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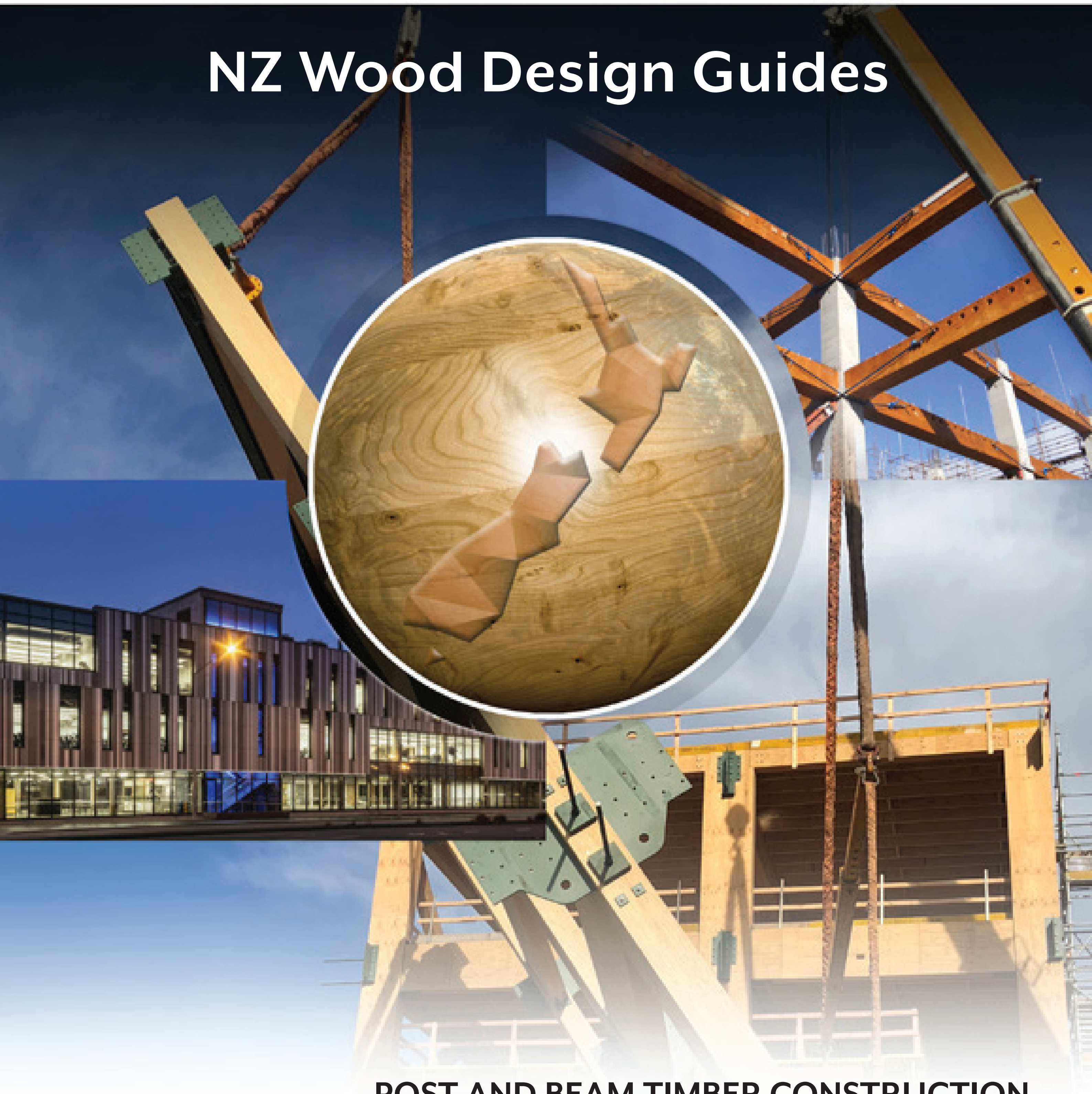

POST AND BEAM TIMBER CONSTRUCTION

Chapter 9.5 | June 2020

Wood Processors & Manufacturers
Association of New Zealand

NZ Wood Design Guides

A growing suite of information, technical and training resources, the Design Guides have been created to support the use of wood in the design and construction of the built environment.

Each title has been written by experts in the field and is the accumulated result of years of experience in working with wood and wood products.

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- Timber, Carbon and the Environment
- Seismic Design
- Reinforcement of Timber Members
- Working Safely with Prefabricated Timber
- Costing Timber Buildings

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NZ Wood Design Guides is a Wood Processors and Manufacturers (WPMA) initiative designed to provide independent, non-proprietary information about timber and wood products to professionals and companies involved in building design and construction.

ACKNOWLEDGEMENTS

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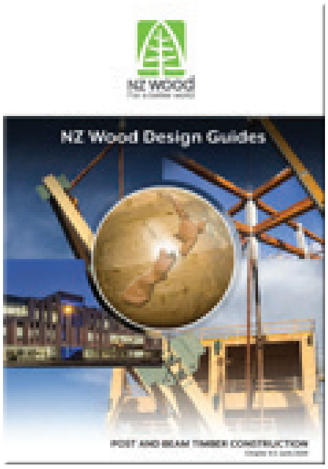

CONTENTS

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1 OVERVIEW

Post and beam construction refers to a system where a buildings' vertical support is built of beams and columns. Compared to conventional light timber framing, timber post and beam construction replaces the need for load bearing walls, allowing for large open spaces.

Post and beam timber construction dates back well over a century in New Zealand and around the world. Auckland's Kauri Timber Building Co built in the 1880s is a four-storey building with an internal post and beam gravity structure. The 2018 restoration of this heritage building highlights the impressive use of Kauri and demonstrates a time-tested structural system.

Kauri Timber Building Co circa 1880s - Auckland. New Zealand Historic Places Trust, Auckland.

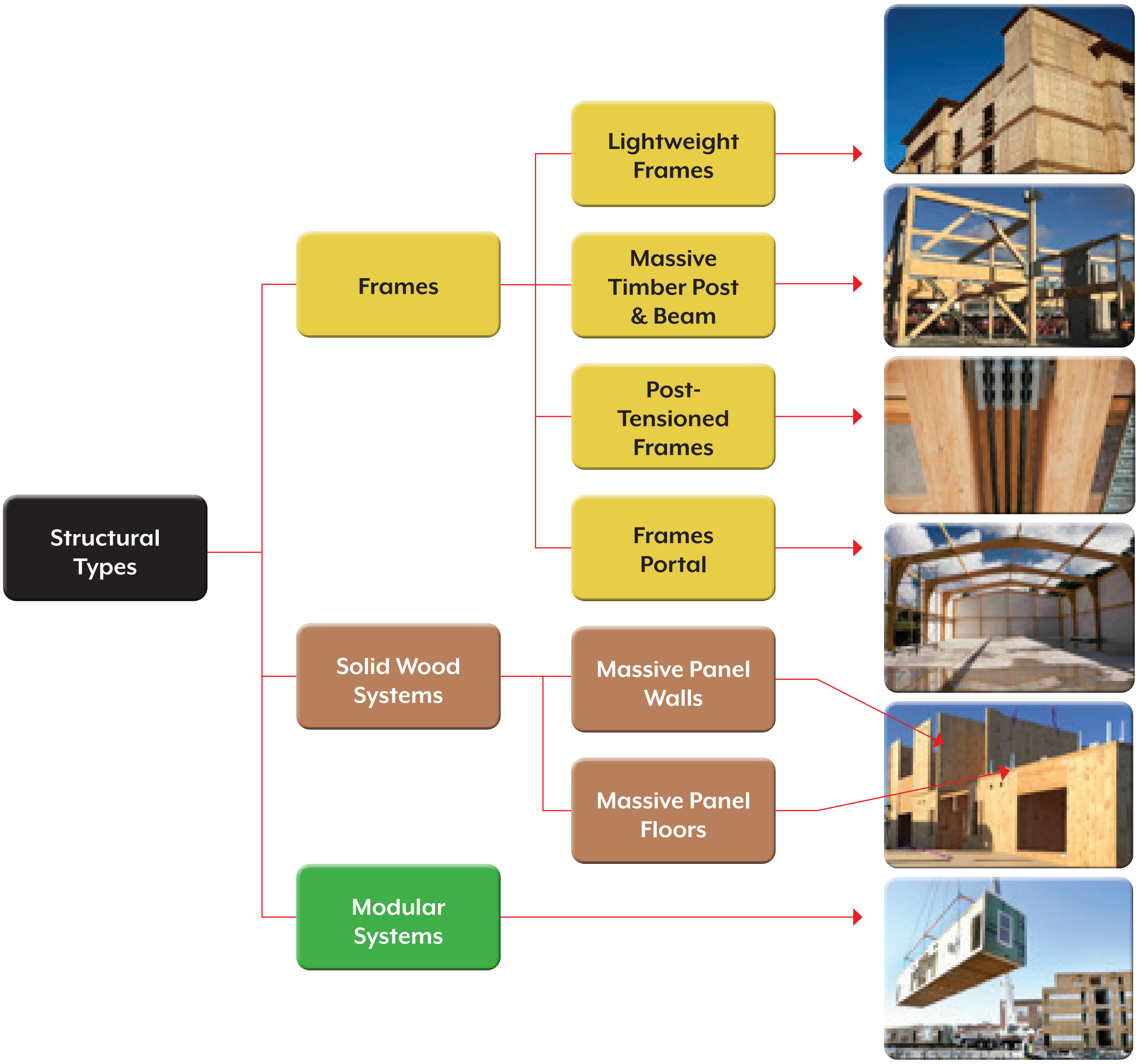
Timber buildings have many advantages beyond the inherent sustainable benefits of using a renewable material. Timber construction is light weight compared to other materials, making it easier to transport and crane into place, and in some situations requires lighter foundations. Timber can be erected efficiently due to the accuracy of prefabrication; this can minimise construction site time and result in a cleaner construction site with less dust, waste and noise. Exposed timber structures also provide the end user with a warm and inviting tactile space. Post and beam construction allows the creation of open, flexible spaces and creates opportunities for more building types to be constructed from timber.

Ground floor of the restored heritage Kauri Timber Building Co (Photo :Patrick Reynolds).

This guide focuses on multi-storey construction that utilises massive timber beam and column elements as the primary gravity load carrying system. Common mass timber available in New Zealand includes Glue Laminated Timber (Glulam), Laminated Veneer Lumber (LVL) and Cross Laminated Timber (CLT) panels.

This is an introductory design guide aimed at providing information and guidance on the planning and concept design of timber post and beam buildings for developers, architects and engineers. References to more detailed design guidance are provided in the relevant sections.

Around the world, the limits of mass timber are being pushed to create exceptional structures. Post and beam buildings suit many applications including commercial, educational, residential, public or institutional. New Zealand is already well on its way in paving the path for timber structures in high seismic zones. In depth case studies of some New Zealand and international post and beam structures can be found in Section 4.0.



Summary of structural timber construction options. WoodSolutions Mid-rise Timber Building Structural Engineering.

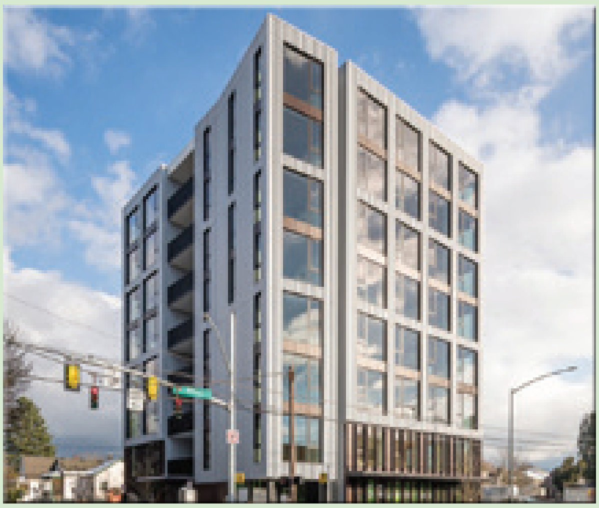
EDUCATION

Beatrice Tinsley Building, Christchurch.
Timber chosen to minimise weight of building, as existing foundations were reused. Also chosen to showcase PRES-Lam system pioneered at University of Canterbury.

