)} \end{cases}$$

$$P_{w,l} = 323.9 \text{ kN, mode (a)}$$

Therefore, the wood capacity, parallel to grain, corresponding to rivet elastic deformation,

$$\Phi_w Q_{we,l} :$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_f k_t \min (P_{w,h}, P_{w,b}, P_{w,l})$$

$$\Phi_w Q_{we,l} = \Phi_w n_p k_f k_t \min (253.7, 354.0, 323.9)$$

$$= 273.4 \text{ kN (failure governed by head tensile plane, mode (a))}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4).

The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.237 < 0.3$$

The connection does not need to be redesigned.

$$\text{Check if } Q_{s,l} = \Phi_w Q_{we,l} \quad (\text{brittle failure mode})$$

$$\text{If } \Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$$

$$273.4 \geq 253.0 \quad (\text{unsatisfied})$$

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ry,l}$. If so, then $Q_{s,l} = \Phi_w Q_{ry,l}$ (mixed failure mode)

Wood capacity, parallel to grain, corresponding to rivet yielding mode, $\phi_w Q_{wy,l}$

$$\phi_w Q_{wy,l} = \phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efy,l}$$

$$t_{ef,l} = t_{efy,l}$$

$$t_{efy,p} = J_p \sqrt{\frac{M_{ry,p}}{f_{hy,90} d_p} + \frac{L_p^2}{2}}, \text{ yielding mode (a)}$$

$$t_{ef,l} = 38.9 \text{ mm}$$

The recalculated wood capacity (by following the same design procedure as defined above):

$$\phi_w Q_{wy,l} = 273.3 \text{ kN}$$

Note that if the yielding mode (b) was governing then the reduction of wood strength would be much higher.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1}) - 1 < 0.3$$

$$0.208 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \phi_r Q_{ry,l}$ (brittle failure mode)

$$\text{If } \phi_w Q_{wy,l} < \phi_r Q_{ry,l}$$

$$273.3 \geq 253.0 \quad (\text{unsatisfied})$$

Thus, check if $\phi_w Q_{wy,l} < \phi_r Q_{ru,l}$. If so, then $Q_{s,l} = \phi_w Q_{wy,l}$ (mixed failure mode)

Ultimate rivet capacity – parallel to grain, $\phi_r Q_{ru,l}$

$$\phi_r Q_{ru,l} = \phi_r Q_{r,l} \text{ in which } f_{n,0} \text{ and } M_{r,l} \text{ equal to } f_{nu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

$$f_{n,0} = f_{nu,0}$$

$$= 90.4 \rho (1 - 0.0037d_l) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$= 55.4 \text{ MPa}$$

$$M_{r,l} = M_{ru,l}$$

$$= 30,000 \text{ Nmm}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\phi_r Q_{ru,l} = \phi_r k_t k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$$

$$= 297.7 \text{ kN (Rivet failure mode: a)}$$

Check if $Q_{s,l} = \phi_w Q_{wy,l}$ (mixed failure mode)

$$\text{If } \phi_w Q_{wy,l} \leq \phi_r Q_{ru,l}$$

$$273.3 \leq 297.7 \text{ OK}$$

Thus, $Q_{s,l} = \phi_r Q_{ru,l}$ (ductile failure mode)

$$Q_{s,l} = 283.9 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N^* = M^*/0.410$$

$$M^* = 100 \text{ kNm}$$

$$N^* = 243.9 \text{ kN}$$

$$Q_s = Q_{s,l}$$

$$= 273.3 \text{ kN}$$

$243.9 \leq 273.3$, OK (Joint mode of failure: ductile)

Adopt 65 mm long rivets with an array of 5 rows by 10 columns, spacing 30 mm by 25 mm along and across the grain, and 150 mm end distance (see Figure 5.14).

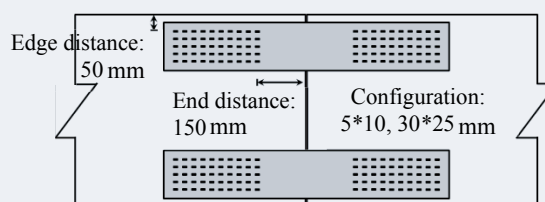


Figure 5.14: Connection configuration.

If ductile behaviour at the connection ultimate capacity is desirable, the failure mode of the connection can be improved from brittle/mixed to ductile by increasing the wood resistance with larger rivet spacing across and along the grain. Spreadsheets can be used to speed up computation and, once they are set up, adjustments in spacing, end and edge distances and capacities for a range of rivet lengths can be evaluated relatively quickly.

5.4 Hanger Connection

For a hanger joint to transfer load from a secondary beam to the primary beam, the rivet connection is arranged as shown in Figure 5.15. The secondary beam rivet plates are installed on opposing faces of the dry wood member, which is of grade GL 10 Radiata Pine glulam.

5.4.1 Design Actions

It is assumed that after taking the effect of the load duration factor (k_t) into account, the critical load combination for the connection design is [1.2G, 1.5Q], as per AS 1170. The design loads acting on the joint are shown in Figure 5.15. The design load acting on the secondary beams is assumed to be distributed evenly across the two joints in the hanger connection. Two strength limit states are of interest: rivet strength and wood strength. An efficient connection design can be made by decreasing the difference between the capacity of the wood and the rivets.

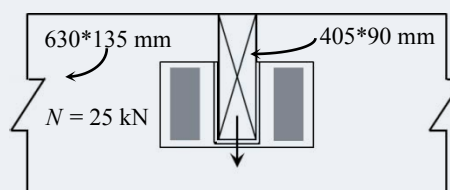


Figure 5.15: Design action.

5.4.2 Connection Geometry

Try 65 mm long rivets with the following configuration for each joint:

Number of rows of rivets parallel to direction of load: $N_R = 4$

Spacing along the grain: $a_1 = 30$ mm

Spacing across the grain: $a_2 = 60$ mm

Half the distance to the adjacent joint on the left side, end distance on the left side: $a_{3C,L} = 1,115$ mm (based on 2,600 mm spacing between secondary beams)

Half the distance to the adjacent joint on the right side, end distance on the right side: $a_{3C,R} = 95$ mm

Unloaded edge distance: $a_{4C} = 225$ mm

Loaded edge distance: $a_{4t} = 225$ mm

Side plate thickness: $t_p = 8$ mm

(The steel side plates need to be checked to have a cross-section adequate for resisting tension and shear forces).

5.4.3 Connection Lateral Resistance

$$Q_s = Q_{s,p}$$

where

$$Q_{s,p} = \begin{cases} \phi_w Q_{we,p} & \text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p} \quad (\text{Brittle mode}) \\ \phi_r Q_{ry,p} & \text{if } \phi_w Q_{wy,p} < \phi_r Q_{ry,p} \leq \phi_w Q_{we,p} \quad (\text{Mixed mode}) \\ \phi_w Q_{wy,p} & \text{if } \phi_r Q_{ry,p} \leq \phi_w Q_{wy,p} < \phi_r Q_{ru,p} \quad (\text{Mixed mode}) \\ \phi_r Q_{ru,p} & \text{if } \phi_r Q_{ru,p} < \phi_w Q_{wy,p} \quad (\text{Ductile mode}) \end{cases}$$

Check if $\phi_w Q_{we,p} < \phi_r Q_{ry,p}$.

