Red Stag CLT Design Guide

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Red Stag CLT Design Guide V1.1

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Document Disclaimer

The Red Stag CLT Design Guide is intended to provide an overview of the structural design principles associated with a simple CLT building, which may include Red Stag CLT floor, wall, and roof panels. A series of indicative span tables for Red Stag CLT has been provided in the guide to support consulting engineers with an indication of CLT panel sizes for various applications.

Currently there is no New Zealand or internationally structural code covering the design of the CLT. As such, it is necessary for consulting engineers to design and certify the design as part of a performance solution.

It is responsibility of Red Stag CLT users to ensure that this CLT Design Guide is appropriate and exercise their own professional judgment when using the Red Stag documents. Full responsibility for design and compliance with the New Zealand Building Code (NZBC) and all relevant New Zealand standards, rests with the design professional specifying the product. Red Stag will not accept any liability for the failure of the any other elements of the building which cause a subsequent failure of a Red Stag CLT products.

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Section 1

Cross Laminated Timber Overview & Introduction

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1. Factory Overview

Red Stag Wood Solutions Limited (Red Stag) is a speciality Engineered Wood Product (EWP) manufacturer focusing on the integration of timber solutions into traditional, mid and high-rise construction. Red Stag is focused on developing new products and solutions to enhance productivity, cost effectiveness and the environmental impact associated with the construction sector. *Figure 1* shows the Red Stag EWP site in Rotorua.

Figure 1: Red Stag's primary EWP site in Rotorua.

Red Stag is the legal entity within the Red Stag Group focusing on structural EWP, including but not limited to Cross Laminated Timber (CLT), Glue Laminated Timber (GLT), Frame and Truss (F&T), advanced stick panelisation and cassette systems. Red Stag has constructed the first phase of New Zealand's largest and most advanced CLT plant. The scale facility has the ability to manufacture panels up to 16.5 x 4.5 x 0.42 m (Length × Width × Depth). *Figure 2* shows panoramic views of the Red Stag EWP manufacturing process in Rotorua.

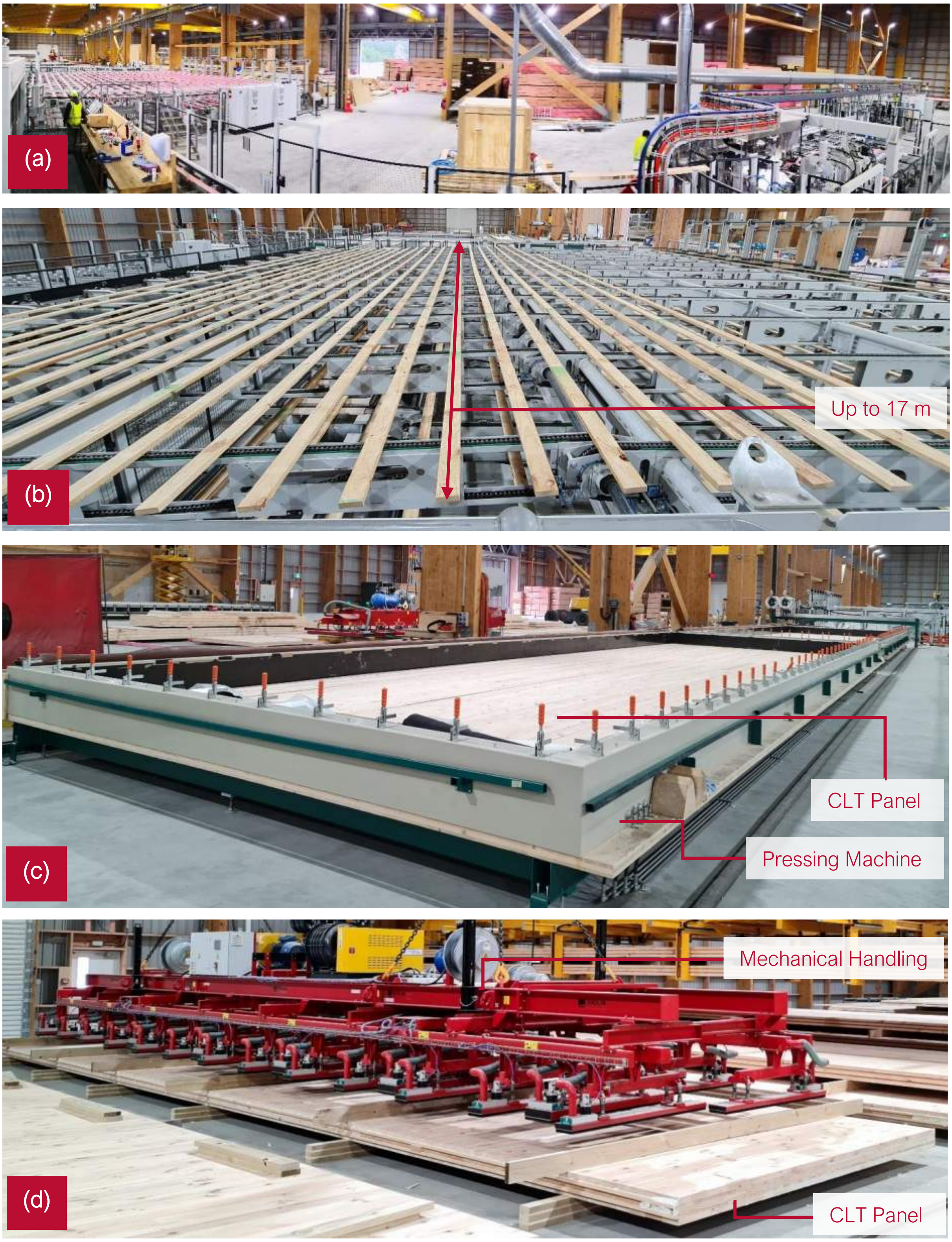

Figure 2: Red Stag's EWP manufacturing facility a) panoramic view of the Red Stag remanufacturing line; (b) 16.5 meter lamella out of the Finger Jointing (FJ) line; (c & d) CLT laminating equipment.

CLT is fundamentally changing the way buildings are designed, manufactured, and constructed. Red Stag's investment and innovation will help CLT to become the backbone for future generations of high performance, low carbon construction, in traditional, mid and high-rise buildings.

New Zealand and the Pacific regions are in the early stages of a CLT construction boom, driven by increasing demand and expanded building code acceptance of mass timber structures. CLT allows developers, designers, and builders to move beyond traditional construction trade-offs to create buildings that are sophisticated, efficient, rapidly assembled, structurally sound, affordable, and aesthetically stunning. As access to high-quality CLT continues to expand in New Zealand, Red Stag is confident that it will become the material of choice across a broad range of market sectors, building types, and geographies.

2. Red Stag's CLT Research & Testing

Red Stag's goal is to develop the most advanced mass timber building systems in New Zealand, making them more widely available, more efficiently produced, compliant to New Zealand standards (including treatment), more cost-effective and of higher quality than ever before (Refer to *Figure 3*).

CLT is much more than simply a structural building material. It is an opportunity to evolve building design and construction, making it easier to create buildings that are elegantly designed, efficiently built, and environmentally responsible, all while providing increased investment returns. To achieve these lofty goals, Red Stag has taken an integrated approach and applied technology to every step in the process. Red Stag is establishing end-to-end mass timber expertise and making unprecedented investment in CLT Research & Development (R&D), testing, manufacturing, design, engineering, and construction. With this level of control and innovation, Red Stag can provide its partners with the most advanced building systems currently available.

Figure 3: Red Stag's CLT Research Projects (Scion, Crown Research Institute focusing on wood products and materials).

Red Stag CLT is a building material that offers a unique combination of efficiency, strength, safety, aesthetics, and environmental benefits to deliver value across the entire construction ecosystem.

2.1. For Developers

The efficiency and accuracy of digital design, combined with Computer Numerical Control (CNC) machined EWP significantly reduces:

- Construction time (reduced holding costs and labour hours).
- On site construction and processing.
- Site nose, dust, and debris.
- Site waste.
- Site health and safety incidents (reduced labour units required on site, reduced hazards, reduced construction time).

2.2. For Owners/Operators

The superior aesthetics and operational efficiencies of mass timber buildings present unique opportunities for design differentiation, high occupancy demand, and long-term asset value growth. The option for exposed CLT generates a robust, aesthetically pleasing substrate that has significantly lower maintenance issues compared to plaster board. Timber buildings have proven to generate higher sales and lease rates compared to traditional construction materials due to the physiological and psychological benefits that exposed timber provides occupants.

2.3. For Architects & Engineers

Red Stag's CLT inherent structural, aesthetic, and biophilic characteristics offer unique design possibilities that blend form, function, user experience, and sustainability. Combining CLT and GLT with large scale five-axis CNC'ing allows for the most complex, advanced designs, and associated Building Information Modelling (BIM) to be seamlessly converted from concepts on paper or screen into reality.

2.4. For Builders

As a prefabricated material, Red Stag CLT moves labour upstream and offsite, reduces site waste and logistics, significantly speeds up site build times, reduces site noise and debris, improves safety (reduced labour units, less time at height, less processing on-site), reduces the impact of weather, and generally mitigates many of the other risks associated with traditional construction on site.

2.5. For Tenants & Citizens

Mass timber buildings are at the forefront of healthy and dynamic communities, providing physiological and psychological benefits to the people who live and work in them, and reducing the environmental impact of construction. The health benefits [1],[20] include, but are not limited to:

- Reduced blood pressure.
- Reduced stress levels.
- Improved attention and focus.
- Greater creativity.
- Faster recovery.
- Reduced pain perception.

3. Environmental & Sustainability

The recent Emissions Gap Report 2020 from the UN Environment Programme (UNEP) found that buildings generate nearly 40 percent of the global annual Carbon Dioxide (CO_2) emissions [2]. Of those total emissions, building materials and construction generates 11 percent of the world's CO_2 emissions annually from embodied carbon emissions, or 'upfront' carbon that is associated with materials and construction processes throughout the whole building lifecycle [3].

Two of the most conventional building materials, concrete and steel, are among the most carbon-intensive to produce, therefore contribute to the majority of the construction sector's CO_2 emissions. Switching to lower carbon footprint alternatives such as CLT can significantly reduce a building's negative environmental impact. Steel and concrete are each responsible for between 5 – 8 percent of global CO_2 emissions, the most significant greenhouse gas causing global warming [4].

In contrast to concrete and steel, CLT is a renewable material that sequesters carbon during its life cycle. CLT is a lighter, stronger, more sustainable alternative to concrete and steel structures. The environmental and sustainability advantages of building with CLT compared with concrete and steel are derived from the inherent qualities of wood as a carbon-capturing material, reduced transportation costs (lighter and less loads as compared to traditional materials), and expedited construction time to further reduce the net CO_2 for associated builds (Refer to *Figure 4*).

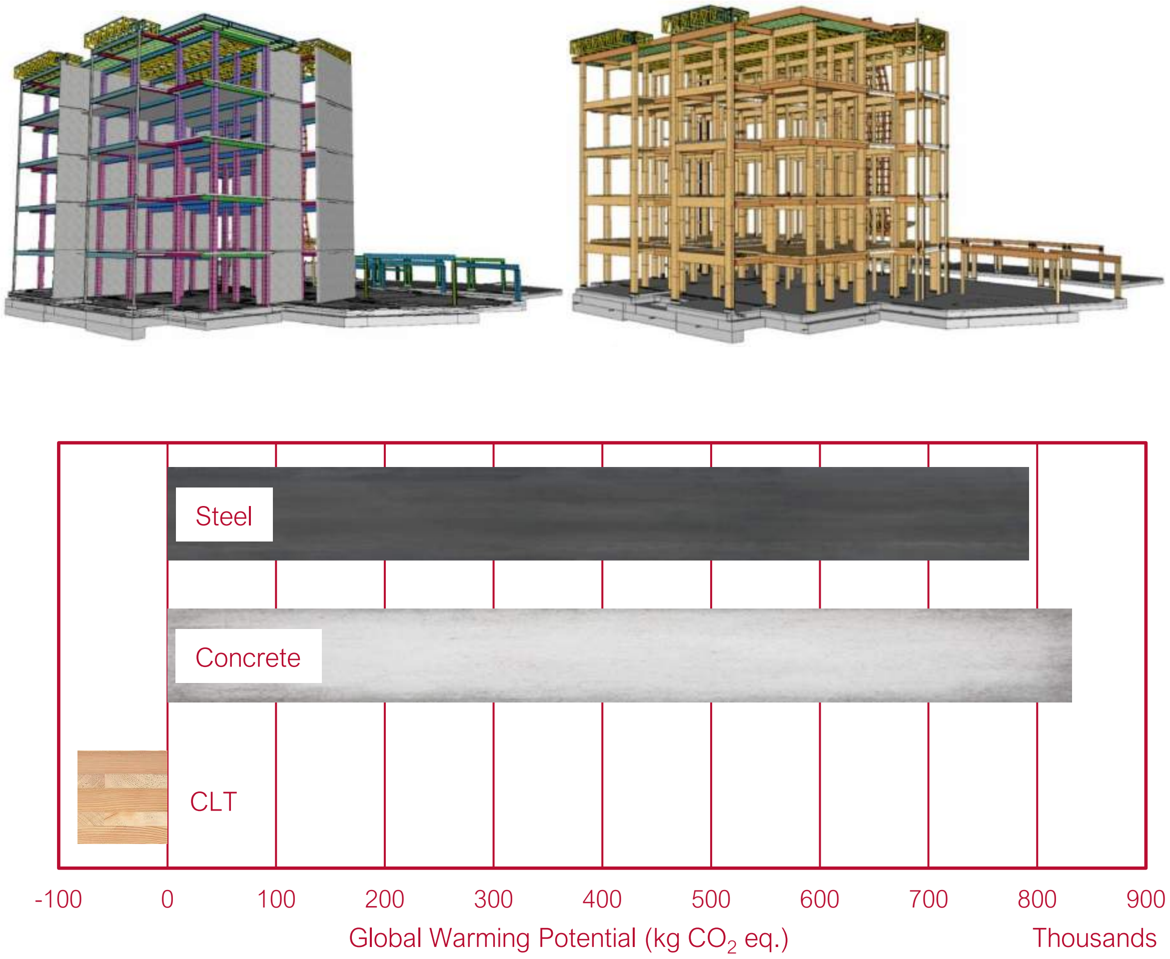

Figure 4: Embodied Carbon of Timber Building Versus Concrete and Steel Building.

3.1. Environmental Advantage of CLT versus Plywood and LVL

Other EWP such as plywood and LVL utilise approximately 10 percent adhesive (glue), often urea-formaldehyde, which can produce hazardous chemicals during recycling or incineration [5]. In contrast, CLT has less than one percent adhesive, and typically uses a bio-based polyurethane. For CLT, the lamella or boards are bonded together with a comparatively smaller amount of adhesive due to the supporting chemical reaction between the natural moisture in the timber and pressure.

4. Cross Laminated Timber

CLT is a high-performance mass timber product that comprises treated, graded boards, which are glued together in a cross-layered manner, where each layer is orientated 90 degrees to each other. Red Stag CLT is manufactured from New Zealand renewable Forest Stewardship Council (FSC) [6] certified forestry, typically in three to eleven layers, with a total thickness ranging from approximately 126 mm to 420 mm depending on the structural requirements (Refer to *Figure 5* - *Figure 7*).

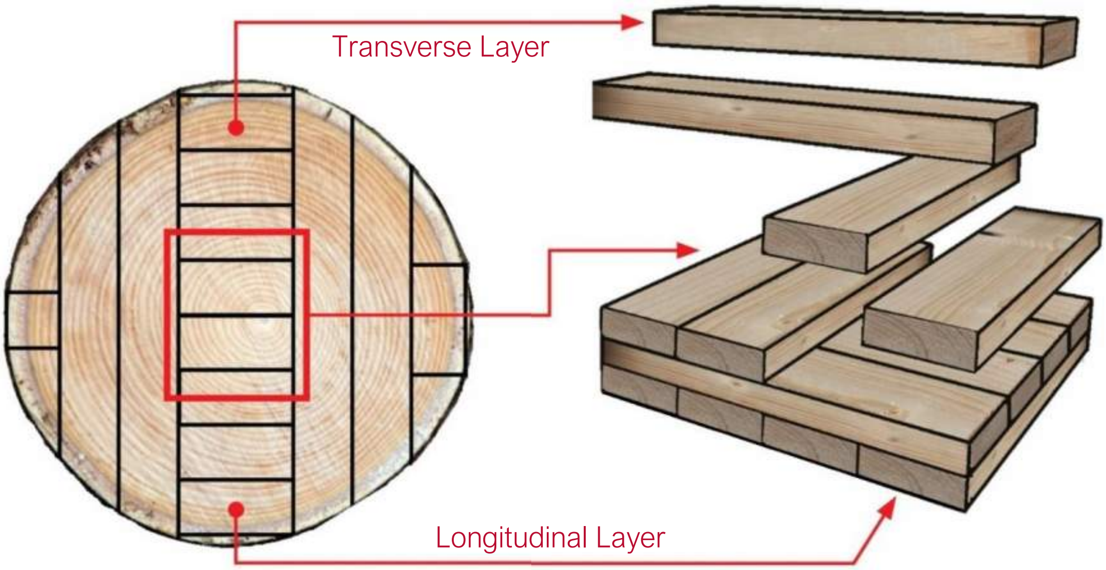

Figure 5: Sawn Log.

Figure 6: Arranging Boards.

4.1. Characteristics

CLT panels gain most of their stiffness from the outer structural layers (defined as longitudinal laminates regardless of length). Transverse laminates help to bind the structural layers, but do not require the same structural properties. Red Stag manufactures panels using specified layer properties, defining the Modulus of Elasticity (MoE in GPa) to align with the performance criteria of the panel (Refer to *Table 1*). Red Stag panels are glued together using Polyurethane Reactive (PUR) adhesive.

The benefits of CLT include design flexibility, rapid installation, reduced mass loading and foundation requirements, exceptionally structural properties, outstanding seismic performance, and a very good fire rating. CLT is a highly cost-effective material compared to concrete and steel and a significant sequester of carbon, making it an environmentally friendly solution for mid to high-rise construction.

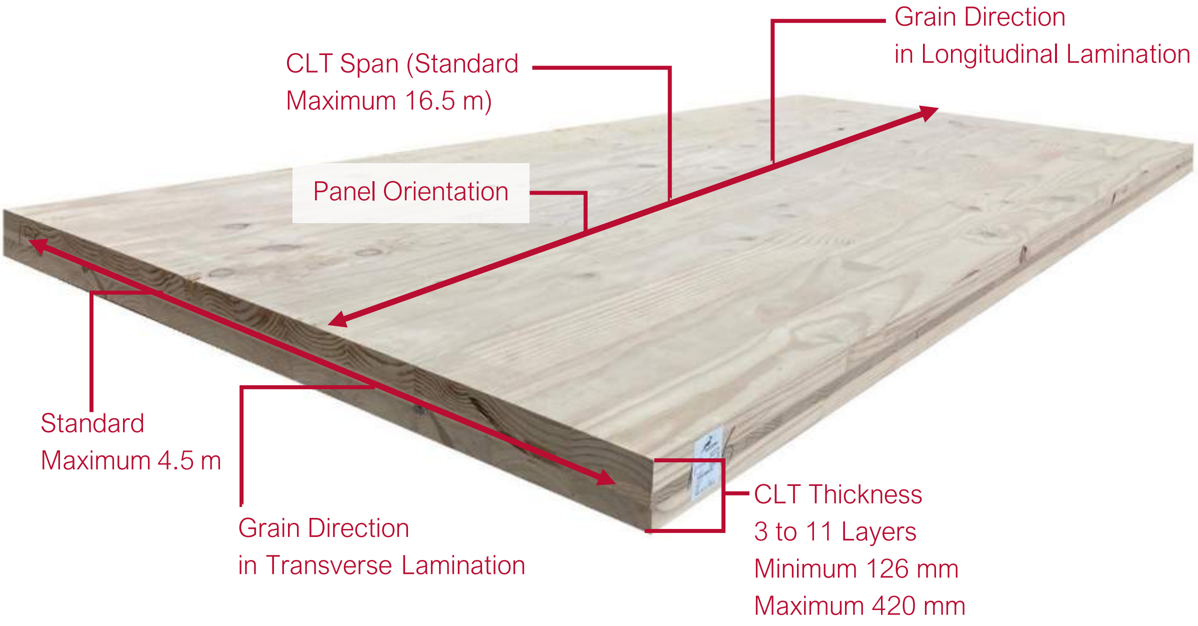

Figure 7: Red Stag CLT panel.

Table 1: Red Stag CLT Structural Material Strength Properties.

Structural Properties	Longitudinal Laminates	Transverse Laminates
Modulus of Elasticity (MoE)	8.0 GPa	6.0 GPa
Bending Strength	14 MPa	10 MPa
Compression Parallel to Grain	18 MPa	15 MPa
Compression perpendicular to Grain	8.9 MPa	8.9 MPa
Tension Strength	6.0 MPa	4.0 MPa
Normal Shear	3.8 MPa	3.8 MPa
Available lamella thickness	42 mm & 20 mm	42 mm & 20 mm
Refer to NZS 3603:1993 [7]		

4.2. CLT Performance Testing

Red Stag manufactured CLT panels and associated feedstock have been tested by professional third parties to ensure the durability, mechanical strength, and fire resistance. As shown in *Figure 8 - Figure 10*, a series of large-scale experimental tests have been conducted on Red Stag CLT products to verify the quality and performance. Destructive large-scale four-point bending tests conducted by SCION [8] confirmed that the Red Stag CLT panels have a sufficient level of stiffness and strength to carry applied structural loads (Refer to *Figure 8*). Testing on short, intermediate, and long-span CLT panels showed their exceptional structural performance under large pure shear forces, pure bending moments, and the combination of both. The SCION test results confirmed that the CLT panels outperformed the theoretical design calculations and associated numerical modelling.

Figure 8: Large scale mechanical testing conducted by SCION; (a) Long span testing, (b) Median span testing, (c) Short span testing.

The glue bond quality and durability of the CLT layers have been assessed by delamination testing. The reported delamination test results by a third-party specialist company showed an average delamination percentage [9] under the standard allowable limit, confirming the glue line bonds are sufficiently durable (Refer to *Figure 9*). In addition to the delamination testing, the large-scale bending experimental tests conducted by SCION verified that there were no adverse issues associated with glue line performance. No glue line failure or board separation was observed during all deflection testing.

Test specimens after delamination test [9]

Figure 9: Delamination test specimens confirming the quality of Red Stag glue line bonds.

The Fire Code is formulated to permit time for occupants to safely leave a burning building before structural collapse or succumbing to heat or smoke inhalation. The code stipulates that the safe evacuation period of up to 60 minutes in New Zealand will cover the vast majority of building types and uses. Large-scale CLT panel fire testing has been conducted by Red Stag to determine the overall fire resistance and fire performance of the panels under structural loads (Refer to *Figure 10*). CLT test specimens were installed in a furnace to investigate a number of parameters such as the structural performance during a fire event, temperature profile and deflection. The third-party fire test report confirmed no structural, integrity or instability failure after more than 60 minutes at 900 degrees Celsius.

Figure 10: Large-scale fire test specimen set-up for the fire testing on Red Stag CLT; (a) Red Stag CLT floor test specimen after fire testing, (b) Red Stag CLT wall test specimen before fire testing.

In addition to the experimental test results and confirming reports from third-party specialists, Red Stag tested and investigated its products numerically. A typical 3D design and associated finite element mesh model for the CLT panels are shown in *Figure 11*.

Red Stag's technical team can provide a comprehensive technical statement, including CLT design calculations, experimental test reports and numerical analysis for each project separately if required by the client [i].

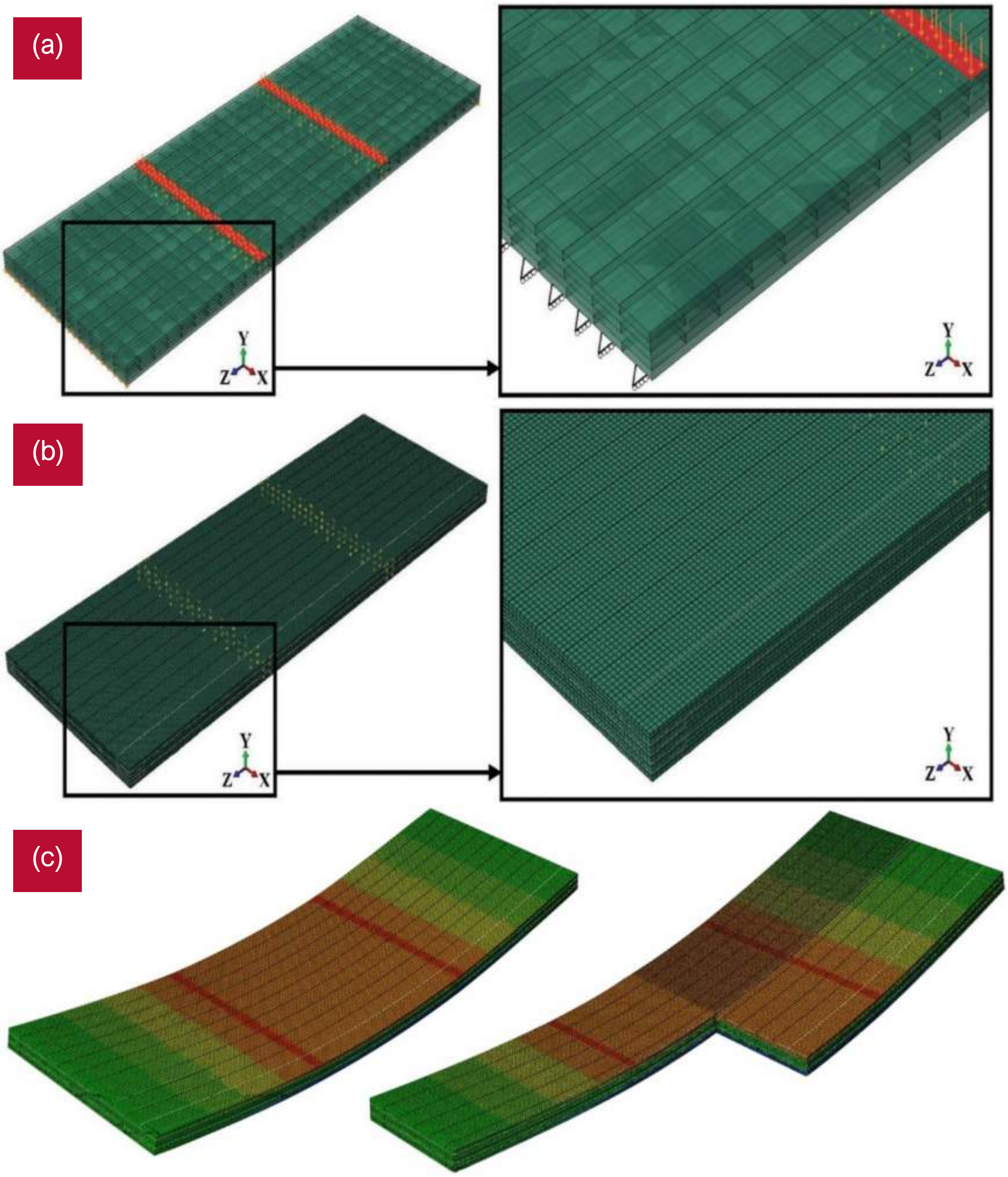

Figure 11: Typical boundary conditions and Finite Element (FE) mesh numerical model using ABAQUS [19] software; (a) FE model boundary conditions (Load and support); (b) FE mesh; (c & d) CLT panel numerical model to determine the deflection and stresses under various load conditions.

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[i] Client requests can be assessed and supported, but the client will need to have their engineering team sign off on all Red Stag modelling and associated calculations. Red Stag will charge all services out at its defined rates.

4.3. Red Stag Testing Facilities

Red Stag regularly checks the quality of the manufactured CLT panels via inhouse testing equipment. Red Stag has invested in the most advanced delamination testing equipment to analyse the glue bond quality between lamellas (Refer to *Figure 12*). Red Stag also confirms the quality of its Finger Joints (FJ) and shear block testing using a high-capacity hydraulic press with integrated load cell (Refer to *Figure 13*). To test beams and EWP sections, Red Stag uses calibrated, third party verified four point bending equipment for routine component analysis and internal Research and Development (Refer to *Figure 12 – Figure 14*).

Figure 12: Delamination testing machine.

Figure 13: Finger joint test equipment and setup.

Figure 14: CLT beam bending testing machine and setup; (a) Isometric end elevation; (b) Front elevation.

Section 2

Cross Laminated Timber Application & Products

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5. Red Stag CLT Panel Applications

Red Stag manufactures CLT panels from locally grown radiata pine for a wide range of structural components. Applications for CLT panels include floors, walls, beams, stairs, and roof/ceiling systems. CLT can resist large forces and loads, making it an effective, cost-effective structural option for multistorey applications.

5.1. Red Stag CLT Floors

Red Stag CLT panels are ideally suited for floor systems, with the ability to span in one or two directions (Refer to *Figure 15)*. Offsite manufacturing allows for panels to be shipped to site as ready-to-install structural components, greatly simplifying the building assembly process and increasing job site productivity and construction speed. The scale of Red Stag's EWP manufacturing plant allows for optimised structural solutions with fewer large format panels, providing the opportunity to install up to 75 square meters per crane lift (Refer to *Figure 16*).

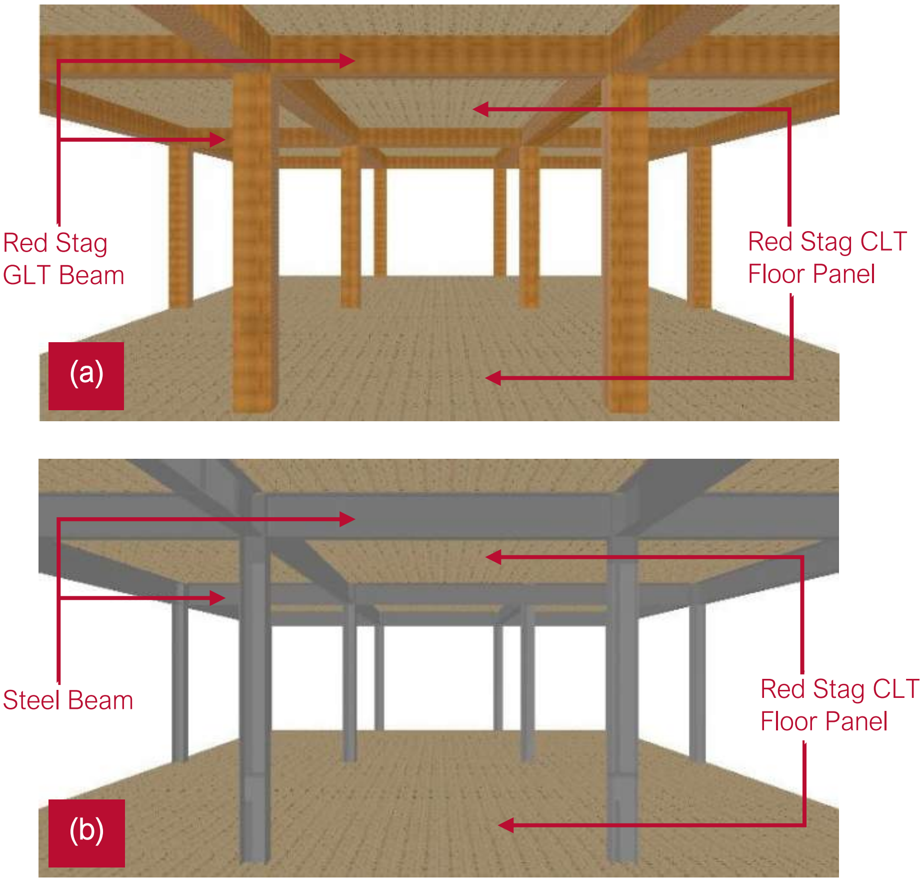


Figure 15: Red Stag CLT floor panel applications in timber or composite structures; (a) Timber system structure; (b) Steel-timber composite structure.

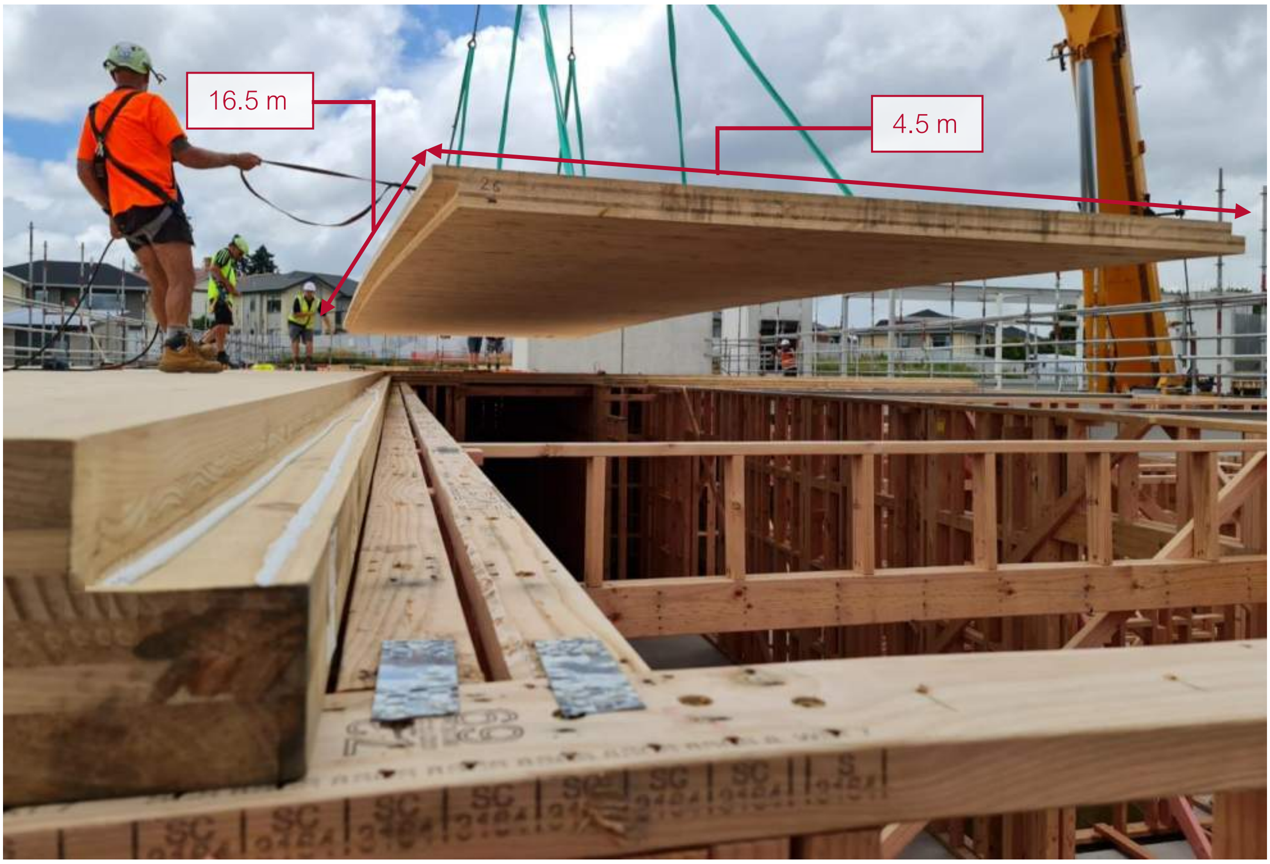
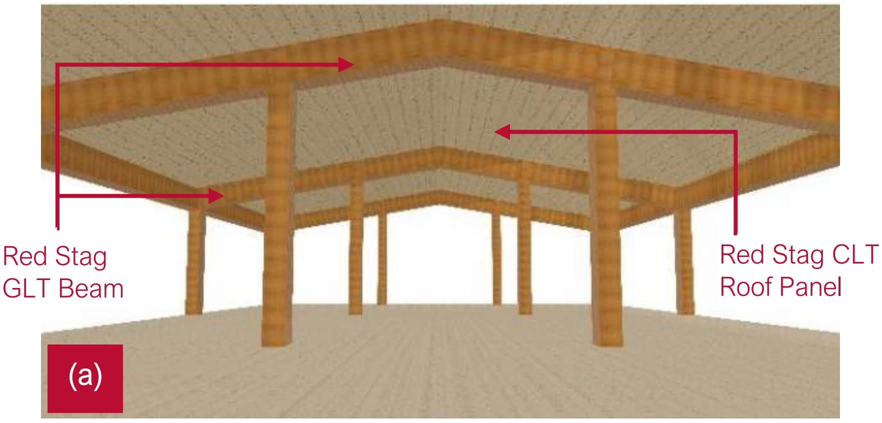


Figure 16: Red Stag CLT floor panels being installed onto Red Stag frames. Installation shows an example of a 75 square meter Red Stag CLT panel being effortlessly installed on site.

5.2. Red Stag CLT Roofs

Red Stag CLT roof panels provide a solution to expediently enclose a building from the weather, while providing the option for a natural timber sarking finish in the interior. CLT roof panels support in providing improved thermal properties (refer to section 5), when combined with secondary insulation [22] (Refer to *Figure 17*).



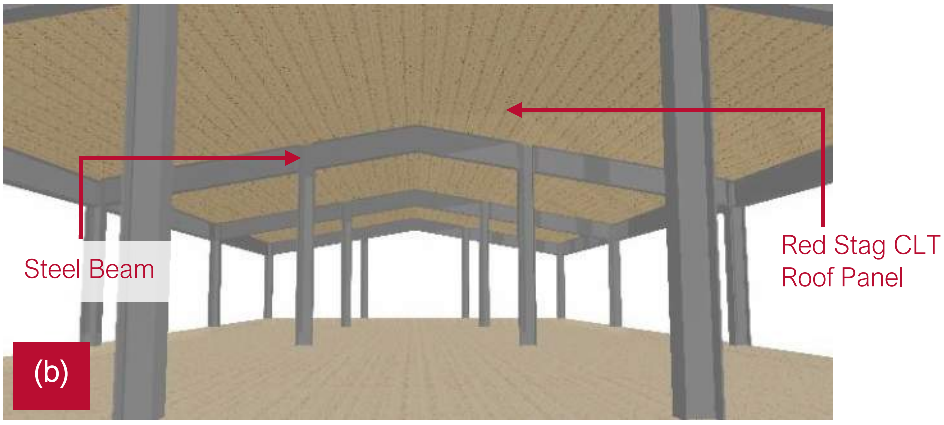


Figure 17: Red Stag CLT roof panel applications in timber or composite structures; (a) Timber system structure; (b) Steel-timber composite structure.

5.3. Red Stag CLT Walls

Red Stag CLT wall panels are a cost-competitive alternative to pre-cast concrete systems. CLT is lighter than pre-cast concrete, simplifying material handling and installation. Red Stag CLT wall panels can be designed for both tradition platform, and balloon wall systems (Refer to *Figure 18*).

Red Stag CLT walls provide improved gravitational load resistance and significant bracing to the structure. CLT walls are especially well suited to internal load bearing walls, lift shafts and stair wells. For mid and higher rise structures, CLT exterior walls provide the benefit of speed and structural performance.

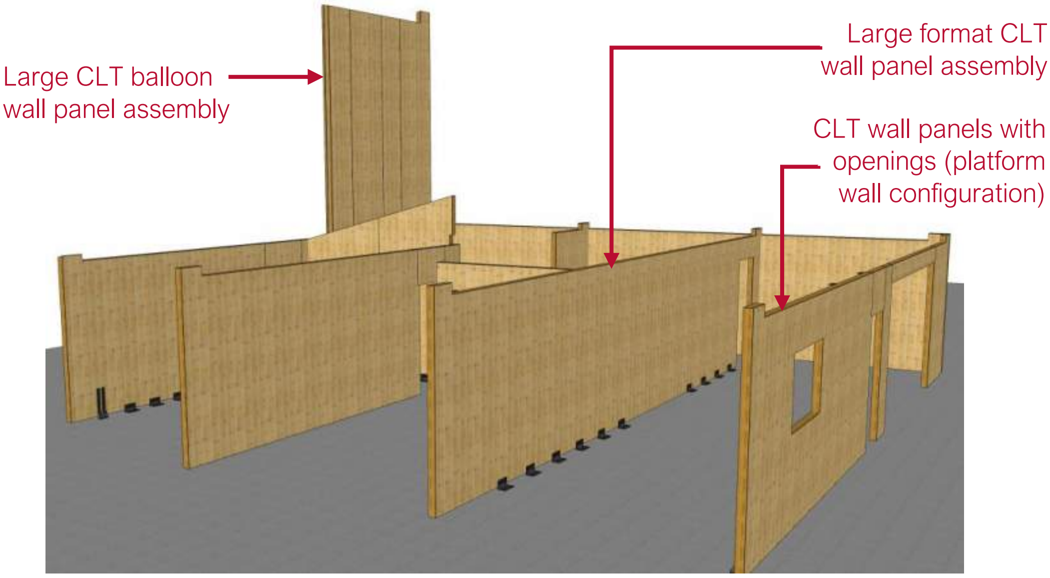


Figure 18: Red Stag CLT Wall panel applications.