COMMERCIAL

Young Hunter House, Christchurch.
Timber chosen to minimise construction time and to facilitate a low damage design with high seismic performance.

RESIDENTIAL



Carbon 12, Portland, US.
Timber was chosen in this 8-storey luxury apartment building to create a sustainable design.

MEDICAL

Hutt Valley Health Hub, Wellington.
Timber chosen to facilitate a low damage design with high seismic performance, and to make the space feel welcoming.

1.1 GRID SPACING AND ELEMENT CONFIGURATION

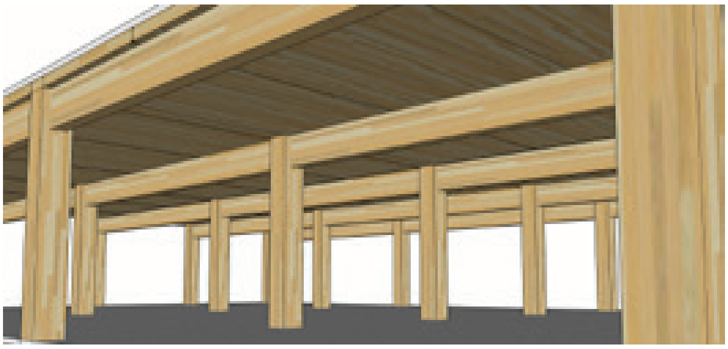
Determining the grid spacing is a critical design factor for mass timber buildings. There is no simple answer for the 'best' grid option as there are benefits and challenges to different layouts. Layouts and member configurations should be determined with input from the whole design team early in the concept design phase. The overall floor depth is dependent on the grid spacing and is often deeper for timber buildings than post and beam construction using other materials.

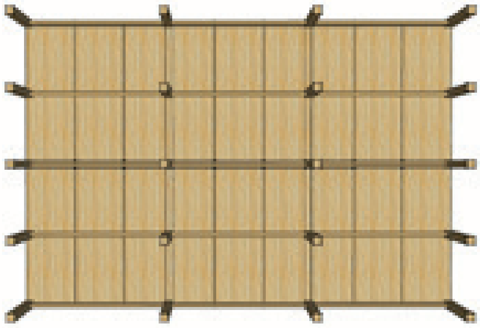
A regular 5m x 5m or 5m x 6m grid spacing will produce an efficient timber post and beam system. It is recommended that this close column spacing is considered first. As the beam spans increase, serviceability criteria (such as vibration) start to govern the designs and the connections between members become more complex. Although possible, achieving a 9m x 9m grid (as often desired for an office building) significantly increases cost and design complexity.

There are numerous configurations for the layout of post and beam structural elements. This section present some of these for consideration, as well as providing examples of typical members sizes required for different grid arrangements.

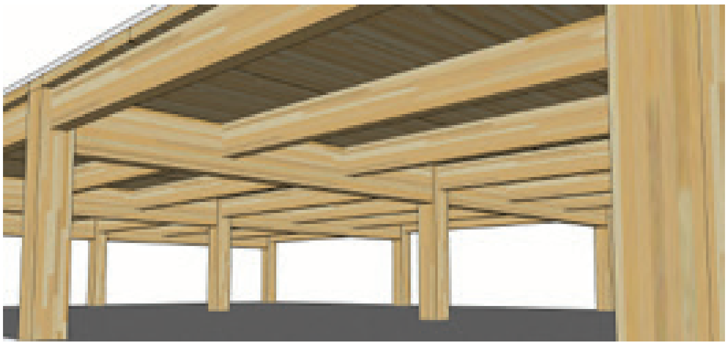
1.1.1 One-way or Two-way Spanning Beams

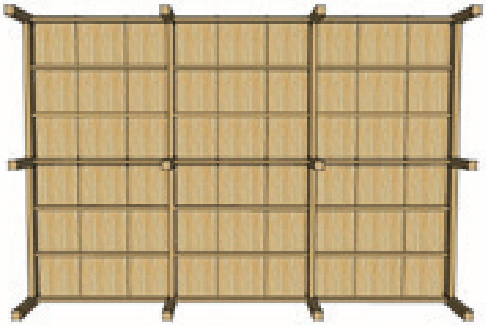
Two common grid layout options are shown below. The first uses a one-way beam system, and the second a two-way beam system.





One-way Beam System.





Two-way Beam System.

A one-way spanning beam system is materially efficient when the span of the floor system in one direction is maximised. A one-way beam configuration also has advantages for the reticulation of services as they can run parallel to the beam lines.

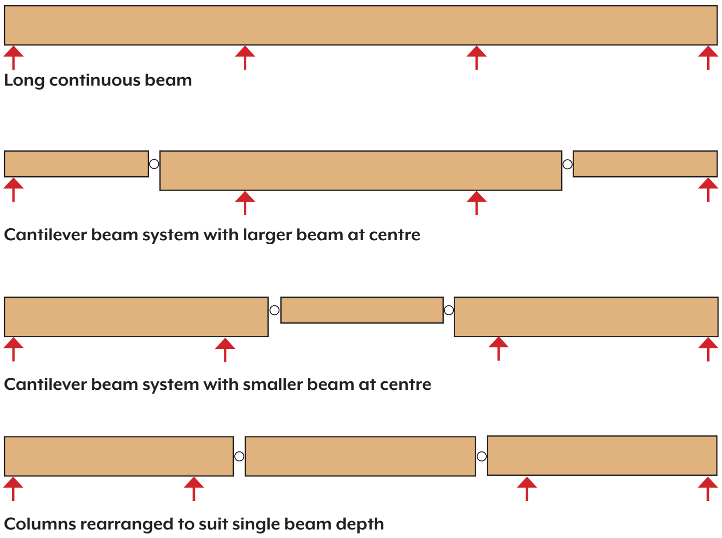
Two-way spanning beam systems are often chosen to provide fewer columns, especially if a mass timber CLT floor is to be used.

A typical office mass timber CLT floor can span up to 6m while a cassette or composite floor can have greater spans up to 10m but will result in a deeper floor build-up. Primary beams can be designed to span up to 9m with satisfactory serviceability performance.

1.1.2 Continuous Beams and Column

The continuity of floors, beams, and columns should all be considered early in the concept design phase when determining the grid spacing. The logistics of transporting and lifting larger elements should form part of this process.

Beams are often designed as simply supported members in post and beam structures; however, continuity over supports can reduce moments and control deflections. Continuity can be achieved with double beams running either side of single columns. Cantilevers in multi-span systems can also be used to reduce member sizes or optimise a single beam depth with uneven support spacing. Beam configurations must be considered in conjunction with columns as their interaction is key.



Beam Support Positions Utilising Cantilevers.

Columns can be single storey, or continuous over 2 or more storeys. Continuous columns mean there are fewer elements to install, fewer column-column connections and less complex connection detailing at nodes. The length of columns from an erection standpoint must also be considered – a very long skinny element could have stability issues during construction.

Detailing of the beam-column interface is important. Continuous beams will need to pass over the support. This can be achieved at the roof level, where the beam can span directly over the column: however, at intermediate levels the beams may need to be fixed to the side of the columns or the column area reduced by a notch. It is important that the connection detail avoids perpendicular to grain bearing on the beams (refer to Section 3.6 Column Design, for more information on perp to grain bearing). A double beam, one each side of the column could be used for continuity; however, fire considerations due to the extra surface area where charring can occur (refer to Section 2.2.3 Fire) could result in larger members.

Similar to beams, floors can also be continuous over supports to help with the distribution of moments, deflection and can allow for a more efficient installation sequence (fewer elements to lift). The benefit of continuous flooring depends on the floor type and build-up requirements of the floor system.

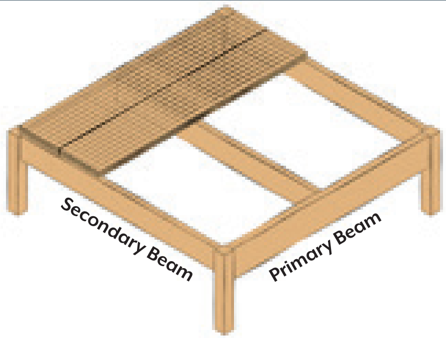
1.1.3 Examples of Post and Beam Element Sizes

The following tables provide examples of element sizes for different grid spacing and element configurations. These are indicative only and should be used as such.

Examples are provided for a CLT flooring on Glulam beams, and Cassette flooring supported by LVL beams; however, any combination of elements is possible: CLT flooring and LVL beams, Cassette flooring and Glulam beams, hybrid combinations, etc. Further possibilities for post and beam components are presented in Section 1.3.

APPROXIMATE MEMBER SIZES – CLT FLOORING WITH GLULAM BEAMS

Layout (Grid)	Secondary Beam (mm x mm)	Primary Beam (mm x mm)	CLT Panel Size
5.0m panel x 5.0m beam	-	180 x 585	5ply/225
5.0m panel x 6.0m beam	-	180 x 675	5ply/225
5.0m panel x 7.0m beam	-	230 x 720	5ply/225
6.0m x 6.0m (secondary beams 3.0m crs)	180 x 585	180 x 765	3ply/135
7.0m x 7.0m (secondary beams 3.5m crs)	180 x 765	230 x 900	5ply/165
8.0m x 8.0m (secondary beams 4.0m crs)	180 x 855	230 x 1035	5ply/195

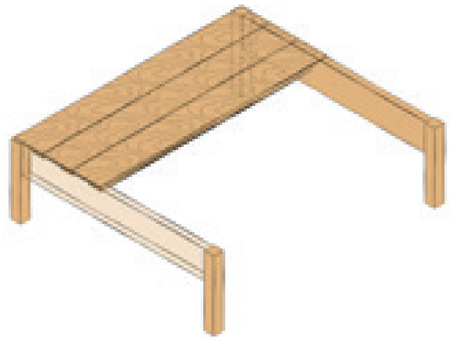


The figure shown is for a two-way beam system where the floor spans between secondary beams. Where there is no secondary beam, the floor spans between primary beams.

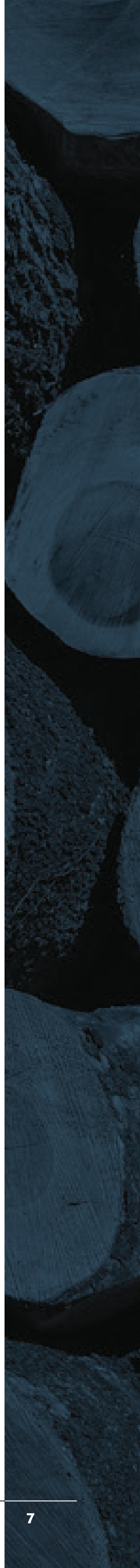
NOTES:
- All member sizing must be confirmed for the conditions of your project.
- Design to NZS AS 1720.1 and AS/NZS 1170.
- Loading: SDL = 1.5kPa; Imposed, Q = 3kPa (imposed area reduction factor, ψ_a, included where applicable).
- Floor Panels assumed continuous over supports (1.25 load increase on internal beam).
- Beams assumed to be simply supported Glulam Grade 10 (GL10).
- Beam sizes are based on strength and vibration checks. The floor plate vibration is designed based on an assumed damping of 3% and a response factor of approx. 8 in line with guidance from SCI P354 (Smith, Hicks & Devine, 2009) and Concrete Centre CCIP-016 (Wilford & Young 2006). See Serviceability Design Section for more information.
- Timber size from this table without additional fire protection achieve 30min fire rating which satisfies the usual sprinkler-protected office requirements.