If so, then $Q_{s,p} = \phi_w Q_{we,p}$ (brittle failure mode)

Rivet capacity corresponding to yielding perpendicular to grain, $\phi_r Q_{ry,p}$

$$\begin{aligned} \phi_r Q_{ry,p} &= \phi_r Q_{ry,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } h_{y,90} \text{ and } M_{ry,p}, \text{ respectively} \\ &= \phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b}) \end{aligned}$$

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for edge grain of glulam}$$

$$n_p = 2$$

$$n_R = 4$$

$$n_C = 4$$

Rivet failure – mode (a)

Determine $P_{rp,a}$ using Section 4.1.3.2(i):

$$P_{rp,a} = X_r \left[J_p f_{h,90} L_p d_p \left(\left(\sqrt{2 + \frac{4M_{r,p}}{f_{h,90} d_p L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.87 \text{ for glulam}$$

$$J_p = 1.0$$

$$\begin{aligned} f_{h,90} &= f_{hy,90} \\ &= 35.9p (1 - 0.0024d_p) 10^{-3} \text{ for glulam (Section 4.1.3.3)} \end{aligned}$$

$$d_p = 6.4 \text{ mm}$$

$$f_{hy,90} = 16.6 \text{ MPa}$$

$$\begin{aligned} M_{r,p} &= M_{ry,p} \\ &= 12,450 \text{ Nmm} \end{aligned}$$

$$L_p = 51.8 \text{ mm}$$

$$f_{ax} = 11.5p d_p (1 - 0.0024d_p) 10^{-3}$$

$$f_{ax} = 34.1 \text{ N/mm}$$

Calculate $P_{rp,a}$:

$$P_{rp,a} = 2.56 \text{ N}$$

Rivet failure – mode (a)**Determine $P_{rp,b}$ using Section 4.1.3.2(ii):**

$$P_{rp,b} = X_r \left[2J_p \sqrt{M_{r,p} f_{h,90} d_p} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$P_{rp,b} = 2.29 \text{ kN}$$

Rivet capacity corresponding to yielding perpendicular to grain, $\Phi_r Q_{ry,p}$

$$\begin{aligned} \Phi_r Q_{ry,p} &= \Phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b}) \\ &= 0.8 \times 0.77 \times 1.0 \times 2 \times 4 \times 4 \times \min(2.56, 2.29) \cdot 10^{-3} \\ &= 45.1 \text{ kN (Yielding mode of failure: b)} \end{aligned}$$

Wood capacity, perpendicular to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,p}$

$$\begin{aligned} \Phi_w Q_{we,p} &= \Phi_w Q_{w,p} \text{ in which } t_{ef,p} \text{ equals to } t_{efe,p} \\ &= \Phi_w k_1 g_{42} k_f n_p \min(P_{s,a}, P_{s,b}) \end{aligned}$$

$$\Phi_w = 0.7$$

$$g_{42} = 0.6 \text{ for multiple joints}$$

Determine characteristic full width splitting resistance, failure mode (a), $P_{s,b}$ using Section 4.1.5.1:

$$P_{s,a} = X_p \eta b C_{fp} \sqrt{\frac{h_e}{1 - \frac{h_e}{h}}} 10^{-3}$$

$$X_p = 1.28 \text{ for glulam}$$

$$\gamma = 2.7 \text{ for glulam}$$

$$h_e = h - a_{4c}$$

$$h_e = 630 - 225 = 405 \text{ mm}$$

$$w_{net} = a_1 (n_R - 1) - 6.4 n_R$$

$$w_{net} = 64.4 \text{ mm}$$

$$a_{3c,L} = 1,115 \text{ mm}$$

$$a_{3c,R} = 95 \text{ mm}$$

$$\eta = \frac{\min(\gamma h_e, a_{3c,L}) + (\gamma h_e, a_{3c,R}) + w_{net}}{2\gamma h_e}$$

$$\eta = 0.573$$

$$b = 135 \text{ mm}$$

$$C_{fp} = 11.1 \text{ N/mm}^{1.5} \text{ for Radiata Pine LVL}$$

$$P_{s,a} = 37.0 \text{ kN}$$

Determine characteristic partial width splitting resistance, failure mode (b), $P_{s,b}$ using Section 4.1.5.2:

$$P_{s,b} = X_p C_{fp} t_{ef,p} \left[w_{net} + \min(\beta h_e, a_{3c,L}) + \min(\beta h_e, a_{3c,R}) \right] 10^{-3}$$

$$\zeta = \frac{a_{4c}}{a_2 (n_c - 1)}$$

$$\zeta = 1.25$$

$$C_t = 1.164$$

$$f_{tp} = 1.19 \text{ MPa}$$

$$\begin{aligned} t_{ef,p} &= t_{efe,p} \text{ (Corresponding to rivet elastic deformation, Section 4.1.5.4)} \\ &= 39.2 \text{ mm} \end{aligned}$$

$$\beta = 1.6 \text{ for glulam}$$

Calculate $P_{s,b}$:

$$P_{s,b} = 56.1 \text{ kN}$$

Therefore, the wood capacity, perpendicular to grain, corresponding to rivet elastic deformation,

$\Phi_w Q_{we,p}$:

$$\Phi_w Q_{we,p} = \Phi_w k_1 k_f g_{42} n_p \min(P_{s,ar} P_{s,b})$$

$$= 0.7 \times 0.77 \times 0.6 \times 1.0 \times 2 \times \min(37.0, 56.1)$$

$$= 24.9 \text{ kN (governing failure, splitting with crack width equal to member thickness, mode (a))}$$

Check if $Q_{s,p} = \Phi_w Q_{we,p}$ (brittle failure mode)

$$\text{If } \Phi_w Q_{we,p} < \Phi_r Q_{ry,p}$$

$$24.9 < 45.1 \quad \text{OK}$$

$$Q_{s,p} = \Phi_w Q_{we,p}$$

$$= 24.9 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q$$

$$N^* = 25 \text{ kN}$$

$$Q_s = Q_{s,p}$$

$$= 24.9 \text{ kN}$$

$$25 \approx 24.9, \text{ OK (governing failure, splitting with crack width equal to member thickness, mode (a))}$$

Adopt 65 mm long rivets with an array of 4 rows by 4 columns, spacing 30 mm by 60 mm along and across the grain, and 50 mm end distance (see Figure 5.16).

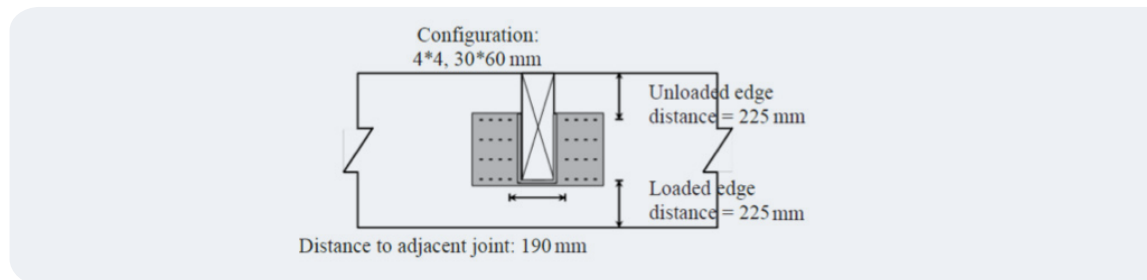


Figure 5.16: Connection configuration.

If ductile behaviour at the connection ultimate capacity is desirable, the failure mode of the connection can be improved from brittle/mixed to ductile by increasing the wood resistance with larger rivet spacing across and along the grain. Spreadsheets can be used to speed up computation and, once they are set up, adjustments in spacing, end and edge distances and capacities for a range of rivet lengths can be evaluated relatively quickly.

5.5 Shear Wall Connections

For a shear wall to resist loads during a design earthquake, a rivet hold-down connection and floor-wall connection are arranged as shown in . The rivet plates are installed on opposing faces of the dry wood member, which is of grade 11 Radiata Pine LVL.

5.5.1 Design Actions

It is assumed that after taking the effect of the load duration factor (k_f) into account, the critical load combination for the connection design is $[G, \psi_c Q, E_u]$ as per AS 1170. The design loads acting on the joint are shown in Figure 5.17.

Two strength limit states are of interest: rivet strength and wood strength. To achieve a targeted system ductility at design drift under ultimate limit state (ULS), the slip of the rivets in the hold-down and floor-wall connections are required to be less than 2 mm and 3 mm, respectively. An efficient connection design can be made by decreasing the difference between the capacity of the wood and the rivets; however the deflection requirements may be critical for the rivet capacity.

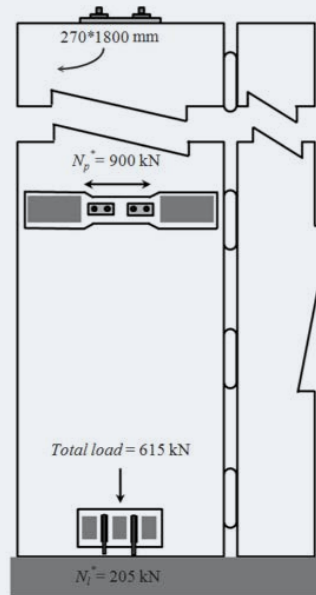


Figure 5.17: Design action.