5.4. Red Stag CLT Lift Shafts

Red Stag CLT lift shaft panels can be erected faster and easier than similar steel and concrete options, while providing exceptional lateral bracing for the building. Elevator and stair shafts can comfortably achieve a one hour fire resistance rating when using a 126 mm thick (or greater) three layer Red Stag CLT panel (Refer to *Figure 19*).

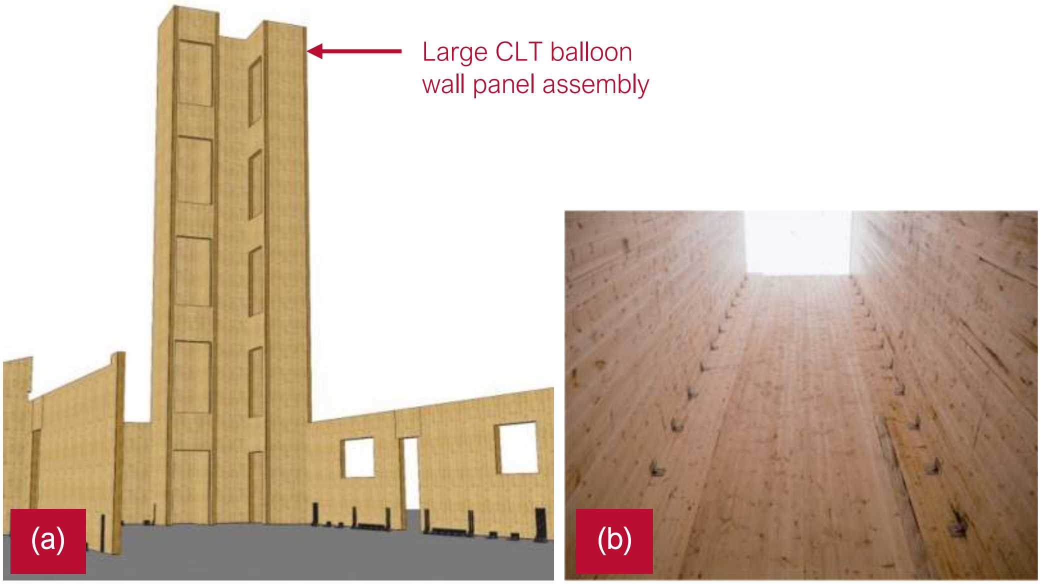


Figure 19: CLT Lift shaft (a) Multi-storey building with CLT lift shafts; (b) Interior view of a CLT *lift shaft.*

5.5. Red Stag CLT Shear Walls and Diaphragms

Red Stag CLT panels offer a great structural solution for timber and hybrid building designs to resist lateral loads generated by earthquakes and wind. Shear transfer between adjacent Red Stag CLT panels is achieved through a variety of metal connector systems and other high-density wood products that are attached with screws or nails (*Figure 20*).

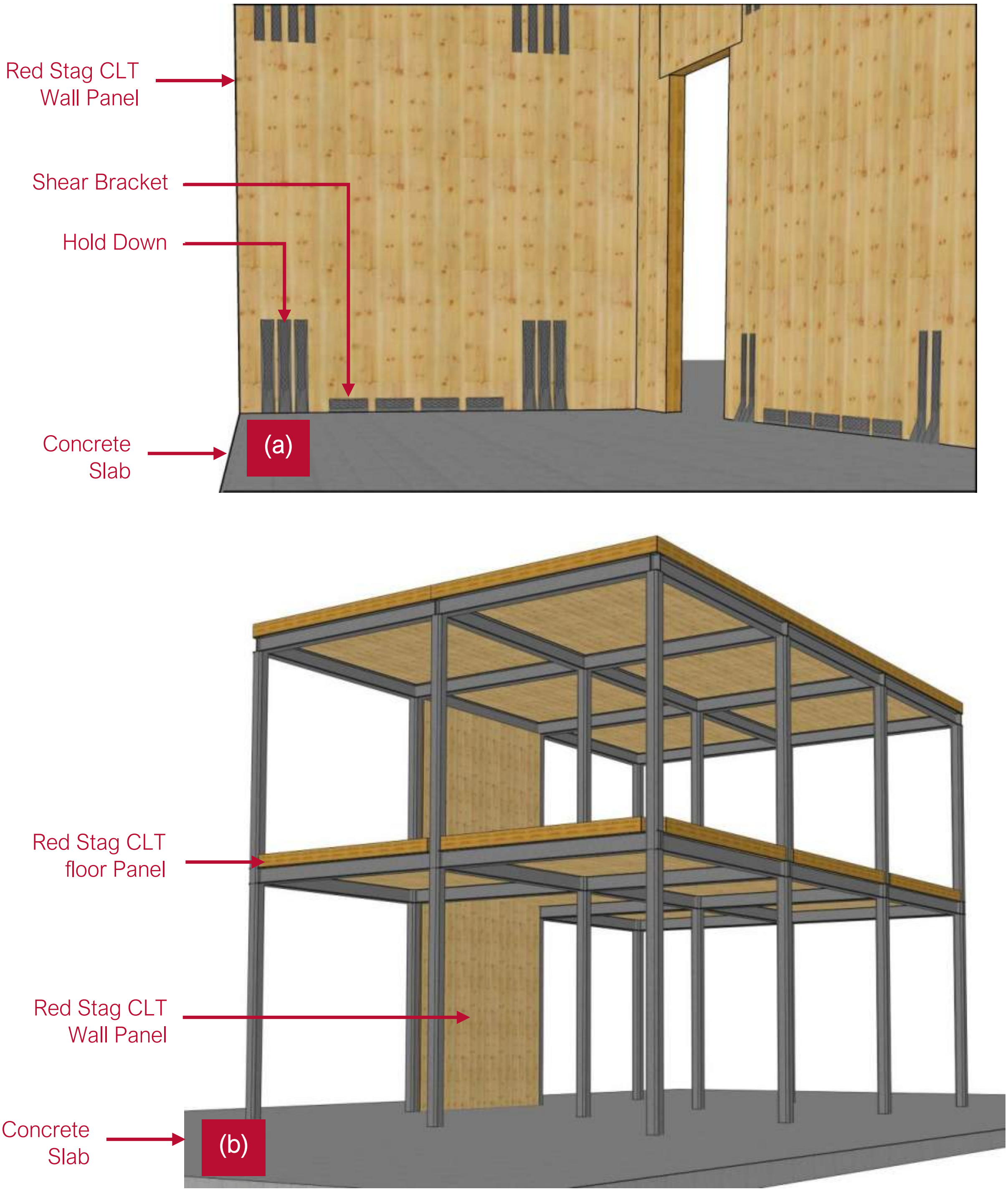


Figure 20: (a) CLT shear wall hold down system; (b) CLT panel diaphragm.

6. Red Stag CLT Panel Configuration Option

Red Stag can create a range of CLT configurations or recipes, including 3, 5, 7, 9 and 11-layer panels in visual and standard grades. A simplified range of CLT panel configurations for floor, roof and wall applications is summarised in *Table 2 to Table 6.* Additional CLT configurations beyond those presented in the tables below may be available based on the client's requirements; however, feedstock references will determine the availability, viability, and cost position of alternate recipes. A significant benefit of CLT and timber is its ability to lock up carbon. For every cubic meter (1 m^3) of timber utilised in a building, it removes 486 kg/m^3 of CO_2 [10] from the atmosphere. The CO_2 is absorbed by the timber and the carbon is stored/sequestered. For every 1 m^3 of CLT, it will sequester 250 kg of locked-in carbon [12-15] (*Figure 21*). To highlight this exceptional environment advantage, Red Stag has calculated the CO_2 benefits for its CLT products and summarised in the CLT panel specification tables below (*Table 4* - *Table 6*). *Table 7* – *Table 13* present the maximum span for cantilevered, simply supported, and continuous CLT floors and roofs based on the FPInnovations [11] CLT design guide and the New Zealand design action standard (AS/NZS 1170.0) [12].

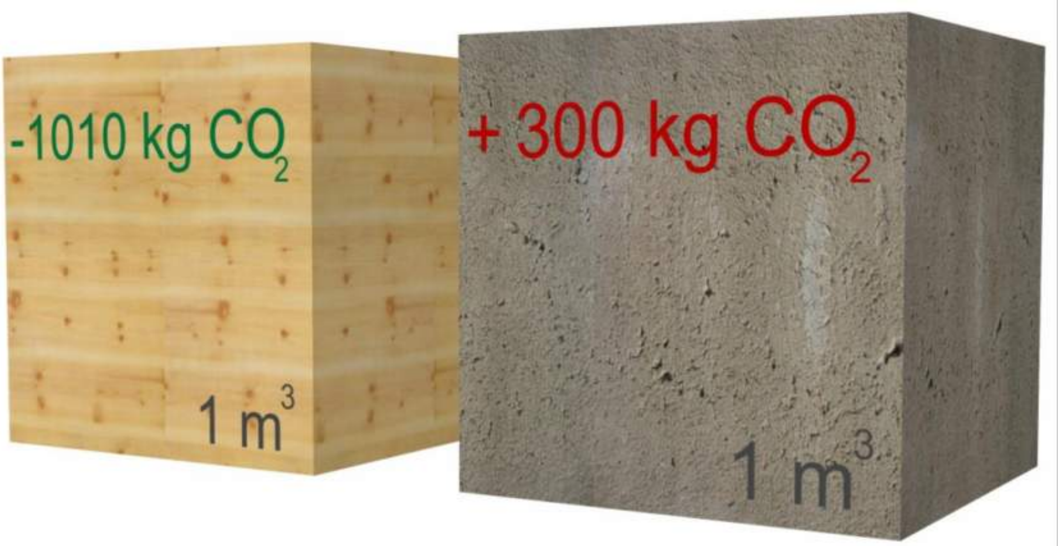


Figure 21: CLT versus Concrete [14-17].

7. Red Stag Lamella Specifications

The Red Stag Timber sawmill focuses on structural timber gauges 45 mm thick with finished board widths between 70 – 290 mm. To produce 140x45 gauged timber, Red Stag Timber cuts 150x50 Rough Sawn (RS), which is then further processes to create the final 140x45 gauging.

Red Stag's CLT plant utilises three primary feedstock thicknesses: 45 mm gauged, 50 mm RS, and 25 mm RS. Subject to the CLT recipe requirements, wherever practically possible, 45 mm thick feedstock will be used to make the processed CLT as economical as possible (reduced price point).

To optimise the utilisable fibre, Red Stag has refined its remanufacturing line to generate 42 mm thick lamella from 45 mm feedstock. *Table 3* details the primary feedstock and finished planed gauges.

The second feedstock option is 25 mm RS, used to create 20 mm lamella. Red Stag tries to limit the use of 20 mm lamellas as it generates the largest cross-sectional wastage through planing and requires the largest volume of defecting to ensure the lamellas run smoothly through the process.

The third primary feedstock option is 50 mm RS, used to create lamella gauges 45 mm thick. 50 mm RS is the least available and most expensive feedstock as it is the pre-MSG feedstock for Red Stag Timber structural timber.

The input raw material price calculations are based on the feedstock gauge; therefore, the price will not decrease if the Client selects a thinner gauge (i.e. 42 mm thick lamellas will be less expensive than 35 mm lamellas due to secondary planing requirements). As Red Stag Timber is a structural mill, predominantly servicing the New Zealand market, the largest majority of the feedstock will have an average MoE of 8 GPa. As such, the longitudinal layers of the Red Stag CLT will generally be specified as 8 GPa, with the majority of the transverse layers being specified up to 6 GPa. Red Stag will have some 10 GPa (and potentially higher) feedstock available; however, will focus its designs around 8 GPa and 6 GPa feedstock to make CLT as economic as practically possible relative to the properties of New Zealand Radiata Pine in the Central North Island.

Red Stag Timber is providing Red Stag with pre-treated feed stock for its EWP. To ensure the quality of the glue bond on the processed EWP, Red Stag minimises the time between final planing, glue application and pressing. To maximise the retained treatment, Red Stag planes as little timber as possible from lamellas. This aligns with the three primary finished gauge options in order of priority/preference: 42, 20, 45 mm.

Table 2: Material Strength Properties

Structural Properties	Longitudinal Laminates		Transverse Laminates
Modulus of Elasticity (MoE)	8 GPa	10 GPa	6.0 GPa
Bending Strength	14 MPa	20 MPa	10 MPa
Compression Parallel to Grain	18 MPa	20 MPa	15 MPa
Compression perpendicular to Grain	8.9 MPa	8.9 MPa	8.9 MPa
Tension Strength	6.0 MPa	8.0 MPa	4.0 MPa
Normal Shear	3.8 MPa	3.8 MPa	3.8 MPa

Refer to NZS 3603:1993 [7]

Table 3: EWP Feedstock Gauge Priority and Associated Commonly Available Post Processed Gauges.

Gauge Priority [a]	Primary Raw Gauges (mm)	Gauged Width (+/- 2 mm)	Gauged Thickness (+/- 1 mm)
1	140x45	137	42
2	100x25	93	20
3	150x50	140	45

a. Gauge priority defines the most cost effective and readily available feedstock gauge.
b. Client accepts treatment retention based on volume of post planning below 42 mm in thickness.

8. Red Stag CLT Panel Specifications

Table 4: Three (3) Layer CLT Panel Specifications

Recipe Priority [a]	1	2
Panel Recipe	**CLT 3/126**	**CLT 3/104**
Layer 1, MoE 8 GPa	42 mm	42 mm
Layer 2, MoE 6 GPa	42 mm	20 mm
Layer 3, MoE 8 GPa	42 mm	42 mm
Panel Self Weight (Static Load)	0.63 kPa	0.52 kPa
Panel Thickness	126 mm	104 mm
Removed CO_2 from Atmosphere	- 100 kg/m^3	- 83 kg/m^3
Created CO_2 by Equivalent Concrete Slab	+ 51 kg/m^3	+ 43 kg/m^3
CLT CO_2 Benefit Compared to a Concrete Slab	151 kg/m^3	126 kg/m^3

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.

Table 5: Five (5) Layer CLT Panel Specifications

Recipe Priority [a]	1	2
Panel Title	**CLT 5/210**	**CLT 5/166**
Layer 1, MoE 8 GPa	42 mm	42 mm
Layer 2, MoE 6 GPa	42 mm	20 mm
Layer 3, MoE 8 GPa	42 mm	42 mm
Layer 4, MoE 6 GPa	42 mm	20 mm
Layer 5, MoE 8 GPa	42 mm	42 mm
Panel Self Weight (Static Load)	1.05 kPa	0.83 kPa
Panel Thickness	210 mm	166 mm
Removed CO_2 from Atmosphere	- 161 kg/m^3	- 127 kg/m^3
Created CO_2 by Equivalent Concrete Slab	+ 82 kg/m^3	+ 64 kg/m^3
CLT CO_2 Benefit Compared to a Concrete Slab	242 kg/m^3	191 kg/m^3

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.

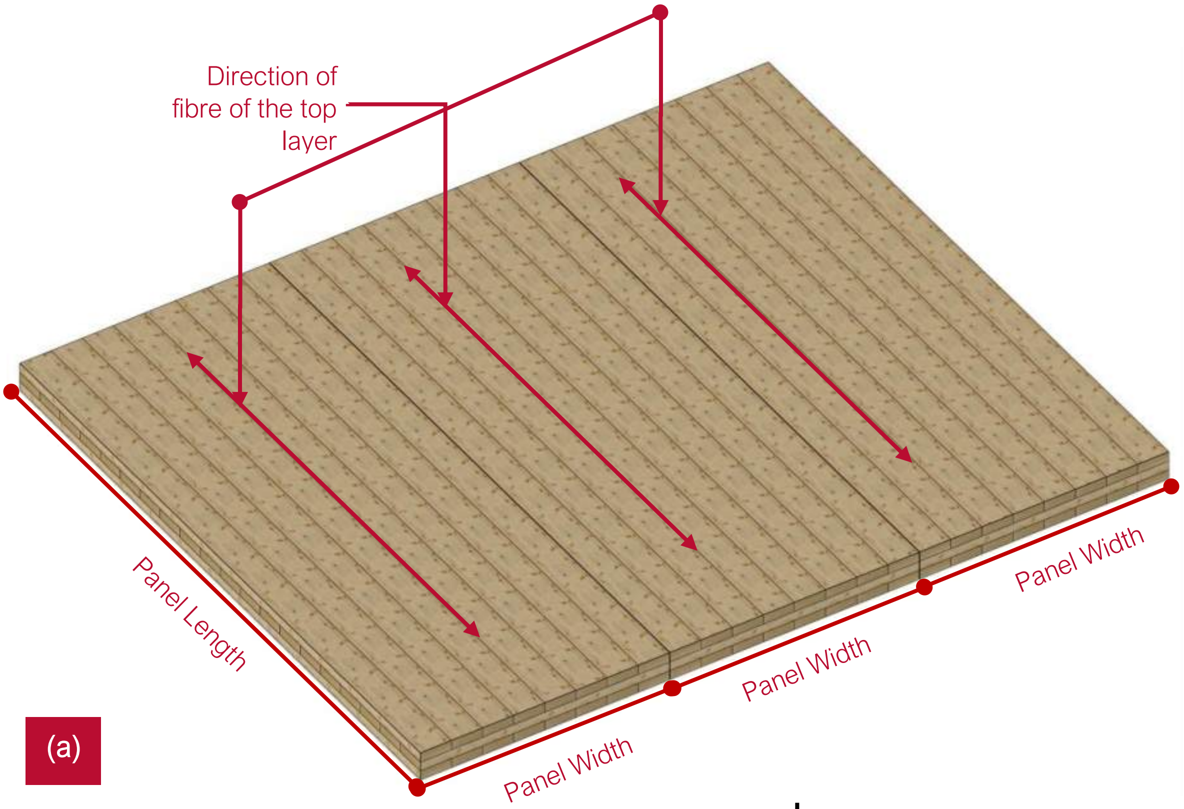
Table 6: Seven (7) Layer CLT Panel Specifications.

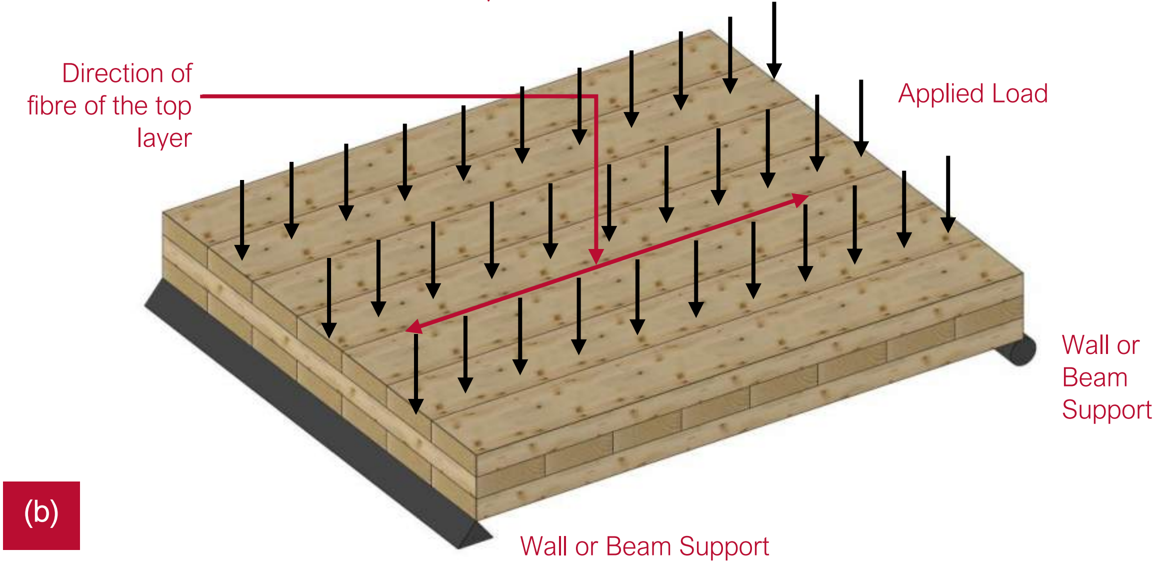
Recipe Priority [a]	1	2
Panel Title	**CLT 7/294**	**CLT 7/228**
Layer 1, MoE 8 GPa	42 mm	42 mm
Layer 2, MoE 6 GPa	42 mm	20 mm
Layer 3, MoE 8 GPa	42 mm	42 mm
Layer 4, MoE 6 GPa	42 mm	20 mm
Layer 5, MoE 8 GPa	42 mm	42 mm
Layer 6, MoE 6 GPa	42 mm	20 mm
Layer 7, MoE 8 GPa	42 mm	42 mm
Panel Self Weight (Static Load)	1.47 kPa	1.14 kPa
Panel Thickness	290 mm	228 mm
Removed CO_2 from Atmosphere	- 419 kg/m^3	- 325 kg/m^3
Created CO_2 by Equivalent Concrete Slab	+ 213 kg/m^3	+ 166 kg/m^3
CLT CO_2 Benefit Compared to a Concrete Slab	633 kg/m^3	490 kg/m^3

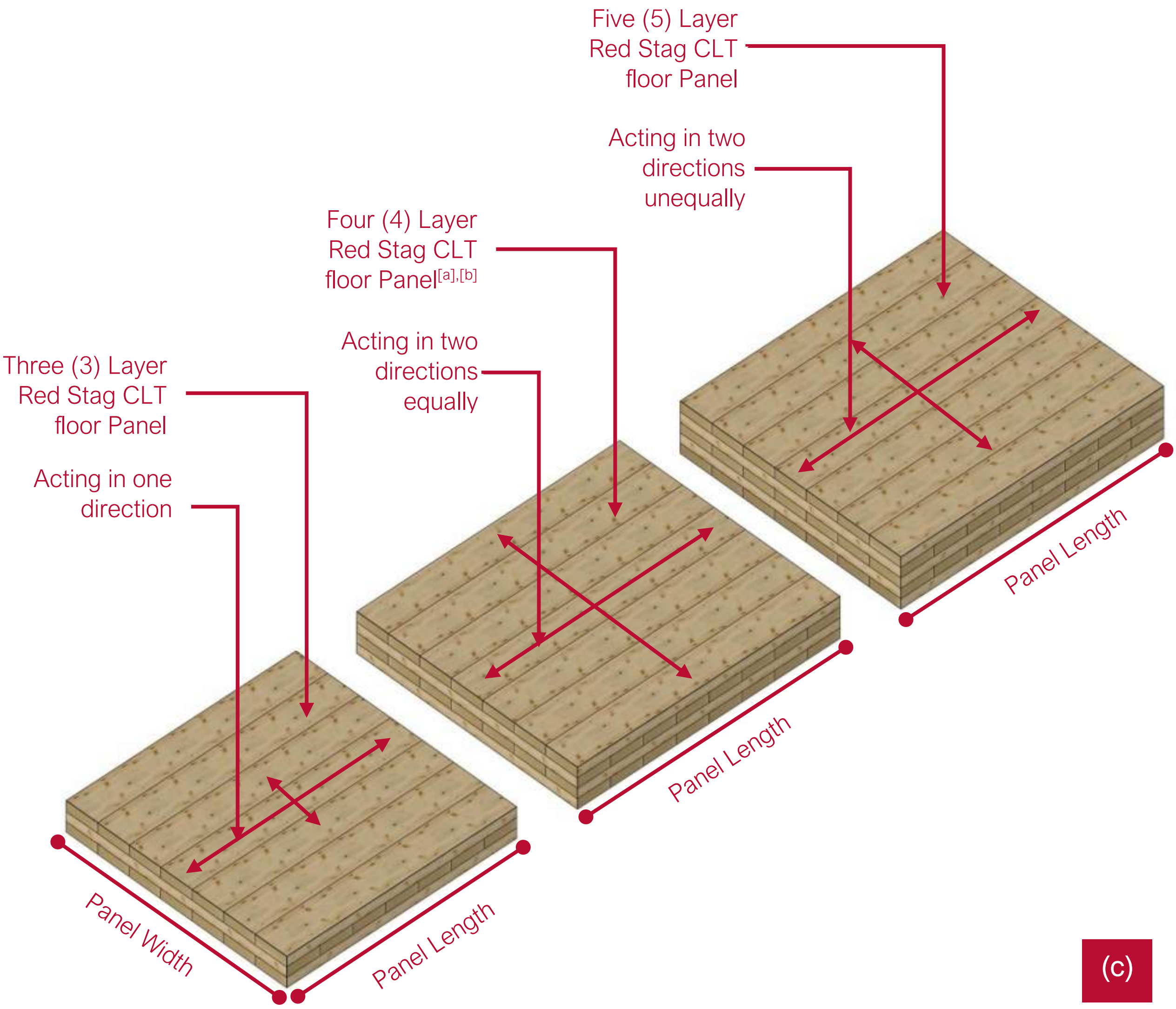
a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.

IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance.

In roof and floor applications, CLT panels are usually placed next to each other in the same direction (Refer to *Figure 22a* and *Figure 22b*), acting as single directional CLT slab. The width of Red Stag CLT panels can be customised but is generally up to 4.5 m wide. Most floor and roof systems are simply supported on two or more walls or beams. In some cases, CLT roof and floor configurations can be built with CLT panels acting in two directions (Refer to *Figure 22c*). Please note that the three (3) layer CLT panel in *Figure 22c* is for illustration purposes only, as at least four layers are required for a two-way action.







[a] Performs in two directions equally, similar to the main direction action of a three-layer CLT panel.
[b] Lighter weight compared to the five-layer panel, with comparable structurally performance.

Figure 22: CLT Floor assemblies (a & b) for three (3) layer CLT panels acting in one direction; (c) one five (5) layer CLT panel acting in both directions. Minimum of five layers of lamella are required to guaranty the CLT performs as a two-way CLT system. "Panel width" depends on the manufacturer and properties of the lamella in each layer. Two acting directions in three (3) layer and five (5) layer asymmetrical CLT panels compared with a four (4) layer symmetrical CLT panel.

Red Stag have utilised the Gamma method presented in the FPInnovations CLT design guide to design its CLT panels for roof or floor applications. The Gamma method takes rolling shear deformation in the transverse laminate(s) into account (Refer to *Figure 23*). Dissimilar to the long spans in CLT roof or floor panels, shorter spans have a higher proportion of rolling shear deformation.

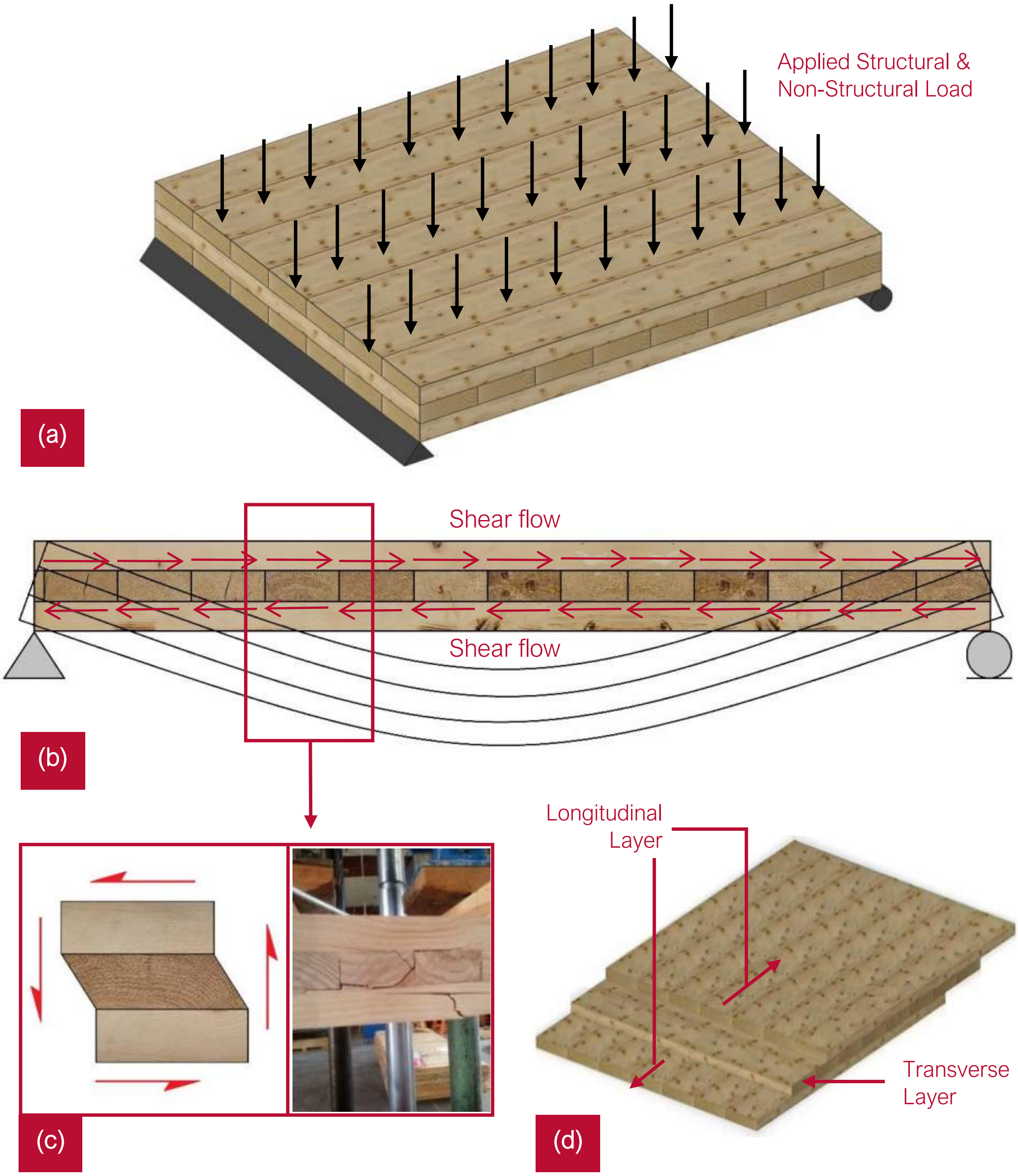


Figure 23: Rolling shear phenomenon; (a) Loaded CLT panel; (b) Shear flow through the panel; (c) Effect of rolling shear; (d) Rolling shear translation to transverse layer.

Red Stag's design guide has calculated bending strength and midspan deflection of the CLT panels for short-term and long-term loading under various load combinations for strength (ultimate), limit state design, and serviceability limit state design (further design details are summarised below).

Strength limit state:

For Long Term Loading: 1.35 G
For Medium Term Loading: 1.2 G + 1.5 Q

Serviceability limit state:

For Short Term Loading: G + 0.7 Q
For Long Term Loading: G + 0.4 Q

G: Gravitational weight of the CLT panel (Refer to *Table 3* - *Table 6*).

$G_{add\text{-}DL}$: Additional dead load on the CLT floor. Assumed as 0.1 kPa for roof applications and 0.5 kPa, 1 kPa or 1.5 kPa for floor applications.

Q: Live load. Assumed as 0.25 kPa for roof applications and 2 kPa, 3 kPa, or 5 kPa for floor applications.

K_2*: Long-term creep factor. 2.0 or 3.0 for the serviceability limit state deflection check for simply supported and cantilever floors, respectively.

*Assumed that the CLT roof and floor remains dry during its service life.

Δ: Midspan deflection calculation result under $k_2(G+G_{SDL}+0.4Q)$. The result should be lower than Span/300 for a simply supported floor/roof and Span/200 for cantilevers.

9.1. Red Stag CLT Floor Vibration Design

Vibration (e.g. harmonics created during the walking/movement across the floor) is another important factor that needs to be taken into account during the design of CLT floor systems. The test results in the FPInnovations CLT design guide [11] shows that the vibrational behaviour of CLT floors is different from lightweight joist floors. The vibrational impact on the span of CLT floors is calculated based on the FPInnovations [11] and Euro Code [13] design methods. These two methods have been verified experimentally by a series of laboratory tests performed by FPInnovations [11] and the European Timber Standards.

- **FP Innovations [11] Vibration Calculation Method:**

Limited Vibration Span (L) ≤ $\frac{1}{9.15} \times \frac{{(EI)_{eff}^{1m}}^{0.293}}{(\rho A)^{0.123}}$

L = Maximum CLT floor span (m).
$(EI)_{eff}$ = Effective stiffness for a 1 m wide panel (N-m^2).
ρ = Density of CLT (kg/m^3).

- **Euro Code 5 [13], Section 7 Vibration Calculation Method:**

Limited Vibration Span (L) ≤ $0.11 \times \frac{\left(\frac{(EI)_{eff}}{10^6}\right)^2}{m^{0.12}}$

L = vibration-controlled span limit (m). Clear span measured from face to face, of the two end supports.
$(EI)_{eff}$ = Effective stiffness for a 1 m wide panel (N-m^2).
m = Density of CLT (kg/m^3).

Floor vibration is a very complex phenomenon, therefore, to minimise the issue, it is recommended for the midspan deflection of CLT floors be restricted to 1 - 2 mm under 1 kN load based on New Zealand Design Action Standards (AS/NZS 1170) [12].

9.2. Continuous Red Stag CLT Floors and Roof Systems

Red Stag's large scale EWP plant can manufacture very large CLT panels for continuous roof or floor applications. A continuous CLT roof or floor has structural advantages compared to simply supported systems. Continuous CLT roof or floor systems have less deflection under similar loading conditions (Refer to *Figures 24* - 25) and provide much larger spans or distance between supports as compared to simply supported CLT floors. Continuous systems may also allow roof or floor members to have a smaller overall depth or bending stiffness as the maximum bending stress and deflection are reduced.

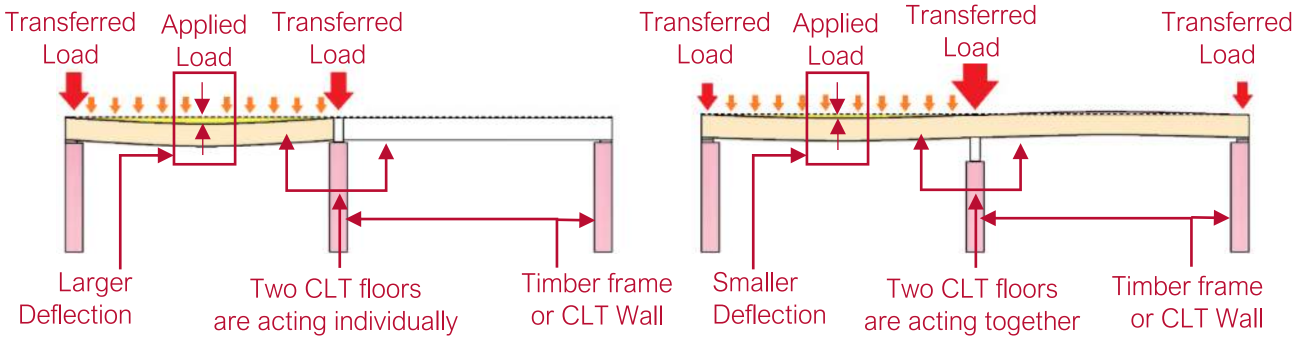
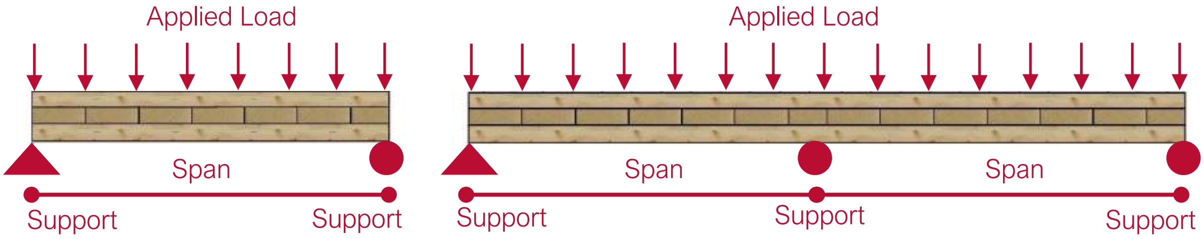


Figure 24: Comparison of deflections between single and double span CLT panels for roof or floor applications.[21]



Single span CLT floor panel

$$\Delta = \frac{5 \times w \times L^4}{384 \times E \times I}$$

W = Applied Load
L = Span
E = Elastic modulus
I = Moment of Inertia

Continuous double span CLT floor panel

$$\Delta = \frac{w \times L^4}{185 \times E \times I}$$

Figure 25: Comparison of deflection calculations for single and double span CLT panels for roof or floor applications [21].

9.3. Red Stag CLT Panel Specifications for Roof and Floor Applications

Red Stag can produce a range of CLT configurations or recipes, including 3, 5, 7, 9 and 11-layer panels in visual and standard grades. Red Stag CLT panels incorporate specified layer properties, defining the MoE to align with the performance criteria of each panel design.

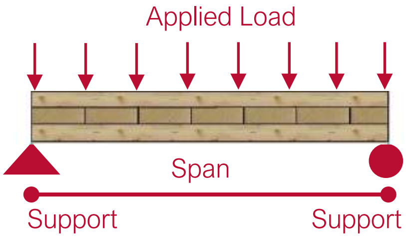
An optimised list of CLT panel configurations for floor and roof applications are summarised in *Table 4 to Table 6*. The maximum span for cantilever, simply supported and continuous CLT floors and roofs based on the FPInnovation CLT design guide, and the New Zealand design action standard (AS/NZS 1170) [12] are summarised in *Table 7* to *Table 13*. Additional CLT configurations beyond those presented in the following tables may be available based on the client's requirements; however, feedstock requirements will determine the availability, viability, and cost position of alternate configurations.

Table 7: Material Strength Properties of lamella for Roof/Floor Applications

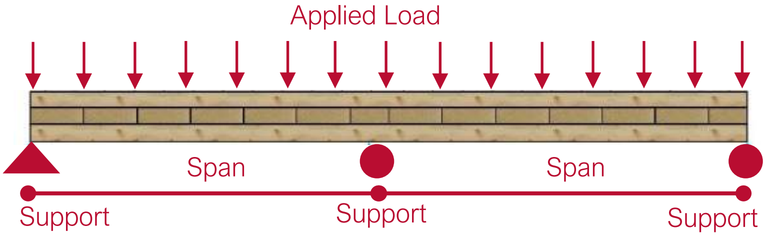
Structural Properties	Longitudinal Laminates	Transverse Laminates
Modulus of Elasticity (MoE)	8.0 GPa	6.0 GPa
Bending Strength	14 MPa	10 MPa
Compression Parallel to Grain	18 MPa	15 MPa
Compression perpendicular to Grain	8.9 MPa	8.9 MPa
Tension Strength	6.0 MPa	4.0 MPa
Normal Shear	3.8 MPa	3.8 MPa
Refer to NZS 3603:1993 [7]		

9.3.1. Three (3) Layer CLT Roof Panel

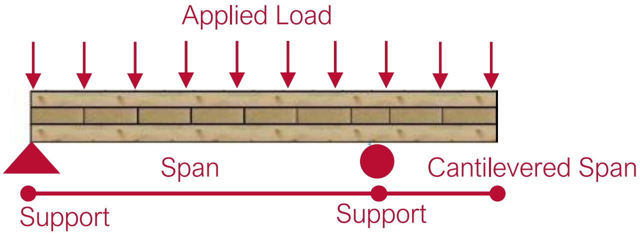
- Applied Loads: Imposed Load = 0.25 kPa, Snow Load = 0 kPa or 3 kPa, CLT Dead Load, Refer to *Table 4.*
- Vibration calculation not considered for roof applications.



Single span (Simply Supported) CLT panel



Double Span (Continuous Two Spans) CLT panel



Cantilevered CLT panel

Table 8: Three (3) Layer CLT Roof Specification for No Snow Zones[a, b, c, d]

Recipe Priority[e]	Panel Title	Thickness	Single Span (Simply Supported)	Double Span (Continuous Two Spans)	Cantilevered
1	CLT 3/126	126 mm	5.18 m	7.01 m	1.69 m
2	CLT 3/104	104 mm	4.57 m	6.15 m	1.35 m

a) Not designed for floor applications.
b) Designed for 0.25 kPa live load, 500 kg/m^3 for CLT, 0.1 kPa additional dead load for non-structural elements.
c) Did not design for vibration.
d) Roofs are designed for 500 kg/m^3 for CLT only (Refer to *Table 4*).
e) Recipe priority defines the most cost-effective Red Stag CLT recipe option.

Table 9: Three (3) Layer CLT Roof Specification for Snow Zones[a, b, c, d, f].