APPROXIMATE MEMBER SIZES – CASSETTE FLOORING WITH LVL BEAMS

Floor Span	Beam Span	Potius Box Beam Cassette Depth (mm)	LVL Beam (mm x mm)
6.0m	6.0m	350	178 x 550
	7.0m		178 x 650
7.0m	6.0m	450	178 x 600
	7.0m		178 x 650
8.0m	7.0m	520	178 x 700
	8.0m		178 x 800



NOTES:
- All member sizing must be confirmed for the conditions of your project.
- Design to NZS AS 1720.1 and AS/NZS 1170.
- Loading: SDL = 1.5kPa; Imposed, Q = 3kPa (imposed area reduction factor, ψ_a, included where applicable). Panel self-weight = 0.4 - 0.6kPa.
- Floor Panels: simply supported based on Potius Box Beam cassette span tables for 30min FRR.
- Beams assumed to be simply supported of LVL13 grade material.
- Beam sizes are based on strength and vibration checks. The floor plate vibration is designed based on an assumed damping of 3% and a response factor of approximately 8 in line with guidance from SCI P354 (Smith, Hicks & Devine, 2009) and Concrete Centre CCIP-016 (Wilford & Young 2006). See Serviceability Design Section for more information.
- Beam depths have been optimised for strength and serviceability, consult with timber supplier on best beam depth to limit offcut wastage.
- Timber size from this table without additional fire protection achieve 30min fire rating which satisfies the usual sprinkler-protected office requirements.



APPROXIMATE MEMBER SIZES – COLUMNS BASED ON AXIAL LOAD			
Glulam GL10 (mm x mm)	**LVL13 (mm x mm)**	**Factored Axial Load 1.2G+1.5ψaQ (kN)**	**Approximate Area Description**
180x180	178x180	150	4m x 5m x 1 storey = 20m^2
225x225	222x200	375	5m x 6m x 2 storeys = 60m^2
270x270	222x260	720	6m x 7m x 3 storeys = 126m^2
315x315	267x270	1145	6m x 7m x 5 storeys = 210m^2
360x360	300x300	1600	6m x 7m x 7 storeys = 294m^2

NOTES:
- The above table is based on a column length of 3.3m (Lay=Lax = 3.3m), and the area examples are based on 2.0kPa permanent and 3kPa imposed load (office). The imposed action reduction factor, ψa, is included as appropriate. Floors are assumed to be simply supported.
- Columns are checked for combined axial and bending with bending taken as the imposed load on one beam multiplied by half of the column depth.
- Design to NZS AS 1720.1 and AS/NZS 1170.
- The characteristic strengths are taken from manufacturer provided strengths (fc'=26MPa for GL10; fc'=38MPa for LVL13).
- Timber sizes from this table without additional fire protection achieve 30min fire rating which satisfies the usual sprinkler-protected office requirements.

1.1.4 Using every material for its strengths

This guide focuses on timber post and beam components; however, these timber elements can be used in conjunction with other materials. Some examples of hybrid applications are:

- Steel or concrete beams incorporated in a timber post and beam structure for longer spans.
- Concrete or steel columns may be advantageous when used in combination with different lateral systems. (Wynn Williams House in Christchurch uses concrete columns with post-tensioned timber beams).
- To create open areas in a mass timber wall building (such as in the Otago Polytechnic Student Village).
- It is also common for a timber post and beam structure to be used to support a concrete floor (such as in Lucas House in Nelson and Kahukura CPIT in Christchurch that both use concrete prestressed rib and infill floors).

1.2 BUILDING HEIGHT

While New Zealand has no specific limit for the height and size of timber structures, compliance with the Building Code must be achieved. The maximum height of timber buildings is dependent on fire performance, as well as practical limits due to size of structural elements, cost, seismic performance and wind sensitivity. Exposed structural timber contributes to the fire load which is not normally accounted for in non-combustible structures and thus makes the fire design more complex. The main limiting factors are safe egress routes and fire fighter access. However, a 2018 case study (SFPE NZ, 2018), demonstrated how a theoretical 30 storey timber apartment building in Auckland could achieve acceptable fire performance. A qualified Fire Engineer with timber building experience should be consulted on this topic.

Around the globe, timber engineering is pushing new heights. There are many universal similarities; however, every country has different building regulations. Australia for instance changed their National Construction Code in 2016 to allow timber buildings up to 25m high (8-9 storeys). The use of alternative solutions; however, led to the design and completion of 25 King Street in Brisbane, which is 10 storeys and 45m tall. Norway currently has the tallest full mass timber building in the world, Mjøstårnet, which is 18 storeys, with the top occupied level at 68m and much of the structural timber exposed. The Ho Ho Building in Vienna, Austria, is even taller at 24 storeys, 84m tall, and achieves this using concrete core shear walls for the lateral system. In the United States, there is a push for acceptance of taller wood buildings, and as such the 2021 International Building Code (IBC) includes provisions for up to 18 storeys for business and residential occupancies (Breneman, 2019).

In New Zealand, seismic design can also be a limiting factor for the size of timber buildings. The building aspect ratio, seismic loading and lateral load resisting system (LLRS) must be considered early in the concept design when considering building height. Timber buildings above 4 storeys in New Zealand are likely to be viewed as an alternative solution and peer review likely requested by Councils. Tall timber buildings are being designed in other seismic regions of the world; examples include: Carbon 12, an 8 storey mass timber apartment building in Portland, Oregon and Brock Commons, an 18 storey CLT panel – column point supported structure with concrete core shear walls in Vancouver, BC. The 2150 Keith Drive project also in Vancouver is expected to be the tallest timber braced frame building in North America at 10 storeys.

Mjøstårnet, Norway: 18 storey post and beam structure .

25 King Street, Brisbane: 10 storey post and beam structure.

1.3 POST AND BEAM CONSTRUCTION COMPONENTS

During the concept design phase of a post and beam structure, the benefits of different types of floors, beams, columns and lateral systems should be explored. The architect and structural engineer should collaborate with other design professionals on the team as well as material suppliers to determine the most suitable options and material availability for the project. Consideration of fire protection, façade and integration of services within the structure is also critical at an early stage and can affect the component choice – refer to Section 2 for more on these topics. An overview of several types of floors, beams and columns are detailed in this section, as well as lateral systems which can be used with post and beam gravity systems. Foundations, podium levels, roof systems and façades are also discussed.

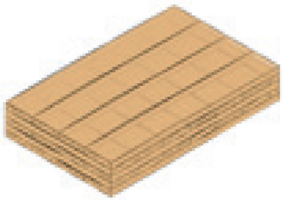
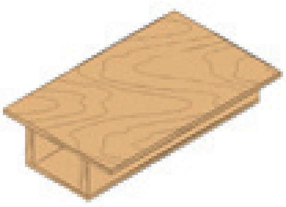
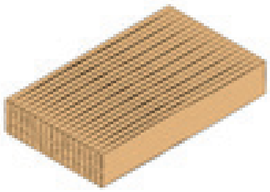
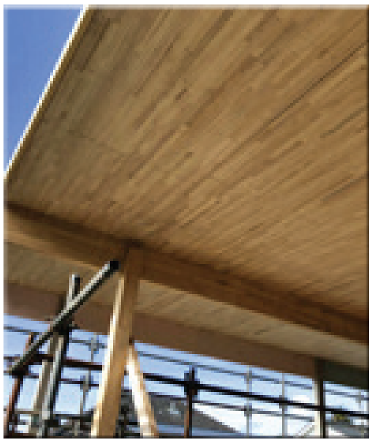
1.3.1 Floors

The floor elements in any mass timber building can have a significant impact on the layout, aesthetic, cost and performance of the structure. Timber floors generally fall into two categories, mass timber floors and timber framing systems. Both types can be prefabricated off site. There are numerous considerations when deciding which type of flooring system to use including:

- **Span** – vibration, strength, deflection.
- **Floor depth** – impact on floor to floor height, supported on beam or face fixed.
- **Topping** – carpet, timber flooring, acoustic mats, concrete screed. Consider construction, weight, acoustics, durability, aesthetics (for example: concrete adds a wet trade and can drip / leach on to other exposed timber if not protected properly).
- **Services Integration** – in floor topping or floating floor, within joist depth, below floor or integrated within beams (see Section 2.2.4).
- **Cost** – unit cost, transportation, installation, finishing.
- **Aesthetics** – exposed, covered, coatings, timber visual grade.
- **Acoustic performance** – required rating, linings, fixings, topping.
- **Tolerance** – moisture effects, construction tolerance.
- **Fire considerations** – rating, spread of flame, linings, penetrations.
- **Support connections** – ease of install, continuous spans, simply supported, durability, fire performance.
- **Diaphragm capability** – connection between panel units, chords, collector connections, fastener edge distances.
- **Supply** – availability, lead time, design advice.
- **Prefabrication** – built on or off site, controlled environment, transportation restrictions.
- **Installation** – temporary support, crane size and hook time, access, safety.

Many of the performance requirements listed above are further discussed in Section 2 of this guide. Non-timber floor systems can also be used in timber post and beam construction. Examples include Ara Kahukura Building in Christchurch which uses a precast concrete rib and infill system. Floor system suppliers often provide span tables for their floor systems. Alternatively, the Wood Solutions Guide number 46 "Wood Construction Systems" provides indicative spans for both floor joists systems and solid CLT floor panels.

Several common timber floor types are discussed in the following table.

FLOOR SYSTEM	FEATURES	EXAMPLES
 **CROSS LAMINATED TIMBER (CLT)** Engineered wood product made up of several layers of timber boards stacked at right angles and glued together on their wide faces. CLT is generally made up of an odd number of laminations from 3 to 7 layers with the outer layers parallel to the major span direction. Panels can be made up to 3.5mx15m but are typically fabricated up to 3.0m x 12.0m based on transportation limitations. Panel thicknesses vary from approx. 105mm to 225mm however can be made up to 315mm (XLam 2017). **NZ manufacturers include:** Red Stag Timber is currently (2020) building a CLT Plant in Rotorua. XLam (fabrication facilities in Australia) supply CLT to NZ.	✓ Potential for two-way spanning system (typically spans up to 6m in principle direction). ✓ Allows for thin floor thickness. ✓ Aesthetics (exposed timber). ✓ Fast installation. ✓ Penetrations for services are easier in two-way system. ✓ Supplier design advice available. ✓ Dimensionally stable compared to other mass timber panels. ✗ Not structurally efficient in terms of wood fibre. ✗ May need to conceal to meet spread of flame requirements in residential and limit fuel for fire design. ✗ Limited supply options in NZ impacts lead times and cost.	
 **CASSETTES / BOX BEAMS** Prefabricated panels consisting of joists, or truss beams, blocking and at least one layer of sheathing. Cassettes come in several forms including box beam floor panels, I-beam or T-beam joists, and timber, steel or hybrid truss beams. **NZ manufacturers include:** MiTek, Potius Building Systems, Pryda, Concision Panelised Technology, CleverCore.	✓ Integration of services in cavities. ✓ Light weight and materially efficient. ✓ Longer span solutions possible. (Typically spans 5-10m). ✓ Insulation & acoustic linings can be included in prefabrication. ✓ Refer to NZ Wood Design Guide 'Floor and Roof Cassette Systems' for more information. ✗ Fire protection often required. ✗ Lifting can be an issue with thin sheathing panels.	
 **GLUE LAMINATED TIMBER (GLULAM) PANELS** This engineered product is made up of timber boards laminated together on edge with all boards running parallel to the span direction. Typical panel depths 90mm to 140mm. **NZ manufacturers include:** Prolam, Techlam, Timberlab, Woodspan PLT, HTL Group.	✓ One-way spanning system (Typically spans up to 6m). ✓ Potentially lesser depth than CLT due to single span direction. ✓ Many supply options in New Zealand. ✗ May require details to accommodate transverse shrinkage. ✗ Reinforcement for penetrations may be required. ✗ Limited width (typ. 900mm) increases number of lifts required unless off-site splice is used. ✗ Sheathing or reinforced concrete topping may be required for diaphragm action.	