The design load acting on the energy dissipaters in the hold-down connection is assumed to be distributed evenly across the three rivet joints. The rivet configuration in the floor–wall connection acts as one joint.

5.5.2 Hold-Down Connection

5.5.2.1 Connection geometry

Try 65 mm long rivets with the following configuration for each joint:

$$N^* = 205.0 \text{ kN}$$

Number of rows of rivets parallel to direction of load: $N_R = 6$

Number of rivets per row: $n_C = 6$

Spacing along the grain: $a_1 = 30 \text{ mm}$

Spacing across the grain: $a_2 = 30 \text{ mm}$

Side plate thickness: $t_p = 8 \text{ mm}$

(The steel side plates need to be checked to have a cross-section adequate for resisting tension and shear forces).

End distance: $a_{gt} = 150 \text{ mm}$

Edge distance: $a_{ec} = 100 \text{ mm}$ (minimum of edge distance and half the distance to an adjacent joint)

The rivet groups on either side of the energy dissipater are considered multiple joints acting parallel to grain and the connection is designed in accordance with Section 4.1.4.5.

5.5.2.2 Connection Lateral Resistance

$$Q_s = Q_{s,l} = \begin{cases} \phi_w Q_{we,l} & \text{if } \phi_w Q_{we,l} < \phi_r Q_{ry,l} \text{ (Brittle mode)} \\ \phi_r Q_{ry,l} & \text{if } \phi_w Q_{wy,l} < \phi_r Q_{ry,l} \leq \phi_w Q_{we,l} \text{ (Mixed mode)} \\ \phi_w Q_{wy,l} & \text{if } \phi_r Q_{ry,l} \leq \phi_w Q_{wy,l} < \phi_r Q_{ru,l} \text{ (Mixed mode)} \\ \phi_r Q_{ru,l} & \text{if } \phi_r Q_{ru,l} < \phi_w Q_{wy,l} \text{ (Ductile mode)} \end{cases}$$

Check if $\Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$.

If so, then $Q_{s,l} = \Phi_w Q_{we,l}$ (brittle failure mode)

Rivet capacity corresponding to yielding parallel to grain, $\Phi_r Q_{ry,l}$

$\Phi_r Q_{ry,l} = \Phi_r Q_{ry,l}$ in which $f_{h,0}$ and $M_{r,l}$ equal to $f_{hy,0}$ and $M_{ry,l}$, respectively

$\Phi_r Q_{ry,l} = \Phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$

$\Phi_r = 0.8$

$k_1 = 1.14$ for load combination [0.9G, Wu]

$k_f = 1.0$ for edge grain of glulam

$n_p = 2$

$n_R = 6$

$n_C = 6$

Rivet failure – mode (a)

Determine $P_{rl,a}$ using Section 4.1.3.1(i):

$$P_{rl,a} = X_r \left[J_p f_{h,0} L_p d_l \left(\left(\sqrt{2 + \frac{4M_{r,l}}{f_{h,0} d_l L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$X_r = 0.93$ for LVL

$J_p = 1.0$

$f_{h,0} = f_{hy,0}$

$= 75.1 \rho (1 - 0.0037 d_l) 10^{-3}$ for LVL (Section 4.1.3.3)

$\rho = 620 \text{ kg/m}^3$ for grade 11 LVL

$d_l = 3.2 \text{ mm}$

$f_{hy,0} = 46.0 \text{ MPa}$

$t_p = 8 \text{ mm}$

$L_p = 53.8 \text{ mm}$

$M_{r,p} = M_{ry,p}$

$= 24,900 \text{ Nmm}$

$f_{ax} = 15.9 \rho d_p (1 - 0.0037 d_p) 10^{-3}$

$d_p = 6.4$

$f_{ax} = 61.6 \text{ N/mm}$

Calculate $P_{rl,a}$:

$P_{rl,a} = 4.22 \text{ N}$

Rivet failure – mode (b)

Determine $P_{rl,b}$ using Section 4.1.3.1(ii):

$$P_{rl,b} = X_r \left[2 J_p \sqrt{M_{r,l} f_{h,0} d_l} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$P_{rl,b} = 4.14 \text{ kN}$

Therefore, the rivet yield capacity parallel to grain,

$\Phi_r Q_{ry,l} = \Phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b})$

$\Phi_r Q_{ry,l} = 271.8$ (Rivet Yielding mode: b)

Wood capacity, parallel to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$

$\Phi_w Q_{we,l} = \Phi_w Q_{w,l}$ in which $t_{el,l}$ equals to $t_{el,e,l}$

$= \Phi_w n_p k_1 k_f \min(P_{w,lr}, P_{w,br}, P_{w,l})$

$\Phi_w = 0.7$

Wood failure – mode (a)**Determine $P_{w,h}$ using Section 4.1.4.1:**

$$P_{w,h} = X_t f_t A_{t,h} (1 + \lambda_1 + \lambda_2) 10^{-3}$$

$$X_t = 1.06 \text{ for LVL}$$

$$f_t = 30 \text{ MPa for grade 11 LVL}$$

$$A_{t,h} = t_{ef,l} w_c$$

$$t_{ef,l} = t_{ef,e,l} \text{ (Corresponding to rivet elastic deformation, Section 4.1.4.4)}$$

$$= 45.7 \text{ mm}$$

$$w_c = a_2 (n_R - 1) = 150 \text{ mm}$$

$$A_{t,h} = a_2 (n_R - 1) = 6855 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

where

$$\psi = \frac{G}{E}$$

$$G = 550 \text{ MPa for grade 11 LVL}$$

$$E = 11,000 \text{ MPa for grade 11 LVL}$$

$$\psi = 0.05$$

$$L_c = a_1 (n_C - 1) = 150 \text{ mm}$$

$$d_z = 89.3$$

$$H = 0$$

$$A_{s,b} = 45,000 \text{ mm}^2$$

$$\lambda_1 = 0.25 \psi L_c (1 - H) \left[\frac{A_{s,b}}{t_{ef,l} A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$\lambda_1 = 0.369$$

$$\lambda_2 = 0.25 \psi L_c (1 - F) \left[\frac{A_{s,l}}{w_c A_{t,h}} + \frac{0.4}{\psi L_c} \right]$$

$$F = 0.220$$

$$A_{s,l} = 27,419 \text{ mm}^2$$

$$\lambda_2 = 0.156$$

Calculate $P_{w,h}$:

$$P_{w,h} = 332.5 \text{ kN, mode (a)}$$

Wood failure – mode (b)**Determine $P_{w,b}$ using Section 4.1.4.2:**

$$P_{w,b} = (1 + \lambda_1 + \lambda_3) 10^{-3} \min = \begin{cases} X_s C_b f_s A_{s,b}, \text{ Mode (a)} \\ X_t f_t w_c d_z, \text{ Mode (c)} \end{cases}$$

$$X_s = 1.02 \text{ for LVL}$$

$$C_b = 0.42$$

$$f_s = 6.0 \text{ MPa for grade 11 LVL}$$

$$\lambda_3 = \frac{t_{ef,l} (1 - F) \left[\frac{5 \psi L_c A_{s,l} + t_{ef,l} w_c^2}{2.5 \psi L_c A_{s,b} + w_c t_{ef,l}^2} \right]}{w_c (1 - H)}$$

$$\lambda_3 = 0.422$$

Calculate $P_{w,b}$:

$$P_{w,b} = (1 + \lambda_1^{-1} + \lambda_3) 10^{-3} \min = \begin{cases} 115668, \text{ Mode (a)} \\ 425961, \text{ Mode (c)} \end{cases}$$

$$C_l = 0.33$$

Calculate $P_{w,l}$:

$$P_{w,l} = (1 + \lambda_2^{-1} + \lambda_3^{-1}) 10^{-3} \min = \begin{cases} 55375, \text{ Mode (a)} \\ 290652, \text{ Mode (b)} \end{cases}$$

$$P_{w,l} = 545.5 \text{ kN, mode (a)}$$

Therefore, the wood capacity, parallel to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,l}$:

$$\begin{aligned} \Phi_w Q_{we,l} &= \Phi_w n_p k_1 k_f \min (P_{w,br}, P_{w,b}, P_{w,l}) \\ &= 0.7 \times 2 \times 1.14 \times 1.0 \times \min (332.5, 395.2, 454.6) = 530.7 \text{ kN} \\ &\quad (\text{failure governed by bottom shear plane, mode (a)}) \end{aligned}$$

Wood failure mode (a) governs failure, therefore no recalculation is required (Section 4.1.4). The wood capacity involves all resisting planes.