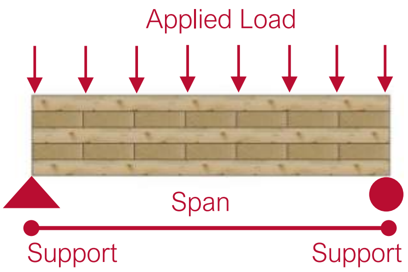
Recipe Priority[e]	Panel Title	Thickness	Simply Supported	Double Span (Continuous Two Spans)	Cantilevered
1	CLT 3/126	126 mm	3.00 m	4.12 m	1.45 m
2	CLT 3/104	104 mm	2.85 m	3.51 m	1.10 m

a) Not designed for floor applications.
b) Designed for 0.25 kPa live load, 500 kg/m^3 for CLT, 0.1 kPa additional dead load for non-structural elements.
c) Did not design for vibration.
d) Roofs are designed for 500 kg/m^3 for CLT only (Refer to *Table 4*).
e) Recipe priority defines the most cost-effective Red Stag CLT recipe option.
f) Snow load assumed as the dead load in the calculation.

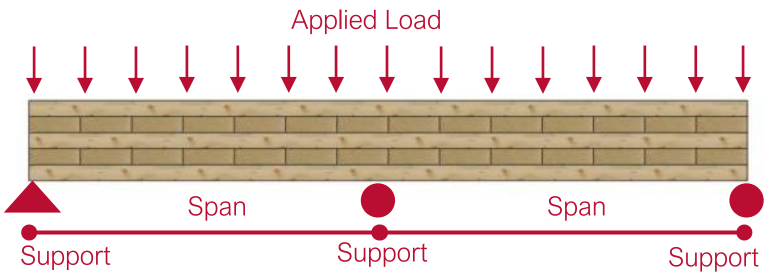
IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance.

9.3.2. Five (5) Layer CLT Roof Panel

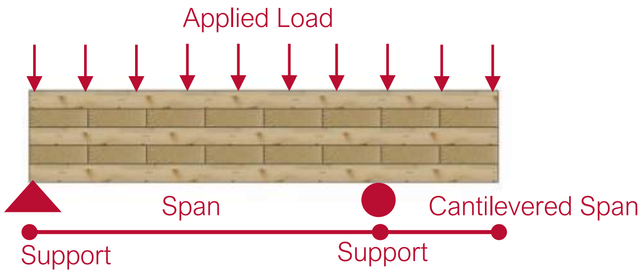
- Applied Loads: Imposed Load = 0.25 kPa, Snow Load = 0 kPa or 3 kPa, CLT Dead Load, Refer to *Table 5*.
- Vibration calculation not considered for roof applications.



Single span (Simply Supported) CLT panel



Double Span (Continuous Two Spans) CLT panel



Cantilevered CLT panel

Table 10: Five (5) Layer CLT Roof Specification for No Snow Zones [a, b, c, d].

Recipe Priority [e]	Panel Title	Thickness	Single Span (Simply Supported)	Double Span (Continuous Two Spans)	Cantilevered
1	CLT 5/210	210 mm	7.04 m [f]	9.93 m [f]	2.15 m
2	CLT 5/166	166 mm	6.25 m	8.36 m	1.85 m

a) Not designed for floor applications.
b) Designed for 0.25 kPa live load, 500 kg/m^3 weight for CLT, 0.1 kPa additional dead load for non-structural elements.
c) Vibration calculation not considered for roof applications.
d) Roofs are designed for 500 kg/m^3 for CLT only (Refer to *Table 5*).
e) Recipe priority defines the most cost-effective Red Stag CLT recipe option.
f) Refer to *Section 7* for three (3) Layer Red Stag CLT Roof design example.

Table 11: Five (5) Layer CLT Roof Specification for Snow Zones [a, b, c, d, f].

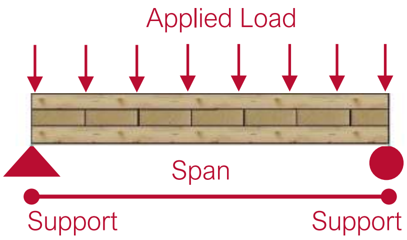
Recipe Priority [e]	Panel Title	Thickness	Single Span (Simply Supported)	Double Span (Continuous Two Spans)	Cantilevered
1	CLT 5/210	210 mm	4.54 m	6.23 m	1.95 m
2	CLT 5/166	166 mm	3.96 m	5.28 m	1.60 m

a) Not designed for floor applications.
b) Designed for 0.25 kPa live load, 500 kg/m^3 weight for CLT, 0.1 kPa additional dead load for non-structural elements.
c) Vibration calculation not considered for roof applications.
d) Roofs are designed for 500 kg/m^3 for CLT only (Refer to *Table 5*).
e) Recipe priority defines the most cost-effective Red Stag CLT recipe option.
f) Snow load assumed as the dead load in the calculation.

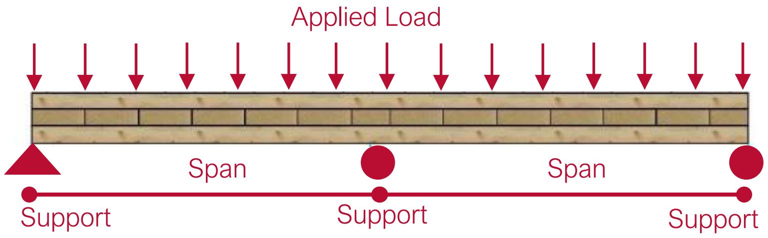
IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance.

9.3.3. Three (3) Layer CLT Floor Panel

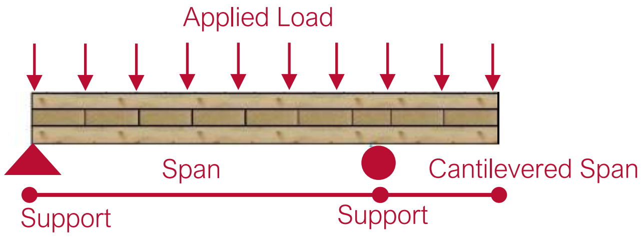
- Applied Loads: Imposed Load = 2 kPa, 3 kPa and 5 kPa,
  CLT Dead Load = Refer to *Table 4*.
- Vibration calculation considered in span performance.



Single span (Simply Supported) CLT panel



Double Span (Continuous Two Spans) CLT panel



Cantilevered CLT panel

Table 12: Three (3) Layer Simply Supported Single Span, Double Span and Cantilevered CLT Floor Specifications [a, b, c].

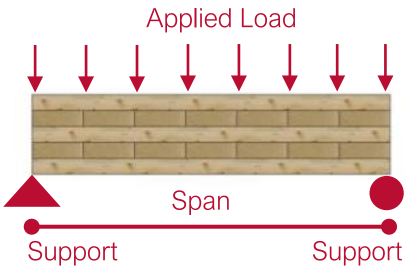
	Recipe Priority [a]	Panel Title	Thickness	Applied Load (kPa)								
				Super Imposed Dead Load 0.5 kPa			Super Imposed Dead Load 1 kPa			Super Imposed Dead Load 1.5 kPa		
				Live Load (Imposed Load)			Live Load (Imposed Load)			Live Load (Imposed Load)		
				2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa
Single span (Simply Supported)	1	CLT 3/126	126 mm	3.85 m [g, f, k]	3.60 m [g, e]	3.23 m [g, e]	3.85 m [g, f,]	3.60 m [g, e]	3.23 m [g, e]	3.85 m [g, f,]	3.60 m [g, e]	3.23 m [g, e]
	2	CLT 3/104	104 mm	3.32 m [g, f]	3.10 m [g, e]	2.78 m [g, e]	3.32 m [g, f]	3.10 m [g, e]	2.78 m [g, e]	3.32 m [g, f]	3.10 m [g, e]	2.78 m [g, e]
Double Span (Continuous Two Spans)	1	CLT 3/126	126 mm	5.21 m [h, f, k]	4.91 m [g, e]	4.43 m [g, e]	4.84 m [g, f]	4.59 m [g, e]	4.20 m [g, e]	4.53 m [g, f]	4.33 m [g, e]	4.01 m [g, e]
	2	CLT 3/104	104 mm	4.49 m [g, f]	4.19 m [g, e]	3.77 m [g, e]	4.13 m [g, f]	3.91 m [g, e]	3.58 m [g, e]	3.86 m [g, f]	3.69 m [g, e]	3.42 m [g, e]
Cantilevered	1	CLT 3/126	126 mm	0.38 m	0.32 m	0.21 m	0.28 m	0.25 m	0.20 m	0.22 m	0.20 m	0.15 m
	2	CLT 3/104	104 mm	0.30 m	0.28 m	0.20 m	0.25 m	0.23 m	0.19 m	0.20 m	0.18 m	0.14 m

a) Recipe priority defines the most cost-effective Red Stag CLT recipe option.
b) Floors are designed for 2 kPa, 3 kPa or 5 kPa Live Load (Imposed Load).
c) Floors are designed for 0.5 kPa, 1 kPa or 1.5 kPa addition Dead Load (Super Imposed Dead Load).
d) Floors are designed for 500 kg/m^3 for CLT (Refer to *Table 4*).
e) Floors are designed for vibration based on the recommended method in FPInnovation CLT design guide.
f) Floors are designed for vibration based on Eurocode 5 section 7.3.
g) Span limited by deflection.
h) Span controlled by vibration.
i) Red Stag design limits for floors are not constrained to this table. If specific floor designs are required, please contact Red Stag.
j) The maximum cantilever span is no less than 2.5 times of the cantilever length.
k) Refer to *Section 7* for three (3) Layer Red Stag CLT Floor design example.

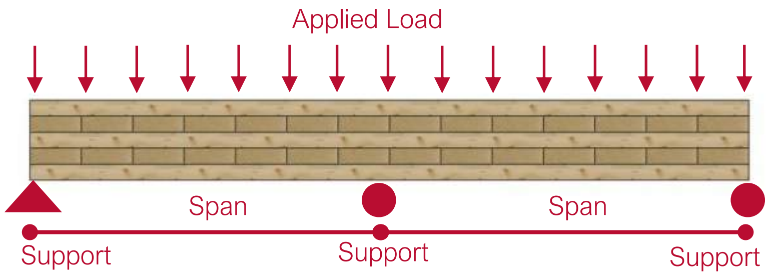
IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance.

9.3.4. Five (5) Layer CLT Floor Panel

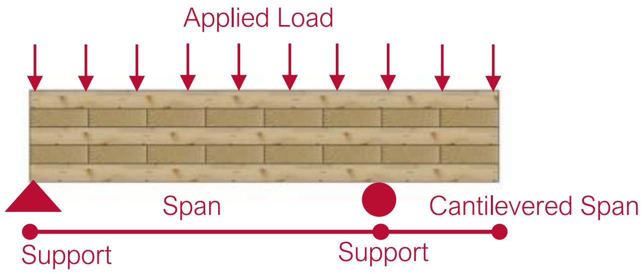
- Applied Loads: Imposed Load = 2 kPa, 3 kPa and 5 kPa,
  CLT Dead Load = Refer to Table 5.
- Vibration calculation considered in span performance.



Single span (Simply Supported) CLT panel



Double Span (Continuous Two Spans) CLT panel



Cantilevered CLT panel

Table 13: Five (5) Layer Simply Supported Single Span, Double Span and Cantilevered CLT Floor Specifications [a, b, c].

	Recipe Priority [a]	Panel Title	Thickness	Applied Load (kPa)								
				Super Imposed Dead Load 0.5 kPa			Super Imposed Dead Load 1 kPa			Super Imposed Dead Load 1.5 kPa		
				Live Load (Imposed Load)			Live Load (Imposed Load)			Live Load (Imposed Load)		
				2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa
Single span (Simply Supported)	1	CLT 5/210	210 mm	5.54 m [g, f]	5.33 m [g,e,k]	4.86 m [g, e]	5.26 m [g, f]	5.01 m [g, e]	4.63 m [g, e]	4.96 m [g, h]	4.76 m [g, e]	4.43 m [g, e]
	2	CLT 5/166	166 mm	4.86 m [g, f]	4.57 m [g, e]	4.15 m [g, e]	4.51 m [g, f]	4.29 m [g, e]	3.95 m [g, e]	4.24 m [g, h]	4.07 m [g, e]	3.78 m [g, e]
Double Span (Continuous Two Spans)	1	CLT 5/210	210 mm	6.37 m [h, f]	5.47 m [h,e,k]	5.47 m [h, e]	6.37 m [h, f]	5.47 m [h, e]	5.47 m [h, e]	6.37 m [h, f]	5.47 m [h, e]	5.47 m [h, e]
	2	CLT 5/166	166 mm	5.89 m [h, f]	4.81 m [h, e]	4.81 m [h, e]	5.89 m [h, f]	4.81 m [h, e]	4.81 m [h, e]	5.76 m [g, h]	4.81 m [h, e]	4.81 m [h, e]
Cantilevered	1	CLT 5/210	210 mm	0.71 m	0.65 m	0.36 m	0.54 m	0.50 m	0.26 m	0.41 m	0.36 m	0.22 m
	2	CLT 5/166	166 mm	0.50 m	0.47 m	0.29 m	0.39 m	0.37 m	0.21 m	0.31 m	0.26 m	0.17 m

a) Recipe priority defines the most cost-effective Red Stag CLT recipe option.
b) Floors are designed for 2 kPa, 3 kPa or 5 kPa Live Load (Imposed Load).
c) Floors are designed for 0.5 kPa, 1 kPa or 1.5 kPa addition Dead Load (Super Imposed Dead Load).
d) Floors are designed for 500 kg/m^3 for CLT (Refer to *Table 5*).
e) Floors are designed for vibration based on the recommended method in FPInnovation CLT design guide.
f) Floors are designed for vibration based on Eurocode 5 section 7.3.
g) Span limited by deflection.
h) Span controlled by vibration.
i) Red Stag design limits for floors are not constrained to this table. If specific floor designs are required, please contact Red Stag.
j) The maximum cantilever span is no less than 2.5 times of the cantilever length.
k) Refer to *Section 7* for five (5) Layer Red Stag CLT Floor design example.

IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance.

10. Red Stag CLT Wall Design

CLT walls are vertical structural members, typically designed to carry gravity loads. Prefabricated CLT walls are significantly lighter in weight compared with precast concrete, and are generally faster to install, and require less transportation and associated logistical management. CLT walls have excellent fire resistance and provide exceptional bracing attributes. The design calculations for CLT walls under axial loads are summarised in *Table 14 and Table 15.* Red Stag is capable of manufacturing both standard and visual grade CLT wall systems, allowing the timber to be exposed to reduced secondary lining costs, improve aesthetics and the occupants' health and well-being [18],[20].

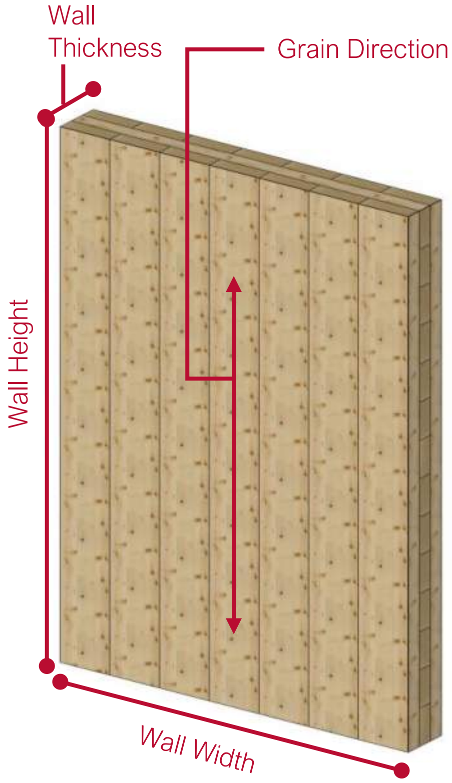


Table 14: Wall Load Carrying of the Three (3) Layer CLT Panel Under Uniformly Distributed Vertical Load.

Recipe Priority [a]	Panel Title	Thickness	Wall Height				Removed CO_2 from Atmosphere	CLT CO_2 Benefit Compared to Concrete Wall
			2.7 m	3.0 m	3.5 m	4.0 m		
1	CLT 3/126	126 mm	300 kN/m	235 kN/m	185 kN/m	140 kN/m	-100 kg/m^3	151 kg/m^3
2	CLT 3/104	104 mm	215 kN/m	190 kN/m	150 kN/m	105 kN/m	- 83 kg/m^3	126 kg/m^3

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.

Table 15: Wall Load Carrying of the Five (5) Layer CLT Panel Under Uniformly Distributed Vertical Load.

Recipe Priority [a]	Panel Title	Thickness	Wall Height				Removed CO_2 from Atmosphere	CLT CO_2 Benefit Compared to Concrete Wall
			2.7 m	3.0 m	3.5 m	4.0 m		
1	CLT 5/210	210 mm	635 kN/m	590 kN/m	520 kN/m	440 kN/m	-161 kg/m^3	242 kg/m^3
2	CLT 5/166	166 mm	485 kN/m	420 kN/m	340 kN/m	255 kN/m	-127 kg/m^3	191 kg/m^3

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.

11. Red Stag CLT Stair Design

Red Stag CLT stairs are a significantly more cost-effective, lighter, more versatile, and faster to install than alternate stair systems. The performance specifications of Red Stag CLT stairs, generally allow them to be installed early in a project to provide safe access during the construction phase. Typically machined out of a solid CLT panel, Red Stag CLT stairs provide a high strength, robust and visually appealing substrate that generally only requires supporting at both ends to create a clean, clear span (Refer to *Figures 26*). Red Stag CLT stairs have an excellent fire rating due to the mass of the solid timber system.

The performance characteristics of the Red Stag CLT stairs are created from the layers under the plane generated from the underside of the treads and risers (the stringer). The machined section to create the treads and risers is effectively non-structural but is still bonded as a homogenous system with the stringer section of the stair substrate. The CLT under the treads and risers forms the stair stringer, which is designed to be capable of handling the bending moment that is created with applied loads, and the self-weight of the stair system. The vibrational performance of the CLT stringer is also calculated to confirm the dynamic behaviour of the Red Stag CLT stairs is not creating an uncomfortable functional environment for the building occupants.

Red Stag can optimise CLT stair designs based on the architectural and structural requirements; however, standardised specifications are summarised in *Table 16*. There are a wide range of CLT connection methods, fasteners, and details to connect Red Stag CLT stairs to landing areas or floor assemblies. Two cost efficient examples of Red Stag stair connections are illustrated in *Figure 27* and *Figure 28*.

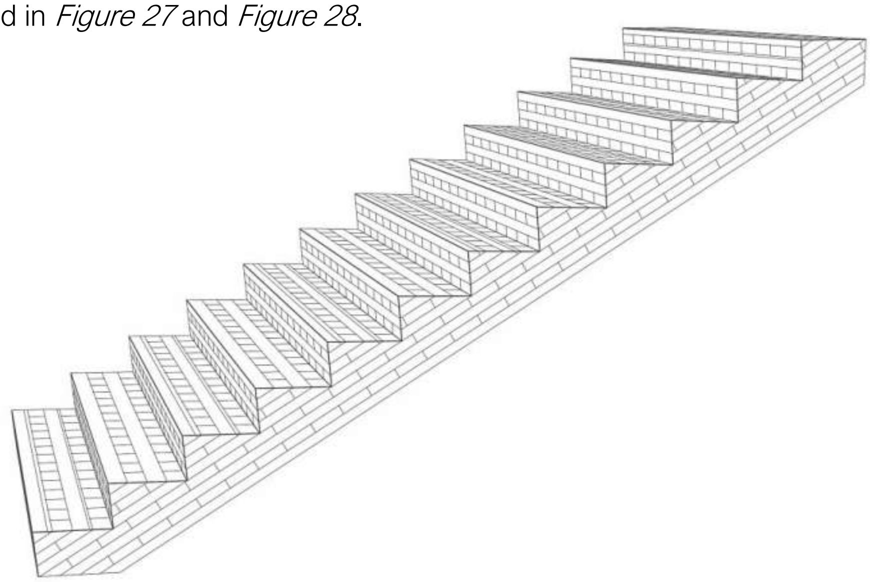


Figure 26: Example of the Red Stag CLT stairs

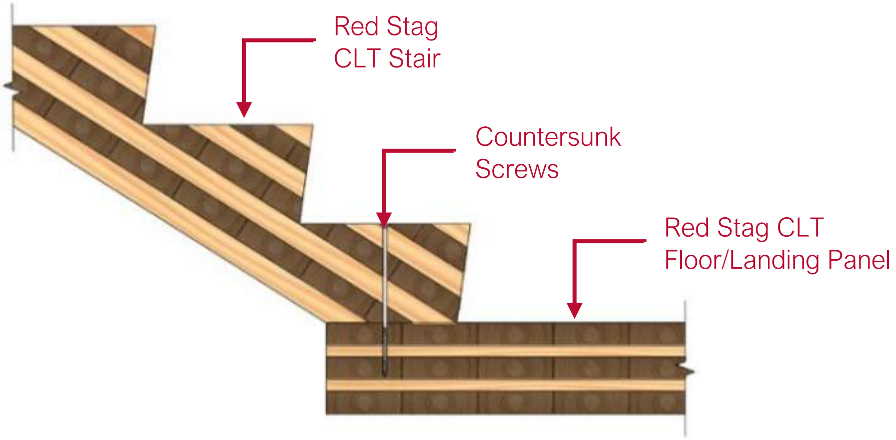


Figure 27: Example of Red Stag CLT stair panel base connection to CLT landing/floor panel.

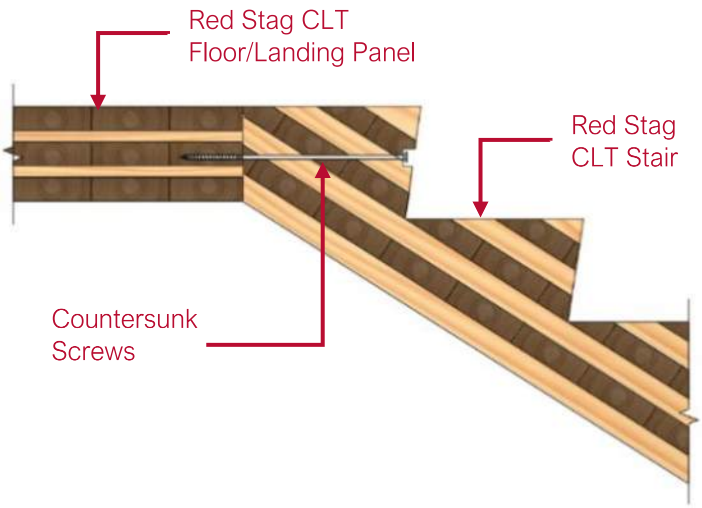


Figure 28: Example of Red Stag CLT stair panel upper connection to CLT landing/floor panel.

Table 17: Red Stag CLT Stair Spans [a, b, c, d, e, f, g]

Panel Title	CLT Panel Stringer	Stringer Thickness	Live Load (Imposed Load)				Removed CO_2 from Atmosphere	CLT Stairs CO2 Benefit Compare to Concrete Stairs
			2 kPa [b]	3 kPa [b]	4 kPa [b]	5 kPa [b]		
CLT7/126/294 [a]	CLT 3/126	126 mm	3.95 m[e]	3.73 m[f, h]	3.49 m[f]	3.31 m[f]	- 100 kg/m^3	151 kg/m^3
CLT9/210/378[a]	CLT 5/210	210 mm	5.47 m[e]	5.47 m[f]	5.19 m[f]	4.96 m[f]	- 161 kg/m^3	242 kg/m^3

a) CLTX/Y/Z, where X = Number of layers, Y = Stringer thickness, Z = Overall panel thickness.
b) Red Stag CLT Stairs are designed for a 2 kPa, 3 kPa, 4 kPa and 5 kPa Live Load (Imposed Load).
c) Red Stag CLT Stairs are designed based on 500 kg/m^3 for the CLT (CLT stringer & CLT Tread & Riser).
d) Red Stag CLT Stairs are designed for vibration based on the FPInnovation method.
e) Span limited by deflection.
f) Span controlled by vibration.
g) The maximum tread and riser dead load are generated by a 332 mm tread depth and 180 mm riser height, reflected in the calculation within *Figure 29*. All other tread/riser combinations reduce the dead loads incorporated in *Figure 29*.
h) Refer to *Section 7* for three (3) Layer Red Stag CLT Stair design example.

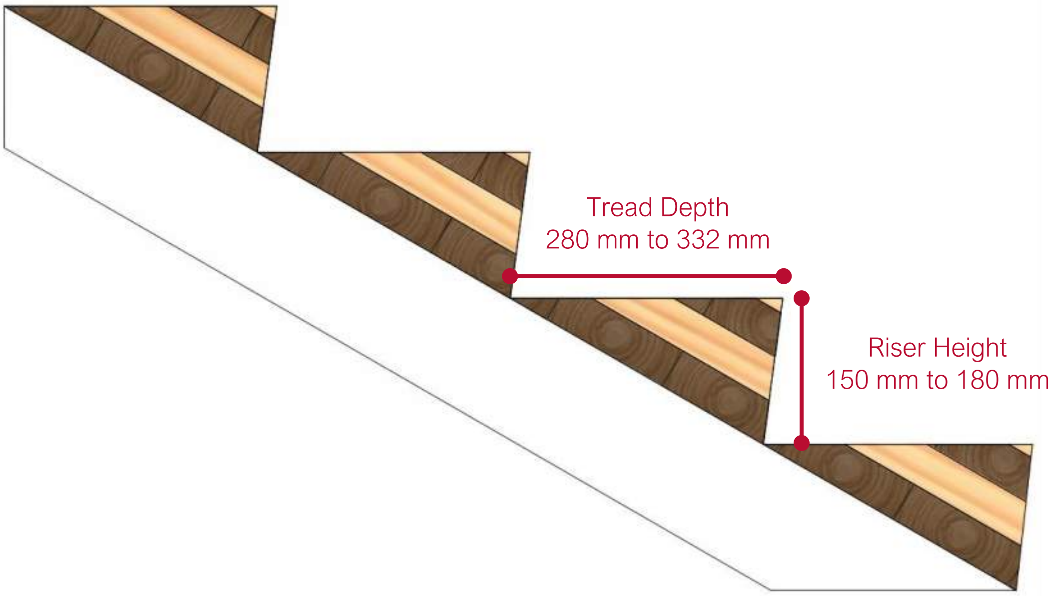
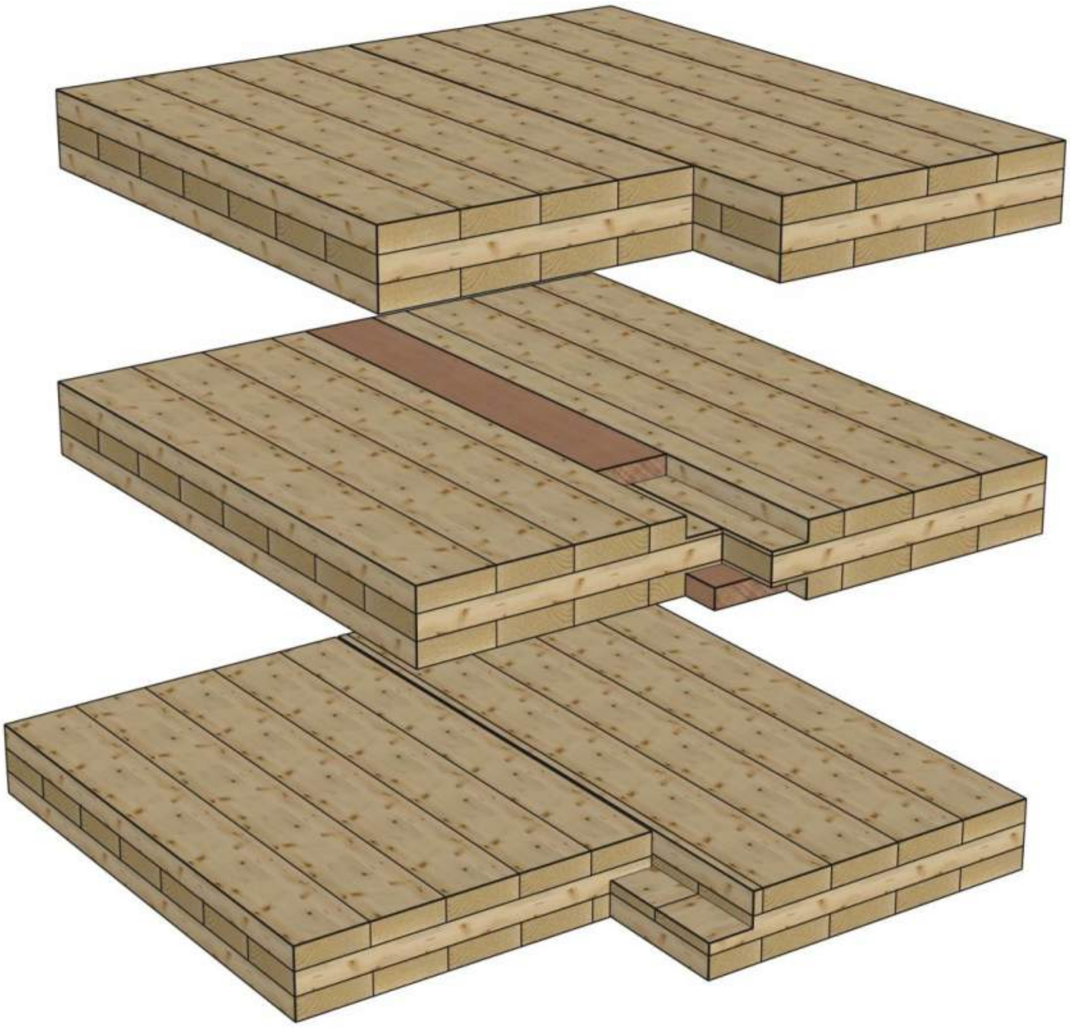


Figure 29: Pitch line, tread, and riser dimensions for common and main private stair ways.

Section 3

Cross Laminated Timber Connections



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12. General Overview of CLT Connections

Screw connections play an essential role in maintaining the integrity of CLT structures by providing supporting strength, stiffness, stability, and ductility. The structural efficiency of a CLT flooring system acting as a rigid or flexible diaphragm, with walls in resisting lateral loads depends on the efficiency of the fastening systems and connection details used to interconnect individual panels and assemblies together. A wide range of partially and fully threaded self-tapping screw options are available from fixing providers (Refer to *Figure 30*). Short self-tapping screws are commonly used for connecting CLT floor panels together, and long self-tapping screws are generally used for connecting CLT floor panels to CLT wall panel assemblies (Refer to *Figure 31 and Figure 32*). There are other types of traditional and innovative fasteners and fastening systems that can also be used in CLT assemblies.

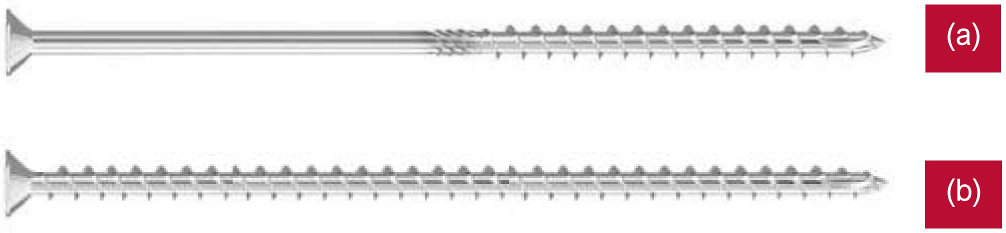


Figure 30: A partially threaded screw versus a fully threaded screw; a) Partially threaded screw, b) Fully threaded screw.

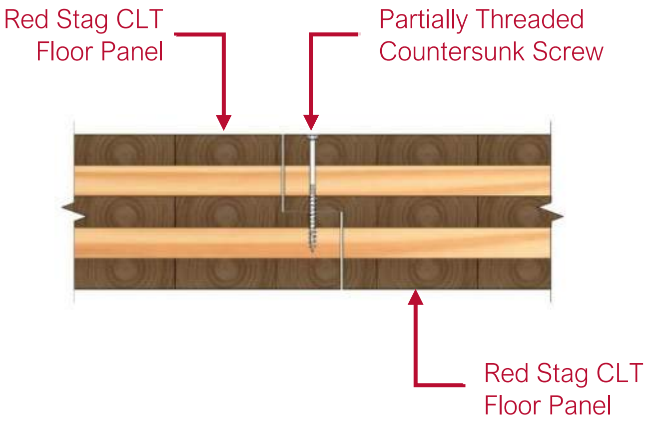


Figure 31: Red Stag CLT floor panel to Red Stag CLT floor panel connection.

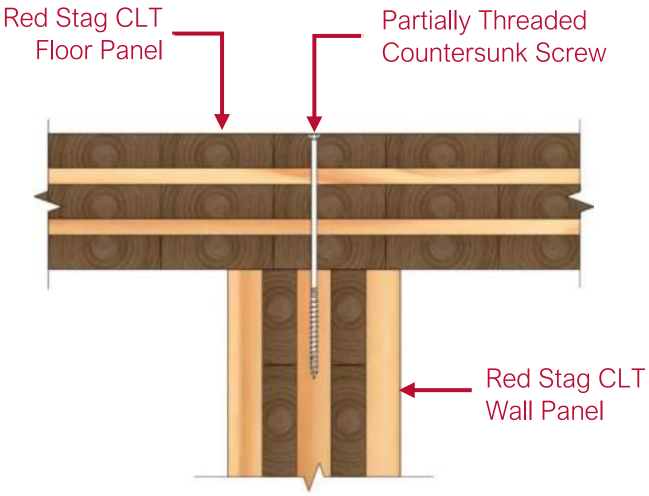


Figure 32: Red Stag CLT floor panel to Red Stag CLT wall panel connection.

13. Butt Joint Connection

The butt joint is the simplest connection type from a fabrication perspective, as the panels only have plumb cuts. Minor processing reduces both machine time and material waste to make it the most efficient joint in factory. But joints are connected via angled self-tapping screws, installed at precise angles. The screws typically penetrate the shear plane at half of the panel thickness, generally at a 45° angle. Intersecting the joint at half the panel thickness, the screws are loaded perpendicular to their longitudinal axis (Refer to *Figure 33* to *Figure 34*).

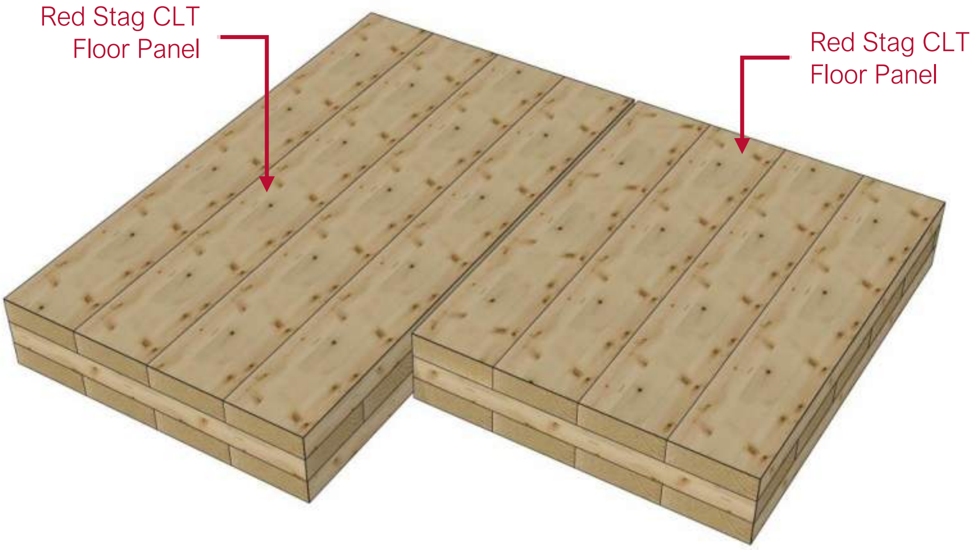


Figure 33: 3D view of butt joint connection.

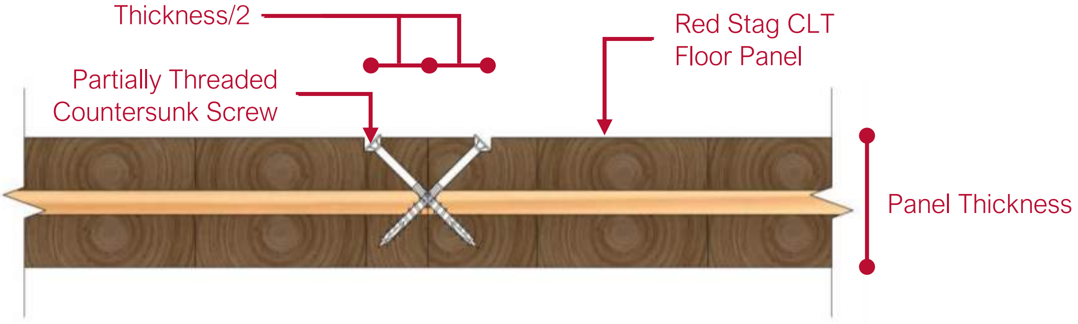


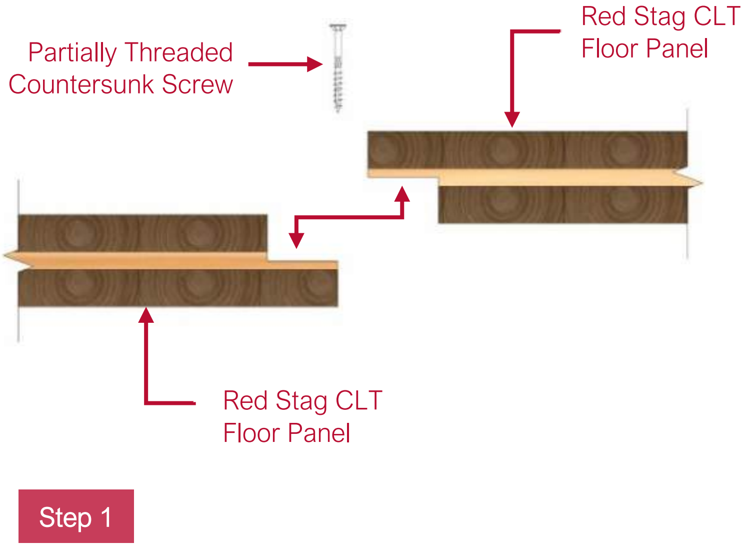
Figure 34: Cross-section detail of butt joint connection.

14. Half-Lap Joint Connection

Half-lap joints require more prefabrication than butt joints and increase the panel wastage for the overlap, but simplify the site installation time. The joints are connected via self-tapping screws, driven at a 90° angle, and act in pure shear at half the panel thickness. Assembly details of the half-lap joint are presented in *Figure 35*. Half-lap joints offer the largest variety of connection performances. Technically half-lap joints can resist in-plane shear and normal forces, but are not considered to be a moment resisting connection (Refer to *Figure 36*).

While the half-lap joint is a very simple connection that facilitates quick assembly, there is a risk of splitting of the cross-section due to the concentration of tension perpendicular to grain stresses in the rebated section.

If the load at the half-lap joint is substantial, there could be a tendency for the panel to split at or near the joint. To minimise the risk, reinforcing screws should be considered (refer to *Figure 37*). Another disadvantage is the loss of fibre and the reduced installed width of the panel in comparison with other types of connections such as butt and spline (refer below) joints. Red Stag offers an 80 mm half-lap to minimize the disadvantage of the fibre loss and balances the fire protection compared to narrower half-lap joint sizes, which transfer heat faster during a fire event (refer to *Figure 38*).