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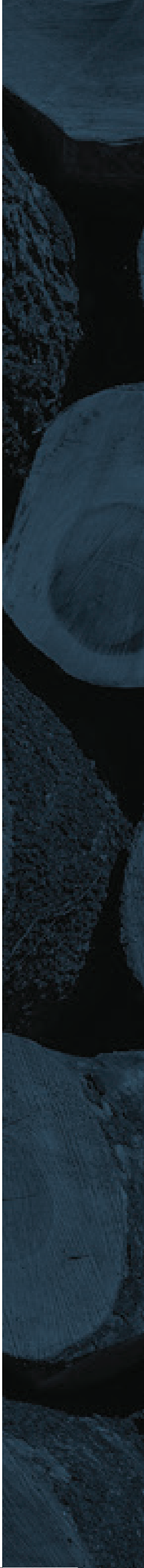
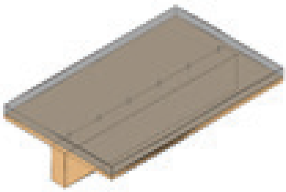
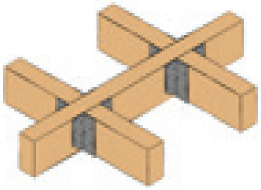
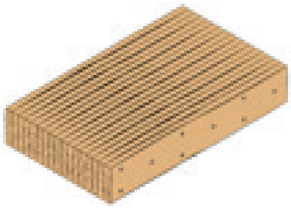
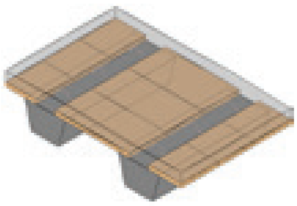
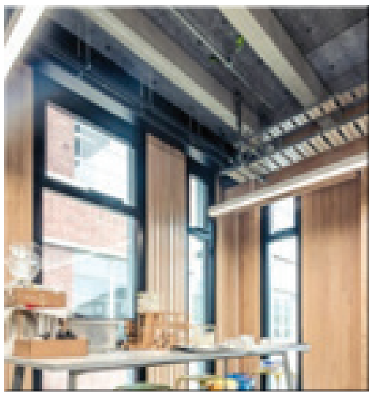
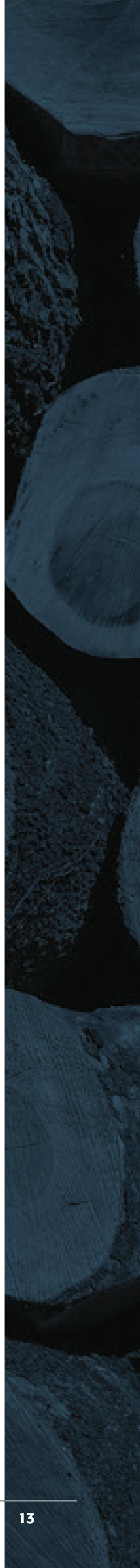


FLOOR SYSTEM	FEATURES	EXAMPLES
 **TIMBER CONCRETE COMPOSITE (TCC)** TCC utilizes the combined strength of timber floor panels (or beams) with the added strength of the concrete topping for the compression flange. Spans up to 12m are possible.	✓ Longer spanning capacity than normal mass timber panels. ✓ Stiffer design with higher mass leading to better vibration and acoustic performance. ✓ Good diaphragm performance and easy to connect into a concrete lateral system. ✓ Increase fire performance with careful design. ✗ Requires additional trade / more coordination. ✗ Preparation for topping pour can be time intensive. ✗ Concrete slurry can leak creating issues with exposed timber. ✗ Adds weight and seismic mass.	
 **TIMBER FRAMING** Traditional timber framing can be used with post and beam structures. Sawn timber or engineered joists can bear on the top of beams or be supported with proprietary brackets similar to light timber frame construction.	✓ Flexibility in construction. ✓ Transportation of smaller elements can be easier. ✓ Can be used as “infill” between other floor systems. ✓ May not require craning. ✗ Does not provide working platform during construction. ✗ Will probably require fire protection. ✗ Additional requirements for acoustic performance. ✗ Limitations on size and capacity for long spans.	
 **NAIL LAMINATED TIMBER (NLT)** NLT is similar to GLT however the laminations are either nailed or screwed instead of glued together. This economical type of mass timber panel along with DLT (dowel laminated timber) are common types of mass timber panels in North America and Europe, however, are not as common in New Zealand.	✓ Easy to fabricate offsite or in place. ✓ One way spanning system (Typically spans up to 6m). ✗ Moisture expansion must be considered in design and detailing. ✗ Reinforcement for penetrations may be required. ✗ Sheathing may be required for diaphragm action.	
 **HYBRID SOLUTIONS** Hybrid floor solutions also work with timber post and beam structures. Concrete rib & infill panels, prestressed concrete panels, or corrugated composite steel and concrete flooring are also options. **NZ manufacturers include:** Stalhton, Preco, Stresscrete, Comflor, Tray-dec.	✓ Long span solution. ✓ Good diaphragm performance and easy to connect into a concrete lateral system. ✓ Low overall floor depth. ✗ Requires additional trade / more coordination. ✗ Timber is not the primary flooring material. ✗ Concrete slurry can leak creating issues with exposed timber. ✗ Adds weight and seismic mass.	



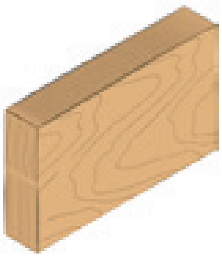
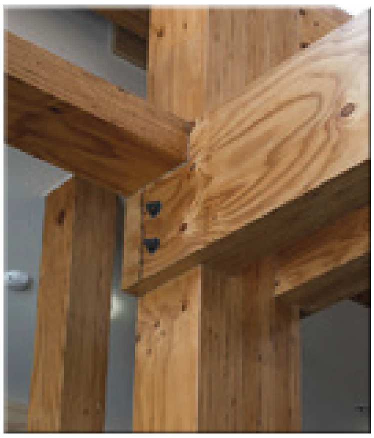
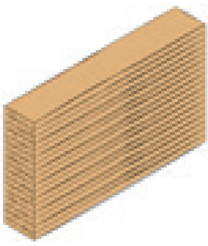
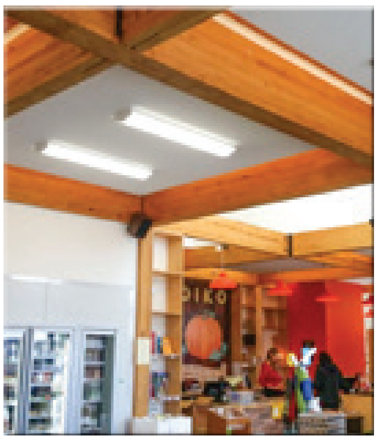
1.3.2 Beams

Beams support the floor elements and transfer load to the columns. Sometimes larger "primary beams" support secondary beams in order to reduce the floor span while maintaining a larger column grid. Some considerations when determining the type of beam element to use include:

- **Span** – vibration, strength, deflection, single or continuous spans to control deflection, camber.
- **Torsion** – eccentric loading.
- **Beam geometry** – lateral buckling, material efficiency, impact on floor to floor height, manufacturer sizing.
- **Integration of services** – within floor, beam penetrations and reinforcement.
- **Cost** – unit cost, transportation, installation, finishing.
- **Aesthetics** – exposed, covered, coatings, timber visual grade.
- **Tolerance** – moisture effects, construction tolerance.
- **Fire considerations** – rating, linings, penetrations.
- **Support connections** – continuous, simply supported, complexity, ease of install, durability, fire, displacement compatibility.
- **Lateral system** – collector beams, diaphragm chords.
- **Supply** – availability, lead time, manufacturer preferred size and grade (refer to Section 3.1 for LVL and Glulam).
- **Prefabrication** – controlled environment, machining, penetrations for services, transportation restrictions.
- **Installation** – temporary support, crane size and hook time, access, safety, buildability.

The most common type of beams used in timber post and beam construction are solid engineered timber beams (LVL or Glulam). The features of these, along with several other beam options are discussed in the following table.

More detail on beam design and an example gravity calculation is presented in Section 3.4. The Wood Solutions Guide number 46 "Wood Construction Systems" provides indicative spans for LVL and Glulam beams less than 500 mm deep.

BEAM TYPE	FEATURES	EXAMPLES
LAMINATED VENEER LUMBER (LVL) Engineered wood product manufactured from thin wood veneer elements which are glued together with a durable adhesive primarily with its grain direction parallel to the main axis of the member. LVL is manufactured in large panels up to 1.2m wide by 18m long and then cut to size. It can be used for beams, columns, floor panels and walls. See Section 3.2 for common grades and sizes.  **NZ manufacturers include:** CHH Futurebuild, Nelson Pine, Juken NZ.	✓ High strength and stiffness compared to Glulam. ✓ Cross banded layers to resist splitting are possible but more expensive. ✓ Readily available in NZ. ✗ Curve and camber achieved by cutting. ✗ Potentially not as aesthetically pleasing as glulam with visible glue lines and potential checking over time.	
GLUE LAMINATED TIMBER (GLULAM) Similar to CLT, glulam consists of laminated elements bonded together with durable, water-resistant adhesives on its flat face. All the laminations run parallel to the length of the member creating a one-way spanning element. Glulam can be made into many sizes and lengths are generally limited by transportation. See Section 3.2 for common grades and sizes.  **NZ manufacturers include:** Prolam, Techlam, Timberlab, HTL Group.	✓ Can be manufactured in almost any size and shape. ✓ Numerous strength grades. ✓ Aesthetics – visually appealing. ✓ Can be precambered or curved in production. ✗ Less strength than equivalent size LVL. ✗ Potential cost premium compared with LVL.	