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.103 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \Phi_w Q_{we,l}$ (brittle failure mode)

$$\text{If } \Phi_w Q_{we,l} < \Phi_r Q_{ry,l}$$

$$530.7 \geq 271.8 \quad (\text{unsatisfied})$$

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ry,l}$.

If so, then $Q_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

Wood capacity, parallel to grain, corresponding to rivet yielding mode, $\Phi_w Q_{wy,l}$

$$\Phi_w Q_{wy,l} = \Phi_w Q_{w,l} \text{ in which } t_{ef,l} \text{ equals to } t_{efy,l}$$

$$t_{ef,l} = t_{efy,l}$$

$$t_{efy,p} = J_p \sqrt{\frac{M_{ry,p}}{f_{hy,90} d_p} + \frac{L_p^2}{2}}, \text{ yielding mode (a)}$$

$$t_{ef,l} = 26.0 \text{ mm}$$

The recalculated wood capacity (by following the same design procedure as defined above):

$$\Phi_w Q_{wy,l} = 410.5 \text{ kN}$$

Note that if the yielding mode (a) governs failure, therefore no recalculation is required (Section 4.1.4).

Check that the contribution of the lateral shear planes is less than 30% of the total joint capacity:

$$(1 + \lambda_2^{-1} + \lambda_3^{-1})^{-1} < 0.3$$

$$0.2075 < 0.3$$

The connection does not need to be redesigned.

Check if $Q_{s,l} = \Phi_r Q_{ry,l}$ (brittle failure mode)

$$\text{If } \Phi_w Q_{wy,l} < \Phi_r Q_{ry,l}$$

$$410.5 \geq 271.8 \quad (\text{unsatisfied})$$

Thus, check if $\Phi_w Q_{wy,l} < \Phi_r Q_{ru,l}$. If so, then $Q_{s,l} = \Phi_w Q_{wy,l}$ (mixed failure mode)

Ultimate rivet capacity – parallel to grain, $\Phi_r Q_{ru,l}$

$$\phi_r Q_{ru,l} = \phi_r Q_{rl} \text{ in which } f_{h,0} \text{ and } M_{r,l} \text{ equal to } f_{hu,0} \text{ and } M_{ru,l}, \text{ respectively}$$

$$\begin{aligned} f_{h,0} &= f_{hu,0} \\ &= 90.4 \rho (1 - 0.0037 d_l) 10^{-3} \text{ for LVL (Section 4.1.3.3)} \\ &= 55.4 \text{ MPa} \end{aligned}$$

$$\begin{aligned} M_{r,l} &= M_{ru,l} \\ &= 30,000 \text{ Nmm} \end{aligned}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\begin{aligned} \phi_r Q_{ru,l} &= \phi_r k_1 k_f n_p n_R n_C \min(P_{rl,a}, P_{rl,b}) \\ &= 319.5 \text{ kN (Rivet failure mode: a)} \end{aligned}$$

Check if $Q_{s,l} = \phi_w Q_{wy,l}$ (mixed failure mode)

$$\text{If } \phi_w Q_{wy,l} \leq \phi_r Q_{ru,l}$$

$$410.5 > 319.5 \text{ (unsatisfied)}$$

Thus, $Q_{s,l} = \phi_r Q_{ru,l}$ (ductile failure mode)

$$Q_{s,l} = 319.5 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q_s$$

$$N^* = 205 \text{ kN}$$

$$Q_s = Q_{s,l}$$

$$Q_s = 319.5$$

$$205.0 < 319.5, \text{ ok (Joint mode of failure ductile)}$$

Joint Deflection – parallel to grain

The joint deflection must not exceed 2 mm

$$\delta_l \leq 2 \text{ mm}$$

$$\delta_l = 4 \left[1 - \sqrt{1 - \frac{N_l^*}{\phi_r Q_{ru,l}}} \right]$$

$$\delta_l = 4 \left[1 - \sqrt{1 - \frac{205}{319.5}} \right]$$

where

$$N_l^* = \text{ultimate design load parallel to grain, kN, for deflection under (ULS)}$$

$$\delta_l = 1.60 \text{ mm}$$

$$1.60 \leq 2 \text{ mm, OK}$$

Adopt 65 mm long rivets with an array of 6 rows by 6 columns, spacing 30 mm by 30 mm along and across the grain, and 150 mm end distance spaced at 200 mm on either side of the energy dissipaters (see Figure 5.18).

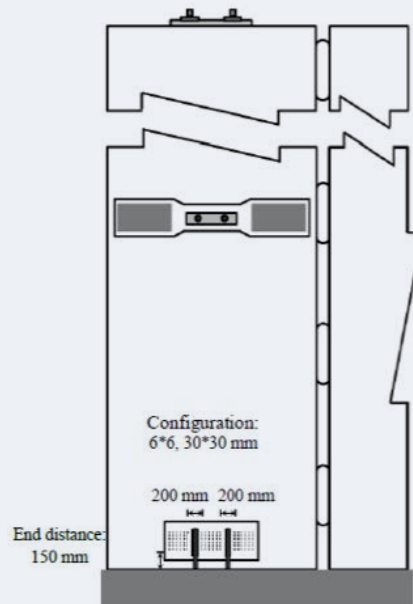


Figure 5.18: Connection configuration of the hold down connection.

5.5.3 Floor–Wall Connection

5.5.3.1 Connection geometry

Try 65 mm long rivets with the following configuration for each joint:

Side plate thickness: $t_p = 8$ mm

(The steel side plates need to be checked to have a cross-section adequate for resisting tension and compression forces).

$N^* = 1,200$ kN

Number of rows of rivets parallel to direction of load: $N_r = 8$

Number of rivets per row: $n_c = 30$ (as two 8*15 rivet joints either side of the connection)

Spacing along the grain: $a_1 = 30$ mm

Spacing across the grain: $a_2 = 30$ mm

Unloaded end distance on the left side: $a_{3C,L} = 3,450$ mm

Unloaded end distance on the right side: $a_{3C,R} = 3,450$ mm

Unloaded edge distance: $a_{4c} = 25$ mm

Loaded edge distance: $a_{4t} = 25$ mm

The two rivet groups are located along the load direction and are connected by the steel plate. There is possibility of splitting only at the unloaded edge of the steel plate. No splitting is possible between the two groups of rivets.