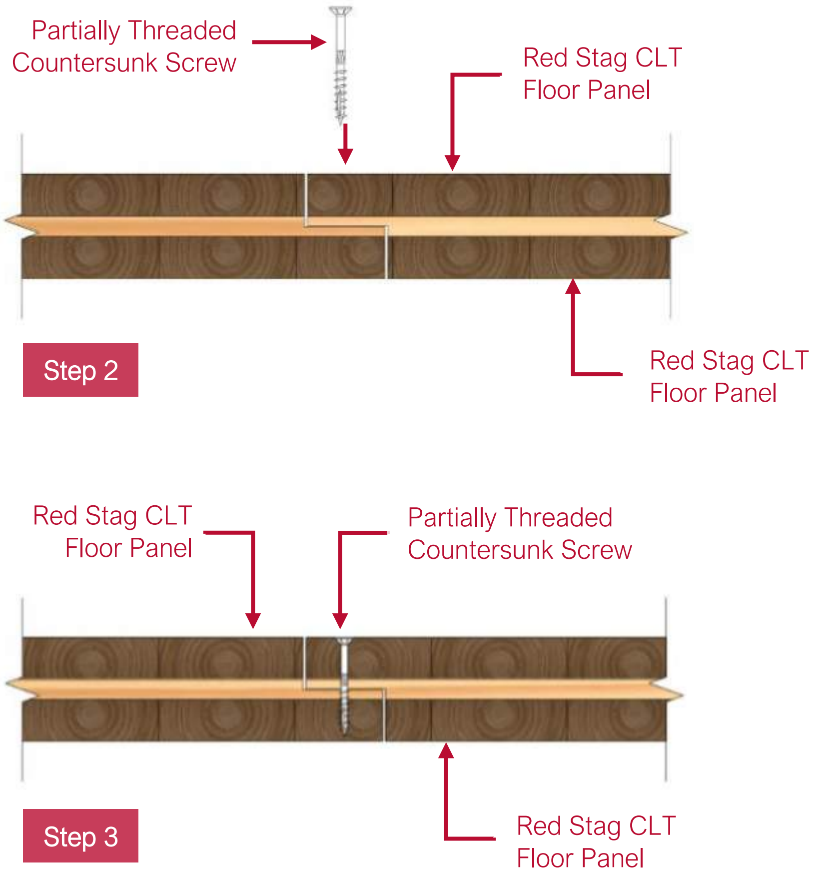


Figure 35: Assembly details of the half-lap joint.

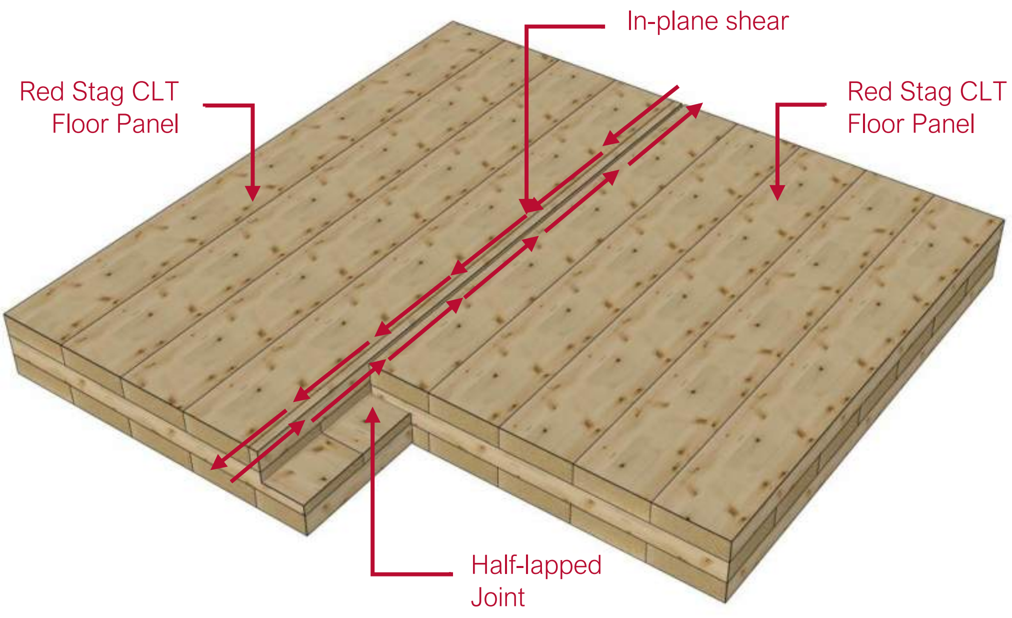


Figure 36: In-plane shear along the half-lap joint between two Red Stag CLT panels.

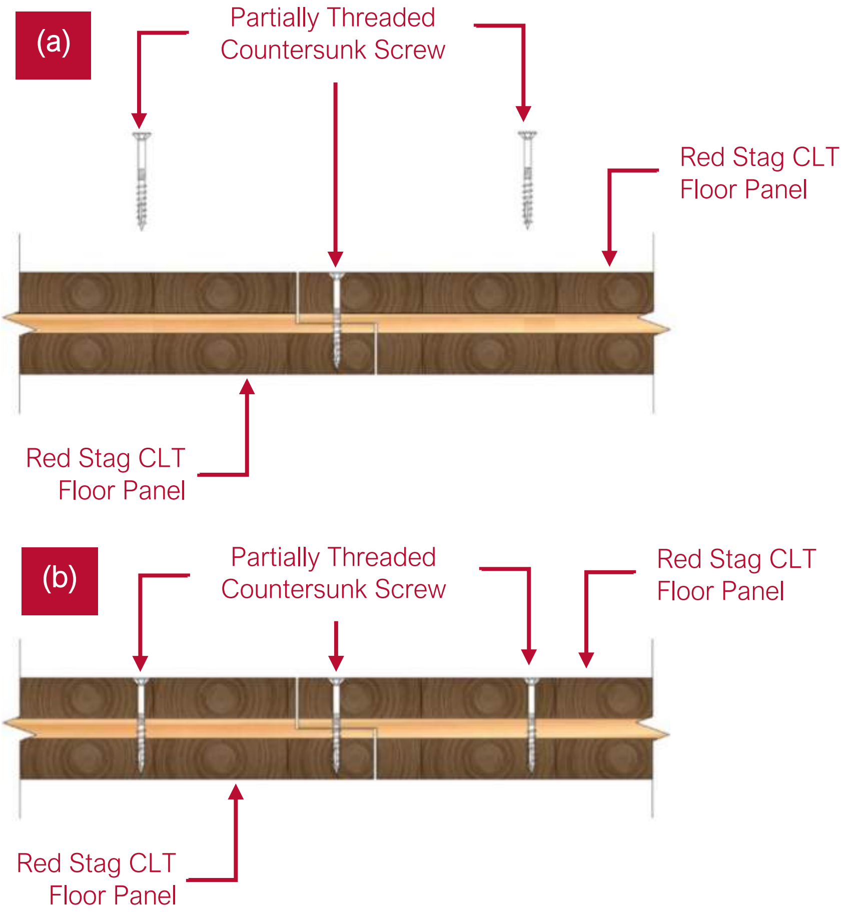


Figure 37: Reinforcing screws to reduce the risk of splitting.

a) Before Reinforcement, b) After Reinforcement.

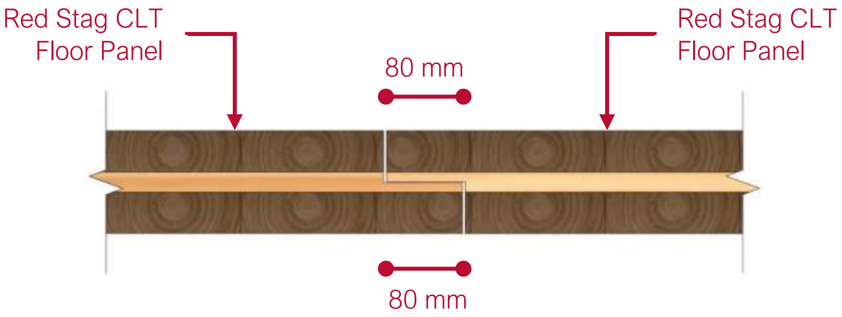


Figure 38: Optimum size half-lap joint (80 mm).

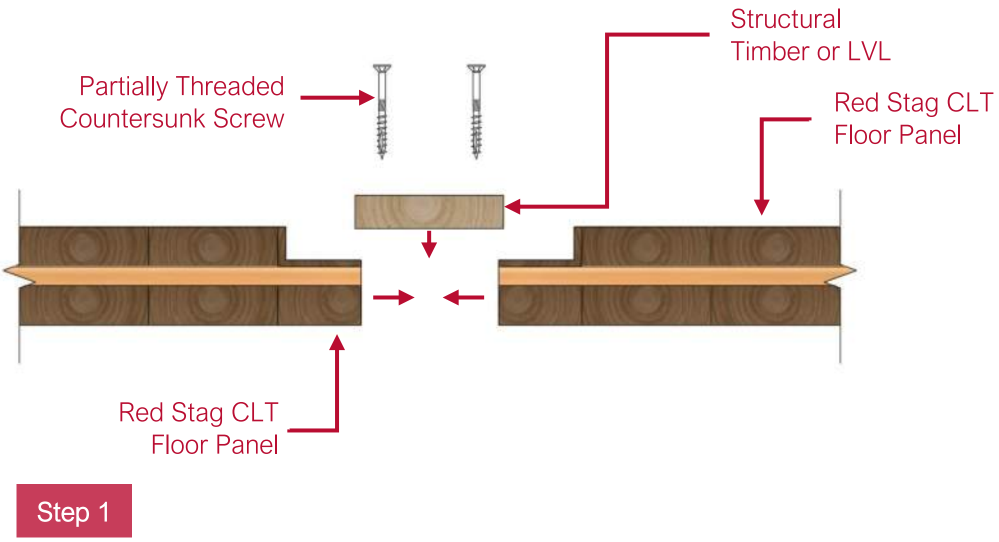
15. Spline Joint Connections

Spline joints are formed by rebating the edge of a butt joint to allow for a spline or board to bridge either side of the joint. Splines are typically made from solid structural timber, ply strips or Laminated Veneer Lumber (LVL) where longitudinal shear is more critical. Splines are fastened with a series of short self-tapping screws, creating a pure shear connection. Assembly details of a single spline joint is presented in *Figure 39*.

If the longitudinal shear along the connection line is very high, a double surface spline joint connection is recommended to increase the strength and stiffness of the connection (*Figure 40*). The four rows of fasteners support in double the number of shear planes resisting the load (Refer to *Figure 41 and Figure 42*).

To provide sufficient clearance between the upper and lower spline joint screw lines or to provide even larger shear resistance, it may be necessary to have one spline wider than the other as represented in in *Figure 43*.

A singe surface spline joint is the second most efficient (butt joints are the most efficient) and cost effective machined joint as it allows for all in factory machining to be processed without flipping panel and it maximises the utilisable panel area (overlaps in lap joints reduce utilisable surface area). Double surface spline joints require panels to be flipped, therefore when combined with dual screw lines on both sides of the panel, create a complex machine and labour-intensive connection detail.



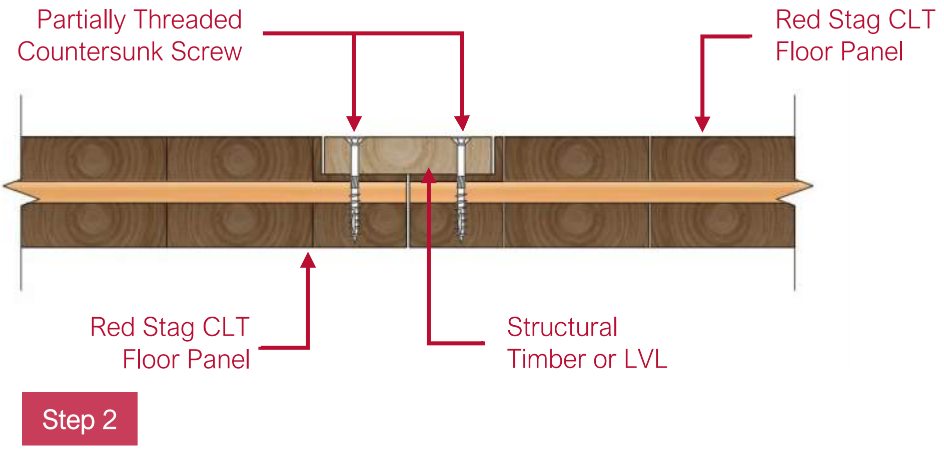


Figure 39: Assembly details of the single surface spline joint.

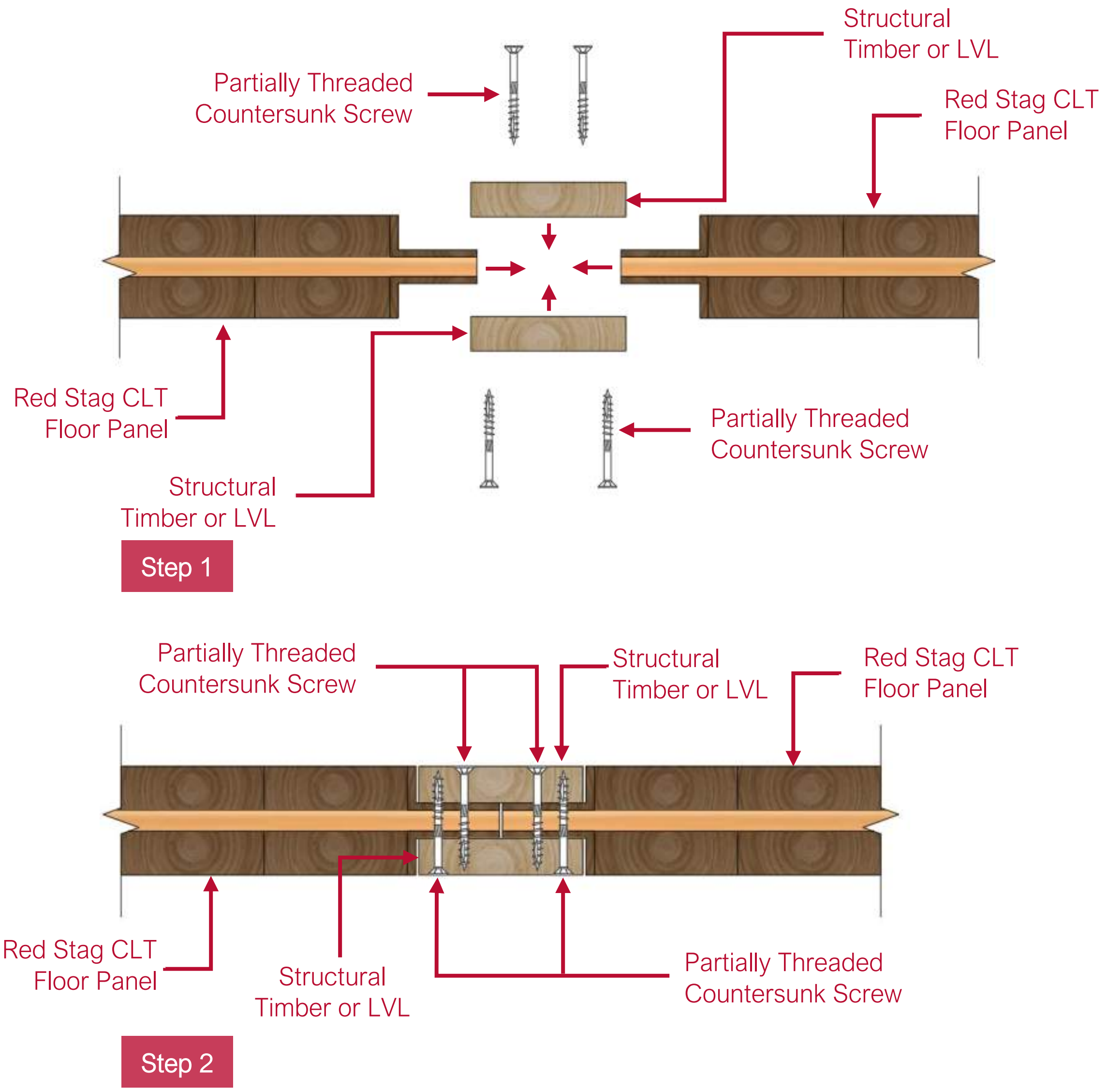


Figure 40: Assembly details of the double surface spline joint.

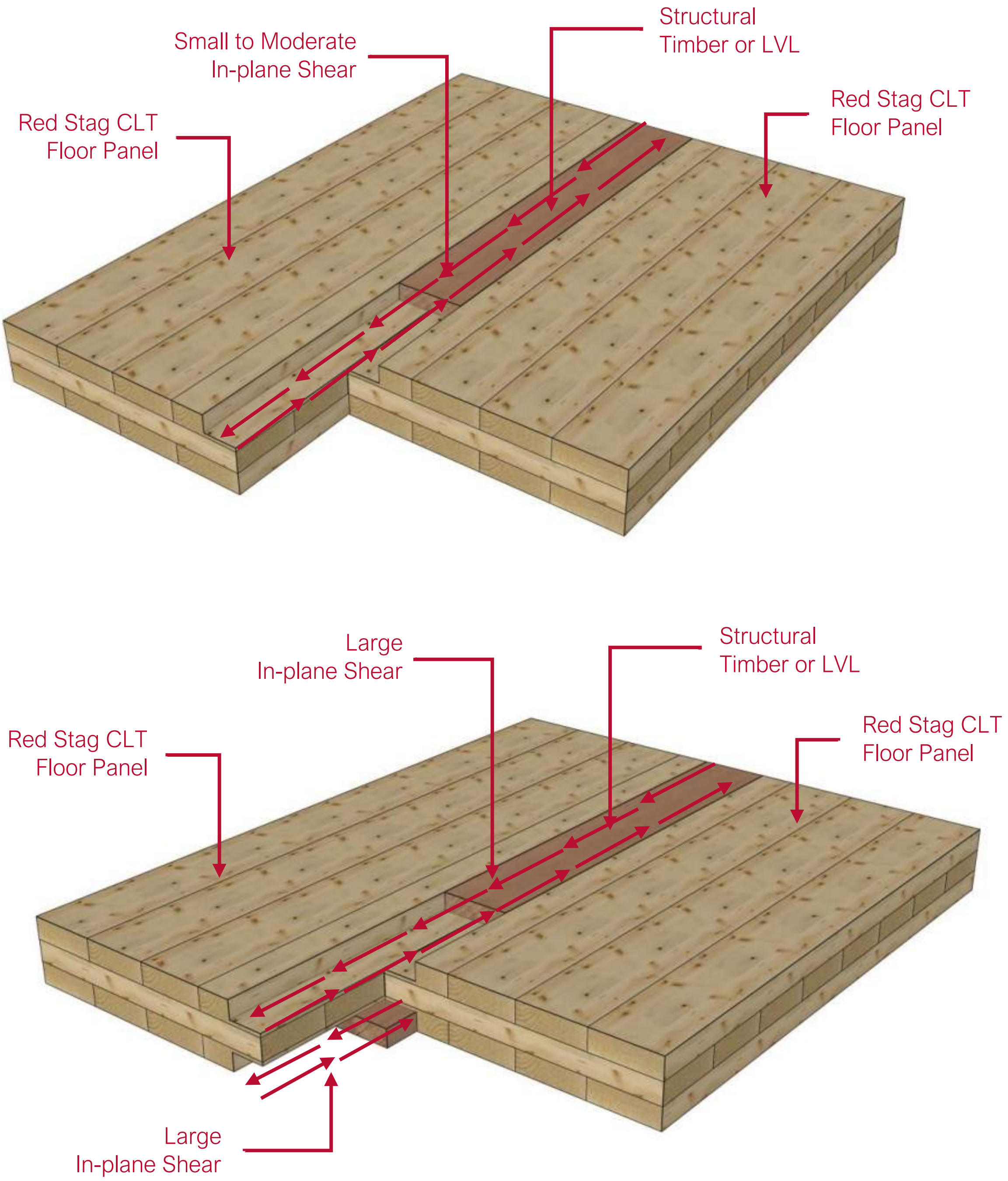


Figure 41: Longitudinal shear along the connection line in single and double surface spline joints.

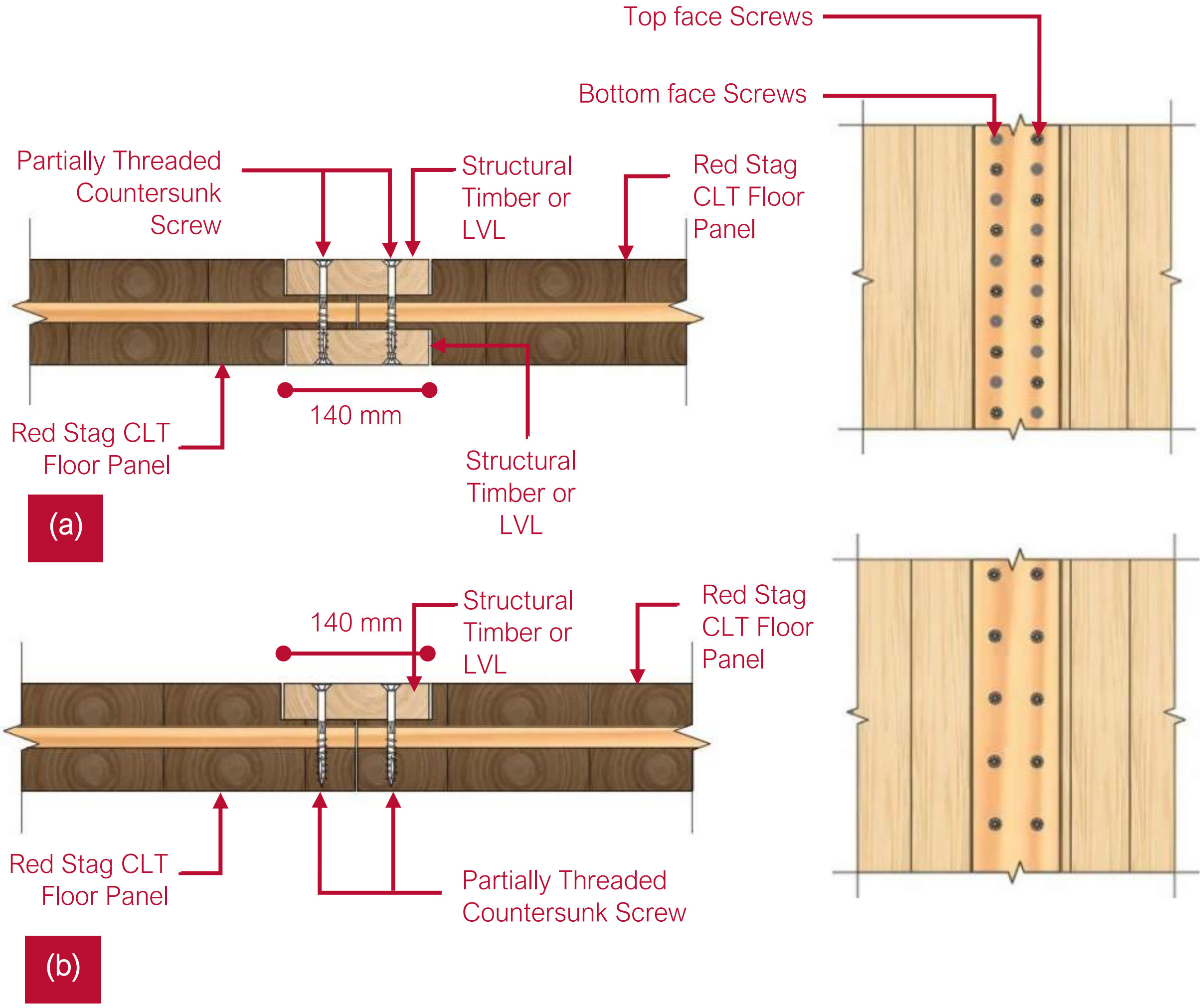


Figure 42: Screw spacing in a single surface spline joint versus a double surface spline joint. Double surface spline joints require sufficient space for double the number of fasteners. a) Double surface spline joint; b) Single surface spline joint.

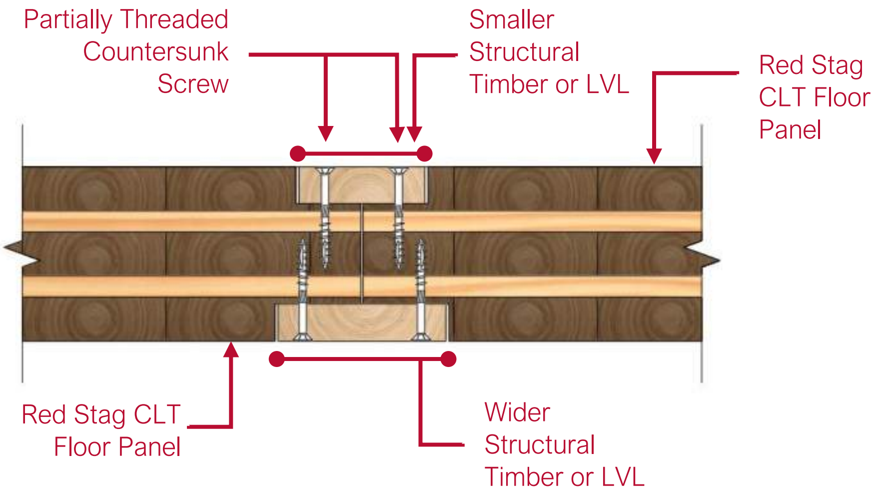


Figure 43: Screw layout for a double surface spline joint with an asymmetric timber spline plate.

16. Common Structural Connections

There are a wide range of CLT connection methods and fasteners available to combine floor, wall, and roof assemblies. A series of some of the most common structural connection details in timber and hybrid buildings are illustrated below in *Figures 44* to *56*.

16.1. Red Stag CLT Wall Panel to Concrete Foundation/Floor Connection

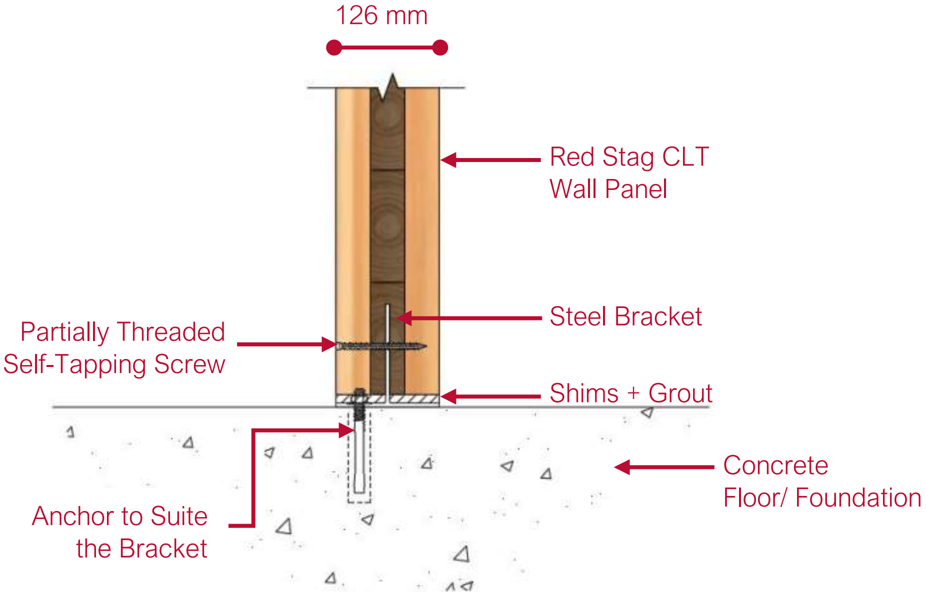


Figure 44: Internal Red Stag CLT wall to the concrete foundation/floor connection.

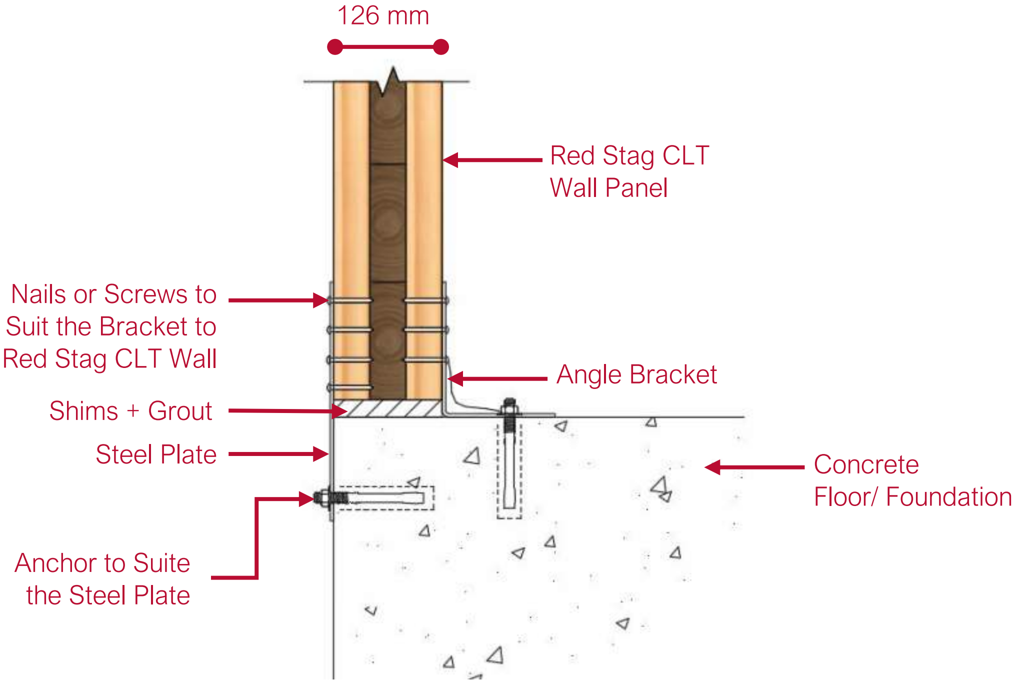


Figure 45: Red Stag CLT wall panel to the concrete foundation/floor (On edge of external walls of the building).

16.2. Red Stag CLT Wall Panel Connection

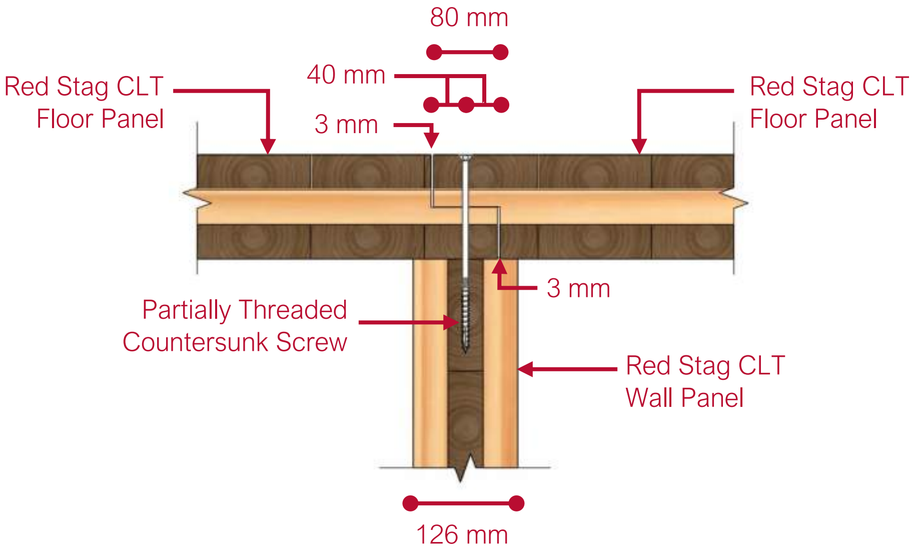


Figure 46: Red Stag three (3) Layer CLT wall panel to CLT floor panel half joint connection.

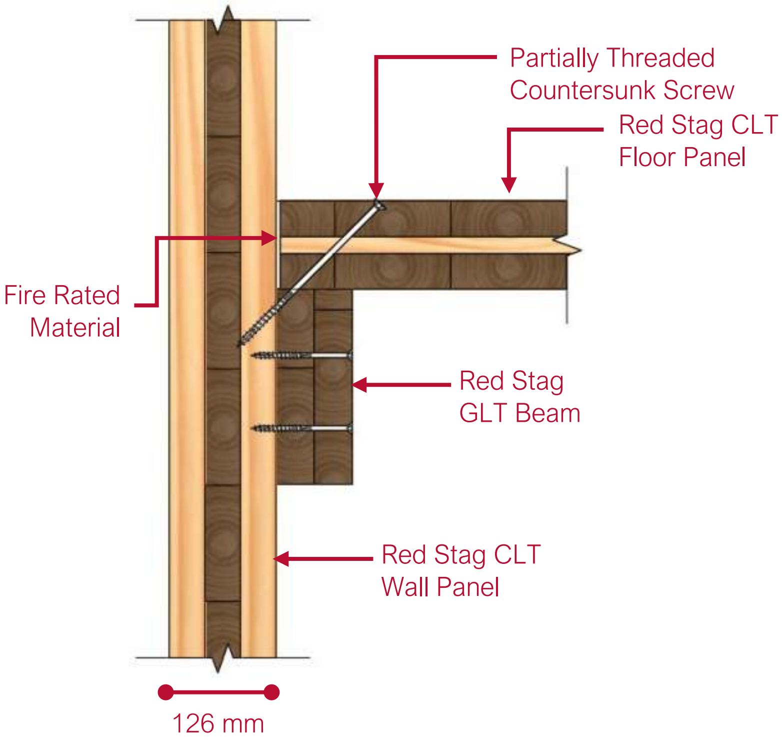


Figure 47: Red Stag CLT wall panel to CLT floor panel (On edge of external walls of building).

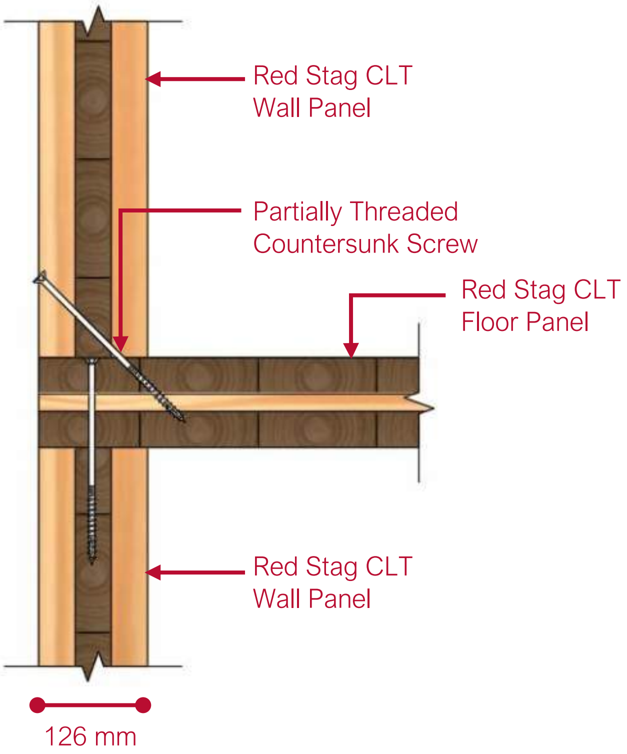


Figure 48: Red Stag CLT wall panel to CLT floor panel.

16.3. Red Stag CLT Roof Panel Connection

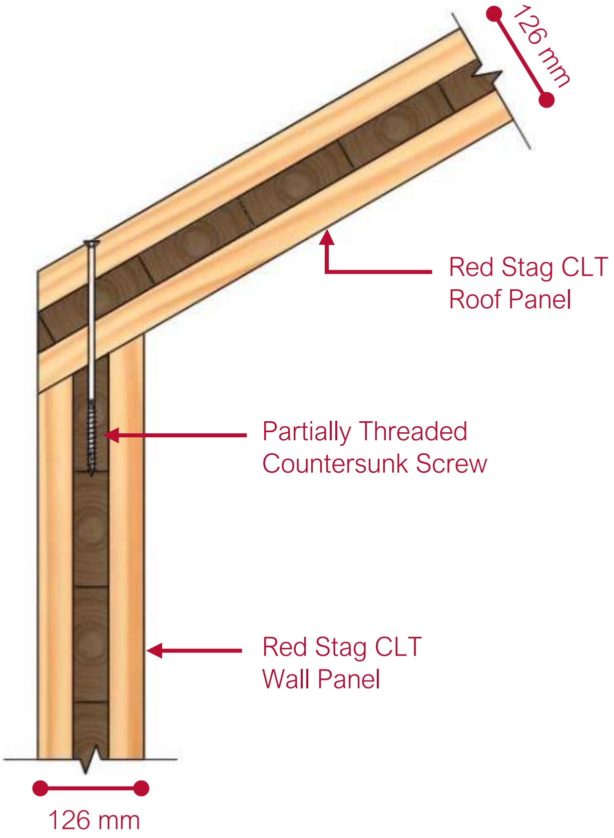


Figure 49: Red Stag three (3) layer CLT roof panel to CLT wall panel connection.

16.4. Mixed Timber Connection to Red Stag CLT Connections

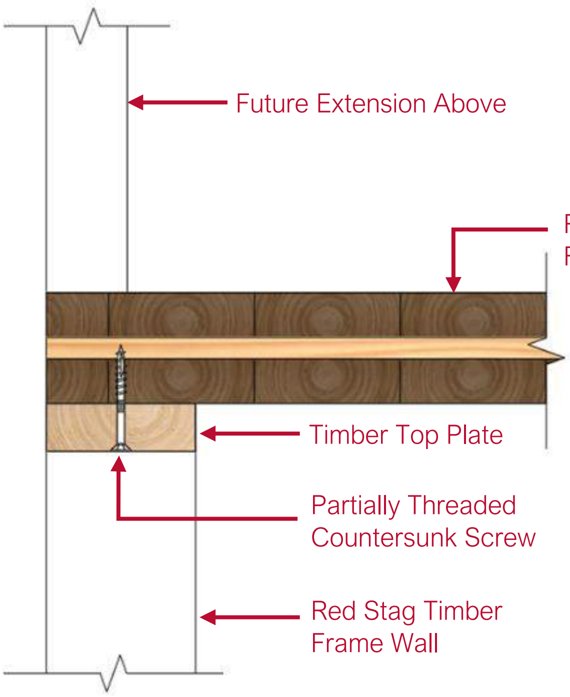


Figure 50: Timber frame wall to Red Stag CLT floor panel connection.

16.5. Red Stag CLT Floor Connection

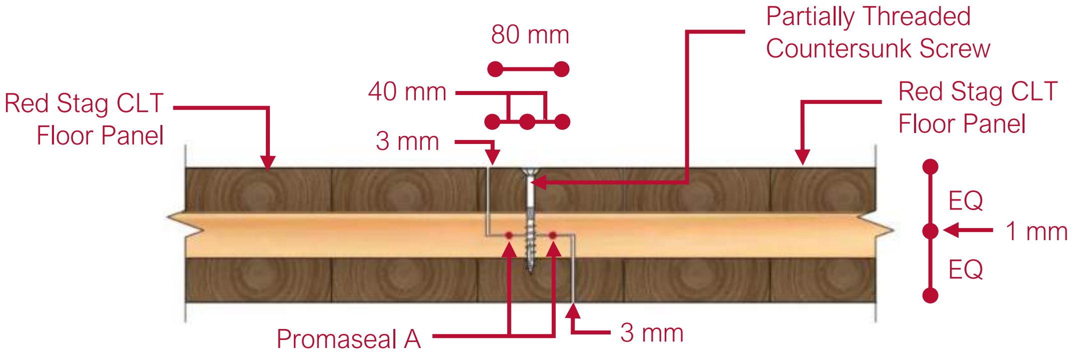


Figure 51: Red Stag three (3) layer CLT floor to floor half-lap joint connection.

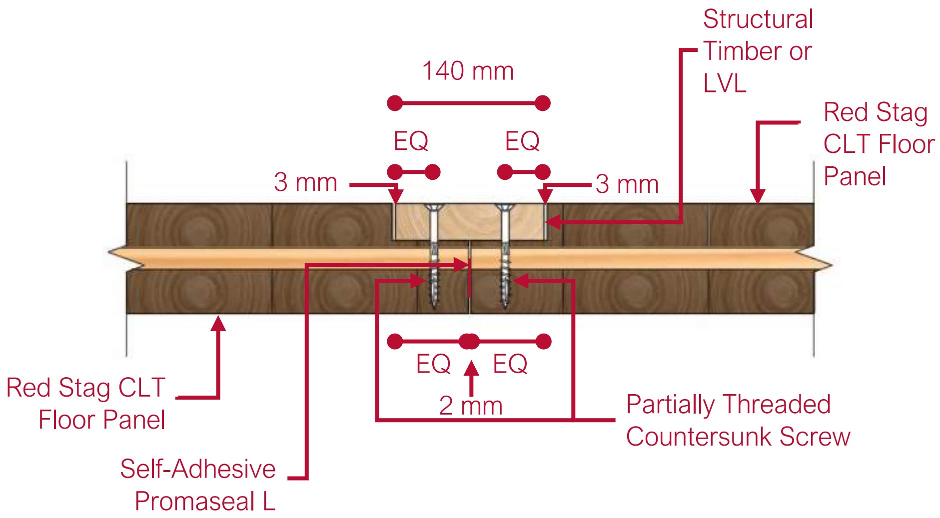


Figure 52: Red Stag three (3) layer CLT floor to floor with spline plate connection.