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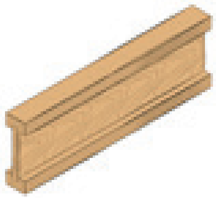
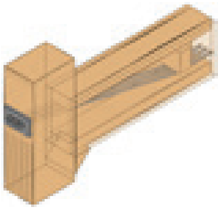
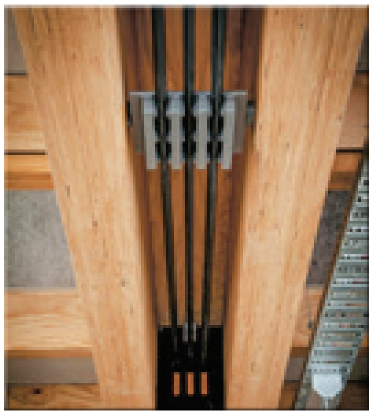
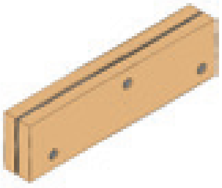
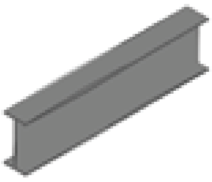
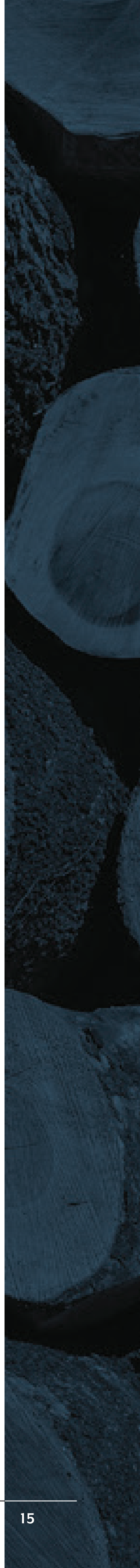
BEAM TYPE	FEATURES	EXAMPLES
BOX OR I-BEAMS  These beams are generally made from sawn timber or LVL flanges, glued or nailed to webs made of plywood, crossbanded LVL or oriented strand board (OSB). Specific design typically required for larger beams. **NZ manufacturers include:** Commercial: Timberlab, Potius Building Systems, Techlam. Residential: Lumberworx, CHH Futurebuild.	✓ Lightweight. ✓ Structurally efficient. ✓ Simple to construct. ✓ Services integration. ✓ Prefabricated or site assembled. ✗ May require fire resistant linings. ✗ I-beams are generally covered (not visible). ✗ More complex to design if not using proprietary product.	
POST-TENSIONED BEAMS  Post-tensioned timber beams use a similar technology to prestressed concrete. The beams are generally made of glulam or LVL 'box' elements with high strength steel bars or tendons running through the cavity and anchored at the ends.	✓ High strength. ✓ Low deflection. ✓ Fewer internal columns or walls. ✓ Incorporation with Pres-Lam lateral technology. ✗ Complex to design. ✗ Consideration of fire required for tendons although often not governing. ✗ Requires good understanding of timber creep and shrinkage. ✗ Timber elements are more likely to be shear governed. ✗ Use of post tensioning does not alter member stiffness or improve vibration performance.	
FLITCH BEAMS  A flitch beam is a composite beam formed with a steel plate sandwiched between two timber elements. The timber elements restrain the thin steel plate from buckling while bending in its strong axis. **NZ manufacturers include:** Residential: MiTek, Pryda.	✓ Stiff beam due to the composite action of the steel plate in its strong direction. ✓ Lesser depth for same span. ✓ Typically used for large residential lintels or where beams are covered. ✗ On site modifications are difficult. ✗ Bolt requirements can be difficult to properly calculate. ✗ Fire protection likely required. ✗ LVL beam is often a more cost-effective solution.	
HYBRID SOLUTIONS  Timber is a great material in many applications, however, in general timber should be used to its strengths. There are instances where the use of steel beams for instance could be a more practical solution within a timber post and beam structure.	✓ May be appropriate for long span solutions. ✓ Could be the right solution where shallow depth required. ✓ High strength connections can be welded. ✓ Can be designed as a ductile link when required. ✗ Fire protection likely required.	

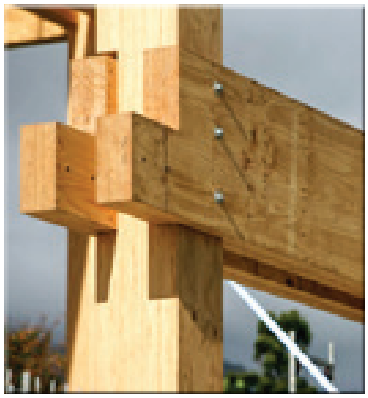
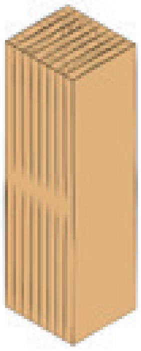
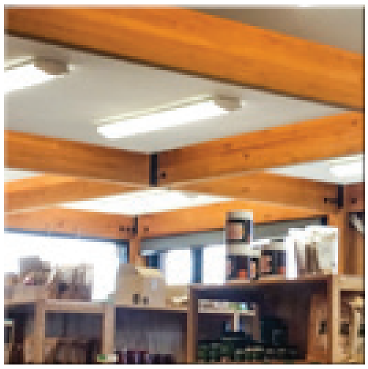
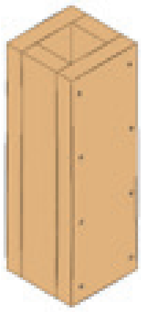
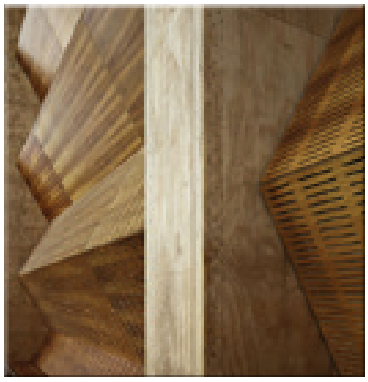
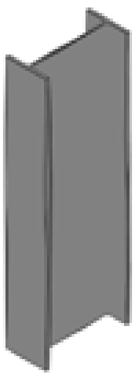
1.3.3 Columns

Column elements are the final step in the gravity load path of the superstructure. They transfer the load from the beams to the foundation. When selecting the column type, many of the same considerations as for beams apply.

- **Strength** – effective length, eccentric loading, deflection, stability of gravity columns under lateral movement.
- **Geometry** – buckling, single or multiple storeys, square, rectangular or box, material efficiency, space constraints.
- **Cost** – unit cost, transportation, installation, finishing.
- **Aesthetics** – exposed, covered, coatings, timber visual grade.
- **Tolerance** – moisture effects, construction tolerance.
- **Fire considerations** – rating, linings.
- **Connections** – complexity, ease of install, durability, fire, displacement compatibility, minimum demands.
- **Lateral system** – Integration with LLRS.
- **Supply** – availability, lead time, manufacturer preferred size and grade (refer to Section 3.2 for LVL and Glulam).
- **Prefabrication** – machining, transportation restrictions.
- **Installation** – temporary support, crane size and hook time, access, safety.
- **Moisture Effects** – temporary and long-term building shrinkage/shortening (refer to Serviceability Design), foundation connection and mitigating construction moisture.

More detail on specific column design and an example gravity calculation is presented in Section 3.6. The most common type of columns used in timber post and beam construction are solid engineered timber (LVL or Glulam). The features of these, along with several other column options are discussed in the following table.

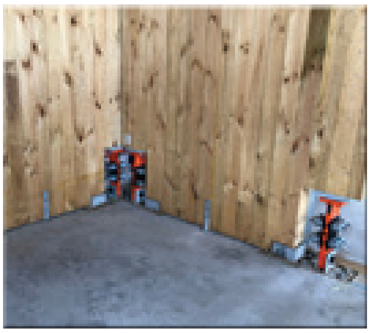


COLUMN TYPE	FEATURES	EXAMPLES
LAMINATED VENEER LUMBER (LVL) Engineered wood product manufactured from thin wood veneer elements which are glued together with a durable adhesive primarily with its grain direction parallel to the main axis of the member. LVL is manufactured in large panels up to 1.2m wide by 18m long and then cut to size. It can be used for beams, columns, floor panels and walls. See Section 3.2 for common grades and sizes. **NZ manufacturers include:** CHH Futurebuild, Nelson Pine, Juken NZ, HTL Group. 	✓ High strength and stiffness compared to Glulam. ✓ Cost effective option. ✗ Potentially not as aesthetically pleasing as glulam with visible glue lines and potential checking over time. ✗ Can be more diffcult to install fasteners due to higher density, however, can result in higher fastener capacity.	
GLUE LAMINATED TIMBER (GLULAM) See beams description. Also note, where members wider than 230mm are required, block glulam can be used. This comes at a cost premium as edge gluing of smaller boards is required (see Section 3.2 for more info). **NZ manufacturers include:** Prolam, Techlam, Timberlab. 	✓ Aesthetics – visually appealing. ✓ Easy to work with. ✓ Large section sizes available. ✗ Potential cost premium compared to LVL.	
BOX OR I SECTION COLUMNS Box columns are composite sections generally made of sawn or engineered timber nailed or glued together. This type of composite column is efficient and light weight. 	✓ Efficient design. ✓ Simple to construct. ✓ Services integration. ✗ More complex to design. ✗ May be labour intensive. ✗ May require fire resistant linings.	
HYBRID SOLUTIONS Columns can be made of alternative materials and incorporated with timber beams and floors. Wynn Williams House is an example in Christchurch that uses concrete columns with post-tensioned LVL beams. 	✓ Use for high demand situations. ✓ Incorporation with lateral system. ✗ Consideration of fire for steel columns. ✗ Need to consider differential creep movement if used in parallel with timber elements. ✗ Intergration of materials requires compatibility of tolerances, structural properties, durability, etc.	

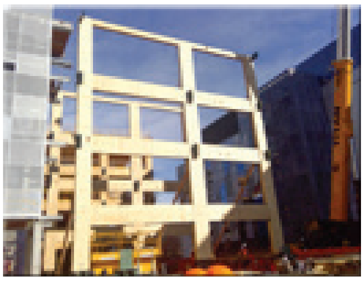
1.3.4 Lateral Load Resisting Systems (LLRS)

Timber post and beam systems are often designed as gravity systems with other lateral load resisting systems. The LLRS transfers horizontal earthquake and wind loads through the structure to the foundation. Considerations for the lateral load design of post and beam structures are discussed in more detail in Section 3.7. Detailed guidance on timber lateral systems can be found in the NZ Wood Guide "Seismic Design".

The LLRS options for post and beam construction predominantly include timber shear walls (CLT or plywood), concrete shear walls, diagonal bracing systems (steel or timber) and moment frames. A high-level overview of these systems is provided in the table below.

ELEMENT	FEATURES	EXAMPLES
LIGHT TIMBER FRAME SHEAR WALLS Light timber frame (LTF) shear walls are typically used in residential applications or areas of buildings with many walls. A sheathing material such as plywood or OSB is fixed to timber framing and used for the shear resistance. This type of LLRS is not common for the larger post and beam construction due to the number of walls required.	✓ Economical, common material. ✓ Fast to construct. ✗ Flexible (less stiff than solid timber wall systems). ✗ Many walls required. ✗ Not common for taller post and beam buildings in seismic regions. ✗ Fire proofing required.	
CLT OR LVL SHEAR WALLS Mass timber shear walls are more common in larger timber buildings than LTF shear walls. In post and beam construction mass timber shear walls can be contained in the core of the building or distributed throughout. Ductility can be provided in the connections (panel joints and hold-downs).	✓ Can be prefabricated off site and installed quickly. ✓ Can be incorporated into seismic resilient systems. ✓ Walls can be concealed in the core of the building. ✗ May have a cost premium compared to a bracing system. ✗ Fire proofing may be required.	
CONCRETE SHEAR WALLS Concrete shear walls are often used as cores centralised within the timber post and beam gravity system.	✓ Stiff system – less drift. ✓ Often fewer shear walls required. ✓ Can incorporate pathways for services, stairs and elevators. ✓ Non-combustible material - can be left exposed/ used as fire wall. ✗ Cost - more expensive than a timber solution. ✗ Slower site construction time. ✗ Introduces new trade to job site. ✗ Differential vertical movement. ✗ Transferring lateral force through the timber diaphragm into the concrete wall can be challenging.	

Continued next page...