5.5.3.2 Connection lateral resistance

$$Q_s = Q_{s,p}$$

where

$$Q_{s,p} = \begin{cases} \phi_w Q_{we,p} & \text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p} \quad (\text{Brittle mode}) \\ \phi_r Q_{ry,p} & \text{if } \phi_w Q_{wy,p} < \phi_r Q_{ry,p} \leq \phi_w Q_{we,p} \quad (\text{Mixed mode}) \\ \phi_w Q_{wy,p} & \text{if } \phi_r Q_{ry,p} \leq \phi_w Q_{wy,p} < \phi_r Q_{ru,p} \quad (\text{Mixed mode}) \\ \phi_r Q_{ru,p} & \text{if } \phi_r Q_{ru,p} < \phi_w Q_{wy,p} \quad (\text{Ductile mode}) \end{cases}$$

$$\text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p}$$

$$\text{If so, then } Q_{s,p} = \phi_w Q_{we,p} \quad (\text{brittle failure mode})$$

Rivet capacity corresponding to yielding perpendicular to grain, $\phi_r Q_{ry,p}$

$$\phi_r Q_{ry,p} = \phi_r Q_{ry,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } h_{y,90} \text{ and } M_{ry,p}, \text{ respectively}$$

$$= \phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b})$$

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ Load duration factor in AS 1720.1 for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for LVL}$$

$$n_p = 2$$

$$n_R = 8$$

$$n_C = 30$$

Rivet failure – mode (a)

Determine $P_{rp,a}$ using Section 4.1.3.2(i):

$$P_{rp,a} = X_r \left[J_p f_{h,90} L_p d_p \left(\left(\sqrt{2 + \frac{4M_{r,p}}{f_{h,90} d_p L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.93 \text{ for LVL}$$

$$J_p = 1.0$$

$$f_{h,90} = f_{hy,90}$$

$$= 49.9 \rho (1 - 0.0037 d_p) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$d_p = 6.4 \text{ mm}$$

$$\rho = 620 \text{ kg/m}^3 \text{ for grade 11 LVL}$$

$$f_{hy,90} = 30.2 \text{ MPa}$$

$$L_p = 28.8 \text{ mm}$$

$$M_{r,p} = M_{ry,p}$$

$$= 12,450 \text{ Nmm}$$

$$f_{ax} = 15.9 \rho d_p (1 - 0.0037 d_p) 10^{-3}$$

$$f_{ax} = 61.6 \text{ N/mm}$$

Calculate $P_{rp,a}$:

$$P_{rp,a} = 4.89 \text{ kN}$$

5.5.3.2 Connection lateral resistance

$$Q_s = Q_{s,p}$$

where

$$Q_{s,p} = \begin{cases} \phi_w Q_{we,p} & \text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p} \text{ (Brittle mode)} \\ \phi_r Q_{ry,p} & \text{if } \phi_w Q_{wy,p} < \phi_r Q_{ry,p} \leq \phi_w Q_{we,p} \text{ (Mixed mode)} \\ \phi_w Q_{wy,p} & \text{if } \phi_r Q_{ry,p} \leq \phi_w Q_{wy,p} < \phi_r Q_{ru,p} \text{ (Mixed mode)} \\ \phi_r Q_{ru,p} & \text{if } \phi_r Q_{ru,p} < \phi_w Q_{wy,p} \text{ (Ductile mode)} \end{cases}$$

$$\text{if } \phi_w Q_{we,p} < \phi_r Q_{ry,p}$$

$$\text{If so, then } Q_{s,p} = \phi_w Q_{we,p} \text{ (brittle failure mode)}$$

Rivet capacity corresponding to yielding perpendicular to grain, $\phi_r Q_{ry,p}$

$$\phi_r Q_{ry,p} = \phi_r Q_{ry,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } h_{y,90} \text{ and } M_{ry,p}, \text{ respectively}$$

$$= \phi_r k_1 k_f n_p n_R n_C \min (P_{rp,a}, P_{rp,b})$$

$$\phi_r = 0.8$$

$$k_1 = 0.77 \text{ Load duration factor in AS 1720.1 for load combination [1.2G, 1.5Q]}$$

$$k_f = 1.0 \text{ for LVL}$$

$$n_p = 2$$

$$n_R = 8$$

$$n_C = 30$$

Rivet failure – mode (a)

Determine $P_{rp,a}$ using Section 4.1.3.2(i):

$$P_{rp,a} = X_r \left[J_p f_{h,90} L_p d_p \left(\left(\sqrt{2 + \frac{4M_{r,p}}{f_{h,90} d_p L_p^2}} \right) - 1 \right) + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$X_r = 0.93 \text{ for LVL}$$

$$J_p = 1.0$$

$$f_{h,90} = f_{hy,90}$$

$$= 49.9 \rho (1 - 0.0037 d_p) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$d_p = 6.4 \text{ mm}$$

$$\rho = 620 \text{ kg/m}^3 \text{ for grade 11 LVL}$$

$$f_{hy,90} = 30.2 \text{ MPa}$$

$$L_p = 28.8 \text{ mm}$$

$$M_{r,p} = M_{ry,p}$$

$$= 12,450 \text{ Nmm}$$

$$f_{ax} = 15.9 \rho d_p (1 - 0.0037 d_p) 10^{-3}$$

$$f_{ax} = 61.6 \text{ N/mm}$$

Calculate $P_{rp,a}$:

$$P_{rp,a} = 4.89 \text{ kN}$$

Rivet failure – mode (a)**Determine $P_{rp,b}$ using Section 4.1.3.2(ii):**

$$P_{rp,b} = X_r \left[2J_p \sqrt{M_{r,p} f_{h,90} d_p} + \frac{L_p f_{ax}}{5.33} \right] 10^{-3}$$

$$P_{rp,b} = 3.46 \text{ kN}$$

Rivet capacity corresponding to yielding perpendicular to grain, $\Phi_r Q_{ry,p}$

$$\begin{aligned} \Phi_r Q_{ry,p} &= \Phi_r k_1 k_f n_p n_R n_C \min(P_{rp,a}, P_{rp,b}) \\ &= 0.8 \times 0.77 \times 1.0 \times 2 \times 8 \times 30 \times \min(4.86, 3.46) \cdot 10^{-3} \\ &= 1024.2 \text{ kN (Yielding mode of failure: b)} \end{aligned}$$

Wood capacity, perpendicular to grain, corresponding to rivet elastic deformation, $\Phi_w Q_{we,p}$

$$\begin{aligned} \Phi_w Q_{we,p} &= \Phi_w Q_{w,p} \text{ in which } t_{ef,p} \text{ equals to } t_{efe,p} \\ &= \Phi_w k_1 g_{42} k_f n_p \min(P_{s,a}, P_{s,b}) \end{aligned}$$

$$\Phi_w = 0.7$$

$$g_{42} = 1$$

Determine characteristic full width splitting resistance, failure mode (b), $P_{s,a}$ using Section 4.1.5.1:

$$P_{s,a} = X_p \eta b C_{fp} \sqrt{\frac{h_e}{1 - \frac{h_e}{h}}} 10^{-3}$$

$$X_p = 1.23 \text{ for LVL}$$

$$\gamma = 2.7 \text{ for LVL}$$

$$h_e = h - a_{4c}$$

$$h_e = 1800 - 30 = 1770 \text{ mm}$$

$$w_{net} = a_1 (\eta_R - 1) - 6.4 \eta_R$$

$$w_{net} = 158.8 \text{ mm}$$

$$a_{3c,L} = 3450 \text{ mm}$$

$$a_{3c,R} = 3450 \text{ mm}$$

$$\eta = \frac{\min(\gamma h_e, a_{3c,L}) + (\gamma h_e, a_{3c,R}) + w_{net}}{2\gamma h_e}$$

$$\eta = 0.499$$

$$b = 270 \text{ mm}$$

$$C_{fp} = 16 \text{ N/mm}^{1.5} \text{ for LVL}$$

$$P_{s,a} = 863.2 \text{ kN}$$

Determine characteristic partial width splitting resistance, failure mode (b), $P_{s,b}$ using Section 4.1.5.2:

$$P_{s,b} = X_p C_{fp} f_{ef,p} [w_{net} + \min(\beta h_e, a_{3c,L}) + \min(\beta h_e, a_{3c,R})] 10^{-3}$$

$$\xi = \frac{a_{4c}}{a_2 (n_c - 1)}$$

$$n_{Cef} = n_c + \frac{L_{gap}}{a_2} - 1$$

(Just for defining the wood capacity)

$$L_{gap} = 900 \text{ mm}$$

$$n_{Cef} = 59$$

$$\zeta = 0.017$$

$$C_t = 5.678$$

$$f_{ip} = 1.45 \text{ MPa}$$

$$t_{ef,p} = t_{efe,p} \text{ (Corresponding to rivet elastic deformation, Section 4.1.5.4)}$$

$$= 40.3 \text{ mm}$$

$$B = 2.4 \text{ for LVL}$$

Calculate $P_{s,b}$:

$$P_{s,b} = 2879.7 \text{ kN}$$

Therefore, the wood capacity, perpendicular to grain, corresponding to rivet elastic deformation,