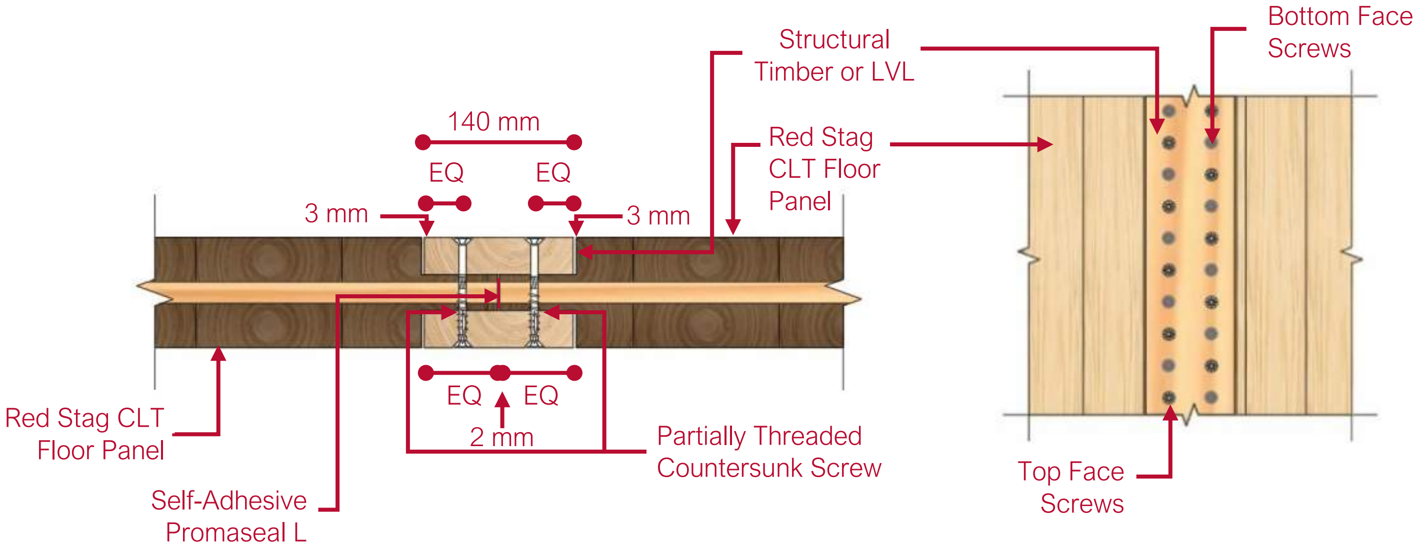


Figure 53: Red Stag three (3) layer CLT floor panel to floor panel with double spline plate connection.

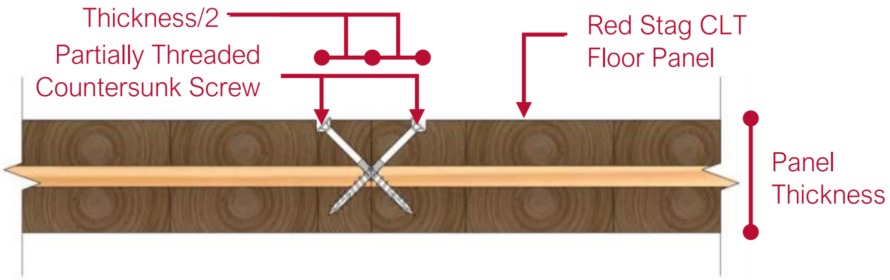


Figure 54: Red Stag three (3) layer CLT floor to floor butt joint connection.

16.6. Red Stag CLT Stair Connection Details

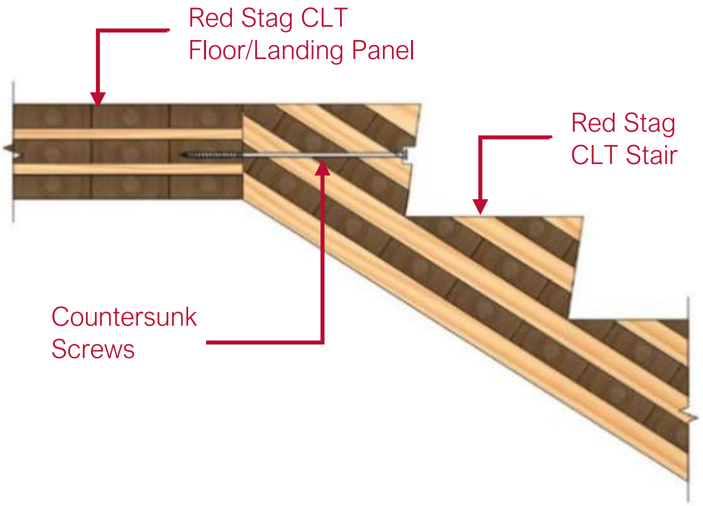


Figure 55: Red Stag CLT stair panel to CLT landing/floor panel connection.

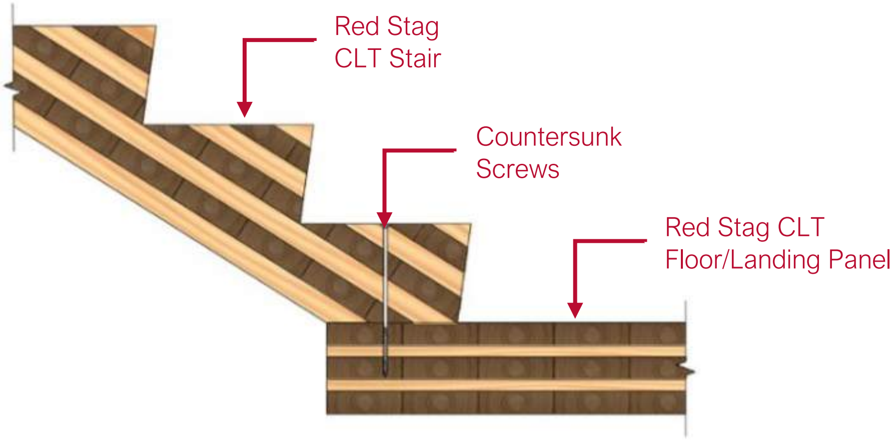


Figure 56: Red Stag CLT stair panel to CLT landing/floor panel connection.

17. Fastener Placement in CLT Panels

a

New clauses were introduced into the Canadian CLT standard to specify the minimum spacing of fasteners installed in the panel edge of CLT. The new requirements are intended to limit issues associated with splitting of timber. For bolts, lag screws, nails and self-tapping screws in the edge of CLT panels, the minimum fastener spacing should be in accordance with *Table 17* and *Figure 57* for three layer panels and *Table 18*, *Table 19* and *Figure 58* for five layer panels.

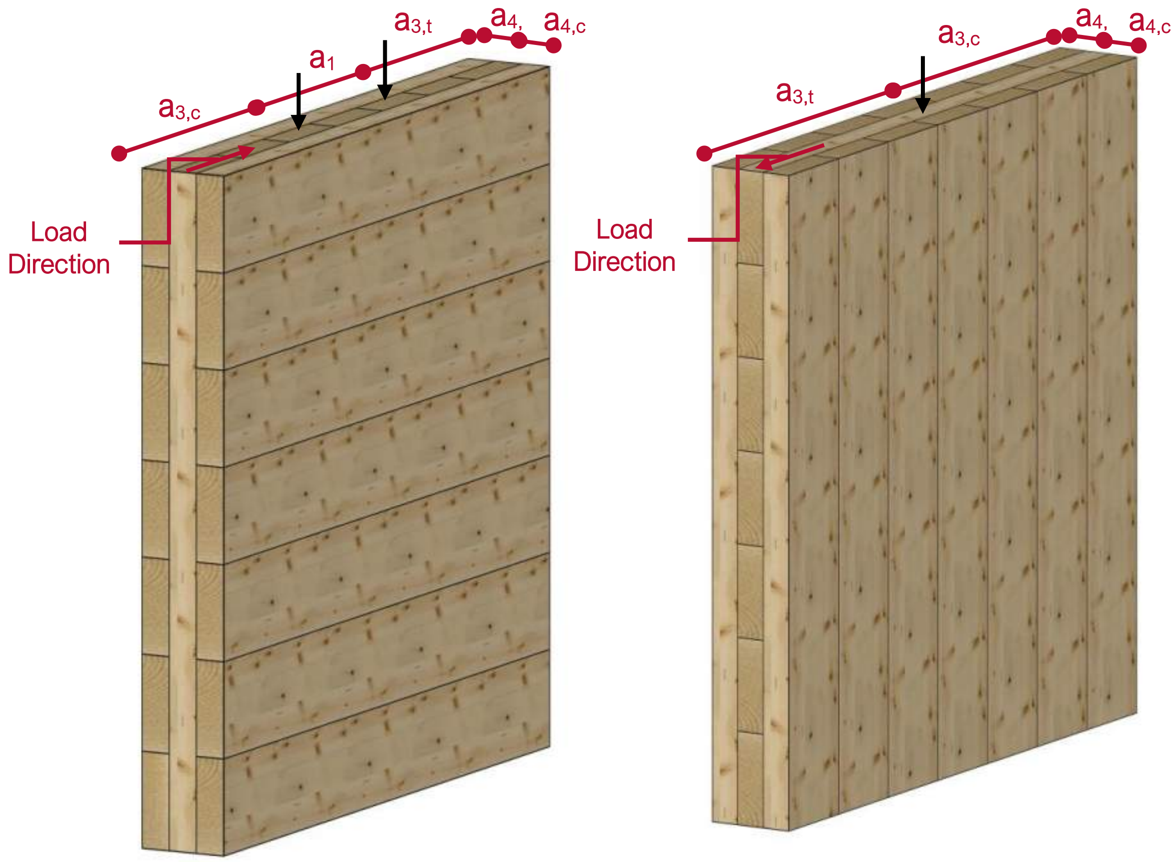


Figure 57: Spacing placement of fasteners on the edge of CLT panels.

Table 17: Spacing of self-tapping screws in CLT Panels [11]

Symbol	Minimum Spacing
a_1	10 × diameter
a_2	3 × diameter
$a_{3,t}$	12 × diameter
$a_{3,c}$	7 × diameter
$a_{4,c}$	5 × diameter

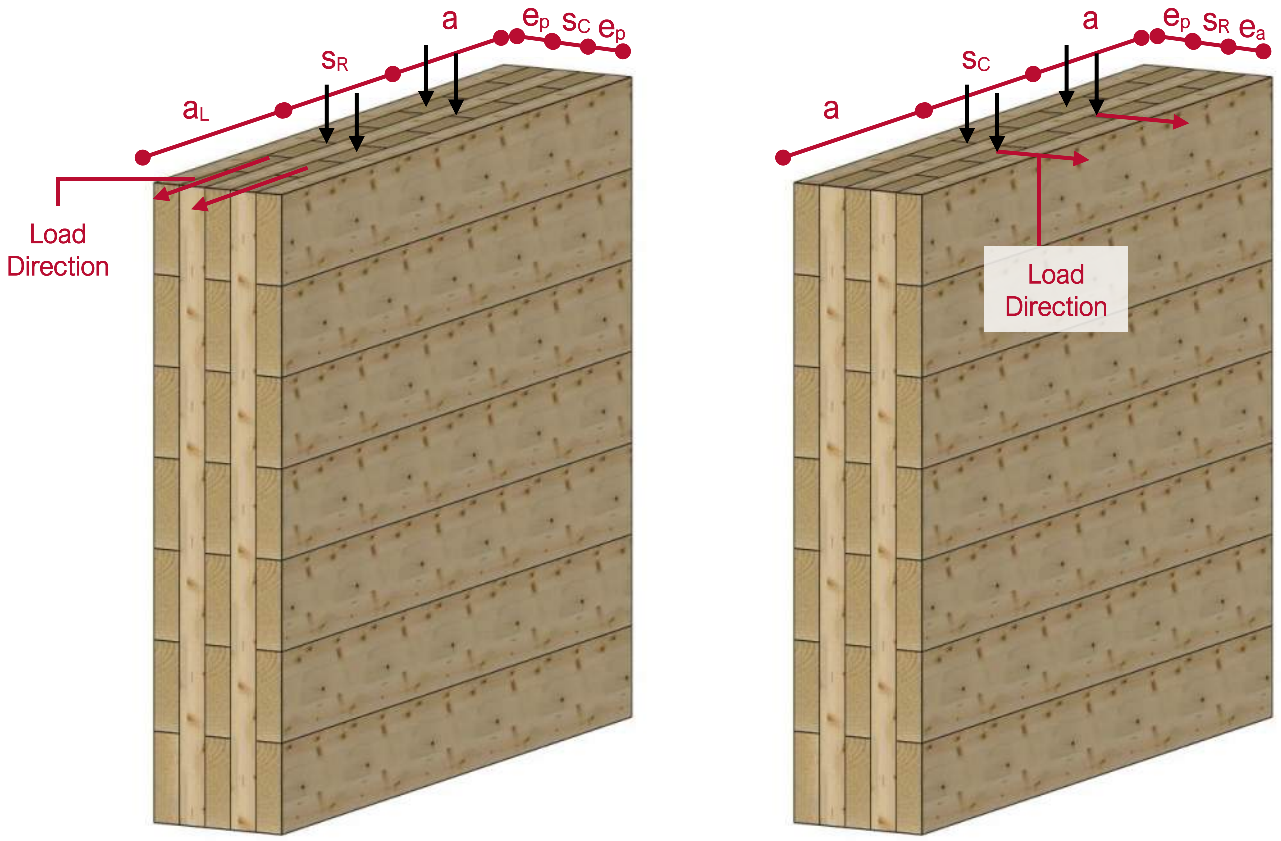


Figure 58: Spacing placement of the fasteners on the edge of CLT panels.

Table 18: Spacing of self-tapping screws and nails in CLT Panels [11]

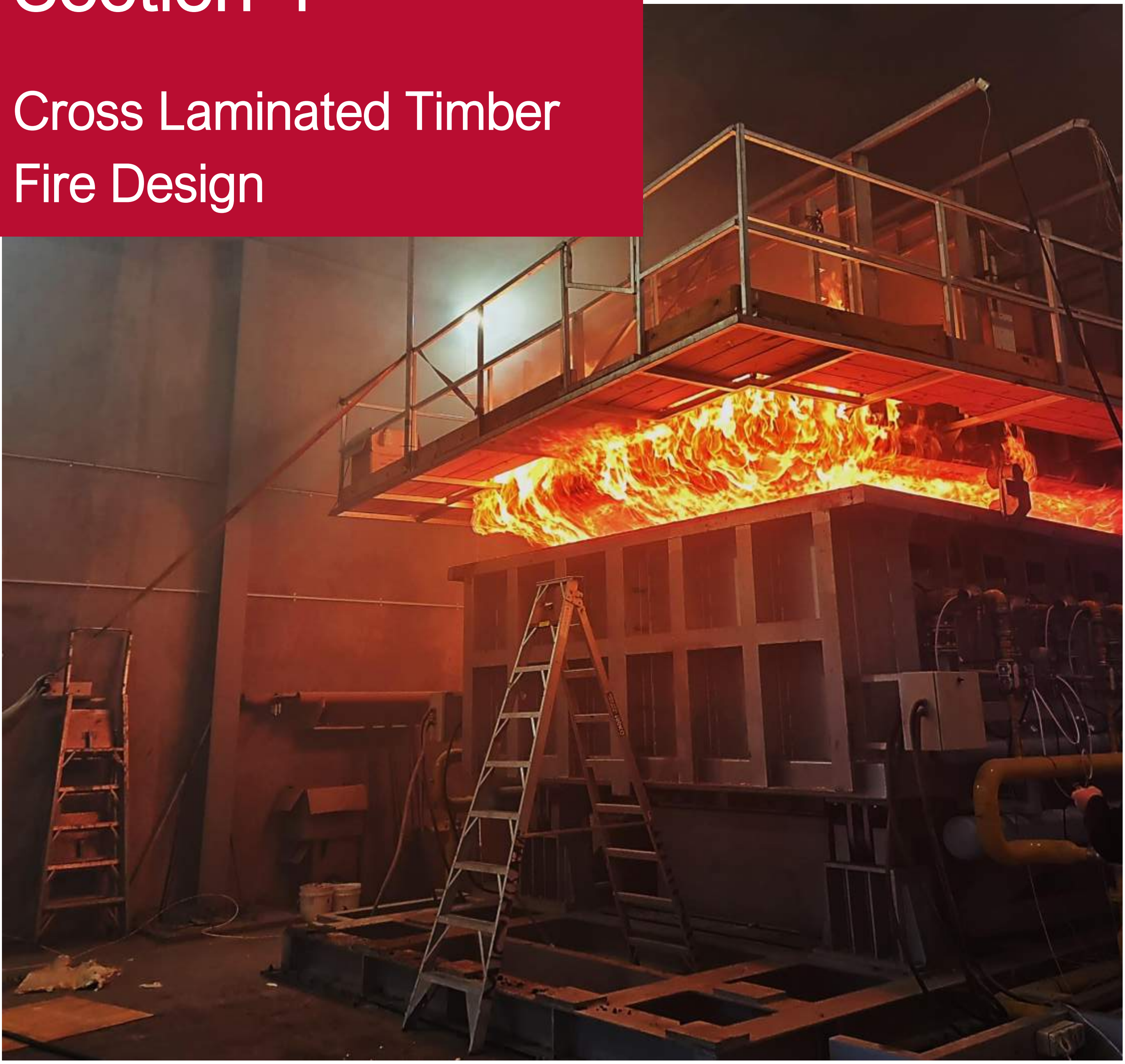
Symbol	Dimension	Minimum Spacing
s_R	Spacing parallel to the load direction	10 × diameter
s_C	Spacing perpendicular to the load direction	4 × diameter
a	End distance	7 × diameter
a_P	Unloaded end distance	7 × diameter
a_L	Loaded end distance	12 × diameter
e	Edge distance	3 × diameter
e_P	Unloaded edge distance	3 × diameter
e_Q	Loaded edge distance	6 × diameter

Table 19: Spacing of bolts and lag screws in CLT Panels [11]

Symbol	Dimension	Minimum Spacing
s_R	Spacing parallel to the load direction	3 × diameter
s_C	Spacing perpendicular to the load direction	3 × diameter
a	End distance	Maximum (4 × diameter or 50 mm)
a_P	Unloaded end distance	Maximum (4 × diameter or 50 mm)
a_L	Loaded end distance	Maximum (4 × diameter or 50 mm)
e	Edge distance	1.5 × diameter
e_P	Unloaded edge distance	1.5 × diameter
e_Q	Loaded edge distance	5 × diameter

Section 4

Cross Laminated Timber Fire Design



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18. CLT Exposed to Fire

If CLT is exposed to fire or an elevated supply of energy, its temperature increases, and the water molecules embedded within the system start to evaporate at 100 °C. At 200 – 300 °C, the long-chain molecules in the cell walls split, producing gaseous and flammable compounds. The gas subsequently enters the surface of the wood where it reacts with oxygen in the air and combusts [23].

These chemical compounds decompose in a process known as “pyrolysis” (whereby gas emissions from combustible components in the wood burst into flame), gradually spreading along the wood, leaving a charring area behind it. This char layer is formed from the carbonaceous residue of pyrolysis, which burns, generating embers. This layer, which has low density and high permeability acts as heat insulation and protects the underlying, undamaged wood.

19. Fire Resistance Rating (FRR) of CLT

The primary objectives for CLT fire designs are to:

1. Maximise the resistance to fire.
2. Prevent the spread of fire.
3. Stop the building collapsing due to fire.
4. Support fire remediation if a fire event occurs.

Fire Resistance and Fire Reaction terms are used when referring to fire protection products:

- **Fire Reaction:** An indication of how CLT responds to fire, whether it flares or contributes to the spread of fire.
- **Fire Resistance:** Measures how well CLT performs in containing the fire, preventing it from spreading elsewhere.

Different construction elements are given a rating for how well they perform during fire testing. This is affected by their resistance to fire and their reaction to fire. Fire rating performance is referred to as FRR in the New Zealand fire safety Acceptable Solutions and Verification Methods (compliance documents).

FRR is described using three numbers that together refer to the structural adequacy (Structural resistance), integrity and insulation. It may be described differently in other jurisdictions (refer to *Figure 59a* to *Figure 59c*).

Common representations of FRR ratings are as follows:

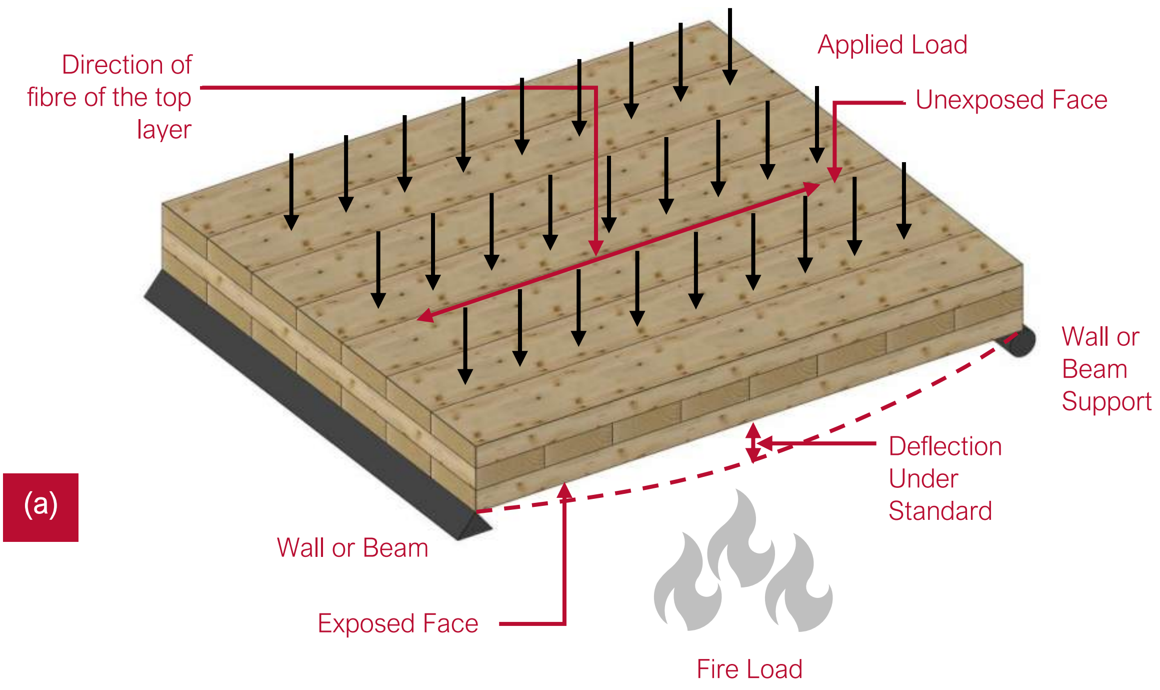
- **30/30/30:** 30 minute Structural Resistance; 30 minutes Integrity; 30 minute Insulation rating.
- **60/60/60:** 60 minute Structural Resistance; 60 minutes Integrity; 60 minute Insulation rating.
- **-/30/60:** Structural Resistance rating not applicable; 30 minutes Integrity; 60 minute Insulation rating.
- **120/-/-:** 120 minute Structural Resistance; Integrity rating not applicable; Insulation rating not applicable.

The FRR numbers refer to the time in minutes for which each of the criteria are satisfied when the element is exposed to temperature, pressure and applied load specified in the test procedure. A dash indicates the reference test or performance is not applicable.

Figure 59a describes the structural adequacy of CLT. This is the ability to support a specified applied load and only applies to loadbearing elements in a structure. The assembly must support the applied load for the duration of the test (relates to the loadbearing function).

Figure 59b describes the element's integrity. This is the ability of the CLT element to prevent hot gasses or flames from penetrating on either side of the element for the defined amount of time. After this time, the element would be at risk of developing cracks or openings, through which hot gases and smoke could pass.

Figure 59c describes the element's insulation. This is the ability to limit the temperature rise on the non-fire face (unexposed face) of the CLT element. The CLT element must prevent the rise in temperature being greater than 180°C at any location, or an average of 140°C measured at several locations, above the initial temperature (relates to the separating function).



(a)

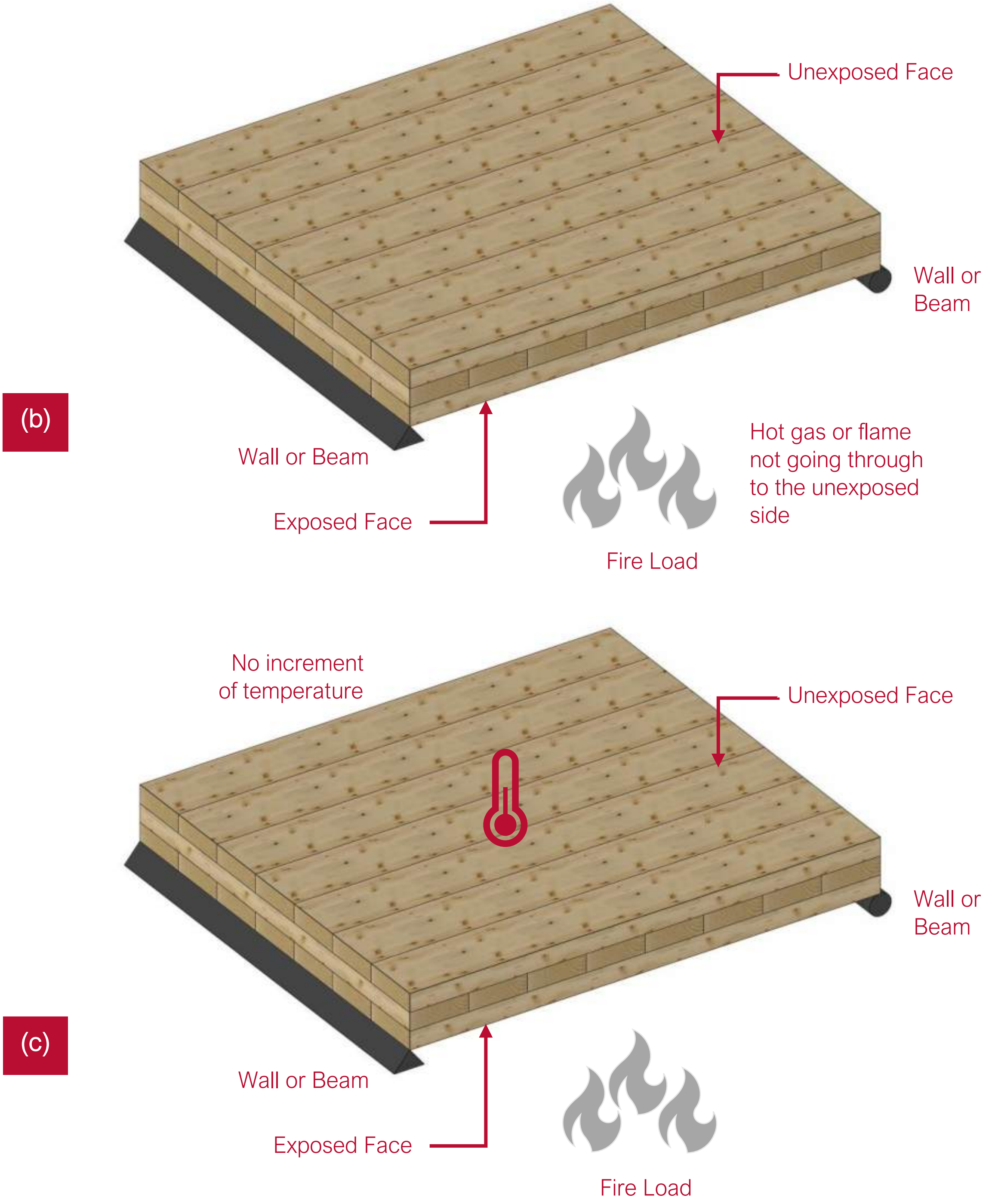


Figure 59: (a) Fire testing confirmed that a 103.5 mm thick Red Stag CLT panel satisfied the structural adequacy for 60 minutes during fire testing, (b) Fire testing confirmed that a 103.5 mm thick Red Stag CLT panel satisfied the integrity requirements for 60 minutes during fire testing, (c) Fire testing confirmed that a 103.5 mm thick Red Stag CLT panel satisfied the insulation requirements for 60 minutes during fire testing.

One of the major advantages of CLT is its natural fire resistance. CLT can be designed to accommodate substantial fire resistance and unlike steel, CLT remains structurally stable when subjected to high temperatures. CLT panels can be produced with fire resistances of 30, 60 and 90 minutes. As a general rule, well designed CLT buildings can provide similar levels of fire safety as steel or concrete buildings. CLT construction typically uses CLT panels for floor and loadbearing walls, which can provide fire-rated compartmentalisation to further reduce the risk of fire spread beyond its point of origin.

20. CLT Charring Behaviour

Red Stag CLT fire resistance is provided by charring created during a fire event. When the surface temperature at the face of Red Stag CLT ramps up 400 degrees Celsius or more, the timber starts to ignite and burn at a constant rate. As the timber burns, it loses its structural strength, and it creates a black layer of char. The char becomes an insulating layer preventing an excessive rise in temperature within the unburnt area(s), maintaining the structural performance of the insulated sections. This process supports in maintain the structural integrity while building occupants can exit the structure (refer to *Figure 60*).

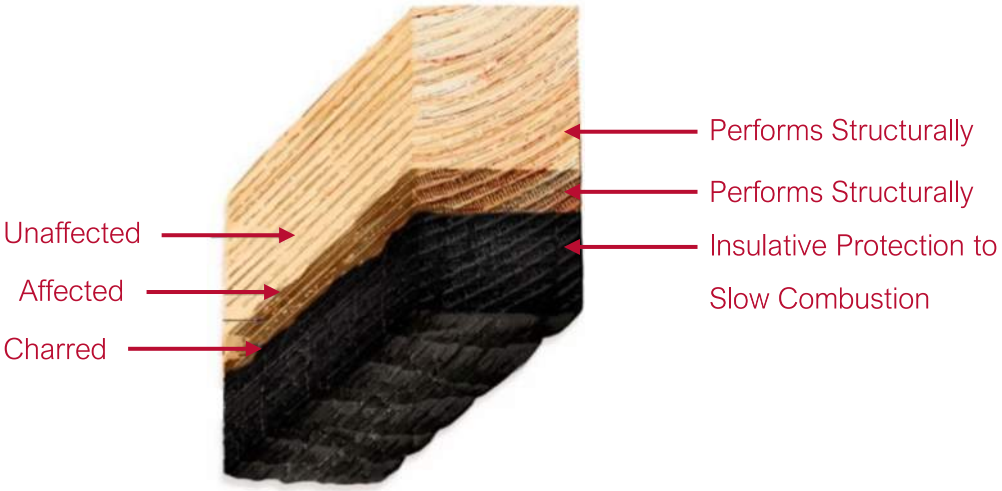


Figure 60: Different phases of degradation of timber in Red Stag CLT panel.

CLT performance in fire conditions has been very well studied, but the performance is not always well understood given the complexities related to char rate being dependent on layer or ply thickness, number of layers and the type of adhesive used. The delamination of multi-layered EWP like CLT depends on the heat resistance of the adhesive bond and the char rate of the timber during the fire event. Red Stag have completed a series of large and pilot scale fire testing on its CLT floor and wall systems to authenticate the structural stability, integrity, and insulation of the products.

The Fire Code is formulated to permit time for occupants to safely leave a burning building before structural collapse or succumbing to heat or smoke inhalation. The code stipulates a safe evacuation period of up to 60 minutes in New Zealand, for most building types and uses. Large-scale CLT fire testing was conducted by Red Stag to determine the overall fire resistance and fire performance of panels under structural loads (*Figure 61*).

The CLT floor and wall test specimens were respectively installed at the top and front of the furnaces to investigate parameters such as the structural performance, temperature profile, and deflection (*Figure 61a and Figure 61b*). The third-party fire test report confirmed no structural, integrity or instability failure after more than 60 minutes.

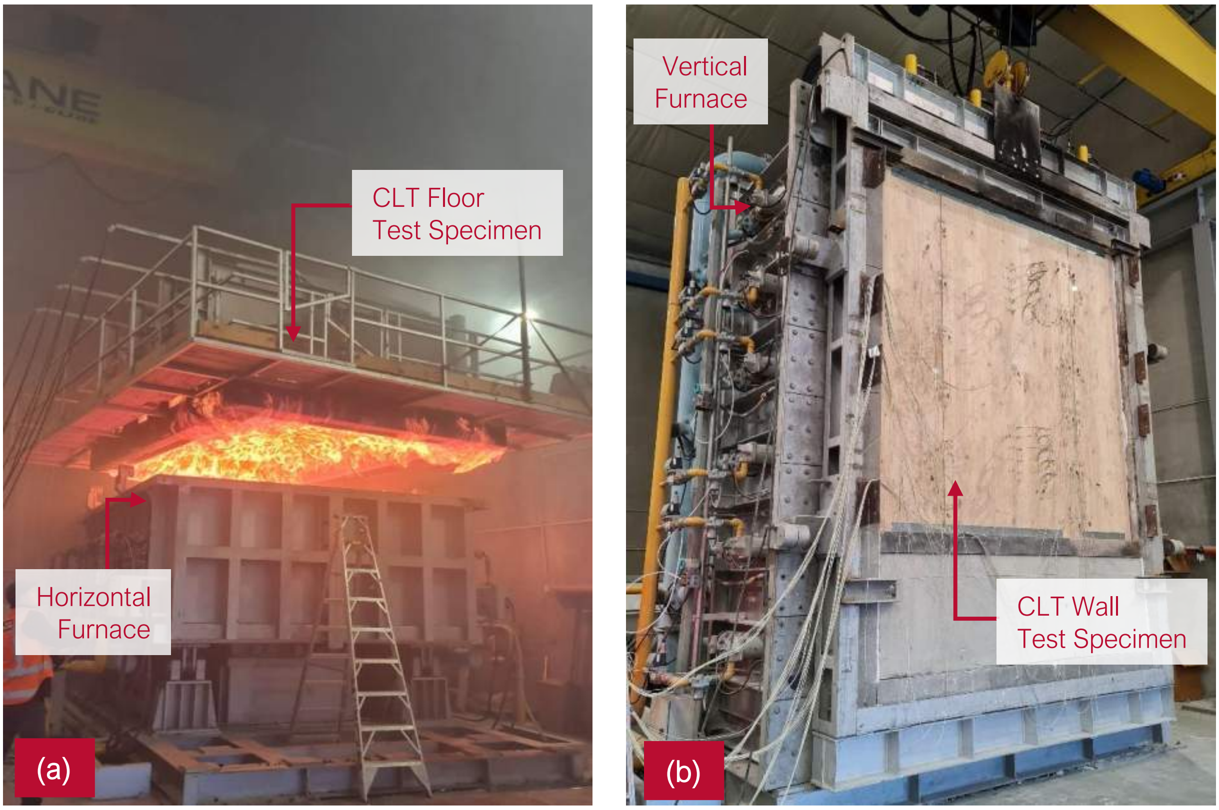
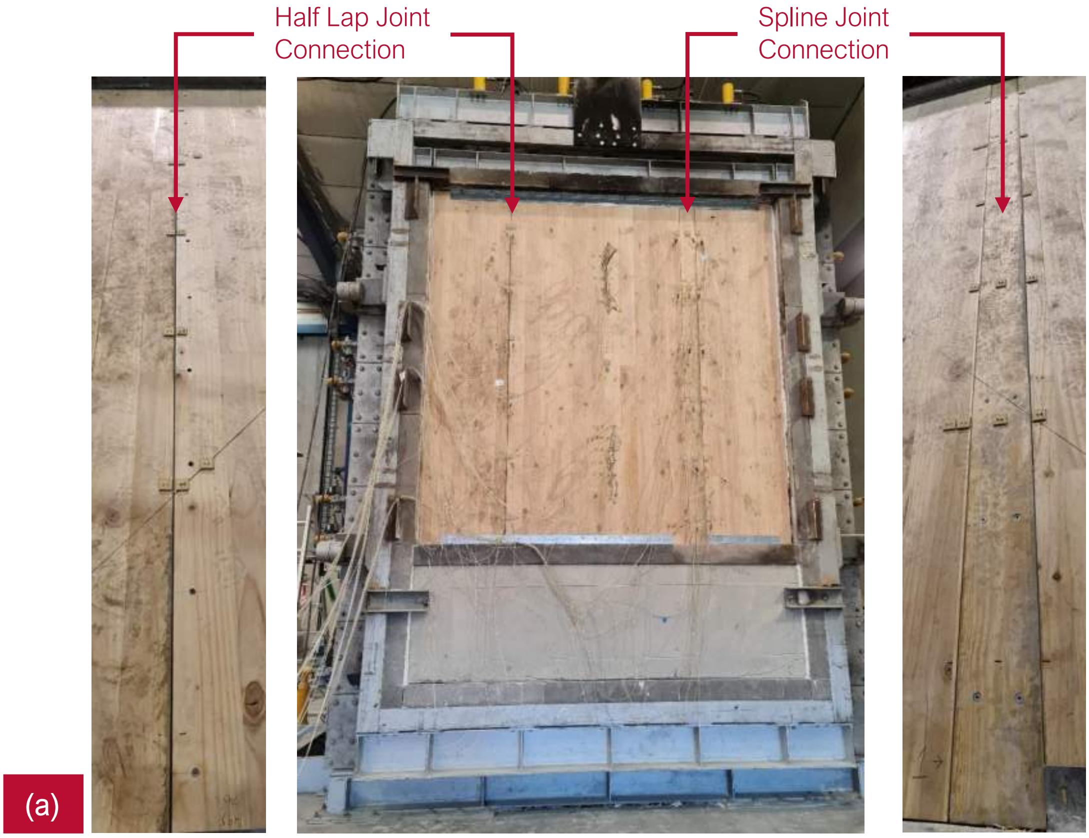


Figure 61: A general view of the large-scale fire test set-up and associated test specimen after the fire test on Red Stag CLT. a) Red Stag CLT floor test specimen after the fire test, b) Red Stag CLT wall test specimen before the fire test.

21. Fire Rated Red Stag CLT Connections

In New Zealand and Australia, there are no modern design rules for the structural fire design of connections in structural timber, including CLT. The only prescribed calculations are in AS/NZS 1720.4 (Timber structures - Part 4: Fire resistance of timber elements), which requires all steel fasteners to be protected from fire by timber cladding, timber plugs, or similar, without any details suitable for modern structures. Consequently, the structural fire design of connections is often undertaken differently for every job, with only enough detail used to satisfy the relevant local authority (or peer reviewer). This is generally achieved using a mixture of calculations from first principles, information from manufacturers of CLT or fasteners, or design methods from Eurocode 5.

Red Stag has tested a number of connections in Red Stag CLT floors and walls to verify the structural stability, integrity, and insulation of the systems. *Figure 62* shows the structurally loaded CLT wall connection fire test (before and after testing). Passive fire connection details based on the engineering fire assessment of the Red Stag CLT are presented in *Figure 63* to *Figure 64*.



(b) *Figure 62*: Large-scale Red Stag CLT wall fire test set-up after testing under structural loading to test CLT connections.

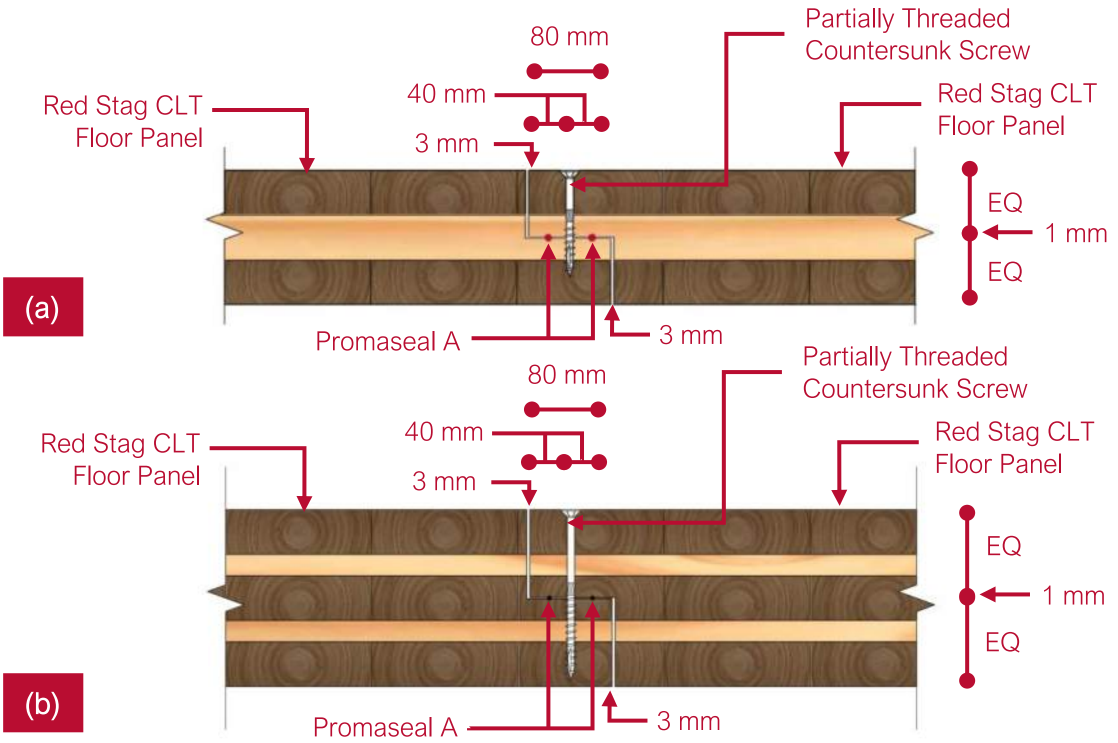


Figure 63: Red Stag CLT Panel to CLT Panel Half Lap Joint Connection [24], [25]. a) Three (3) Layer Red Stag CLT Panel, b) Five (5) Layer Red Stag CLT Panel.