ELEMENT	FEATURES	EXAMPLES
TIMBER MOMENT FRAMES Moment frames have been used in timber construction for a long time. They are often known as portal frames which are covered in further detail in NZ Wood design guide "Portal Knee Connections". Multi-story moment frames are less common, however, have been used in timber structures including the Beatrice Tinsley building at the University of Canterbury.	✓ Can be realised through Pres-Lam seismic resistant system or other forms of beam-column moment connections. ✓ Safety in design – preassembly at ground level. ✗ Larger crane required if pre-assembled in large sections. ✗ Limited height due to frame flexibility.	
TIMBER AND STEEL DIAGONAL BRACING Timber and steel diagonal bracing systems are being used more often in timber post and beam structures. They can provide an elegant lateral solution which can be tied into the building's aesthetics.	✓ Fast to install – concurrent install with posts and beams. ✓ Frames can be preassembled on the ground. ✓ Damping devices can be included to increase resilience. ✗ Timber braces can become relatively large with higher forces introduced. ✗ Particular attention required for detailing connections.	
DIAGRID FRAMES Diagrid frames are an efficient structural system that combine gravity and lateral resisting elements. Diagrids remove the need for vertical columns as the diagonals resist both gravity and lateral forces. This technology has been used in some of the world's most impressive timber structures.	✓ Structurally efficient. ✓ Removes need for vertical columns. ✓ Stiff lateral capacity. ✓ Aesthetically pleasing. ✗ Design can be complex. ✗ Potential cost premiums.	

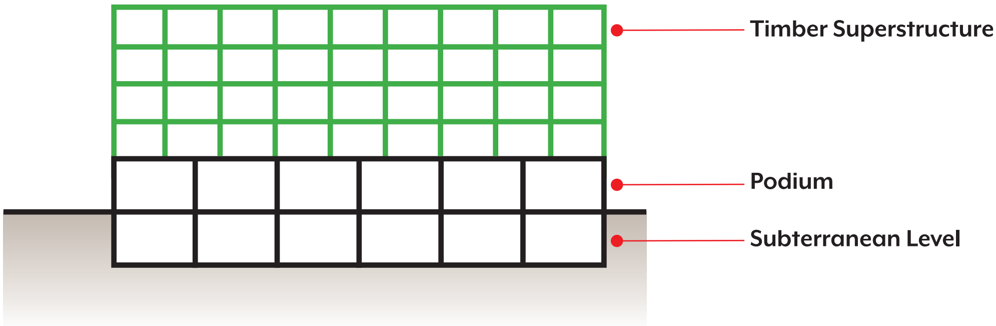
All of the LLRS described above can be designed to include new technology and devices to enhance seismic performance by adding damping and/or recentering to the structural system. Examples of such systems include:

- **Tectonus** – NZ designed friction-based damping device with a special configuration that can produce damping and recentering. This proprietary product is being used in post and beam buildings including the Hutt Valley Health Hub (Lower Hutt, NZ) and the Fast + Epp Head Office (Vancouver, Canada). Designers should contact Tectonus for more information and design guidance.
- **Pres-Lam** – NZ designed post-tensioned timber building system. Post-tensioning is used in conjunction with dissipation devices to add damping and recentering to the structure. Pres-Lam technology is patented in New Zealand and Australia by PTL Structural Consultants who should be contacted for use. Post and beam buildings that use the Pre-Lam technology include the Massey University CoCA building (Wellington, NZ), the Trimble building (Christchurch, NZ), NMIT Arts and Media Building (Nelson, NZ).
- **Buckling Restrained Braces (BRB)** – BRB's are an effective structural solution for seismic resilient structures and have been used in steel construction for many years. Research is underway at the University of Auckland and University of Christchurch on the performance of BRB's in timber buildings, and it is likely that this technology will be incorporated more regularly with timber post and beam structures. The Catalyst Building in Spokane, Washington is the first building to utilize CLT shear walls with buckling-restrained braces as ductile hold-down elements.
- **Friction Springs** – friction springs can be used to absorb energy in an LLRS. Friction springs can be tuned to achieve the desired damping for a specific project. Ringfeder friction springs have been used in New Zealand buildings including in the steel K-braces of the Tait Communications Headquarters in Christchurch.

1.3.5 Foundations and Podium Levels

The foundation design for timber post and beam construction is like that of other building types. The type of foundation required will depend on the size of the building and local ground conditions. Concrete foundations are the most common, but timber piles may also be an option for some buildings.

Timber structures are significantly lighter than the equivalent size concrete structure; therefore, the foundations can often be lighter also. The benefits of less demand on a building's foundations are considerable. Often a shallow, rather than a piled foundation system can be used, resulting in less excavation and less foundation material being required. All of this can lead to faster construction and cost savings.



Podium Construction

Timber post and beam construction lends itself to structures with a regular grid layout. However, often in mixed use developments, there is a desire for a change in layout at the ground floor or basement. To achieve such transitions, it is common for timber post and beam structures to be built on top of a concrete or steel podium. The use of one or two podium levels are well suited for ground floor carpark, retail and restaurant use, and provide fire separation from the other commercial or residential use in the timber stories above. Podiums must be carefully designed to transfer any offset vertical or horizontal design actions. The seismic design of such a system is also important if transferring from the timber LLRS to a concrete or steel LLRS.

T3 Atlanta - 6 storey post and beam, over one story podium (StructureCraft Builders).

Prefabricated timber elements are fabricated with a high level of accuracy, it is therefore important that the receiving structure also be constructed to a high level of accuracy. Timber connections will provide some tolerance, however, the set out of the receiving structure, particularly if it involves cast in place elements must be carefully managed.

1.3.6 Roof Systems

The roof system of a post and beam building can be supported by beams and columns similar to the floor levels below. The beams can be angled to suit the roof pitch and designed for the appropriate roof loading. However, efficient long span roof assemblies can also be designed to allow some columns to be removed at the top level. Trusses, tied frames, arches and portal frames can allow for additional flexibility in roof structures. Columns can also be designed as cantilevers to support the roof level eliminating the need for bracing.

Green Roof. Photo: Martin Tessler.

Arched Glulam Lecture Hall. Photo: Martin Tessler.

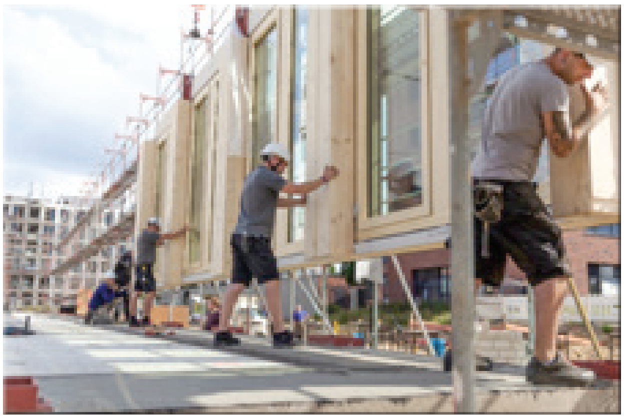
Post and Beam Atrium.

The Centre for Interactive Research on Sustainability (CIRS) at the University of British Columbia in Vancouver, Canada incorporates timber post and beam and long-span glulam arched beams which supports a living roof.

1.3.7 Façade

The façade system of a timber post and beam building requires consideration in the concept design phase – many of the considerations are common to steel or concrete structures. Some considerations include:

- **Serviceability Requirements** – deflection requirements for the system, short and long-term considerations.
- **Perimeter Beam** – is a perimeter beam required to support the façade?
- **Slab offset** –floor slab extension past column/beam (cantilever), this may be more of an issue for one way spanning floor systems.
- **Durability** – envelope, weather proofing, maintenance program, condensation on supporting timber elements.
- **Lateral System** – Integration with lateral system along the perimeter of the building.
- **Fire performance** – combustible materials must be designed to reduce the risk of spread of fire over multiple storeys.
- **Constructability** – tolerance for construction, prefabrication or preassembly offsite (LCT One Building).



Life Cycle Tower One is an eight-storey office building in Dornbirn, Austria. The façade panels incorporated pre-fixed columns to improve installation time by reducing the number of lifts required.

2 CONSIDERATIONS FOR POST AND BEAM CONSTRUCTION

This section provides an overview of things that should be considered when designing with timber post and beam construction. The topics are divided into three sections; Project Drivers, Performance Requirements and Constructability.

2.1 PROJECT DRIVERS

2.1.1 Cost

The cost of timber post and beam construction depends on numerous factors and are in many situations comparable to the equivalent steel or concrete construction. A key to achieving a cost-effective timber building is designing to maximise the benefits of timber from the concept stage. The cost of this construction type has value not only in the short-term capital cost, but also in other non-direct ways. A study commissioned by Naylor Love compared the carbon emissions and costs of a timber versus steel and concrete commercial building. They found that you can currently achieve about 90 percent reduction in carbon emissions for as low as 3-4% cost premium (Steeman, 2019). A few driving factors which impact cost for building with timber include:

- **Foundation Costs** – due to the reduced weight of the structure, potential savings in foundations.
- **Speed of Construction** – prefabrication allows for quick installation and programme efficiency.
- **Reduced size of plant on site** – smaller cranes and other plant can typically be used.
- **Reduced team on site** – fewer people are typically required to assemble timber post and beam structures.
- **Return on Investment** – Green Star-certified buildings have higher return on investment than counterparts (NZGBC 2018).
- **Indirect costs** – quiet and clean construction site, environmental and social benefits.

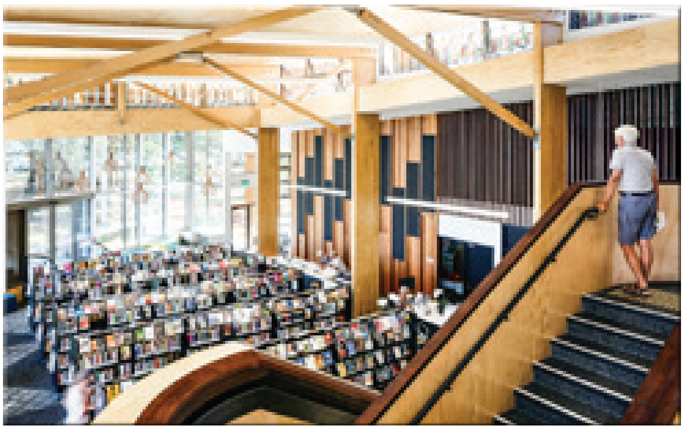
This not an exhaustive list as there are many more considerations for the cost of timber post and beam buildings. The NZ Wood Design Guide 'Costing Timber Buildings' provides more detailed information on this topic.

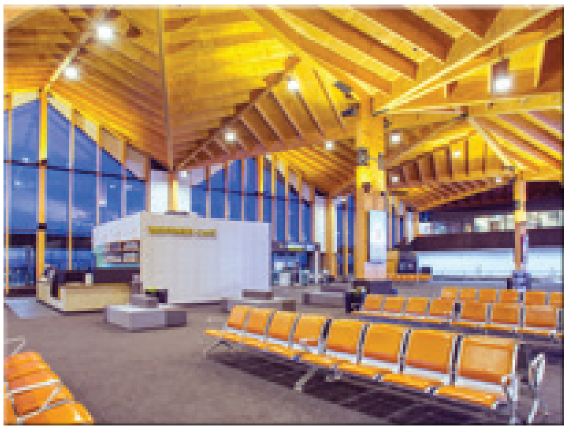
2.1.2 Environmental Sustainability

It is well known that timber has environmental benefits over other mainstream construction materials. It is the only structural material that can be grown with sun and water! The NZ Wood Design Guide 'Timber Carbon and the Environment' provides background and context on the Carbon footprints of buildings made from wood.

Additional benefits of timber post and beam construction are the future flexibility of space use that is provided due to the open plan structure compared to light timber frame structures where walls can limit the use of spaces. Post and beam structures are a structurally efficient use of timber and can be designed for deconstruction. The Circl pavilion in Amsterdam, is a timber post and beam building designed using long, unnotched members that are fully demountable. This will make them easier to re-use at the end of its useful life and contribute to a circular economy.

CIRCL Pavilion, Amsterdam.





Devonport Library, Athfield Architects.

Nelson Airport, Studio Pacific Architecture.