$\Phi_w Q_{we,p}$:

$$\Phi_w Q_{we,p} = \Phi_w k_1 k_f g_{42} n_p \min(P_{s,a}, P_{s,b})$$

$$= 0.7 \times 0.77 \times 1.0 \times 1.0 \times 2 \times \min(863.2, 2879.7)$$

$$= 930.5 \text{ kN (governing failure, splitting with crack width equal to member thickness, mode (a))}$$

Check if $Q_{s,p} = \Phi_w Q_{we,p}$ (brittle failure mode)

$$\text{If } \Phi_w Q_{we,p} < \Phi_r Q_{ry,p}$$

$$930.5 < 1024.2 \quad \text{OK}$$

$$Q_{s,p} = \Phi_w Q_{we,p}$$

$$= 930.5 \text{ kN}$$

Check joint ultimate lateral resistance:

$$N^* \leq Q$$

$$N^* = 900 \text{ kN}$$

$$Q_s = Q_{s,p}$$

$$= 930.5 \text{ kN}$$

$$900 \leq 930.5, \text{ OK (governing failure, splitting with crack width equal to member thickness, mode (a))}$$

Ultimate rivet capacity – perpendicular to grain, $\Phi_r Q_{ru,p}$

$$\Phi_r Q_{ru,p} = \Phi_r Q_{r,p} \text{ in which } f_{h,90} \text{ and } M_{r,p} \text{ equal to } f_{hu,90} \text{ and } M_{ru,p}, \text{ respectively}$$

$$f_{h,90} = f_{hu,90}$$

$$= 60.2 \rho (1 - 0.0037 d_p) 10^{-3} \text{ for LVL (Section 4.1.3.3)}$$

$$M_{r,p} = M_{ru,p}$$

$$= 15,000 \text{ Nmm}$$

The recalculated rivet ultimate capacity (by following the same design procedure as defined above):

$$\Phi_r Q_{ru,p} = 1199.5 \text{ kN (Rivet failure mode: b)}$$

Joint deflection – perpendicular to grain

The joint deflection must not exceed 3 mm

$$\delta_p \leq 3 \text{ mm}$$

$$\delta_p = 5.5 \left[1 - \sqrt{1 - 0.99 \frac{N_p^*}{\Phi_r Q_{ru,p}}} \right]$$

$$\delta_p = 5.5 \left[1 - \sqrt{1 - 0.99 \frac{900}{1199.5}} \right]$$

$$\delta_p = 2.71 \leq 3 \text{ mm, OK}$$

Adopt 65 mm long rivets with an array of 8 rows by 15 columns, spacing 30 mm by 30 mm along and across the grain, the two arrays will be spaced 900 mm apart with 30 mm loaded and unloaded edge distances, 3450 mm end distances on to the left and right side (see Figure 5.19).

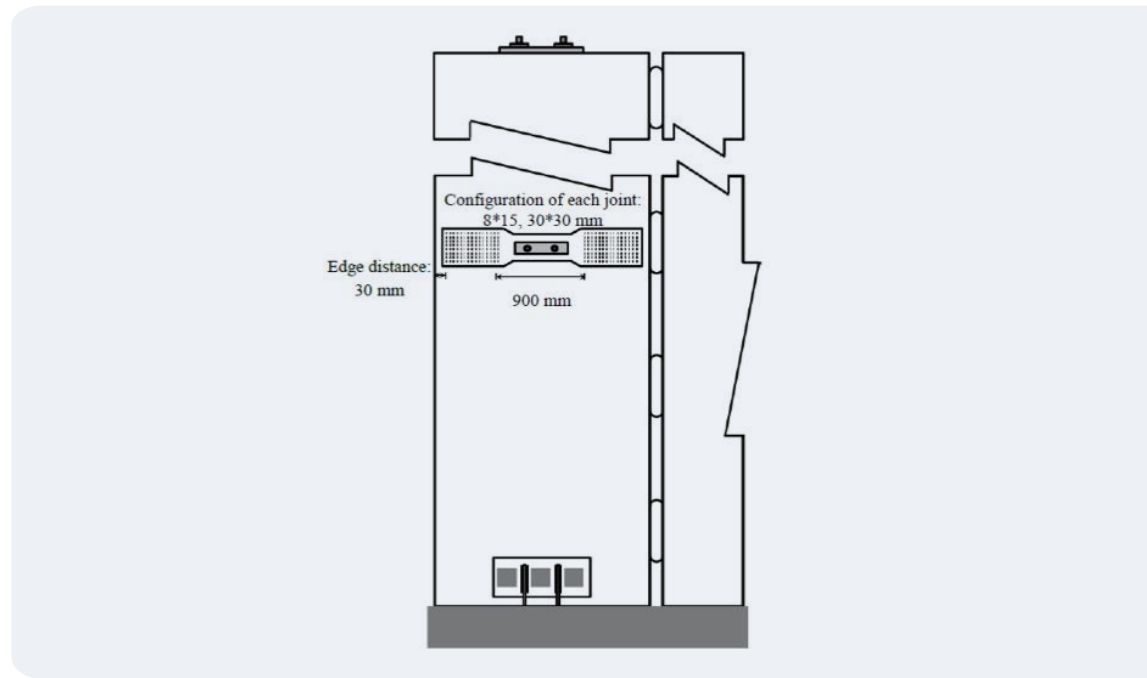


Figure 5.19: Connection configuration of the floor–wall connection.

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A

Appendix A - Case Studies, Reference Capacity Tables, Adjustment Factors

A1 Case Studies

A1.1 Carterton Event Centre

Timber rivets were used for the first time in New Zealand in 2011, in the timber truss connections of the Carterton Event Centre (Figure 1.4). The trusses were constructed using LVL members supplied by Juken New Zealand Ltd. The auditorium trusses in the building were up to 24.6m long and 4.8m high, so each was delivered to the site in two pieces. The riveted connection used easily managed components that allowed the required mid-span splice connection to be completed without specialist lift equipment.

Use of the rivets allowed the fabricator, McIntosh Timber Laminates, to save more than \$30,000 on this project when compared to the detailed bolted connection option. The rivets also allowed for adjustments on-site that would not have been possible with bolted fastenings. The timber rivets were found very user friendly; both in the work shop and onsite, with significantly less visual impact and material cost compared to the conventional fasteners.

A1.2 Trimble Building in Christchurch

In another project by TimberLab Solutions Ltd. (formerly McIntosh Timber Laminates Ltd.), the use of rivets in the connections of the structure and energy dissipating system of the building (Figure 1.5) demonstrates the advantages of this timber fastener.

The Trimble building in south-west Christchurch was damaged by the September 2010 and February 2011 earthquakes. The new building was a design-build project, which was undertaken originally by Mainzeal and Opus, commencing in February 2012.

The building holds more than 6,000 m² of office space over two levels and utilises LVL Post tension frames in one direction and post tension walls in the other to resist seismic loads (Refer to WoodSolutions Design Guide for information of post tension timber beams and walls). The LVL for this building was supplied by Carter Hold Harvey Ltd.

The principal structural engineer from Opus and the structural design team leader for the Trimble project found that the compact timber rivets provided high strength and stiff connections to take significant seismic loads.

Table A2.1: Reference design capacity (kN) for a double-sided joint, loaded parallel to grain, using Radiata Pine LVL grade 11 (spacing $a_1=25$ mm; $a_2=25$ mm).

Rivet Length, L_r (mm)	Member Thickness, b (mm)	Rivets per a row n_c	Number of rows n_R				
			6	8	10	12	14
40	90	6	199	265	331	397	464
		8	264	353	441	530	618
		10	241	327	415	504	593
		12	206	278	351	426	501
		14	186	249	314	380	447
	135	6	199	265	331	397	464
		8	234	321	409	497	586
		10	256	350	444	540	636
		12	267	362	460	559	658
		14	283	384	487	591	695
65	135	6	278	371	464	557	650
		8	316	482	543	659	775
		10	363	482	607	733	861
		12	408	533	665	800	957
		14	462	593	735	881	1029
	180	6	278	371	464	557	650
		8	347	471	597	725	854
		10	397	534	675	817	961
		12	469	619	775	935	1096
		14	533	694	864	1040	1217
90	180	6	253	337	428	521	625
		8	337	449	562	674	786
		10	421	562	702	842	983
		12	505	657	816	980	1147
		14	590	708	870	1039	1212
	225	6	253	337	428	521	615
		8	337	449	562	674	786
		10	421	449	562	674	786
		12	505	674	842	1011	1179
		14	590	780	963	1153	1146

Notes:

- (1) Member depth is assumed to be two times the joint depth, $h = 2 \times a_2(n_R - 1)$.
- (2) The joint is located at the centre of the member.
- (3) End distance is considered based on minimum requirements.
- (4) The value of k_1 , k_{12} and k_t factors are assumed to be equal to one.
- (5) Steel plate is considered to be 10 mm thick.
- (6) Ultimate design capacity of 40, 65 and 90 mm long rivets under ductile failure is calculated as 2.76, 3.87 and 4.09 kN per rivet, respectively.