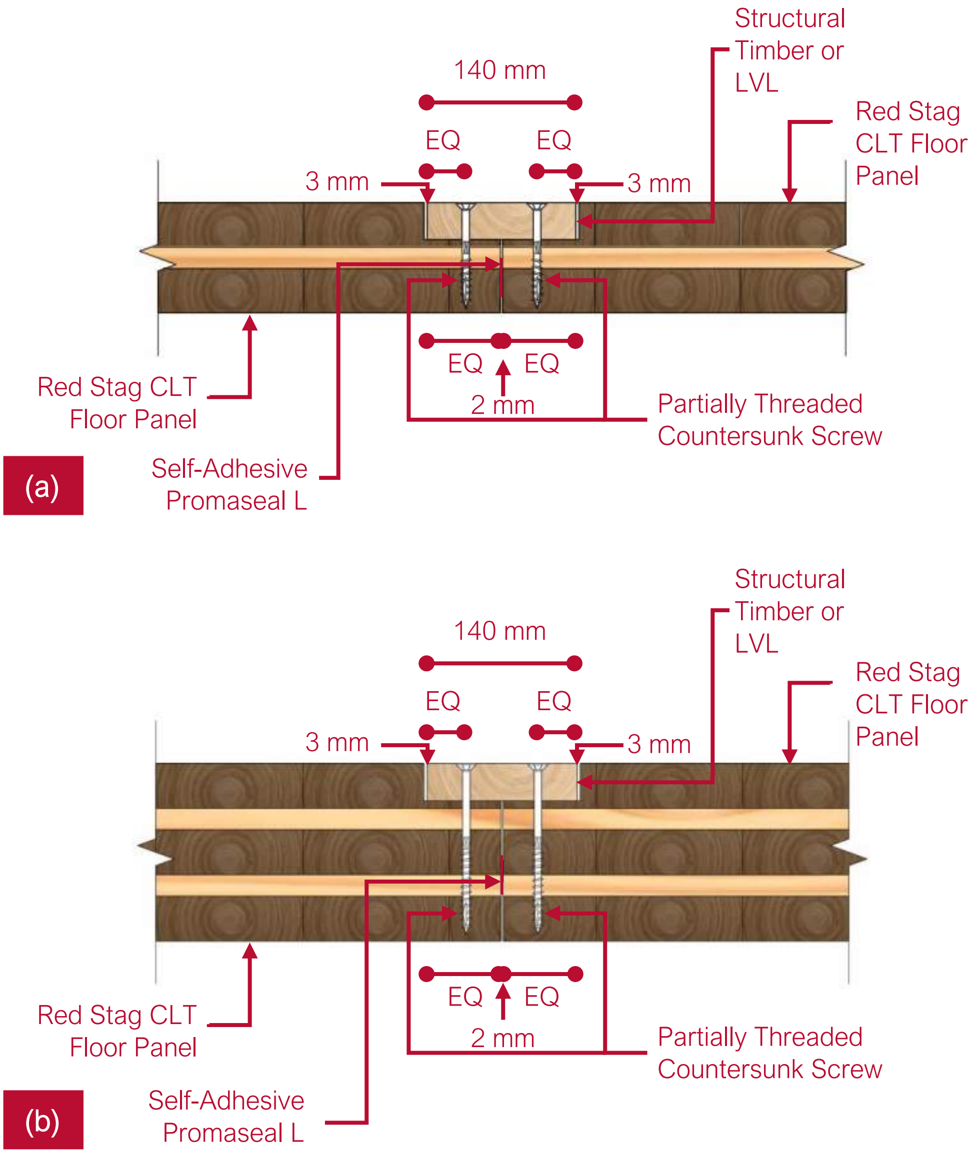


Figure 64: Red Stag CLT Panel to CLT Panel Spline Connection [24], [25]. a) Three (3) Layer Red Stag CLT Panel, b) Five (5) Layer Red Stag CLT Panel.

22. Fire Penetrations

Any holes or penetrations for services must be constructed in a way that the fire performance of the CLT member is not compromised. Penetrations through the fire rated CLT floors or walls are required to have specific fire sealing or collar systems to maintain the integrity and installation. Although recent Canadian testing has shown that solutions for service penetrations in light timber frames are equally effective for protecting penetrations through solid wood panels, Red Stag have completed a wide range of large and full scale fire testing on penetrations through CLT wall and floor assemblies to ensure on the fire performance of Red Stag CLT. *Figure 65* and *Figure 66* illustrate fire penetration test configurations (pipes and cables) on Red Stag CLT floor and wall panels.

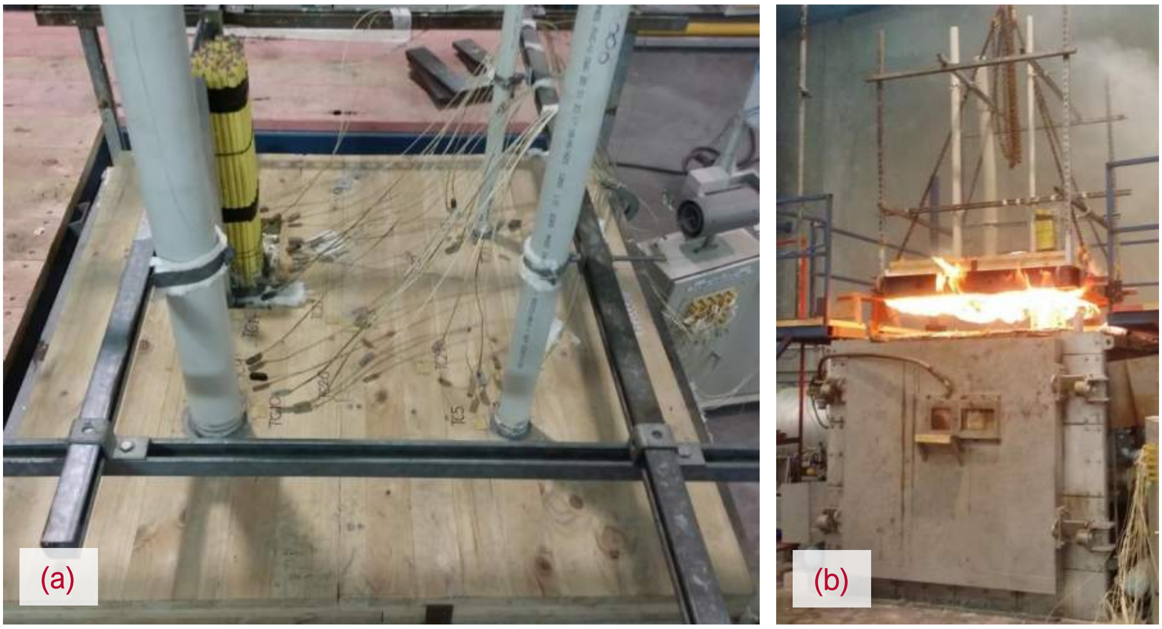
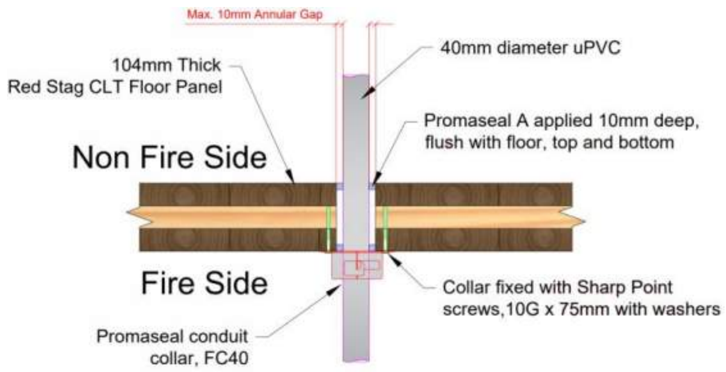


Figure 65: Various service (pipes and cables) fire tests on Red Stag CLT floor panels [26]. a) Specimen before the fire test, b) Specimen after the fire test.

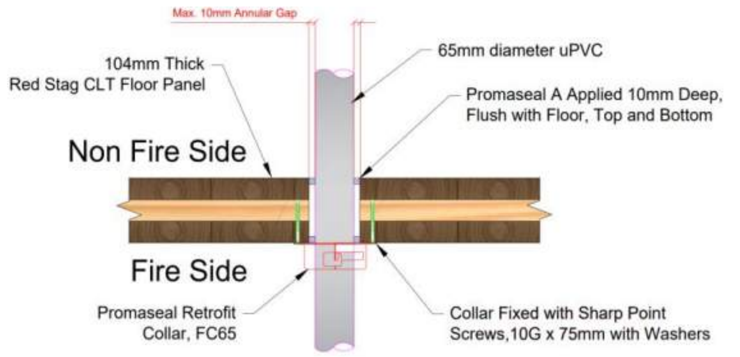
Figure 66: Various service (pipes and cables) fire tests on Red Stag CLT wall panels [26]. a) Specimen before the fire test, b) Specimen after the fire test.

The fire test results on Red Stag CLT are summarised in *Table 20*. Fire penetration testing was completed in accordance with AS 1530.4: 2014 (Methods for fire tests on building materials, components, and structures. Part 4: Fire-resistance test of elements of construction) and fire assessments.

<table>
<tr><th colspan="2"><i>Table 20</i>: Red Stag Panel Fire Rated Penetration Details [24],[26]</th></tr>
<tr><th colspan="2">Red Stag Fire Rated Penetration Detail for Ø40 mm uPVC Pipe</th></tr>
<tr><td>Type of service penetration</td><td rowspan="8">
</td></tr>
<tr><td>40 mm diameter uPVC</td></tr>
<tr><td>Fire stopping system</td></tr>
<tr><td>Promaseal A
Promaseal FC40 Collar</td></tr>
<tr><td>Type of CLT element</td></tr>
<tr><td>104 mm Red Stag CLT Floor</td></tr>
<tr><td>FRR (minutes)</td></tr>
<tr><td>-/60/60</td></tr>
</table>

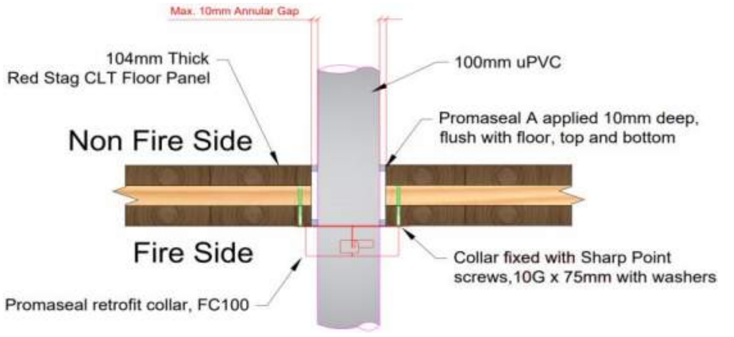
Red Stag Fire Rated Penetration Detail for Ø65 mm uPVC Pipe

Type of service penetration	65 mm diameter uPVC
Fire stopping system	Promaseal A Promaseal FC65 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



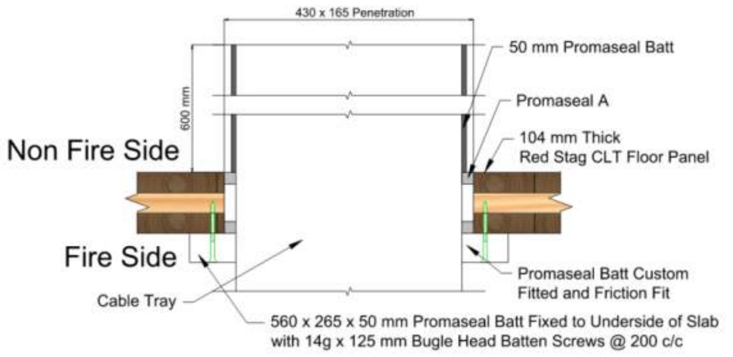
Red Stag Fire Rated Penetration Detail for Ø100 mm uPVC Pipe

Type of service penetration	100 mm diameter uPVC
Fire stopping system	Promaseal A Promaseal FC100 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



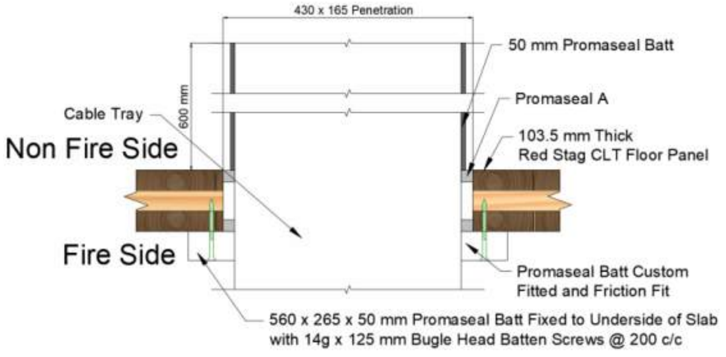
Fire Rated Penetration Detail for Comms Cable – D1 Configuration

Type of service penetration	D1 Cable Configuration
Fire stopping system	Promaseal A Two layer of 50 mm Promaseal Batt
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/30



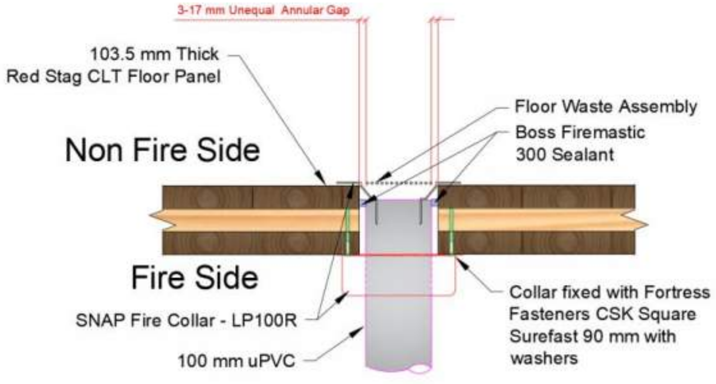
Fire Rated Penetration Detail for Comms Cable – D2 Configuration

Type of service penetration	D2 Configuration 60 Cable Bundle - Metal Cable Tray
Fire stopping system	Promaseal A Two layer of 50 mm Promaseal Batt
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/30



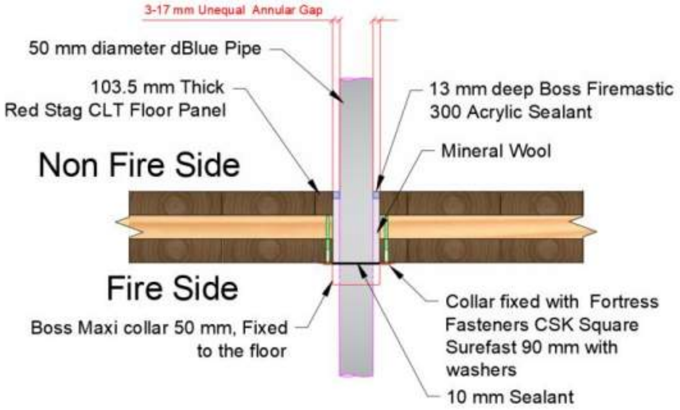
Red Stag Fire Rated Penetration Detail for Ø100 mm uPVC Pipe with Floor Waste Assembly

Type of service penetration	100 mm uPVC Pipe Floor Waste Assembly with Grate
Fire stopping system	Boss Firemastic 300 Sealant SNAP Fire Collar-LP100R
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



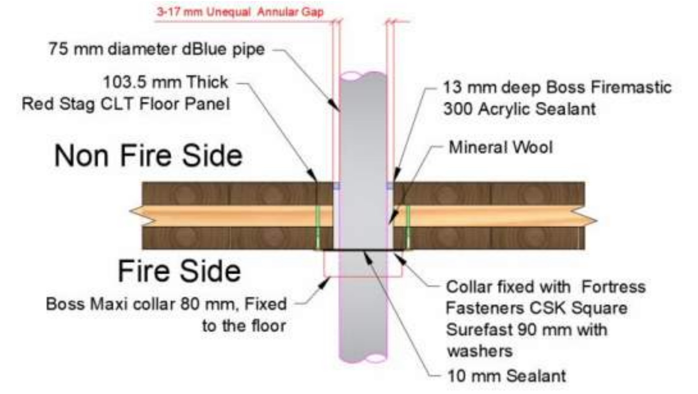
Red Stag Fire Rated Penetration Detail for Ø50 mm dBlue Pipe

Type of service penetration	50 mm Diameter dBlue Pipe
Fire stopping system	Boss Firemastic 300 Acrylic Sealant Boss Maxi FC50 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



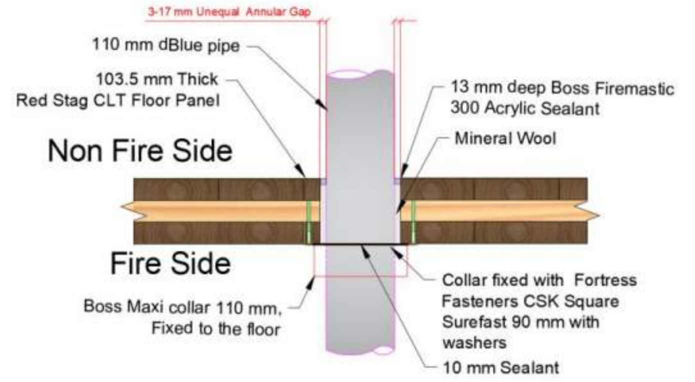
Red Stag Fire Rated Penetration Detail for Ø75 mm dBlue Pipe

Type of service penetration	75 mm Diameter dBlue Pipe
Fire stopping system	Boss Maxi Collar 80 mm Boss Firemastic 300 Sealant
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



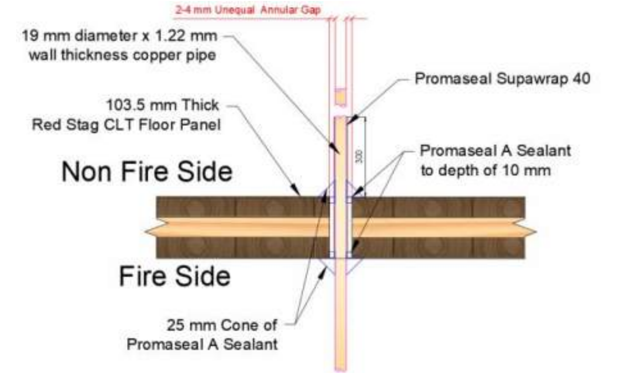
Red Stag Fire Rated Penetration Detail for Ø110 mm dBlue Pipe

Type of service penetration	110 mm Diameter dBlue Pipe
Fire stopping system	Boss Maxi Collar 80 mm Boss Firemastic 300 Sealant
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



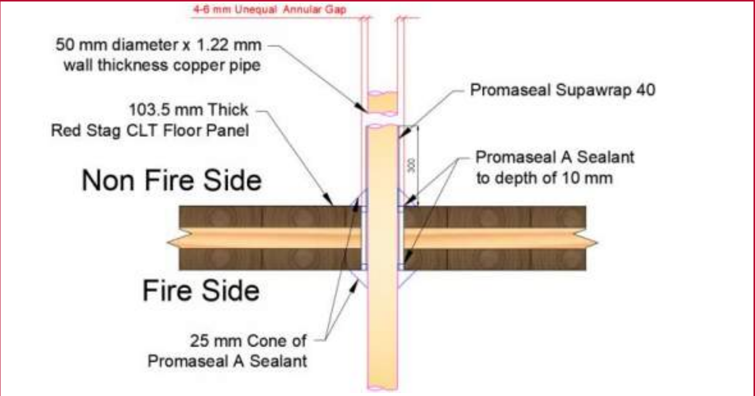
Red Stag Fire Rated Penetration Detail for Ø19 mm Copper Pipe

Type of service penetration	19 mm Diameter Copper Pipe
Fire stopping system	Promat Supawarp 40 Promaseal-A Sealant
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



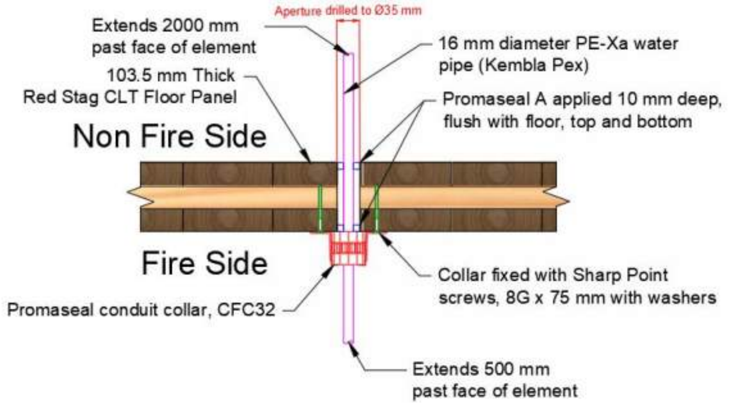
Red Stag Fire Rated Penetration Detail for Ø50 mm Copper Pipe

Type of service penetration	50 mm Diameter Copper Pipe
Fire stopping system	Promat Supawarp 40 Promaseal-A Sealant
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



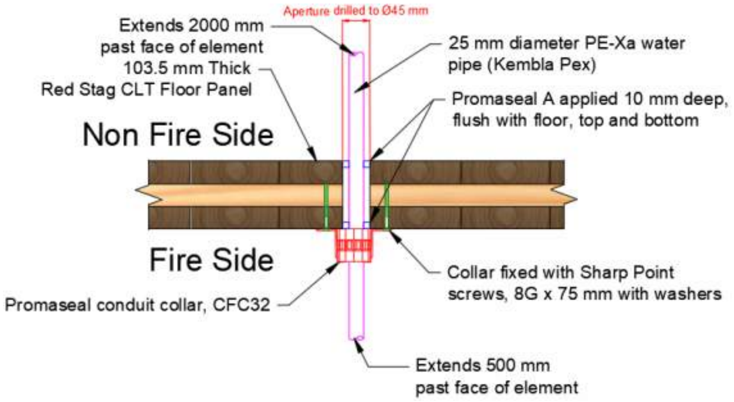
Red Stag Fire Rated Penetration Detail for Ø16 mm PE-Xa Water Pipe (Kembla Pex)

Type of service penetration	16 mm Diameter PE-Xa Water Pipe
Fire stopping system	Promaseal A Promaseal CFC32 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



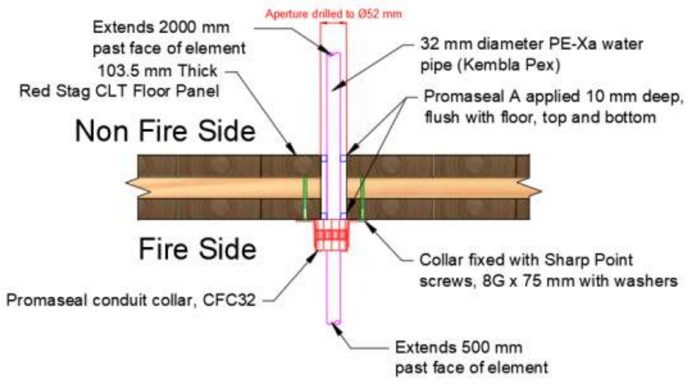
Red Stag Fire Rated Penetration Detail for Ø25 mm PE-Xa Water Pipe (Kembla Pex)

Type of service penetration	25 mm Diameter PE-Xa Water Pipe
Fire stopping system	Promaseal A Promaseal CFC32 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/30



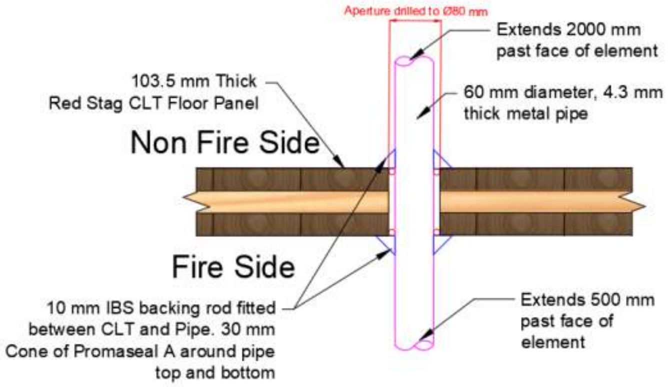
Red Stag Fire Rated Penetration Detail for Ø32 mm PE-Xa Water Pipe (Kembla Pex)

Type of service penetration	32 mm Diameter PE-Xa Water Pipe
Fire stopping system	Promaseal A Promaseal CFC32 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/30/30



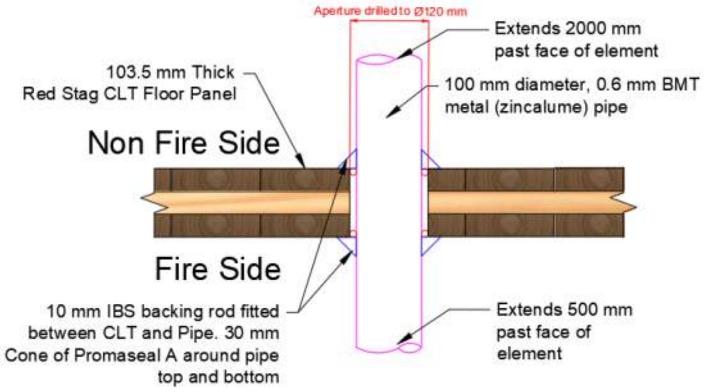
Red Stag Fire Rated Penetration Detail for Ø60 mm, 4.3 mm thick Metal Pipe

Type of service penetration	60 mm Diameter, 4.3 BMT Metal Pipe
Fire stopping system	Promaseal-A 10 mm IBS Backing Rod
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/30



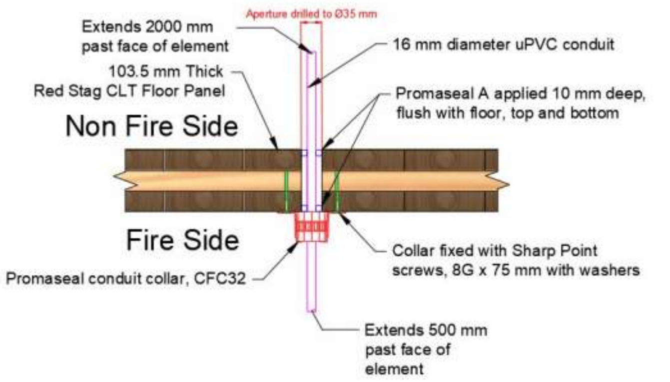
Red Stag Fire Rated Penetration Detail for Ø100 mm, 0.6 BMT Metal (Zincalume) Pipe

Type of service penetration	100 mm Diameter, 0.6 BMT Metal Pipe
Fire stopping system	Promaseal-A 10 mm IBS Backing Rod
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/-



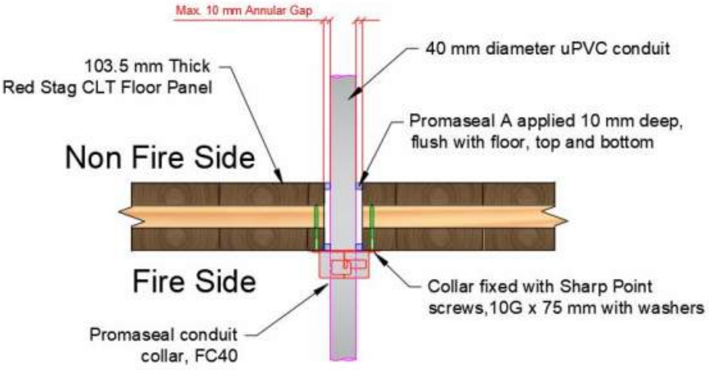
Red Stag Fire Rated Penetration Detail for Ø16 mm uPVC Conduit filled with 3-core TPS Cables

Type of service penetration	16 mm Diameter uPVC Conduit
Fire stopping system	Promaseal A Promaseal CFC32 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



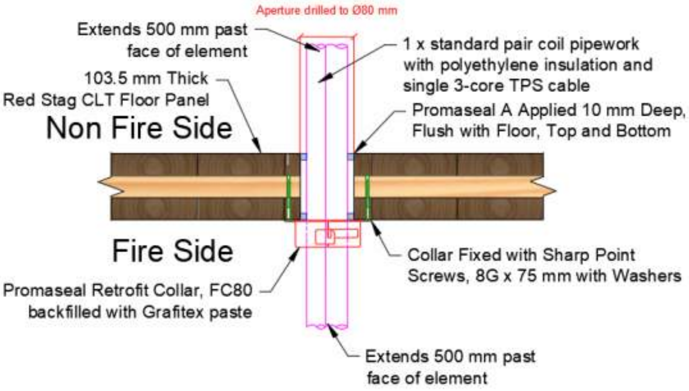
Red Stag Fire Rated Penetration Detail for Ø40 mm uPVC Conduit filled with 3-core TPS Cables

Type of service penetration	40 mm Diameter uPVC Conduit
Fire stopping system	Promaseal A Promaseal FC40 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



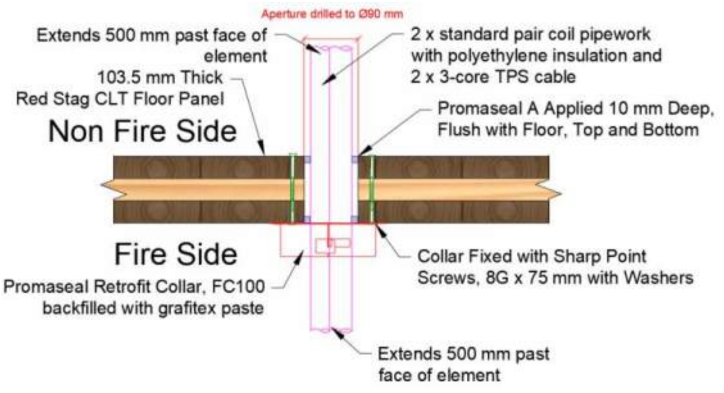
Red Stag Fire Rated Penetration Detail for Single STD Pair Coil & 2.5 mm 3C TPS

Type of service penetration	Single STD Pair Coil & 2.5 mm 3C TPS
Fire stopping system	Promaseal A Promaseal FC80 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/30/30



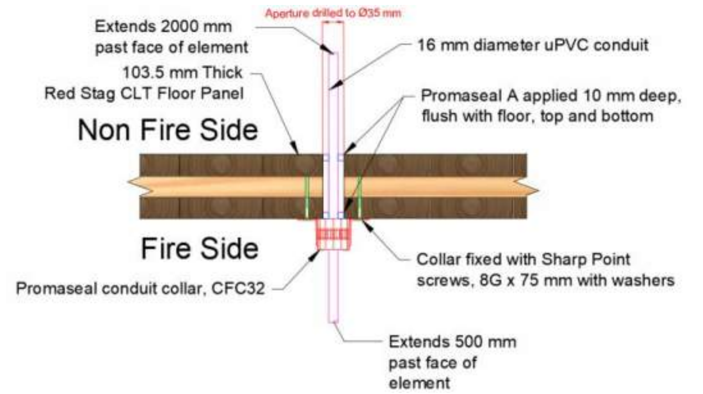
Red Stag Fire Rated Penetration Detail for Double STD Pair Coil & 2.5 mm 3C TPS

Type of service penetration	Double STD Pair Coil & 2.5 mm 3C TPS
Fire stopping system	Promaseal A Promaseal FC100 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/30/30



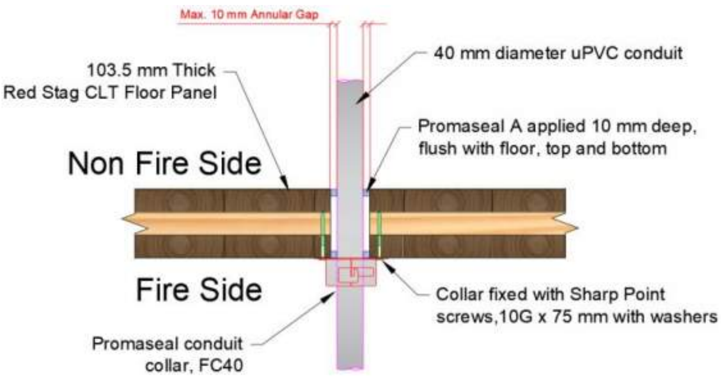
Red Stag Fire Rated Penetration Detail for Ø16 mm uPVC Conduit

Type of service penetration	16 mm uPVC Conduit
Fire stopping system	Promaseal A Promaseal CFC32 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



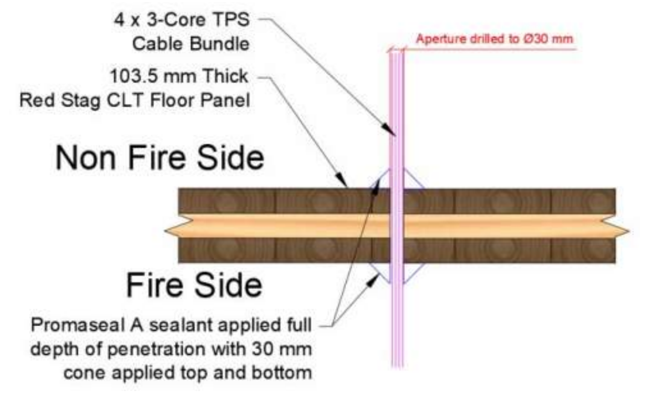
Red Stag Fire Rated Penetration Detail for Ø40 uPVC Conduit

Type of service penetration	40 mm uPVC Conduit
Fire stopping system	Promaseal A Promaseal FC40 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



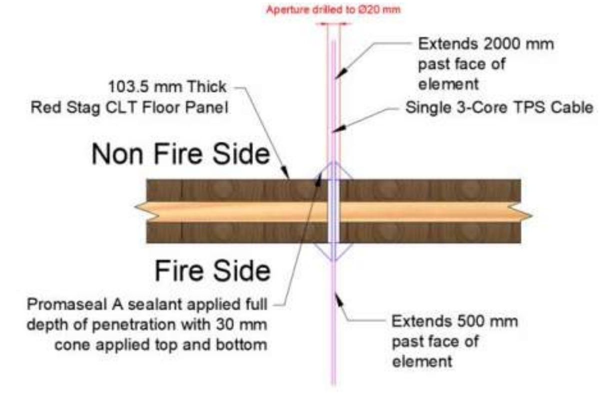
Red Stag Fire Rated Penetration Detail for 4 x 3-core TPS Cable Bundle

Type of service penetration	4 x 3-core TPS Cable Bundle
Fire stopping system	Promaseal A
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



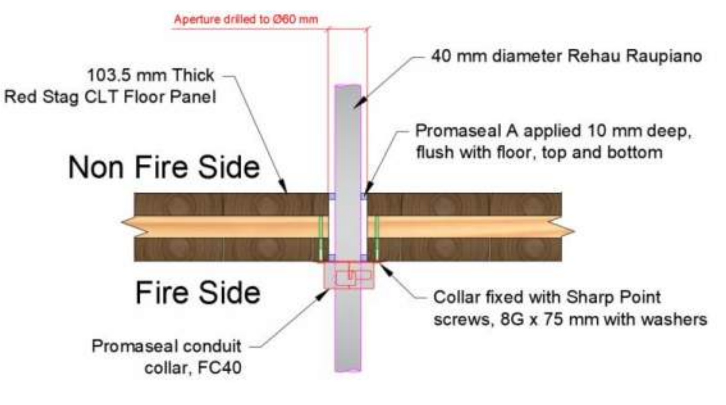
Red Stag Fire Rated Penetration Detail for Single 3-core TPS Cable

Type of service penetration	Single 3-core TPS Cable
Fire stopping system	Promaseal A
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



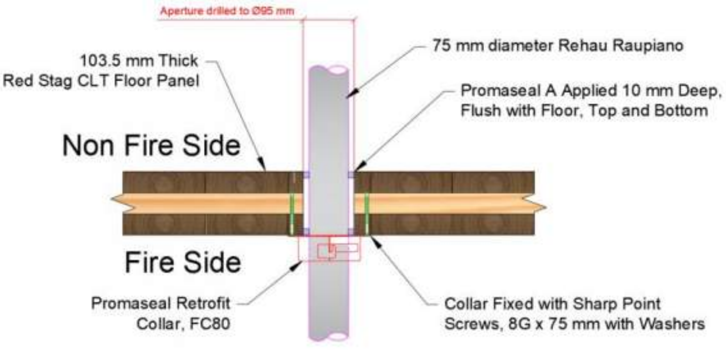
Red Stag Fire Rated Penetration Detail for Ø40 mm Rehau Raupiano Pipe

Type of service penetration	40 mm Diameter Rehau Raupiano Pipe
Fire stopping system	Promaseal A Promaseal FC40 Collar
Type of CLT element	104 mm Red Stag CLT Floor
FRR (minutes)	-/60/60



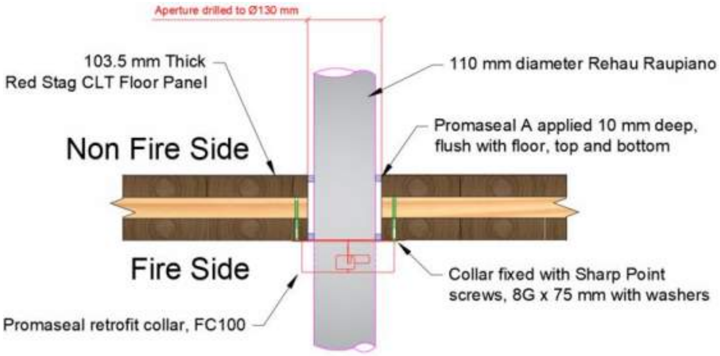
Red Stag Fire Rated Penetration Detail for Ø75 mm Rehau Raupiano Pipe

Type of service penetration
75 mm Diameter Rehau Raupiano Pipe
Fire stopping system
Promaseal A Promaseal FC80 Collar
Type of CLT element
104 mm Red Stag CLT Floor
FRR (minutes)
-/60/60



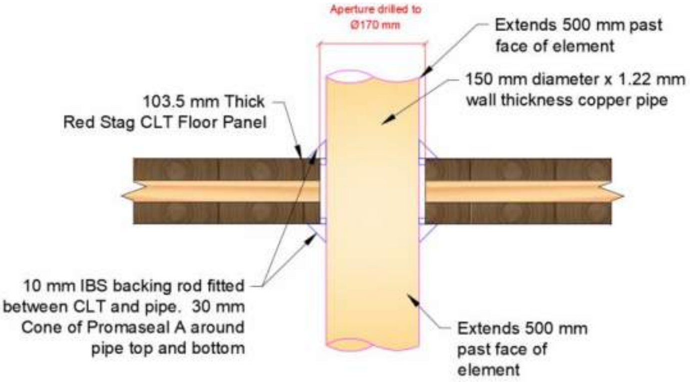
Red Stag Fire Rated Penetration Detail for Ø110 mm Rehau Raupiano Pipe

Type of service penetration
110 mm Diameter Rehau Raupiano Pipe
Fire stopping system
Promaseal A Promaseal FC100 Collar
Type of CLT element
104 mm Red Stag CLT Floor
FRR (minutes)
-/60/60



Red Stag Fire Rated Penetration Detail for Ø150 mm Copper Pipe

Type of service penetration
150 mm Diameter Copper Pipe
Fire stopping system
Promaseal-A 10 mm IBS Backing
Type of CLT element
104 mm Red Stag CLT Floor
FRR (minutes)
-/60/60



The fire report assessment based on the large scale structurally loaded experimental test has confirmed a 60 minute fire resistance for three-layer and five-layer load bearing Red Stag CLT floors (*Table 21* and *Table 22*). The large-scale CLT panel fire testing on Red Stag products based on AS 1530.4:2014 has been conducted by third-party testing facilities to determine the overall fire resistance and fire performance of the panels under structural loads. The third-party fire testing confirmed no structural, integrity or instability failure after more than 60 minutes at 900 degrees Celsius.