2.1.3 Aesthetics and Well-being

Timber naturally provides a beautiful aesthetic. The many variations of species and intricacies of wood align with human senses. Exposed timber is warm, rich and creates an environment conducive to human wellbeing and can lead to stress reduction (Fell, 2010). Biophilic design is the connection of occupants of indoor spaces to the natural environment through use of sunlight, plants and natural materials including wood. The 2015 report, Wood as a Restorative Material in Healthcare Environments by FPInnovations shows that the use of wood and other natural materials has positive health benefits for humans in the built environment. In the commercial realm wood can also be attributed to increased productivity. The Pollinate 2018 report claims that office productivity can be increase by 8% and well-being increased by 13%. There are many more studies in this area that show a trend of the positives of wood in built environments. Often the best way to achieve these benefits are through the exposure of structural timber.
Refer to NZ Wood Design Guide 'Social and Health Benefits of Timber Construction' for more information.

2.1.4 Maintenance and Durability

Dry timber is a durable material which can last for centuries. Nonetheless care must be taken with timber structures to ensure their longevity. The timber in post and beam buildings is generally enclosed inside the building envelope and requires minimal maintenance. Interior timbers not exposed to moisture should be inspected periodically to ensure the quality and performance of the elements have not degraded. Exterior timbers exposed to weather will require more regular maintenance to ensure that strength and aesthetics are maintained (periodic sanding, coating, etc.). Product manufacturers often provide specific warranties and maintenance criteria for their products which can be found in their technical resources.

All structural timber which cannot be kept dry must be chemically treated or be shown to have adequate durability (i.e. be a naturally durable species). Interior timber will generally require little or no treatment as it falls in the Hazard Class H1.1 or H1.2. Coatings supplied by the manufacturer to protect against moisture and UV during construction are often specified and should be discussed with manufacturers during the design phase.

If non-durable timber is exposed to the elements it can be made more durable through higher levels of treatment to prevent deterioration. The durability of timber through treatment is classified into 6 Hazard Classes, H1 to H6, as referenced above. The NZ Wood Design Guide "Trees, Timber, Species & Properties" outlines these Hazard Classes and typical uses.

2.1.5 Moisture Effects

Moisture effects are the changes in timber properties and dimensions with changes in humidity and temperature. Generally, timber tends to shrink and swell perpendicular to the grain and moisture ingress is greater at the end grain. Moisture effects must be taken into consideration in the design and detailing of timber projects. Effective ways to protect timber structures from moisture include detailing to allow for shrinkage, protecting wood from direct moisture contact, and allowing wood to breathe once in place to release moisture. Refer to Section 2.3 Design for Construction for further information on moisture effects during construction.

More information on the mechanism of moisture change and effect on wood can be found in the NZ Wood Design Guides "Trees, Timber, Species & Properties" and "Construction Guidance".

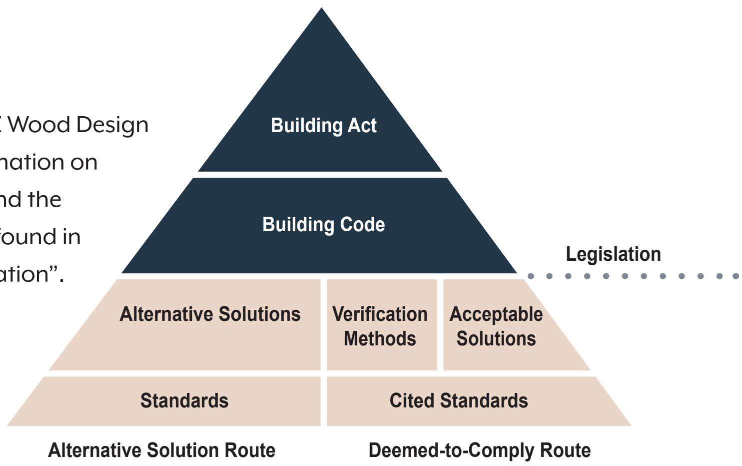
2.1.6 Safety in Design

Safety in design (SiD) is a great opportunity to contribute to the short, medium and long-term safety of structures. Intelligent designs aim to anticipate and eliminate potential risks. SiD should be applied in the planning and design stage to be effective throughout construction, modification and demolition of the structure. Post and beam structures have ample opportunities for SiD, some items to consider include:

- **Safe Construction Methods** – design to eliminate higher risk construction tasks such as work at heights. Prefabrication inherently includes this as tasks are done in a controlled environment. Determine further opportunities for assembly of elements at ground level, such as braced frames, roof elements, etc. Timber components can often be constructed with temporary safety barriers attached before being lifted into place. The lightweight nature of timber can also reduce the number of truck and crane movements required.
- **Future Adaptability** – minimise construction difficulty if the structures are updated or altered.
- **Maintenance** – working with the design team and other stakeholders to identify the best and safest ways to maintain the structure.
- **Low Damage Design** – design the structure for low damage in the event of earthquake or other events. If the structure includes fuses, ensure they easily accessible for replacement after a design level event.
- **Building End of Life** – Design for ease of demolition for the end of the structure's life. Post and beam buildings often inherently include ease of dismantling due to how prefabricated elements are assembled on site.

2.1.7 Consenting

The consenting process is covered in detail in the NZ Wood Design Guide "Consenting Timber Buildings". Further information on compliance, specifically regarding prefabrication and the benefit of robust quality assurance systems can be found in the NZ Wood Design Guide "Designing for Prefabrication".



Building Regulatory Framework.

2.1.8 Procurement

The local supply of timber products can be a defining factor on projects. There are numerous timber product options for post and beam structures, nonetheless early supplier engagement is key for the success of timber projects. Section 5 of the NZ Wood Design Guide "Designing for Prefabrication" discusses the process of procurement in more detail.

2.2 PERFORMANCE REQUIREMENTS

It is key to understand the performance requirements for timber post and beam structures early in the design phase. Often, deflection, vibration, connection detailing or fire safety considerations govern the design. Several important considerations are included in this section.

2.2.1 Structural Performance

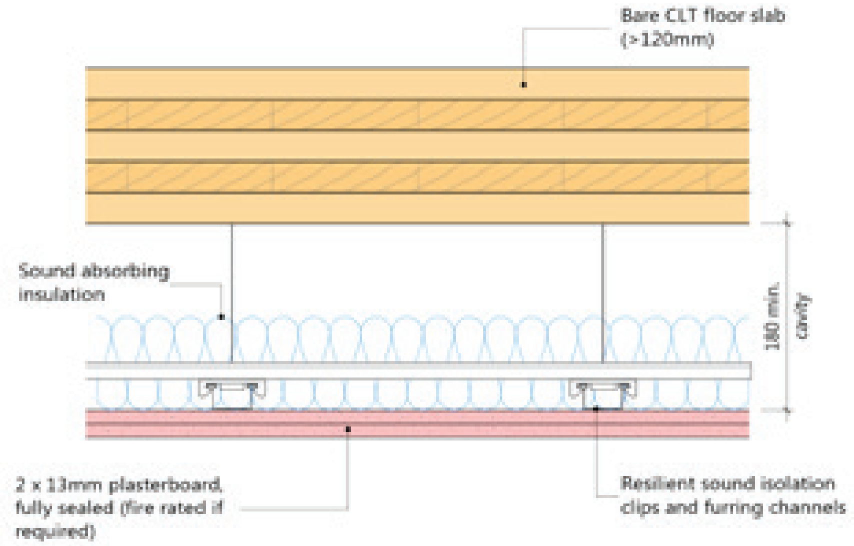
The building code defines the minimum structural performance required for a building. The structural performance includes ensuring the design is serviceable, stable and safe. Limit states for Serviceability, Stability and Strength are prescribed; however, client requirements may be more stringent.

The Serviceability limit state includes consideration of deflection and vibration, the limits for these should be determined by the designer or the client to ensure the building is fit-for-purpose. Deflection and vibration often govern the design of timber beams and floor systems due to their high stiffness relative to mass.

The structural performance of beams and columns, including designing considering vibration, is discussed in more detail in Section 3 of this guide "Structural Design".

2.2.2 Acoustics

Acoustic performance is an importance consideration for timber buildings whether they be light timber frame or mass timber. Timbers' high strength to density ratio makes it an ideal structural material, however, this ratio can lead to less desirable sound insulation performance between adjacent spaces. Sound transmission is divided into airborne sources (speech, music) and impact sources (footsteps, door slams). Sound is not only transferred through direct paths such as through air or walls but also through indirect paths. Any sound which is indirectly transferred is known as flanking transmission and includes, for example, sound transmitted through the floor joists beneath a separating partition wall.



Basic CLT foor with resiliently attached suspended ceiling.

In New Zealand, acoustic performance is measured based on two main descriptors: Sound Transmission Class (STC) for airborne sound and Impact Sound Class (IIC). The higher the STC or IIC ratings, the better the sound insulation of the element. The New Zealand Building Code specifies in Clause G6 that the STC rating of walls, floors and ceilings between residential units shall be no less than 55 and that the IIC for inter-tenancy floors shall be no less than 55. For other building types, acoustic performance is selected by the owner or developer. The Ministry of Education, for example, provides guidance for school buildings. The current and future use of the building and spaces should be considered when determining minimum levels of acoustic performance. Owners and tenants may demand acoustic comfort and privacy, or it might be desirable to isolate noise from building services. It is recommended to get early input from an acoustic consultancy on setting design criteria and providing assistance with design.

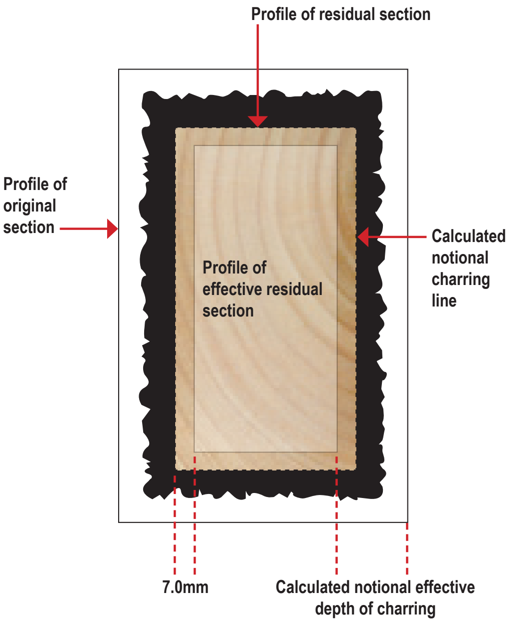
In post and beam structures, the acoustic treatment of floor systems may influence the floor weight and thickness due to the addition of toppings and ceilings. There are many options to achieve the desired acoustic ratings. In commercial post and beam structures, it is possible to leave the ceiling exposed and use an acoustic mat and topping on the floor to achieve the appropriate acoustic rating. The NZ Wood Design Guide "Acoustics" cover this topic in more detail.