Table A1.2: Reference design capacity (kN) for a double-sided joint, loaded parallel to grain, using Radiata Pine glulam GL8 (spacing $a_1=25$ mm; $a_2=25$ mm).

Rivet Length, L_r (mm)	Member Thickness, b (mm)	Rivets per a row n_c	Number of rows n_R				
			6	8	10	12	14
40	90	6	85	116	148	180	212
		8	96	130	165	201	236
		10	81	109	138	167	197
		12	71	95	120	145	170
		14	75	90	109	132	155
	135	6	97	134	171	208	245
		8	128	175	222	270	318
		10	136	185	235	285	336
		12	129	175	221	269	316
		14	121	163	206	250	294
65	135	6	117	160	203	247	291
		8	131	176	222	268	315
		10	147	193	241	291	341
		12	169	218	270	324	378
		14	160	203	249	297	347
	180	6	126	172	220	267	314
		8	146	196	248	300	353
		10	167	221	278	336	394
		12	198	259	323	389	455
		14	226	291	361	433	506
90	180	6	156	213	271	329	387
		8	170	226	285	344	404
		10	184	240	300	360	422
		12	205	261	322	385	449
		14	231	286	349	414	481
	225	6	163	222			
		8	180	240			
		10	197				
		12	224				
		14	255				

Notes:

- (1) Member depth is assumed to be two times the joint depth, $h = 2 \times a_2(n_R - 1)$.
- (2) The joint is located at the centre of the member.
- (3) End distance is considered based on minimum requirements.
- (4) The value of k_1 , k_{12} and k_2 factors are assumed to be equal to one.
- (5) Steel plate is considered to be 10 mm thick.
- (6) Ultimate design capacity of 40, 65 and 90 mm long rivets under ductile failure is calculated as 2.08, 2.62 and 2.98 kN per rivet, respectively.

Table A1.3: Reference design capacity (kN) for a double-sided joint, loaded perpendicular to grain, of Radiata Pine LVL grade 11 (spacing $a_1=25$ mm; $a_2=25$ mm).

Rivet Length, L_r (mm)	Member Thickness, b (mm)	Rivets per a row n_c	Number of rows n_R				
			6	8	10	12	14
40	90	6	24	26	29	31	33
		8	30	32	33	34	36
		10	33	34	36	37	
		12	36	37	39	40	41
		14	39	40	41	42	43
	135	6	24	26	29	31	33
		8	32	34	36	39	41
		10	39	41	44	46	48
		12	47	49	51	54	56
		14	54	56	59	61	63
65	135	6	40	42	45	47	50
		8	45	47	49	52	54
		10	50	52	54	56	58
		12	54	56	58	59	61
		14	58	60	62	63	65
	180	6	41	45	49	53	57
		8	54	58	62	66	70
		10	67	69	72	74	77
		12	72	75	77	79	82
		14	78	80	82	84	86
90	180	6	53	57	60	63	67
		8	60	63	66	69	72
		10	67	69	72	74	77
		12	72	75	77	79	82
		14	78	80	82	84	86
	225	6	53	58	63	65	73
		8	69	74	80	85	90
		10	83	86	90	93	96
		12	91	93	96	99	102
		14	97	100	103	105	108

Notes:

- (1) Member depth is assumed to be two times the joint depth, $h = 2 \times a_2(n_c - 1)$.
- (2) The joint is located at the centre of the member.
- (3) End distances on the left and right sides of the joint are assumed to be large enough that they do not affect the joint wood capacity.
- (4) The value of k_1 , g_{42} and k_f factors are assumed to be equal to one.
- (5) Steel plate is considered to be 10 mm thick.
- (6) Ultimate design capacity of 40, 65 and 90 mm long rivets under ductile failure is calculated as 2.72, 3.23 and 3.44 kN per rivet, respectively.

Table A1.4: Reference design capacity (kN) for a double-sided joint, loaded perpendicular to grain, using Radiata Pine glulam GL8 (spacing $a_1=25$ mm; $a_2=25$ mm)

Rivet Length, L_r (mm)	Member Thickness, b (mm)	Rivets per a row n_c	Number of rows n_R				
			6	8	10	12	14
40	90	6	15	17	19	21	23
		8	20	22	23	25	27
		10	24	26	28	29	30
		12	27	28	29	31	32
		14	29	30	31	32	33
	135	6	15	17	19	21	23
		8	20	22	23	25	27
		10	24	26	28	30	32
		12	28	30	32	34	36
		14	32	34	36	38	40
65	135	6	6	29	33	36	40
		8	33	37	39	41	43
		10	38	40	42	44	46
		12	41	42	44	46	48
		14	43	45	47	48	50
	180	6	26	29	33	36	40
		8	33	37	40	43	47
		10	41	44	47	51	54
		12	48	51	55	58	61
		14	55	59	62	65	67
90	180	6	34	38	42	47	51
		8	43	47	52	55	58
		10	50	53	55	58	61
		12	54	57	59	61	64
		14	58	60	62	65	67
	225	6	34	38	42	47	51
		8	43	47	52	56	60
		10	52	57	61	65	70
		12	62	66	70	75	79
		14	71	75	78	81	84

Notes:

- (1) Member depth is assumed to be two times the joint depth, $h = 2 \times a^2(n_c - 1)$.
- (2) The joint is located at the centre of the member.
- (3) End distances on the left and right sides of the joint are assumed to be large enough that they do not affect the joint wood capacity.
- (4) The value of k_1 , g_{42} and k_f factors are assumed to be equal to one.
- (5) Steel plate is considered to be 10 mm thick.
- (6) Ultimate design capacity of 40, 65 and 90 mm long rivets under ductile failure is calculated as 1.62, 2.16 and 2.27 kN per rivet, respectively.

A3 Adjustment Factors

A3.1 Adjustment Factor for Tension Parallel to Grain

X_t = adjustment factor for tension parallel to grain

$$= \left(\frac{f_{t,m}}{f_{t,k}} \right) \left(\frac{Q_{wk,l}}{Q_{wm,l}} \right) = \left(\frac{1 - 1.645 COV_{w,l}}{1 - 1.645 COV_t} \right)$$

= 1.06 for LVL

= 1.19 for glulam

= 1.29 for sawn timber

where

COV_t = coefficients of variation for the conducted tensile strength material property tests, parallel to grain

= 0.12 for LVL

= 0.24 for glulam

= 0.30 for lumber (estimated by adding half the difference between LVL and glulam)

$COV_{w,l}$ = maximum coefficients of variation for the conducted connection wood strength tests, parallel to grain

= 0.09 for LVL

= 0.17 for glulam

= 0.21 for lumber (estimated by adding half the difference between LVL and glulam)

m and k indices stand for the mean and characteristic values, respectively.