Table 21: Assessment outcome for loadbearing three (3) layer Red Stag CLT floors [a, b, 27]

Panel Title	Thickness	Layer 1	Layer 2	Layer 3	FRL
CLT3/103.5 [c]	103.5 mm	8 GPa, 34.5 mm	6 GPa, 34.5 mm	8 GPa, 34.5 mm	60/60/60
CLT3/126	126 mm	8 GPa, 42 mm	6 GPa, 42 mm	8 GPa, 42 mm	60/60/60
CLT3/135	135 mm	8 GPa, 45 mm	6 GPa, 45 mm	8 GPa, 45 mm	60/60/60

a. Three (3) layer Red Stag CLT floor systems may consist of either spline or lap joints.
b. Both surfaces of the three (3) layer Red Stag CLT floor systems were unprotected during the fire event.
c. Experimentally tested [27].

Table 22: Assessment outcome for loadbearing five (5) layer Red Stag CLT floors [a, b, 27]

Panel Title	Thickness	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	FRL
CLT5/130 [c]	130 mm	8 GPa, 35 mm	6 GPa, 20 mm	6 GPa, 20 mm	6 GPa, 20 mm	8 GPa, 35 mm	60/60/60
CLT5/166	166 mm	8 GPa, 42 mm	6 GPa, 20 mm	6 GPa, 42 mm	6 GPa, 20 mm	8 GPa, 42 mm	60/60/60
CLT5/210	210 mm	8 GPa, 42 mm	6 GPa, 42 mm	6 GPa, 42 mm	6 GPa, 42 mm	8 GPa, 42 mm	60/60/60

a. Five-layer Red Stag CLT floor systems may consist of either spline joint or lap joint.
b. Both surfaces of the five-layer Red Stag CLT floor systems were unprotected during fire event.
c. Experimentally tested [27].

Table 23 to *Table 26* summarise the expected structural fire capacity of the Red Stag CLT floors considering different laminations, loading conditions and FRR. The tables are developed based on the third-party assessment with specific super imposed dead and live load for 30 minute or 60 minute FRR. The calculations for three (3) layer and five (5) layer CLT panels have been developed based on the full size experimental fire test results of three and five layer Red Stag CLT panels.

Table 23: Maximum span for three (3) layer simply supported single span Red Stag CLT floor panel for 30 minutes FRR [a] [28]

Panel Title	Applied Load (kPa)								
	Super Imposed Dead Load 0.5 kPa			Super Imposed Dead Load 1 kPa			Super Imposed Dead Load 2 kPa		
	Live Load (Imposed Load)			Live Load (Imposed Load)			Live Load (Imposed Load)		
	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa
CLT 3/104	3.30 m	3.00 m	2.40 m	3.00 m	2.80 m	2.30 m	2.60 m	2.50 m	2.10 m
CLT 3/126	3.80 m	3.60 m	2.80 m	3.50 m	3.30 m	2.70 m	3.10 m	2.90 m	2.50 m

a. Three-layer Red Stag CLT floor design assumes an unprotected surface during fire event.

Table 25: Maximum span for three (3) layer simply supported single span Red Stag CLT floor panel for 60 minutes FRR [a] [28]

Panel Title	Applied Load (kPa)								
	Super Imposed Dead Load 0.5 kPa			Super Imposed Dead Load 1 kPa			Super Imposed Dead Load 2 kPa		
	Live Load (Imposed Load)			Live Load (Imposed Load)			Live Load (Imposed Load)		
	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa
CLT 3/104	3.00 m	3.00 m	2.40 m	3.00 m	2.80 m	2.30 m	2.60 m	2.50 m	2.10 m
CLT 3/126	3.60 m	3.20 m	2.40 m	3.20 m	3.00 m	2.30 m	2.70 m	2.50 m	2.10 m

a. Three-layer Red Stag CLT floor design assumes an unprotected surface during fire event.

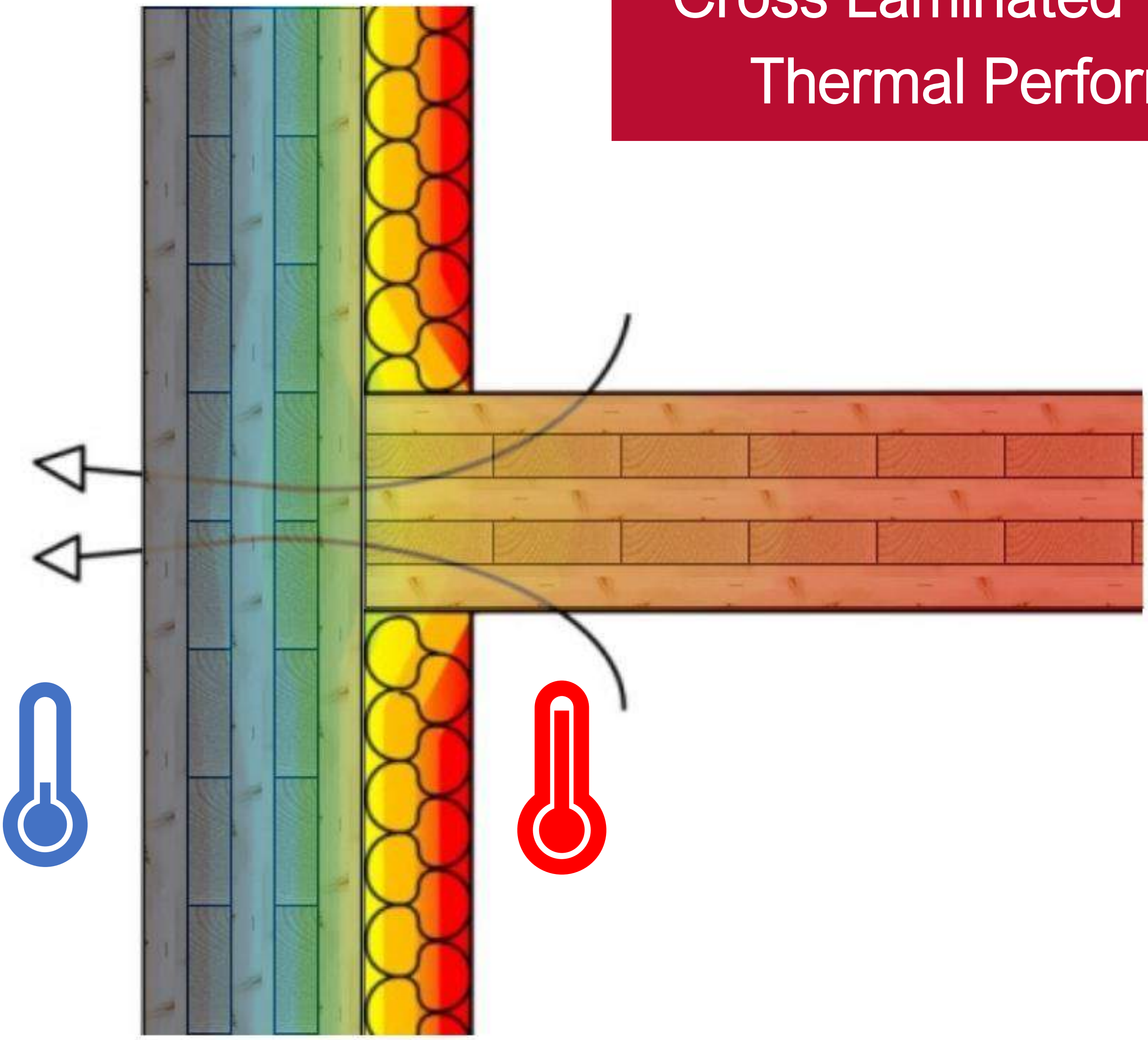
Table 26: Maximum span for five (5) layer simply supported single span Red Stag CLT floor panel for 30 or 60 minutes FRR [a] [29]

Panel Title	Applied Load (kPa)								
	Super Imposed Dead Load 0.5 kPa			Super Imposed Dead Load 1 kPa			Super Imposed Dead Load 2 kPa		
	Live Load (Imposed Load)			Live Load (Imposed Load)			Live Load (Imposed Load)		
	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa	2 kPa	3 kPa	5 kPa
CLT 5/166	4.90 m	4.60 m	3.70 m	4.50 m	4.30 m	3.60 m	4.00 m	3.80 m	3.30 m
CLT 5 /210	5.60 m	5.30 m	4.40 m	5.30 m	5.0 m	4.20 m	4.70 m	4.50 m	3.90 m

a. Five-layer Red Stag CLT floor design assumes an unprotected surface during fire event.

Section 5

Cross Laminated Timber Thermal Performance



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24. CLT Thermal Performance & Energy Efficiency

A significant benefit of CLT is its thermal performance. CLT is a solid monolithic timber system, with a relatively airtight configuration generated by glued layers of perpendicular lamella (boards) [30]. The natural insulative properties of timber, combined with the airtightness and mass of CLT creates a high performing thermal system compared to most other structural construction materials (Refer to *Figure 67* and *Figure 6* & 7 in Section 1).

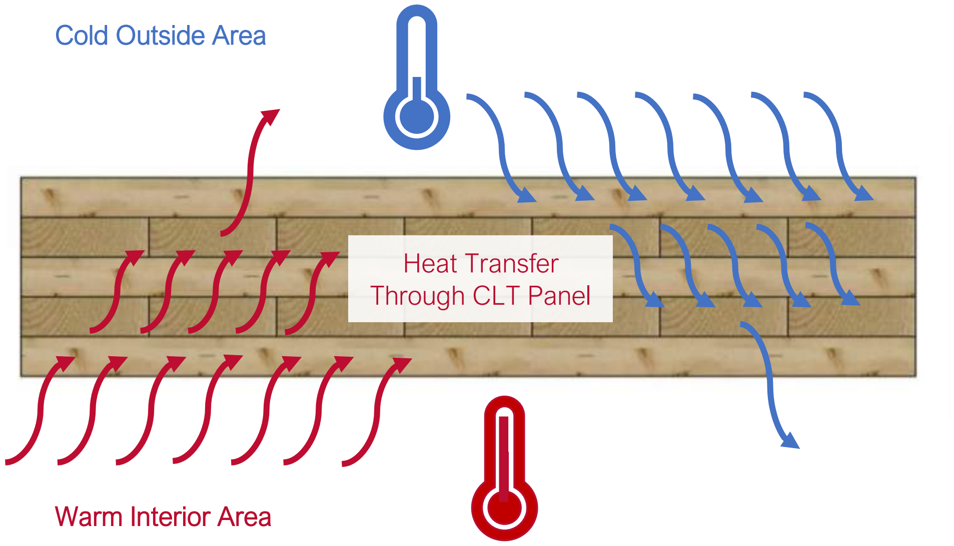

Figure 67: Thermal performance of the CLT building

The Red Stag CLT production process utilises face gluing with side hydraulic pressure to minimise the gap in boards in each layer to optimise the air tightness as much as practically possible [31] (Refer to *Figure 68* and *Figure 69*).

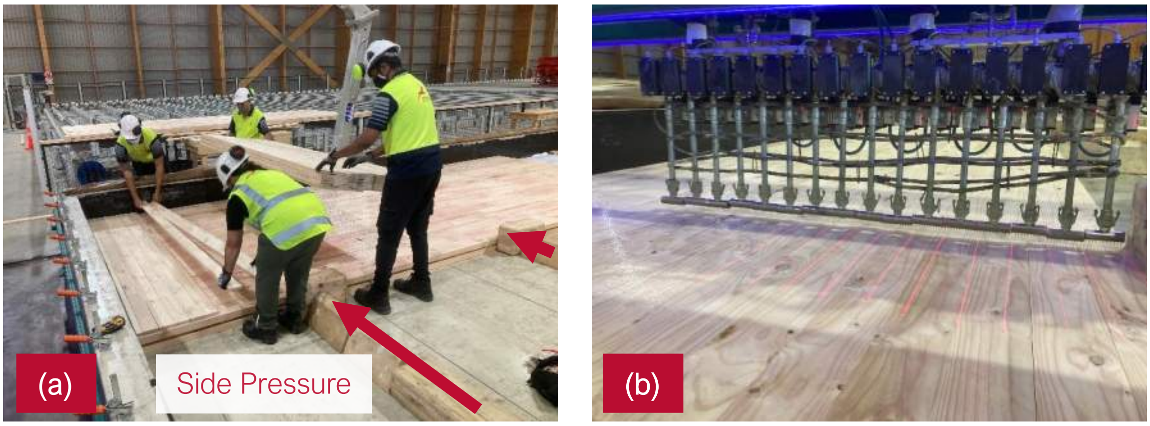

Figure 68: Red Stag Manufacturing line; (a) Layer arrangement with side pressure, (b) Adhesive distribution, (c) Hydraulic side pressure and Vacuum Membrane, (d) Final Red Stag CLT Product.

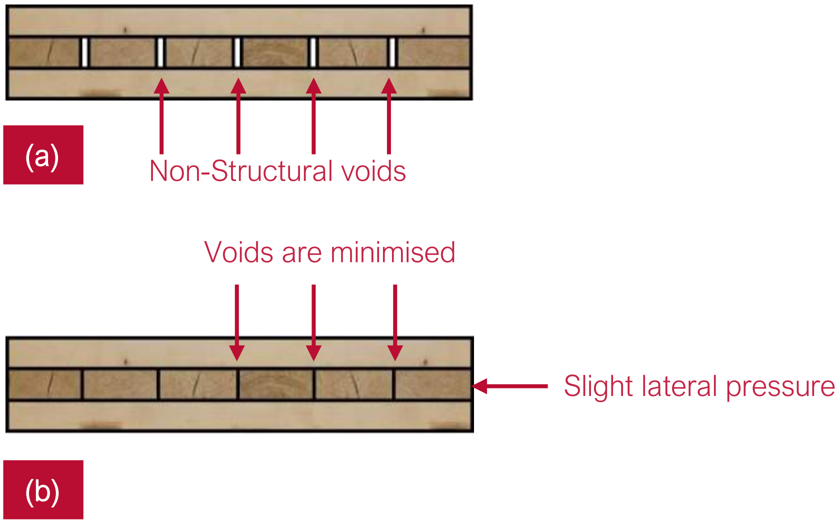

Figure 69: CLT panel manufacturing with and without lateral pressure.
a) CLT panel with non-structural voids, b) CLT panel with lateral pressure to minimise voids.

The advanced planing facilities at Red Stag generate edge tolerances of +/- 0.1 mm to further support the airtightness between lamellas.

CLT billets are then machined into panels using specialty large scale CNC equipment (*Figure 70*). Red Stag's CNC equipment can machine to precise tolerances, for panel joints and penetrations. The tight CNC tolerances allow for all jointing and penetrations to minimise airflow, supporting in generating an extremely tight building envelope.

Figure 70: CNC equipment with precise cutting capability.

CLT buildings trap in heat and regulate the internal environment and airflow up to 90 percent more efficiently than traditional structures. The increased thermal performance is primarily achieved by the high thermal mass of CLT systems. This results in the building temperature being stable throughout the day, keeping the structure warm in winter and cool in the summer, greatly reduce heating and cooling costs. The insulation performance of CLT structures can reduce the need for additional insulation and associated secondary costs.

24.1. Thermal Performance of Red Stag CLT

Thermal conductivity is a measure of the heat flow via conduction through a cross section of a material when a temperature gradient exists. The thermal conductivity of structural wood is much less than the conductivity of metals. The conductivity of structural softwood at 12 percent moisture content is in the range of 0.12 to 1.196 W/mK compared with 230 for aluminium, 50 for steel, 1.6 for concrete, 1.05 for glass, 1 for plaster, and 0.0.22 for Gypsum plasterboard [33], [41].

Red Stag CLT is a solid wood product, providing thermal mass. The key measure of CLT's thermal performance is the R-Value (insulating ability), which is related to the CLT panel thickness. The thicker the CLT, the greater the R-value or thermal performance.

The commonly used R-value for wood is 1.25 per 25.4 mm (1") of thickness. On that basis, a 210 mm thick Red Stag CLT panel would have an R-Value of 10.33. Softwood in general has approximately one-third the thermal insulating performance of a comparable thickness of fiberglass batt insulation, but approximately 10 times that of concrete and masonry, and 400 times that of solid steel [32],[34].

Table 27 to *Table 29* detail the thermal resistance (R-value) of CLT for various thicknesses of Red Stag CLT [35].

Table 27: Approximate R-Value of Three (3) Layer Red Stag CLT Panels

Recipe Priority [a]	1	2
Panel Recipe	**CLT 3/126**	**CLT 3/104**
Layer 1, Radiata Pine	42 mm	42 mm
Layer 2, Radiata Pine	42 mm	20 mm
Layer 3, Radiata Pine	42 mm	42 mm
Panel Thickness	126 mm	104 mm
Thermal Resistance (R-Value) [b, 42]	1.05 m^2·°C/W	0.86 m^2·°C/W
Conductivity [b, 42]	0.84 W/mK	0.69 W/mK

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.
b. Based on the NZS4214, Table E, softwoods (e.g. pine) at 12% moisture content, density of 450 kg/m^3, thickness of 18 mm, conductivity of 0.120 W/mK. The unit of measure is m^2·°C/W and assumes a single solid wood plank (Not CLT).

IMPORTANT: If a project is less than 200 m^3, Red Stag can only provide recipe priority 1 options unless agreed prior with the client. Recipe priority 2 or alternates are only available based on available feedstock and production capacity. If a project requires an alternate recipe to priority 1 options, please coordinate with Red Stag in advance

Table 28: Approximate R-Value of Five (5) Layer Red Stag CLT Panels

Recipe Priority [a]	1	2
Panel Recipe	CLT 5/210	CLT 5/166
Layer 1, Radiata Pine	42 mm	42 mm
Layer 2, Radiata Pine	42 mm	20 mm
Layer 3, Radiata Pine	42 mm	42 mm
Layer 4, Radiata Pine	42 mm	20 mm
Layer 5, Radiata Pine	42 mm	42 mm
Panel Thickness	210 mm	166 mm
Thermal Resistance (R-Value) [b], [42]	1.75 m^2·°C/W	1.38 m^2·°C/W
Conductivity [b], [42]	1.40 W/mK	1.10 W/mK

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.
b. Based on the NZS4214, Table E, softwoods (e.g. pine) at 12% moisture content, density of 450 kg/m3, thickness of 18 mm, conductivity of 0.120 W/mK. The unit of measure is m2·°C/W and assumes a single solid wood plank (Not CLT).

Table 29: Approximate R-Value of Seven (7) Layer Red Stag CLT Panels

Recipe Priority [a]	1	2
Panel Recipe	CLT 7/294	CLT 7/228
Layer 1, Radiata Pine	42 mm	42 mm
Layer 2, Radiata Pine	42 mm	20 mm
Layer 3, Radiata Pine	42 mm	42 mm
Layer 4, Radiata Pine	42 mm	20 mm
Layer 5, Radiata Pine	42 mm	42 mm
Layer 6, Radiata Pine	42 mm	20 mm
Layer 7, Radiata Pine	42 mm	42 mm
Panel Thickness	294 mm	228 mm
Thermal Resistance (R-Value) [b], [42]	2.45 m^2·°C/W	1.90 m^2·°C/W
Conductivity [42]	1.96 W/mk	1.52 W/mk

a. Recipe priority defines the most cost-effective Red Stag CLT recipe option.
b. Based on the NZS4214, Table E, softwoods (e.g. pine) at 12% moisture content, density of 450 kg/m3, thickness of 18 mm, conductivity of 0.120 W/mK. The unit of measure is m2·°C/W and assumes a single solid wood plank (Not CLT).

Section 6

Cross Laminated Timber Penetrations & Chasing

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25. Penetrations and Chasing Through CLT

CLT floor systems support in simplifying the installation of utilities and services, to reduce time and cost on-site. This can include, but not be limited to mechanical and HVAC ducting, plumbing services, electrical, etc (Refer to *Figure 71*).

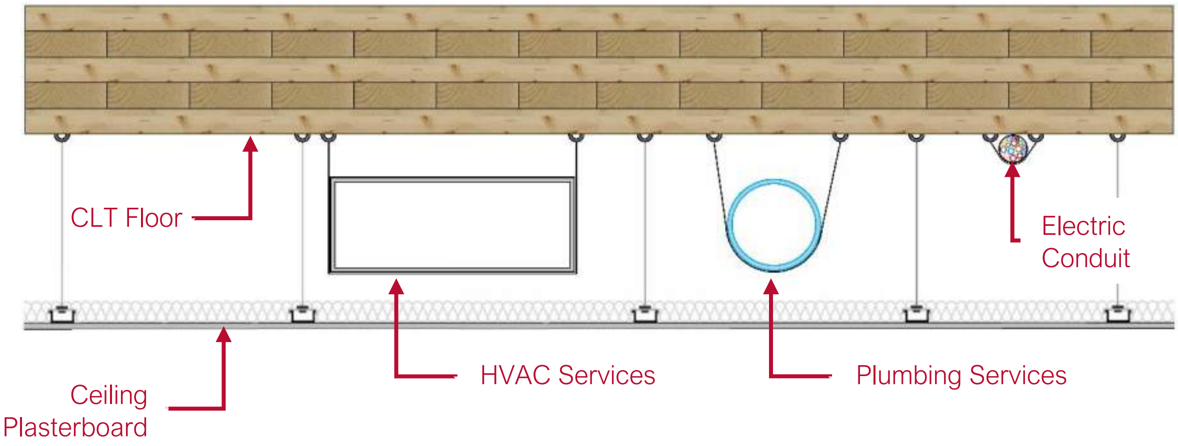
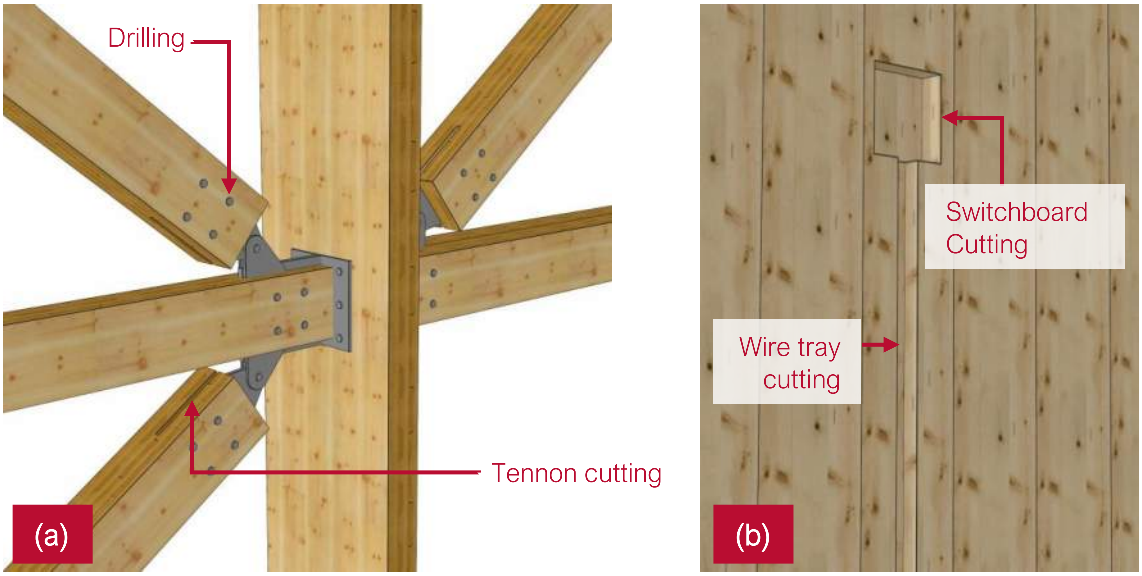


Figure 71: Cross-section view of suspended or direct fix utilities under CLT floor systems. Note: Ceiling line interfaces will require additional nogging in stick framed walls to support lining fixing under suspended ceilings.

Depending on the design, the underside of CLT floors can be left exposed. Suspended ceiling or bulkheads could be used where services are to be concealed (e.g., bathroom and wet areas).

Depending on the connection details, or system design, more complex jointing or machining may be required in factory via advance CNC processing. Examples of more detailed machining options are illustrated in *Figure 72*.



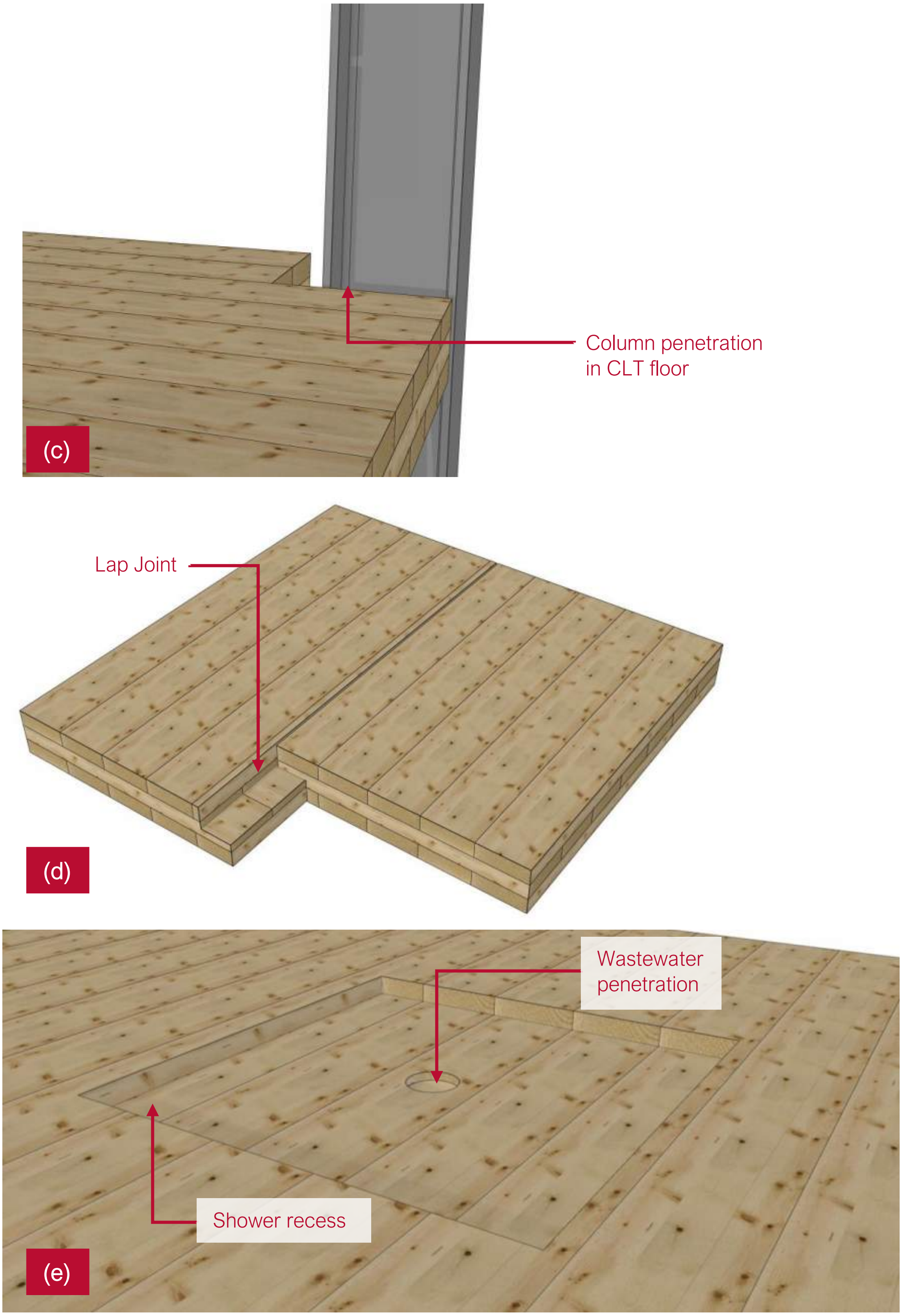
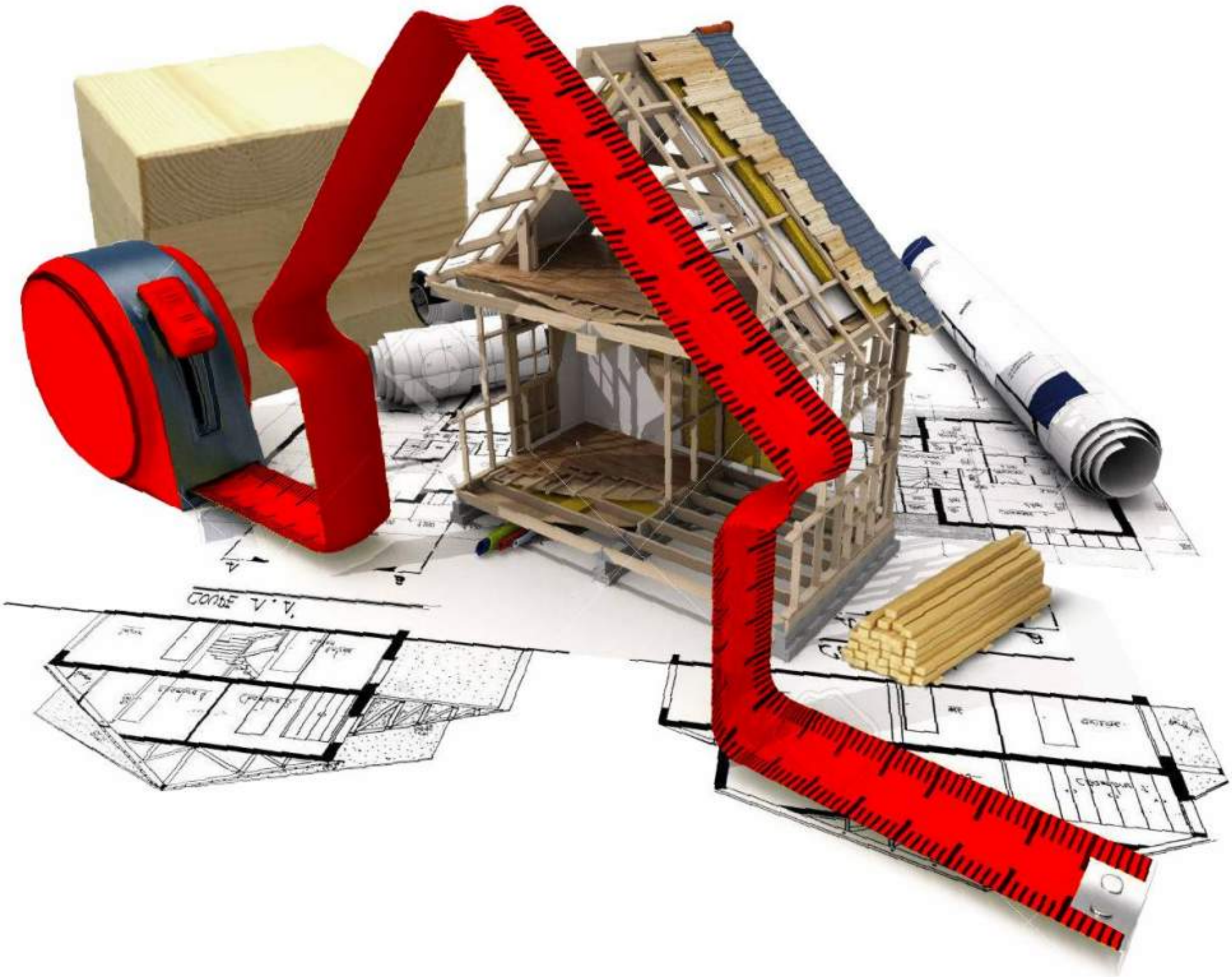


Figure 72: Penetrations and chasing through the Red Stag CLT panels.
a) Slots and drilling for CLT members (beam, column and bracings, b) Electrical penetrations for walls, c) Column penetrations in floors, d) Lap joint, e) Shower tray.

Section 7

Cross Laminated Timber Design Calculation



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26. Overview

The Cross Laminated Timber (CLT) design examples in this section are provided to assist the market with the design and specification of Red Stag CLT. The technical examples provided have been developed based on the Canadian FPInnovation CLT Handbook, NZS 3603 Timber Structures Standard, NZS 1170 Structural Design Actions and the EN 1995-1-1 Eurocode 5 Design of Timber Structures (Refer to the *Table 30* below). This document is intended as a guide only (not a specification basis) to support in calculating and designing CLT members. Please refer to the relevant standards for further information to ensure that the project engineer, designer or specifier confirm the basis for each design to ensure it is fit for purpose and does not simply rely on the examples in this section.

Table 30: Referenced standards and documents utilised in the CLT floor design example.

The Red Stag CLT Floor Design Calculation Example has been developed in Conjunction with the Following Standards:
CLT Design Guide: FPInnovations CLT Handbook 2011, Chapter 3, Structural Design of CLT Elements. FPInnovations CLT Handbook 2011, Chapter 7, Vibration Performance of CLT Floors. Canadian CLT Handbook has been used as the primary design basis for Red Stag CLT to confirm the bending strength.
NZS 3603:1993: NZS 3603:1993 Timber Structures Standard is currently under review with an anticipated 2022 revision. Timber characteristics information from the New Zealand Timber Standard is used in Red Stag CLT floor design calculations.
AS/NZS 1170.1: AS/NZS 1170.1:2002 Structural design actions - Part 1: Permanent, imposed, and other actions. Permanent loads, imposed loads and load combinations from the New Zealand structural design action standard are used in Red Stag CLT design calculations.
EN 1995-1-1: EC 5: EN 1995-1-1:2004+A1:2008 - Eurocode 5: Design of timber structures. Vibration of the Red Stag CLT floor design example is calculated based on the recommended method in EN 1995-1-1:2004+A1:2008 - Eurocode 5, Section 7.5.

27.1. CLT Floor Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

Figure 73: Red Stag CLT Panel Cross-Section

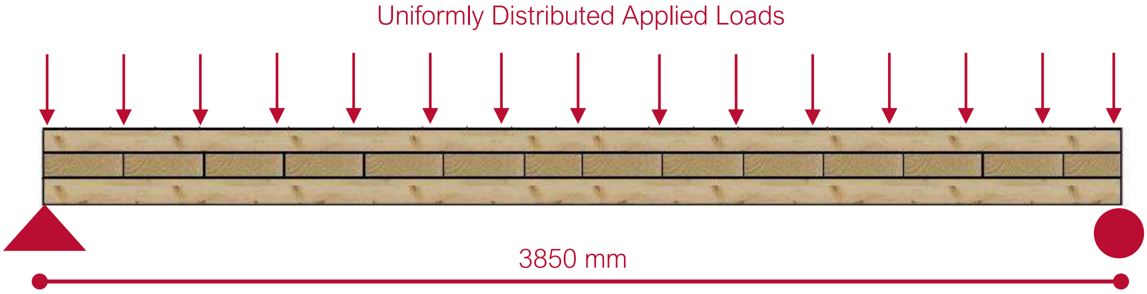

Figure 74: Red Stag CLT Panel Elevation

27.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3

Additional Dead Load = 0.5 kPa

Live Load = 2.0 kPa - Refer to AS/NZS 1170.1 [37]

27.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 3850 mm = 3.85 m

b = Width of the CLT panel = 1 m [37]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

$\overline{h_i}$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h_1}$ = 42 mm

$A_i = b_i \times h_i$ [38]

A_1 = (42×1000) = 42000 mm^2

A_2 = (42×1000) = 42000 mm^2

$$I_1 = \frac{b_i \times {h_i}^3}{12} \text{ [38]}$$

$$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000 \text{ mm}^4$$

$$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000 \text{ mm}^4$$

E_1 = 8000 MPa [36]

E_2 = 8000 MPa [36]

$$\gamma_1 = \frac{1}{1+\Pi^2 \times \frac{E_1 \times A_1}{\mathrm{L}^2} \times \frac{h_1}{G_R \times b}} \text{ [38]}$$

$$\gamma_2 = \frac{1}{1+\Pi^2 \times \frac{E_3 \times A_3}{\mathrm{L}^2} \times \frac{h_2}{G_R \times b}} \text{ [38]}$$

where $\frac{h_i}{G_R \times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2\times8000\times42000}{3850^2}\times\frac{42}{37.5\times1000}} = 0.89$$

$$\gamma_2 = \frac{1}{1+\frac{3.14^2\times8000\times42000}{3850^2}\times\frac{42}{37.5\times1000}} = 0.89$$

$\overline{a}_1 = \frac{h_1}{2} + \frac{\overline{h_1}}{2}$ [38]

$\overline{a}_2 = \frac{h_2}{2} + \frac{\overline{h_1}}{2}$ [38]

$$\overline{a}_1 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$$\overline{a}_2 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$EI_{eff\,//} = \sum_{i=1}^{2}(E_i I_i + \gamma_i E_i A_i {a_i}^2)$ [38]

$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 {a_1}^2) + (E_2 I_2 + \gamma_2 E_2 A_2 {a_2}^2)$ [38]

$EI_{eff} = (8000\times6174000+0.889\times8000\times42^2) + (8000\times6174000+0.889\times8000\times42^2) = 6\times10^{11}+6\times10^{11} = 1.152\times10^{12}$ N.mm²

$$I_{eff} = \frac{1.152\times10^{12}}{8000} = 1.44\times10^{8}\ \text{mm}^4$$

27.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = \varnothing\times F_b\times\frac{I_{eff}}{(\delta_1 a_1 \times 0.5 h_1)}$ $(E_1 = E_2)$ [38]

$F_b = 14$ MPa [36]

$\varnothing = 0.9$ [36], [38]

$$M_r = 0.9\times14\times\frac{1.44\times10^{8}}{(0.89\times42+0.5\times42)}\times10^{-6} = 31.12 \text{ kN.m}$$

27.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.44 \times 10^8}{0.5 \times 126} \times 10^{-6} = 28.81$ kN.m

27.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 126 × (5/1000) = 0.63 kPa

Additional Dead Load = 0.5 kPa.

Live Load = 2 kPa on Floor

$M^* = \frac{(1.2 \times (0.63+0.5) + 1.5 \times 2) \times 3.85^2}{8} = 8.07$ kN.m

$M^* = \frac{(1.35 \times (0.63+0.5)) \times 3.85^2}{8} = 3.14$ kN.m

27.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}} = 31.12$ kN.m $\geq M^* = 8.07$ kN.m √ ok

$M_{r\ \text{Mechanical jointed method}} = 31.12$ kN.m $\geq M^* = 3.14$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 28.81$ kN.m $\geq M^* = 8.07$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 28.81$ kN.m $\geq M^* = 3.14$ kN.m √ ok

27.8. Deflection Check

$$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^4}{(384\times(EI_{eff}\,)}$$ [38], [39]

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight} + \text{Additional Dead Load}\,)+0.4\times\text{Live Load}\,)\times 3850^4}{(384\times(EI_{eff}\,))}$$

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((0.63+0.5)+0.4\times2)\times3850^4}{(384\times(1.152\times10^{12}\,)} = 4.79 \text{ mm}$$

Creep Factor (K_2) = 2

Long term deflection = 4.79 × 2 = 9.58 mm → long term deflection

Long term deflection = 9.58 $\leq \Delta^{*} = \frac{3850}{400}$ = 9.625 mm √ ok

27.9. Vibration Check

$$f = \frac{3.142}{2L^2}\sqrt{\frac{(EI)^{1m}_{eff}}{\rho\ A}}$$ [40]

$\rho \times A$ = m = is the mass per unit area in kg/m^2.

L = is the floor span in m.

m = linear mass of the CLT for a 1-m wide panel (kg/m).

EI_{eff} = effective bending stiffness.

$$f = \frac{3.142}{2\times3.85^2}\sqrt{\frac{1.152\times10^{12}}{500\ \times(1\times\frac{126}{1000})}} = 14.33 \geq 8\text{Hz}$$ √ ok

28.1. CLT Floor Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

Figure 75: Red Stag CLT Panel Cross-Section

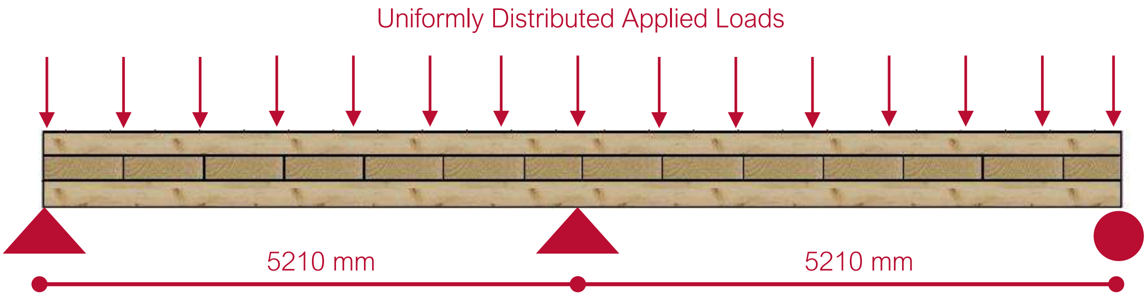

Figure 76: Red Stag CLT Panel Elevation

28.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3

Additional Dead Load = 0.5 kPa

Live Load = 2.0 kPa - Refer to AS/NZS 1170.1 [37]

28.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 5210 mm = 5.21 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

$\overline{h}_i$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h}_1$ = 42 mm

$A_i = b_i \times h_i$ [38]

$A_1 = (42\times1000) = 42000\ \text{mm}^2$

$A_2 = (42\times1000) = 42000\ \text{mm}^2$

$I_1 = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^2$

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^2$

E_1 = 8000 MPa [36]

E_2 = 8000 MPa [36]

$\gamma_1 = \frac{1}{1+\Pi^2\times\frac{E_1\times A_1}{L^2}\times\frac{h_1}{G_R\times b}}$ [38]

$\gamma_2 = \frac{1}{1+\Pi^2\times\frac{E_3\times A_3}{L^2}\times\frac{h_2}{G_R\times b}}$ [38]

where $\frac{h_i}{G_R\times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]

E_{90} = 266.67 MPa

G_0 = 500 MPa

G_R = 50 GPa [38]

E_0= MoE for transvers layers = 6000 MPa [36]

E_{90} = 200 MPa

G_0 = 375 MPa

G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5210^2}\times\frac{42}{37.5\times 1000}} = 0.936$$

$$\gamma_2 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5210^2}\times\frac{42}{37.5\times 1000}} = 0.936$$

$$a_1 = \frac{h_1}{2} + \frac{\overline{h_1}}{2}$$ [38]

$$a_2 = \frac{h_2}{2} + \frac{\overline{h_1}}{2}$$ [38]

$$a_1 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$$a_2 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$$EI_{eff\,//} = \sum_{i=1}^{2}(E_i I_i + \gamma_i E_i A_i {a_i}^2)$$ [38]

$$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 {a_1}^2) + (E_2 I_2 + \gamma_2 E_2 A_2 {a_2}^2)$$ [38]

$$\begin{aligned} EI_{eff} &= (8000\times 6174000+0.936\times 8000\times 42^2) + (8000\times 6174000+0.936\times 8000\times 42^2) \\ &= 6\times 10^{11}+6\times 10^{11} \\ &= 1.208\times 10^{12} \text{ N.mm}^2 \end{aligned}$$

$$I_{eff} = \frac{1.208\times 10^{12}}{8000} = 1.51\times 10^{8} \text{ mm}^4$$

28.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$$M_r = \text{Ø}\times F_b\times\frac{I_{eff}}{(\delta_1 a_1 \times 0.5 h_1)} \quad (E_1 = E_2)$$ [38]

F_b = 14 MPa [36]

Ø = 0.9 [36], [38]

$$M_r = 0.9\times 14\times\frac{1.51\times 10^8}{(0.936\times 42+0.5\times 42)}\times 10^{-6} = 31.55 \text{ kN.m}$$

28.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.51 \times 10^8}{0.5 \times 126} \times 10^{-6} = 30.21$ kN.m

28.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 126 × (5/1000) = 0.63 kPa.

Additional Dead Load = 0.5 kPa.

Live Load = 2 kPa on Floor

$M^* = \frac{(1.2 \times (0.63+0.5) + 1.5 \times 2) \times 5.21^2}{8} = 14.78$ kN.m

$M^* = \frac{(1.35 \times (0.63+0.5)) \times 5.21^2}{8} = 5.75$ kN.m

28.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}} = 31.55$ kN.m $\geq M^* = 14.78$ kN.m √ ok

$M_{r\ \text{Mechanical jointed method}} = 31.55$ kN.m $\geq M^* = 5.75$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 30.21$ kN.m $\geq M^* = 14.78$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 30.21$ kN.m $\geq M^* = 5.75$ kN.m √ ok

28.8. Deflection Check

$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^4}{(384\times(EI_{eff}\ )}$ [38], [39]

$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight} + \text{Additional Dead Load})+0.4\times\text{Live Load})\times 3850^4}{(384\times(EI_{eff}))}$

$\Delta_{\text{CLT Deflection}} = \frac{5\times((0.63+0.5)+0.4\times 2)\times 5210^4}{(384\times(1.208\times 10^{12})}$ = 15.32 mm

Creep Factor (K_2) = 2

Long term deflection = $\frac{15.32}{2.4}\times 2$ = 12.77 mm → Long term deflection

Long term deflection = 12.77 mm **≤** $\Delta^* = \frac{5210}{400}$ = 13.025 mm √ ok

28.9. Vibration Check

$f = \frac{3.142}{2L^2}\sqrt{\frac{(EI)^{1m}_{eff}}{\rho\ A}}$ [40]

$\rho \times A = m$ = is the mass per unit area in kg/m^2.

L = is the floor span in m.

m = linear mass of the CLT for a 1-m wide panel (kg/m).

EI_{eff} = effective bending stiffness.

$f = \frac{3.142}{2\times 5.21^2}\sqrt{\frac{1.208\times 10^{12}}{500\ \times(1\times\frac{126}{1000})}}$ = 8.02 **≥** 8Hz √ ok

29. Five Layer Single Span CLT Floor Design Calculation Example

29.1. CLT Floor Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

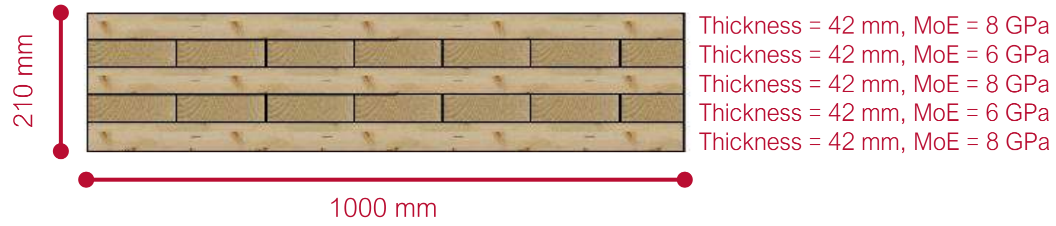

Figure 77: Red Stag CLT Panel Cross-Section

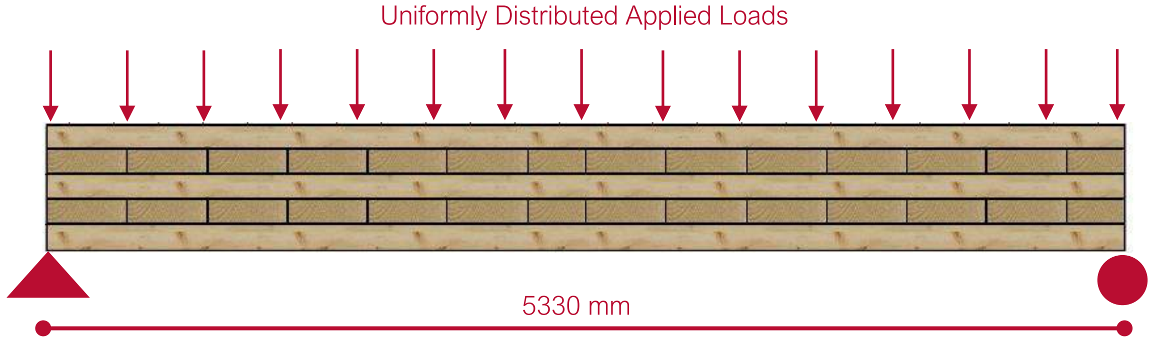

Figure 78: Red Stag CLT Panel Elevation

29.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3.

Additional Dead Load = 0.5 kPa

Live Load = 3.0 kPa - Refer to AS/NZS 1170.1 [37]

29.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 5330 mm = 5.33 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

$h_1 = 42$ mm

$h_2 = 42$ mm

$h_3 = 42$ mm

$\overline{h}_i$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h}_1 = 42$ mm

$\overline{h}_2 = 42$ mm

$A_i = b_i \times h_i$ [38]

$A_1 = (42 \times 1000) = 42000$ mm^2

$A_2 = (42 \times 1000) = 42000$ mm^2

$A_3 = (42 \times 1000) = 42000$ mm^2

$I_i = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000$ mm^4

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000$ mm^4

$I_3 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000$ mm^4

$E_1 = 8000$ MPa [36]

$E_2 = 8000$ MPa [36]

$E_3 = 8000$ MPa [36]

$\gamma_2 = 1$ [38]

$\gamma_1 = \frac{1}{1 + \Pi^2 \times \frac{E_1 \times A_1}{L^2} \times \frac{\overline{h}_1}{G_R \times b}}$ [38]

$$\gamma_3 = \frac{1}{1+\Pi^2 \times \frac{E_3 \times A_3}{L^2} \times \frac{\overline{h_2}}{G_R \times b}}$$ [38]

where $\frac{h_i}{G_R \times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$\gamma_2 = 1$ [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2 \times 8000 \times 42000}{5330^2} \times \frac{42}{37.5 \times 1000}} = 0.884$$

$$\gamma_3 = \frac{1}{1+\frac{3.14^2 \times 8000 \times 42000}{5330^2} \times \frac{42}{37.5 \times 1000}} = 0.884$$

$$\overline{a}_1 = \frac{h_1}{2} + \overline{h_1} + \frac{h_2}{2}$$ [38]

$$\overline{a}_2 = \frac{h_2}{2} + \overline{h_2} + \frac{h_3}{2}$$ [38]

$$\overline{a}_1 = \frac{42}{2} + 42 + \frac{42}{2} = 82 \text{ mm}$$

$$\overline{a}_2 = \frac{42}{2} + 42 + \frac{42}{2} = 82 \text{ mm}$$

$$EI_{eff\,//} = \sum_{i=1}^{2} (E_i I_i + \gamma_i E_i A_i {a_i}^2)$$ [38]

$$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 {a_1}^2) + I_2 + (E_3 I_3 + \gamma_3 E_3 A_3 {a_3}^2)$$ [38]

$EI_{eff} = 4.34 \times 10^{12}$ N.mm^2

$$I_{eff} = \frac{4.34 \times 10^{12}}{8000} = 5.43 \times 10^8 \text{ mm}^4$$

29.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{(\delta_1 a_1 \times 0.5h_1)}$ $(E_1 = E_2)$ [38]

$F_b = 14$ MPa [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{5.43 \times 10^8}{(0.884 \times 84 + 0.5 \times 42)} \times 10^{-6} = 71.76$ kN.m

29.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{5.43 \times 10^8}{0.5 \times 210} \times 10^{-6} = 28.81$ kN.m

29.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 210 × (5/1000) = 1.08 kPa.

Additional Dead Load = 0.5 kPa.

Live Load = 2 kPa on Floor

$M^* = \frac{(1.2 \times (1.08 + 0.5) + 1.5 \times 3) \times 5.33^2}{8} = 22.59$ kN.m

$M^* = \frac{(1.35 \times (1.08 + 0.5)) \times 5.33^2}{8} = 8.26$ kN.m

29.7. Bending Capacity Check

$M_{r \text{ Mechanical jointed method}}$ = 71.76 kN.m ≥ M^*= 22.59 kN.m √ ok

$M_{r \text{ Mechanical jointed method}}$ = 71.76 kN.m ≥ M^*= 8.26 kN.m √ ok

$M_{r \text{ Simplified method}}$ = 65.13 kN.m ≥ M^*= 22.59 kN.m √ ok

$M_{r \text{ Simplified method}}$ = 65.13 kN.m ≥ M^*= 8.26 kN.m √ ok

29.8. Deflection Check

$$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^4}{(384\times(EI_{eff}\,)}$$ [38], [39]

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight + Additional Dead Load })+0.4\times\text{Live Load })\times 5330^4}{(384\times(EI_{eff}\,))}$$

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((1.08+0.5)+0.4\times3)\times5330^4}{(384\times(4.34\times10^{12}\,)} = 6.66 \text{ mm}$$

Creep Factor (K_2) = 2

Long term deflection = 6.66 × 2 = 13.31 mm → long term deflection

Long term deflection = 13.31 ≤ $\Delta^* = \frac{5330}{400}$ = 13.325 mm √ ok

29.9. Vibration Check

$$L \leq 0.11 \frac{(\frac{(EI)_{eff}}{10^6})^{0.293}}{m^{0.123}}$$ [41]

L = vibration -controlled span limit in m.

L = is the floor span in m.

m = linear mass of the CLT for a 1-m wide panel (kg/m).

EI_{eff} = effective bending stiffness.

$$L \leq 0.11 \frac{(\frac{4.34\times10^{12}}{10^6})^{0.293}}{(1.0\times0.210\times500)^{0.123}} = 5.47 \text{ m} \geq 5.33 \text{ m}$$ √ ok

30.1. CLT Floor Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

Figure 79: Red Stag CLT Panel Cross-Section

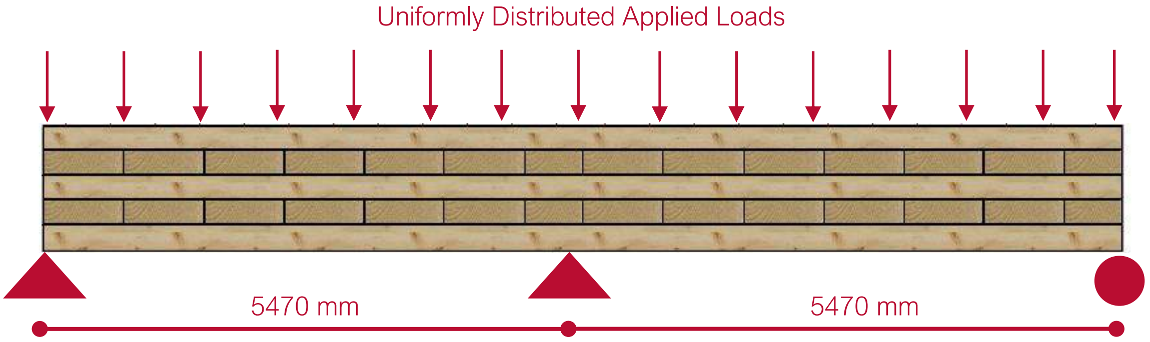

Figure 80: Red Stag CLT Panel Elevation

30.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3.

Additional Dead Load = 0.5 kPa

Live Load = 3.0 kPa - Refer to AS/NZS 1170.1 [37]

30.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 5470 mm = 5.47 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

h_3 = 42 mm

$\overline{h}_i$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h}_1$ = 42 mm

$\overline{h}_2$ = 42 mm

$A_i = b_i \times h_i$ [38]

A_1 = (42×1000) = 42000 mm^2

A_2 = (42×1000) = 42000 mm^2

A_3 = (42×1000) = 42000 mm^2

$I_i = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000 \times 42^3}{12}$ = 6174000 mm^4

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12}$ = 6174000 mm^4

$I_3 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12}$ = 6174000 mm^4

E_1 = 8000 MPa [36]

E_2 = 8000 MPa [36]

E_3 = 8000 MPa [36]

$\gamma_2 = 1$ [38]

$\gamma_1 = \frac{1}{1 + \Pi^2 \times \frac{E_1 \times A_1}{L^2} \times \frac{\overline{h_1}}{G_R \times b}}$ [38]

$$\gamma_3 = \frac{1}{1+\Pi^2\times\frac{E_3\times A_3}{L^2}\times\frac{\overline{h_2}}{G_R\times b}}$$ [38]

where $\frac{h_i}{G_R\times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5470^2}\times\frac{42}{37.5\times 1000}} = 0.890$$

$$\gamma_3 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5470^2}\times\frac{42}{37.5\times 1000}} = 0.890$$

$$\overline{a_1} = \frac{h_1}{2} + \overline{h_1} + \frac{h_2}{2} - a_2$$ [38]

$$\overline{a_2} = \frac{h_2}{2} + \overline{h_2} + \frac{h_3}{2} - a_2$$ [38]

$a_2 = 0$

$$\overline{a_1} = \frac{42}{2} + 42 + \frac{42}{2} - 0 = 82 \text{ mm}$$

$$\overline{a_2} = \frac{42}{2} + 42 + \frac{42}{2} - 0 = 82 \text{ mm}$$

$$EI_{eff\,//} = \sum_{i=1}^{2}(E_i I_i + \gamma_i E_i A_i a_i^2)$$ [38]

$$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 a_1^2) + I_2 + (E_3 I_3 + \gamma_3 E_3 A_3 a_3^2)$$ [38]

$EI_{eff} = 4.37\times10^{12}$ N.mm^2

$$I_{eff} = \frac{4.37\times10^{12}}{8000} = 5.46\times10^{8}\text{ mm}^4$$

30.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{(\delta_1 a_1 \times 0.5 h_1)}$ $(E_1 = E_2)$ [38]

$F_b = 14$ MPa [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{5.46 \times 10^8}{(0.890 \times 84 + 0.5 \times 42)} \times 10^{-6} = 71.84$ kN.m

30.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5 h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{5.46 \times 10^8}{0.5 \times 210} \times 10^{-6} = 65.50$ kN.m

30.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 210 × (5/1000) = 1.08 kPa.

Additional Dead Load = 0.5 kPa.

Live Load = 3 kPa on Floor

$M^* = \frac{(1.2 \times (1.08 + 0.5) + 1.5 \times 3) \times 5.33^2}{8} = 22.59$ kN.m

$M^* = \frac{(1.35 \times (1.08 + 0.5)) \times 5.33^2}{8} = 8.26$ kN.m

30.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}}$ = 71.84 kN.m ≥ M^*= 22.59 kN.m √ ok

$M_{r\ \text{Mechanical jointed method}}$ = 71.84 kN.m ≥ M^*= 8.26 kN.m √ ok

$M_{r\ \text{Simplified method}}$ = 65.50 kN.m ≥ M^*= 22.59 kN.m √ ok

$M_{r\ \text{Simplified method}}$ = 65.50 kN.m ≥ M^*= 8.26 kN.m √ ok

30.8. Deflection Check

$$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^4}{(384\times(EI_{eff}\ )}$$ [38], [39]

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight}+\text{Additional Dead Load}\ )+0.4\times\text{Live Load}\ )\times 5470^4}{(384\times(EI_{eff}\ ))}$$

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((1.08+0.5)+0.4\times 3)\times 5470^4}{(384\times(4.37\times 10^{12}\ )} = 6.66 \text{ mm}$$

Creep Factor (K_2) = 2

Long term deflection = $\frac{7.34}{2.4}\times 2$ = 6.12 mm → long term deflection

Long term deflection = 6.12 ≤ $\Delta^* = \frac{5470}{400}$ = 13.675 mm √ ok

30.9. Vibration Check

$$L \leq 0.11\,\frac{(\frac{(EI)_{eff}}{10^6})^{0.293}}{m^{0.123}}$$ [41]

L = vibration -controlled span limit in m.

L = is the floor span in m.

m = linear mass of the CLT for a 1-m wide panel (kg/m).

EI_{eff} = effective bending stiffness.

$$L \leq 0.11\,\frac{(\frac{4.37\times 10^{12}}{10^6})^{0.293}}{(1.0\times 0.210\times 500)^{0.123}} = 5.47 \text{ m} \geq 5.47 \text{ m}$$ √ ok

31.1. CLT Floor Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

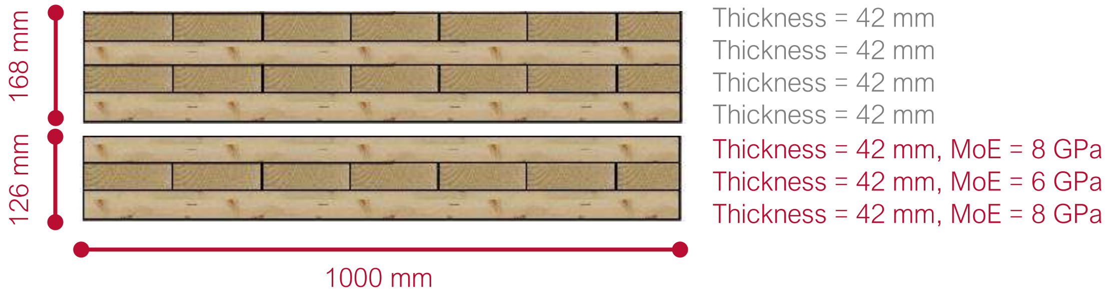

Figure 85: Red Stag CLT Panel Cross-Section

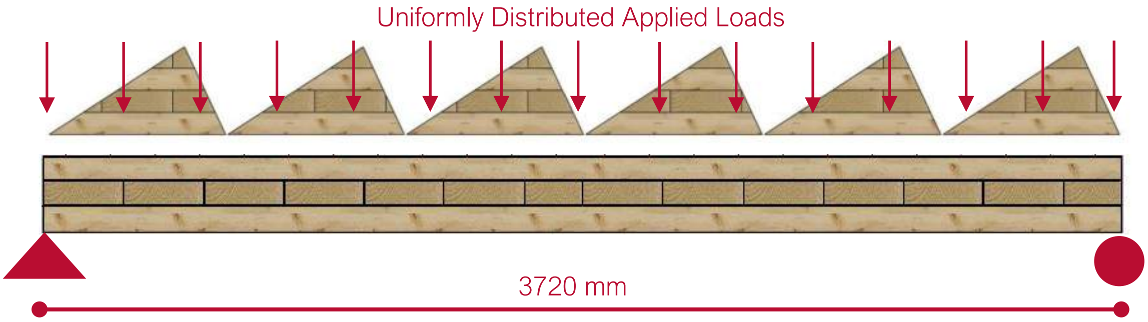

Figure 86: Red Stag CLT Panel Elevation

31.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3.

Additional Dead Load (Trade & Riser Weight) = 0.3 kPa

Live Load = 3.0 kPa - Refer to AS/NZS 1170.1 [37]

31.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 3850 mm = 3.72 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

$\overline{h_i}$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h_1}$ = 42 mm

$A_i = b_i \times h_i$ [38]

$A_1 = (42\times1000) = 42000\ \text{mm}^2$

$A_2 = (42\times1000) = 42000\ \text{mm}^2$

$I_1 = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^4$

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^4$

E_1 = 8000 MPa [36]

E_2 = 8000 MPa [36]

$\gamma_1 = \frac{1}{1+\Pi^2\times\frac{E_1\times A_1}{L^2}\times\frac{\overline{h_1}}{G_R\times b}}$ [38]

$\gamma_2 = \frac{1}{1+\Pi^2\times\frac{E_3\times A_3}{L^2}\times\frac{\overline{h_2}}{G_R\times b}}$ [38]

where $\frac{h_i}{G_R \times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2 \times 8000 \times 42000}{3720^2} \times \frac{42}{37.5 \times 1000}} = 0.882$$

$$\gamma_2 = \frac{1}{1+\frac{3.14^2 \times 8000 \times 42000}{3720^2} \times \frac{42}{37.5 \times 1000}} = 0.882$$

$$\overline{a}_1 = \frac{h_1}{2} + \frac{h_1}{2} \text{ [38]}$$

$$\overline{a}_1 = \frac{h_2}{2} + \frac{h_1}{2} \text{ [38]}$$

$$\overline{a}_1 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$$\overline{a}_2 = \frac{42}{2} + \frac{42}{2} = 42 \text{ mm}$$

$$EI_{eff\,//} = \sum_{i=1}^{2} (E_i I_i + \gamma_i E_i A_i {a_i}^2) \text{ [38]}$$

$$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 {a_1}^2) + (E_2 I_2 + \gamma_2 E_2 A_2 {a_2}^2) \text{ [38]}$$

EI_{eff} = $(8000 \times 6174000 + 0.882 \times 8000 \times 42^2)$ + $(8000 \times 6174000 + 0.882 \times 8000 \times 42^2)$ = $5.72 \times 10^{11} + 5.72 \times 10^{11}$= 1.145×10^{12} N.mm^2

$$I_{eff} = \frac{1.145 \times 10^{12}}{8000} = 1.43 \times 10^8 \text{ mm}^4$$

31.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{(\delta_1 a_1 \times 0.5h_1)}$ $(E_1 = E_2)$ [38]

$F_b = 14$ MPa [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.145 \times 10^8}{(0.882 \times 42 + 0.5 \times 42)} \times 10^{-6} = 31.05$ kN.m

31.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.43 \times 10^8}{0.5 \times 126} \times 10^{-6} = 28.63$ kN.m

31.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 126 × (5/1000) = 0.63 kPa.

Additional Dead Load = 0.5 kPa.

Live Load = 3 kPa on Stair Stringer

$M^* = \frac{(1.2 \times (0.63+0.3) + 1.5 \times 3) \times 3.725^2}{8} = 9.77$ kN.m

$M^* = \frac{(1.35 \times (0.63+0.3)) \times 3.725^2}{8} = 2.43$ kN.m

31.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}} = 31.05\ \text{kN.m} \geq M^{*} = 9.77\ \text{kN.m}$ √ ok

$M_{r\ \text{Mechanical jointed method}} = 31.05\ \text{kN.m} \geq M^{*} = 2.43\ \text{kN.m}$ √ ok

$M_{r\ \text{Simplified method}} = 28.62\ \text{kN.m} \geq M^{*} = 9.77\ \text{kN.m}$ √ ok

$M_{r\ \text{Simplified method}} = 28.62\ \text{kN.m} \geq M^{*} = 2.43\ \text{kN.m}$ √ ok

31.8. Deflection Check

$$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^{4}}{(384\times(EI_{eff}\,)}$$ [38], [39]

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight} + \text{Additional Dead Load}\,)+0.4\times\text{Live Load}\,)\times3720^{4}}{(384\times(EI_{eff}\,))}$$

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((0.63+0.3)+0.4\times3)\times3720^{4}}{(384\times(1.145\times10^{12}\,)} = 4.64\ \text{mm}$$

Creep Factor (K_2) = 2

Long term deflection = 4.64 × 2 = 9.28 mm → long term deflection

Long term deflection = 9.28 $\leq \Delta^{*} = \frac{3720}{400}$ = 9.30 mm √ ok

31.9. Vibration Check

$$L \leq 0.11\,\frac{(\frac{(EI)_{eff}}{10^{6}})^{0.293}}{\text{m}^{0.123}}$$

L = vibration -controlled span limit in m.
m = linear mass of the CLT for a 1-m wide panel (kg/m).
EI_{eff} = effective bending stiffness.

$$L \leq 0.11\,\frac{(\frac{1.145\times10^{12}}{10^{6}})^{0.293}}{(1.0\times0.126\times500)^{0.123}} = 3.94\ \text{m}$$

Vibration span = 3.94 ≥ Maximum length of the CLT panels = 3.72 m √ ok

32.1. CLT Roof Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

Figure 81: Red Stag CLT Panel Cross-Section

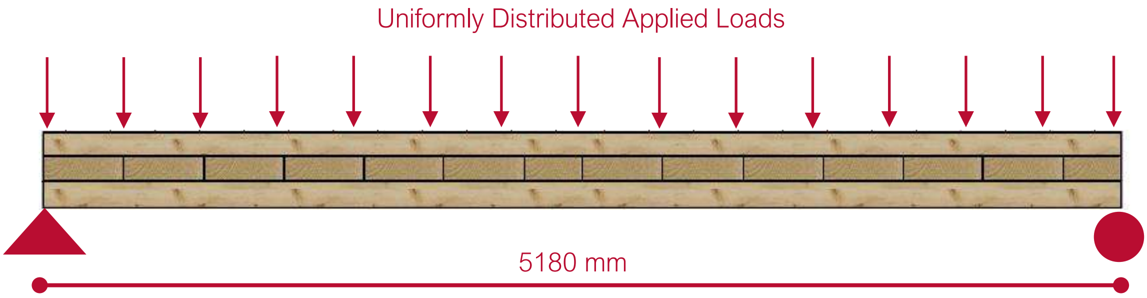

Figure 82: Red Stag CLT Panel Elevation

32.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3.

Additional Dead Load = 0.1 kPa

Live Load = 0.25 kPa - Refer to AS/NZS 1170.1 [37]

32.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 5180 mm = 5.18 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

$\overline{h_i}$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h_1}$ = 42 mm

$A_i = b_i \times h_i$ [38]

$A_1 = (42 \times 1000) = 42000$ mm^2

$A_2 = (42 \times 1000) = 42000$ mm^2

$I_1 = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000$ mm^4

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000 \times 42^3}{12} = 6174000$ mm^4

E_1 = 8000 MPa [36]

E_2 = 8000 MPa [36]

$\gamma_1 = \frac{1}{1+\Pi^2 \times \frac{E_1 \times A_1}{L^2} \times \frac{\overline{h_1}}{G_R \times b}}$ [38]

$\gamma_2 = \frac{1}{1+\Pi^2 \times \frac{E_3 \times A_3}{L^2} \times \frac{\overline{h_2}}{G_R \times b}}$ [38]

where $\frac{h_i}{G_R \times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5180^2}\times\frac{42}{37.5\times 1000}} = 0.935$$

$$\gamma_2 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{5180^2}\times\frac{42}{37.5\times 1000}} = 0.935$$

$\overline{a}_1 = \frac{h_1}{2} + \frac{h_1}{2}$ [38]

$\overline{a}_1 = \frac{h_2}{2} + \frac{h_1}{2}$ [38]

$\overline{a}_1 = \frac{42}{2} + \frac{42}{2} = 42$ mm

$\overline{a}_2 = \frac{42}{2} + \frac{42}{2} = 42$ mm

$EI_{eff\,//} = \sum_{i=1}^{2}(E_iI_i + \gamma_iE_iA_i{a_i}^2)$ [38]

$EI_{eff\,//} = (E_1I_1 + \gamma_1E_1A_1{a_1}^2) + (E_2I_2 + \gamma_2E_2A_2{a_2}^2)$ [38]

$EI_{eff} = (8000\times 6174000+0.935\times 8000\times 42^2) + (8000\times 6174000+0.935\times 8000\times 42^2) = 6.038\times 10^{11}+6.038\times 10^{11}= 1.207\times 10^{12}$ N.mm^2

$I_{eff} = \frac{1.207\times 10^{12}}{8000} = 1.509\times 10^8$ mm^4

32.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = Ø\times F_b\times\frac{I_{eff}}{(\delta_1 a_1 \times 0.5h_1)}$ $(E_1 = E_2)$ [38]

$F_b = 14$ MPa [36]

Ø = 0.9 [36], [38]

$M_r = 0.9\times 14\times\frac{1.509\times 10^8}{(0.935\times 42+0.5\times 42)}\times 10^{-6} = 31.55$ kN.m

32.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.509 \times 10^8}{0.5 \times 126} \times 10^{-6} = 30.19$ kN.m

32.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2 \times \text{Dead Load} + 1.5 \times \text{Live Load}) \times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35 \times \text{Dead Load}) \times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 126 × (5/1000) = 0.63 kPa.

Additional Dead Load = 0.1 kPa.

Live Load = 0.25 kPa on Roof

$M^* = \frac{(1.2 \times (0.63+0.1) + 1.5 \times 0.25) \times 5180^2}{8} = 4.20$ kN.m

$M^* = \frac{(1.35 \times (0.63+0.1)) \times 5180^2}{8} = 3.67$ kN.m

32.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}} = 31.55$ kN.m $\geq M^* = 4.20$ kN.m √ ok

$M_{r\ \text{Mechanical jointed method}} = 31.55$ kN.m $\geq M^* = 3.67$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 30.19$ kN.m $\geq M^* = 4.20$ kN.m √ ok

$M_{r\ \text{Simplified method}} = 30.19$ kN.m $\geq M^* = 3.67$ kN.m √ ok

32.8. Deflection Check

$$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^{4}}{(384\times(EI_{eff}\,)}$$ [38], [39]

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight} + \text{Additional Dead Load}\,)+0.4\times\text{Live Load}\,)\times 8150^{4}}{(384\times(EI_{eff}\,))}$$

$$\Delta_{\text{CLT Deflection}} = \frac{5\times((0.63+0.1)+0.4\times 0.25)\times 5180^{4}}{(384\times(1.207\times 10^{12}\,)} = 6.44 \text{ mm}$$

Creep Factor (K_2) = 2

Long term deflection = 6.44 × 2 = 12.89 mm → long term deflection

Long term deflection = $12.89 \leq \Delta^{*} = \frac{5180}{400} = 12.95$ mm √ ok

33.1. CLT Roof Panel Design – Longitudinal Direction

Calculation of the longitudinal members is based on the FPInnovation CLT design guide Mechanical jointed and simplified methods.

Figure 83: Red Stag CLT Panel Cross-Section

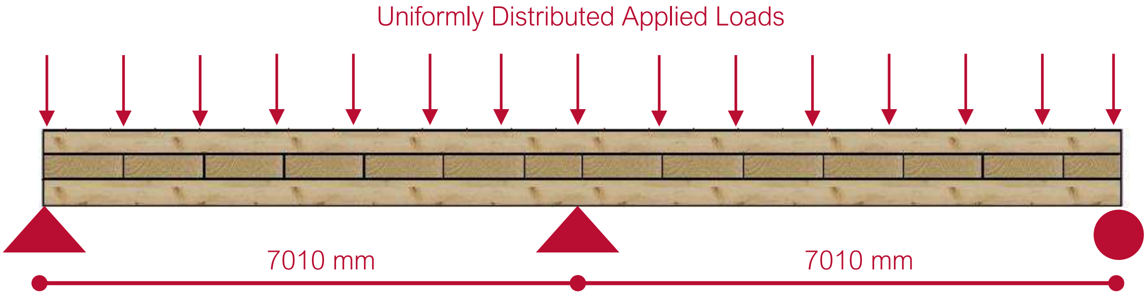

Figure 84: Red Stag CLT Panel Elevation

33.2. Assumption and Applied Loads:

Strength Reduction Factor (Ø) = 0.9 [36]

Bending Strength (F_b) = 14 MPa [36]

CLT Weight = 0.63 kPa - Calculated based on a Red Stag CLT density of 500 kg/m^3.

Additional Dead Load = 0.1 kPa

Live Load = 0.25 kPa - Refer to AS/NZS 1170.1 [7]

33.3. Calculation of the Effective Bending Stiffness using the Mechanical Jointed Beam Theory (Gamma Method)

L = Span of panels = 7010 mm = 7.01 m

b = Width of the CLT panel = 1 m [38]

h_i = Thickness of board layers in direction of action [38]

h_1 = 42 mm

h_2 = 42 mm

$\overline{h}_i$ = Thickness of board layers in direction perpendicular to actions [38]

$\overline{h}_1$ = 42 mm

$A_i = b_i \times h_i$ [38]

$A_1 = (42\times1000) = 42000\ \text{mm}^2$

$A_2 = (42\times1000) = 42000\ \text{mm}^2$

$I_1 = \frac{b_i \times {h_i}^3}{12}$ [38]

$I_1 = \frac{b \times {h_1}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^2$

$I_2 = \frac{b \times {h_3}^3}{12} = \frac{1000\times42^3}{12} = 6174000\ \text{mm}^2$

$E_1 = 8000$ MPa [36]

$E_2 = 8000$ MPa [36]

$\gamma_1 = \frac{1}{1+\Pi^2\times\frac{E_1\times A_1}{L^2}\times\frac{\overline{h}_1}{G_R\times b}}$ [38]

$\gamma_2 = \frac{1}{1+\Pi^2\times\frac{E_3\times A_3}{L^2}\times\frac{\overline{h}_2}{G_R\times b}}$ [38]

where $\frac{h_i}{G_R\times b}$ = slip modulus due to shear deformation between layers and G_R = shear modulus perpendicular to the grain or rolling shear modulus [38].

E_0= MoE for longitudinal layers = 8000 MPa [36]	E_0= MoE for transvers layers = 6000 MPa [36]
E_{90} = 266.67 MPa	E_{90} = 200 MPa
G_0 = 500 MPa	G_0 = 375 MPa
G_R = 50 GPa [38]	G_R = 37.5 GPa [38]

L = span in mm (simple span; in direction of action //) [38]

$$\gamma_1 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{7010^2}\times\frac{42}{37.5\times 1000}} = 0.9636$$

$$\gamma_2 = \frac{1}{1+\frac{3.14^2\times 8000\times 42000}{7010^2}\times\frac{42}{37.5\times 1000}} = 0.9636$$

$a_1 = \frac{h_1}{2} + \frac{\overline{h_1}}{2}$ [38]

$a_1 = \frac{h_2}{2} + \frac{\overline{h_1}}{2}$ [38]

$a_1 = \frac{42}{2} + \frac{42}{2}$ = 42 mm

$a_2 = \frac{42}{2} + \frac{42}{2}$ = 42 mm

$EI_{eff\,//} = \sum_{i=1}^{2}(E_i I_i + \gamma_i E_i A_i {a_i}^2)$ [38]

$EI_{eff\,//} = (E_1 I_1 + \gamma_1 E_1 A_1 {a_1}^2) + (E_2 I_2 + \gamma_2 E_2 A_2 {a_2}^2)$ [38]

$EI_{eff} = (8000\times 6174000+0.9636\times 8000\times 42^2) + (8000\times 6174000+0.9636\times 8000\times 42^2)$

$= 1.241\times 10^{12}$ N.mm^2

$I_{eff} = \frac{1.241\times 10^{12}}{8000} = 1.55\times 10^8$ mm^4

33.4. Calculation of Bending Strength using the Mechanically Jointed Beams Theory (Gamma Method)

$M_r = \varnothing\times F_b\times\frac{I_{eff}}{(\delta_1 a_1 \times 0.5h_1)}$ $(E_1 = E_2)$ [38]

F_b = 14 MPa [36]

$\varnothing$ = 0.9 [36], [38]

$M_r = 0.9\times 14\times\frac{1.51\times 10^8}{(0.9636\times 42+0.5\times 42)}\times 10^{-6} = 31.55$ kN.m

33.5. Calculation of Bending Strength using the Simplified Method

$M_r = \varnothing \times F_b \times \frac{I_{eff}}{0.5h_1}$ [38]

$F_b = 14$ [36]

$\varnothing = 0.9$ [36], [38]

$M_r = 0.9 \times 14 \times \frac{1.55 \times 10^8}{0.5\times126}\times10^{-6} = 31.80$ kN.m

33.6. Calculation of Applied Bending Moment

$M^* = \frac{(1.2\times\text{Dead Load} + 1.5\times\text{Live Load})\times Span^2}{8}$ [38], [39]

$M^* = \frac{(1.35\times\text{Dead Load})\times Span^2}{8}$ [38], [39]

Dead Load = CLT Weight + Additional Dead Load

CLT Weight = CLT Thickness × Timber Weight = 126 × (5/1000) = 0.63 kPa.

Additional Dead Load = 0.1 kPa.

Live Load = 0.25 kPa on Roof

$M^* = \frac{(1.2\times(0.63+0.1) + 1.5\times0.25)\times7.01^2}{8} = 7.68$ kN.m

$M^* = \frac{(1.35\times(0.63+0.1))\times7.01^2}{8} = 6.73$ kN.m

33.7. Bending Capacity Check

$M_{r\ \text{Mechanical jointed method}}$ = 31.80 kN.m ≥ M^*= 7.68 kN.m √ ok

$M_{r\ \text{Mechanical jointed method}}$ = 31.80 kN.m ≥ M^*= 6.73 kN.m √ ok

$M_{r\ \text{Simplified method}}$ = 31.03 kN.m ≥ M^*= 7.68 kN.m √ ok

$M_{r\ \text{Simplified method}}$ = 31.03 kN.m ≥ M^*= 6.73 kN.m √ ok

33.8. Deflection Check

$\Delta_{\text{CLT Deflection}} = \frac{5\times(\text{Uniformly Distributed Applied Load})\times Span^4}{(384\times(EI_{eff}\ )}$ [38], [39]

$\Delta_{\text{CLT Deflection}} = \frac{5\times((\text{CLT Weight} + \text{Additional Dead Load})+0.4\times\text{Live Load})\times7010^4}{(384\times(EI_{eff}))}$

$\Delta_{\text{CLT Deflection}} = \frac{5\times((0.63+0.1)+0.4\times0.25)\times7010^4}{(384\times(1.241\times10^{12}\ )}$ = 21.03 mm

Creep Factor (K_2) = 2

Long term deflection = $\frac{21.03}{2.4}\times 2$ = 17.52 mm → Long term deflection

Long term deflection = 17.52 mm $\leq \Delta^{*} = \frac{7010}{400}$ = 17.52 mm √ ok

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[40] Section 7, European Design of Timber Structures, series of European standards (EN) related to construction, Eurocode 5: Design of timber structures (abbreviated EN 1995 or, informally, EC 5) describes how to design buildings and civil engineering works in timber, using the limit state design.

[41] Section 7, FPInnovation CLT Hand Book, FPInnovations is a private Canadian organisation that specialist in the creation of solutions in support of the Canadian forestry sector.

[42] New Zealand Standard, Methods of Determining the Total Thermal Resistance of Parts of Building (NZS 4214) (2006) Provides methods of determining the thermal resistance of building components and elements consisting of thermally homogeneous layers, in steady-state environmental conditions. (online on 2022) Website Link: https://www.standards.govt.nz/shop/nzs-42142006/

Contact Details:

Website:	redstag.co.nz
General Enquiries & Quotation Requests:	ewp@redstag.co.nz
General Accounts & Finance Team Enquires:	accounts@redstag.co.nz
Phone:	0800 RED STG (0800 733 784) Office +64 7 843 5797