A3.2 Adjustment Factor for Longitudinal Shear

X_s = adjustment factor for longitudinal shear

$$X_s = \left(\frac{f_{s,m}}{f_{s,k}} \right) \left(\frac{Q_{wk,l}}{Q_{wm,l}} \right) = \left(\frac{1 - 1.645 COV_{w,l}}{1 - 1.645 COV_{sl}} \right)$$

= 1.02 for LVL

= 0.96 for glulam

= 0.93 for lumber

where

COV_s = coefficients of variation for the conducted longitudinal shear strength material property tests

= 0.10 for LVL

= 0.15 for glulam

= 0.18 for lumber (estimated by adding half the difference between LVL and glulam)

A3.3 Adjustment Factor for Tension Perpendicular to Grain

X_p = adjustment factor for tension perpendicular to grain

$$X_p = \left(\frac{f_{tp,m}}{f_{tp,k}} \right) \left(\frac{Q_{wk,p}}{Q_{wm,p}} \right) = \left(\frac{1 - 1.645 COV_{w,p}}{1 - 1.645 COV_{tp}} \right)$$

= 1.23 for LVL

= 1.28 for glulam

= 1.31 for lumber

where

COV_{tp} = coefficients of variation for the conducted tensile strength material property tests, perpendicular to grain

= 0.18 for LVL

= 0.25 for glulam

= 0.29 for lumber (estimated by adding half the difference between LVL and Glulam)

where

$COV_{w,p}$ = maximum coefficients of variation for the conducted connection wood strength tests, perpendicular to grain

= 0.08 for LVL

= 0.15 for glulam

= 0.19 for lumber (estimated by adding half the difference between LVL and glulam)

A3.4 Adjustment Factor for Rivet Characteristic Resistance

$X_r = 1 - 1.645COV_r$

= 0.93 for LVL

= 0.87 for glulam

= 0.84 for lumber

where

COV_r = maximum coefficients of variation for the conducted connection rivet strength tests

= 0.04 for LVL

= 0.08 for glulam

= 0.10 for lumber (estimated by adding half the difference between LVL and glulam)

A3.5 Adjustment Factor for Characteristic Withdrawal resistance

$X_{ax} = 1 - 1.645COV_{ax}$

= 0.84 for LVL

= 0.61 for glulam

= 0.49 for lumber

where

COV_{ax} = coefficients of variation for the conducted rivet withdrawal strength tests

= 0.10 for LVL

= 0.24 for glulam

= 0.31 for lumber (estimated by adding half the difference between LVL and glulam).

B

Appendix B - Notation

The symbols and letters used in this Design Guide are listed below:

A_{tb}	effective tensile area of bottom wood block
A_{th}	area of head plane subjected to tensile stress
A_{tl}	effective tensile area of lateral wood blocks
$A_{t,b}$	area of head plane subjected to tensile stress
$A_{s,l}$	areas of side lateral planes subjected to shear stress
A_{sb}	area of bottom plane subjected to shear stress
A_{sl}	area of lateral planes subjected to shear stress
a	unloaded edge distance
a_1	minimum parallel-to-grain rivet spacing
a_2	minimum perpendicular-to-grain rivet spacing
a_{3t}	loaded rivet end distance for parallel-to-grain loading
a_{3c}	unloaded rivet end distances
a_{4t}	loaded rivet edge distance
a_{4c}	unloaded rivet edge distance
b	timber thickness
C_{tp}	fracture parameter
C_t	coefficient depending on unloaded edge distance and joint length
C_l	factor accounting for embedding and withdrawal interaction effect
COV_{tp}	coefficients of variation for the conducted tensile strength material property tests – perpendicular to grain
COV_r	maximum coefficients of variation for the conducted connection rivet strength tests
COV_{ax}	coefficients of variation for the conducted rivet withdrawal strength tests
d_l	rivet cross-section dimension bearing on the wood – parallel to grain
d_p	rivet cross-section dimension bearing on the wood – perpendicular to grain
d_z	bottom distance
E	modulus of elasticity – parallel to grain
f_{ax}	withdrawal resistance per millimetre of penetration
f_h	wood embedment strength
$f_{h,u}$	wood ultimate embedment strength
$f_{h,y}$	wood yielding embedment strength
$f_{h,0}$	wood embedment strength – perpendicular to grain
$f_{h,90}$	wood embedment strength – perpendicular to grain
f_s	member characteristic longitudinal shear strength
f_t	wood mean strength in tension – parallel to grain
f_{tp}	wood mean strength in tension – perpendicular to grain
g_{42}	modification factor for interaction effect on a grid system specified in AS 1720.1
G	modulus of rigidity – parallel to grain

h	member depth
h_e	effective member depth
J_p	side plate factor
k_f	modification factor for joint position effect
k_1	duration of load, (timber) specified in AS 1720.1
k_4	moisture condition, (timber) specified in AS 1720.1
k_6	temperature (timber) specified in AS 1720.1
k_{12}	stability factor, (timber) specified in AS 1720.1
L_p	rivet penetration depth
L_r	rivet length
M_r	moment capacity of rivet
$M_{r,l}$	moment capacity of rivets – parallel to grain
$M_{r,p}$	moment capacity of rivets – perpendicular to grain
$M_{r,u}$	ultimate moment capacity of rivet
$M_{r,y}$	yielding moment capacity of rivet
N	applied load
N^*_1	serviceability design load, parallel to grain, for deflection under (SLS)
n_p	number of plates
n_C	number of rivet columns
n_R	number of rivet rows parallel to direction of the load
P	applied load
P_{ax}	characteristic withdrawal resistance
P_r	fastener capacity
$P_{r,y/d}$	yield capacity of fastener
$P_{r,ult}$	ultimate capacities of fastener
$P_{s,a}$	characteristic resistance for full width splitting – mode (a)
$P_{s,b}$	characteristic resistance for partial width splitting
P_w	load-carrying capacity of wood
$P_{w,b}$	maximum load causing failure on bottom plane
$P_{w,h}$	maximum load causing failure on head plane
$P_{w,l}$	maximum load causing failure on lateral planes
$P_{rl,a}$	characteristic strength, parallel to grain, for rivet failure mode (a)
$P_{rl,b}$	characteristic strength, parallel to grain, for rivet failure mode (b)
$P_{w,tel,e}$	load-carrying capacities of wood corresponding to tef,e
$P_{w,tel,y}$	load-carrying capacities of wood corresponding to tef,y
$P_{rp,a}$	characteristic strength, perpendicular to grain, for rivet failure mode (a)
$P_{rp,b}$	characteristic strength, perpendicular to grain, for rivet failure mode (b)
$P_{c,ult}$	connection ultimate resistance
Q_s	joint design lateral resistance
$Q_{we,l}$	design wood block tear-out resistance, parallel to grain, corresponding to rivet elastic deformation
$Q_{ry,l}$	design rivet yielding resistance – parallel to grain

$Q_{wy,l}$	design wood block tear-out resistance, parallel to grain, corresponding to rivet yielding mode
$Q_{ru,l}$	design rivet ultimate resistance – parallel to grain
$Q_{re,l}$	design rivet resistance corresponding to the rivet elastic deformation – parallel to grain
$Q_{ru,l}$	design rivet resistance corresponding to the rivet ultimate deformation – parallel to grain
$Q_{we,p}$	design wood block tear-out resistance, perpendicular to grain, corresponding to rivet elastic deformation
$Q_{ry,p}$	design rivet yielding resistance – perpendicular to grain
$Q_{wy,p}$	design wood block tear-out resistance, perpendicular to grain, corresponding to rivet yielding mode
$Q_{ru,p}$	design rivet ultimate resistance – perpendicular to grain
$Q_{re,p}$	design rivet resistance corresponding to the rivet elastic deformation – perpendicular to grain
$Q_{ru,p}$	design rivet resistance corresponding to the rivet ultimate deformation – perpendicular to grain
N^*	design force
t_{ef}	wood effective thickness
$t_{ef,e}$	wood effective thickness for brittle failure mode
$t_{ef,l}$	effective wood thickness – parallel to grain
$t_{ef,y}$	wood effective thickness for mixed failure mode
t_p	side plate thickness
w_{net}	net section of joint width
X_r	adjustment factor for characteristic resistance
X_t	adjustment factor for tension strength – parallel to grain
X_p	adjustment factor for tension – perpendicular to grain
X_s	adjustment factor for longitudinal shear
X_{ax}	adjustment factor for characteristic withdrawal resistance
β	effective crack length coefficient for partial width splitting
γ	effective crack length coefficient for full width splitting
δ	deflection of the joint due to rivet slip
ϕ	capacity factor
ϕ_w	capacity factor of wood
ϕ_r	capacity factor of rivet
ζ	factor depending on unloaded edge distance and joint
θ	angle
ρ	wood design density at 12% moisture content



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