2.2.3 Fire

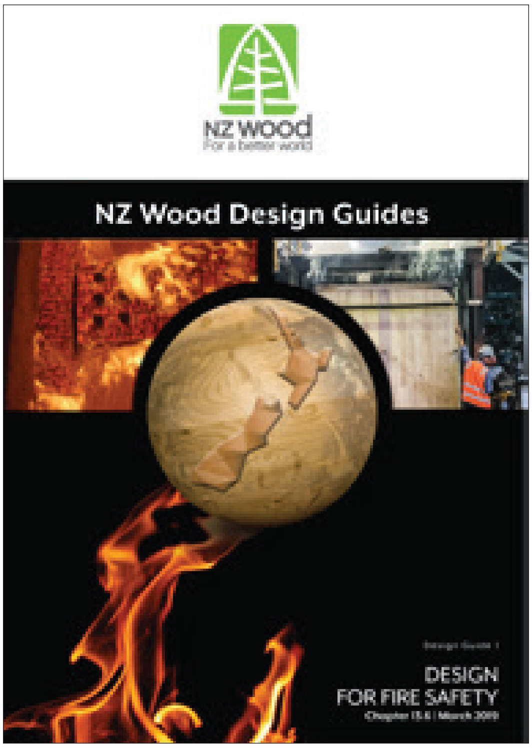
Timber buildings, whether constructed of light timber or mass timber can be designed to provide fire performance similar to other construction materials. Techniques to achieve the desired fire resistance include using a sacrificial layer of timber or protective plasterboards. Protecting timber with fire-rated sheet materials is often the method of fire protection for light timber buildings in which small timber elements are used. For modern timber post and beam construction, the large mass timber elements have an inherent ability to provide fire resistance. Large timber members burn slowly and surface charring of the wood allows an insulating layer to form that provides some protection to the underlying timber. This means the timber elements in post and beam construction can often be left exposed in many circumstances. When designing post and beam buildings, the timber elements must be checked to ensure there will be sufficient strength remaining in the char affected sections to withstand gravity loads after the fire event.

Acceptable Solutions and Verification Methods to meet the building code specify minimum fire resistance ratings (structural adequacy, integrity and insulation) that are easily achieved with timber post and beam construction. The ratings required depend on the building use and active fire protection measures installed. AS/NZS 1720.4 outlines the requirements for fire design including the notional charring rate on mass timber members. An example char calculation is included in the beam design section of this guide. Note that charring of CLT typically behaves differently due to the polyurethane adhesives commonly used - designers should refer to manufacturer guidance for CLT fire performance.

In addition to fire resistance ratings, surface finishes to control the early spread of fire and production of smoke in certain types of buildings also require designer's attention. For post and beam construction, the heavy beams and columns are typically excluded from the spread of flame requirements, however exposed timber panels or permanent formwork on the underside of floor/ceiling systems must be considered in exit ways, Importance Level 4 buildings, crowd uses and sleeping areas (except in household units). Exposed timber flooring (at least 12mm thick) typically meets Critical Radiant Flux (CRF) requirements. Note that currently CLT is not covered by the acceptable solutions in AS/NZS 1720.4. The NZ Wood Design Guide "Design for Fire Safety" covers this topic in more detail.

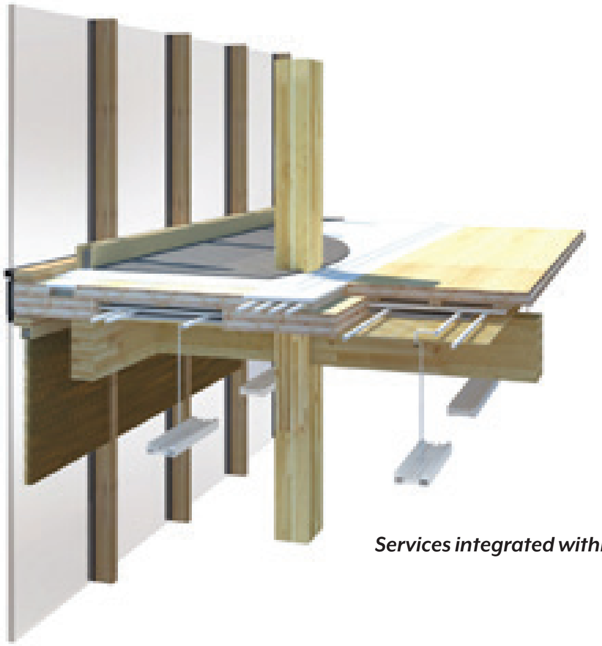


Charred Section – NZ Wood Design Guide "Design for Fire Safety."



2.2.4 Integration of Services

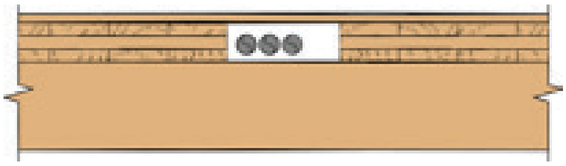
The most successful mass timber projects take an integrated design approach with architecture, structure and services. Thoughtful design can allow for services to be integrated into the structural floor system. In terms of installation, timber is also a material that can easily be fixed to, allowing for fast installation. Several options for integrating services in post and beam structures are highlighted below.



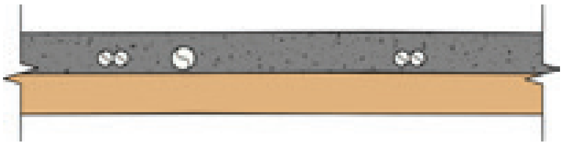
Services integrated within the floor depth.

Gapped CLT Panels, Wood Innovation Design Centre, Prince George, Canada. Michael Green Architecture.

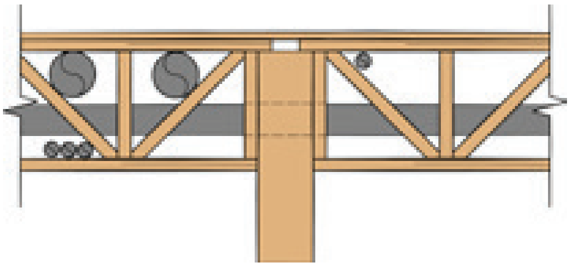
Gapped Floor Panels allow for smaller services (sprinklers, power, data) to run linearly between the panels while larger services can run between the beams. A concrete floor topping or smaller timber members can span between the larger floor panels.



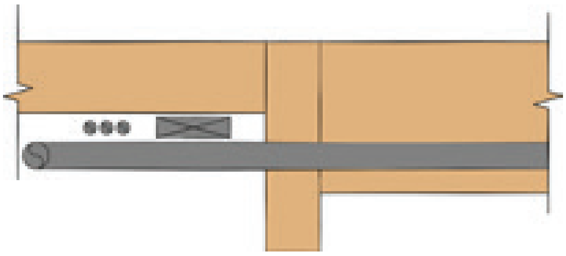
Thick Topping or Raised Floor can be used to hide services above the floor panels while leaving the underside exposed.



Cassettes offer good opportunities for services to be integrated into the floor depth. The services may be covered up by ceiling linings or exposed.



Varying Grid Spacing the columns can be spaced closer together in certain areas to allow for a shallower beam depth for services to run beneath. This works well along corridors.



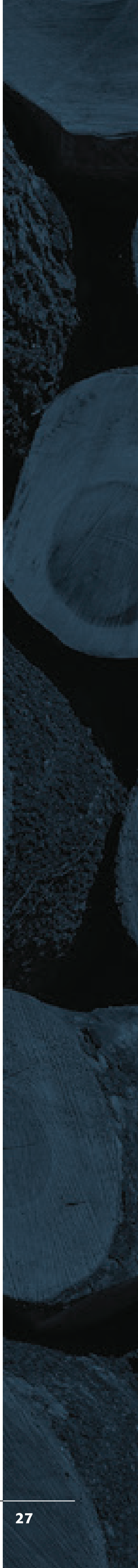
Suspended Services or Beam Penetrations. Services can be left exposed suspended beneath the floors and beams or with specific design they can run through penetrations in the main beams.

Timber beams are often optimised to reduce costs and material, as such beams are often highly stressed. Therefore, the addition of holes through a beam for services needs careful design. There is a limit to the size and number of penetrations that can be achieved without increasing the beam depth. Often, a beam will require reinforcing with screws or cross laminations to accommodate penetrations. There are also highly stressed areas of beams in which penetrations should be avoided (such as close to the supports or close to the top or bottom of the section). Refer to the NZ Wood Design Guide "Reinforcement of Timber" for design information around holes and notches in beams. The guide provides methods for designing reinforcement and simple guidelines for the size and location of penetrations in timber beams.

Product manufacturers often specify certain allowances for penetrations in their products. Another reference for guidance on penetrations through timber members is the *American Institute of Timber Construction (AITC) Technical Note 19*.

The designers of International House, Sydney, took an innovative approach to design the large beam penetrations. A hybrid-glulam beam with two vertical layers of LVL was designed for this case where the penetrations were significantly larger and closer spaced than that normally allowed by the design codes. Extensive work was done in this specific case including finite element modelling and further physical testing on a trial beam to understand and verify the stresses around the penetrations (Butler, 2016). This goes to show the versatility and capability of the material.

Penetrations in Beams for Services – International House Sydney. Lendlease Design.
Photo: Ben Guthrie, The Guthrie Project.

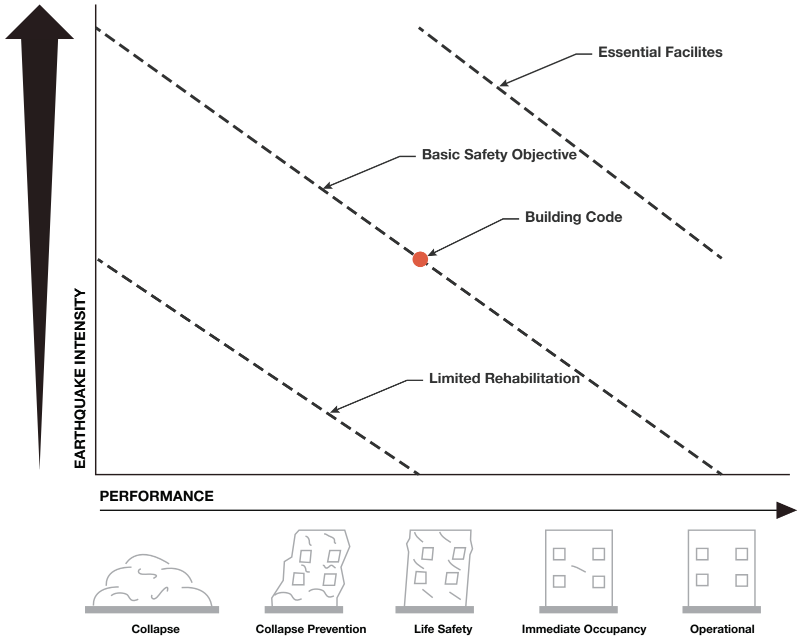


2.2.5 Resilience

Compliance with the building codes provides a minimum level of required performance. Building owners may take a long-term view and look at designing enhanced resiliency in addition to the building code in setting performance objectives. The more resiliency a structure is designed for, the better its ability to undergo an extreme event with minimal damage and disruption and the quicker pre-event function can be recovered.

The performance objective of the structure should be determined early in a project. This should include discussion on magnitude of loss anticipated from different level seismic events, the acceptable downtime and the robustness of the building to suit future demands.

As discussed in the lateral load resisting systems section, several seismic damage resistant systems have been developed and utilised in timber buildings in New Zealand to create resilient structures. This area is developing quickly with a lot of research and technology coming out of New Zealand. The resiliency of post and beam structures greatly depends on the lateral load resisting system and robustness must be considered in the connections and detailing of the post and beam gravity system in relation to the lateral system and demand. See Section 3.7 Lateral Design for more on this topic.



Building Performance Scale.

2.3 DESIGN FOR CONSTRUCTION

Rapid construction on site is one of the big advantages of timber post and beam construction; however, to achieve this the construction must be carefully planned and designed for. When done well, timber post and beam buildings using prefabrication can have very successful construction programs and can be used where tight site constraints exist. This section discusses some topics to optimise the post and beam construction process. Refer to the NZ Wood Design Guide “Construction Guidance” for further information on constructability.

2.3.1 Erection and Sequencing

It is important to understand how the structure will be erected early in the design process as this can have significant impact on the success of a construction project. While installing the prefabricated elements, crane time is an important factor with significant associated costs. Utilising the crane efficiently to keep the installation rolling smoothly is important and needs to be considered in the design process. Designing connections that require little time for stabilisation so that the element can be released from the crane is one key consideration. For instance, beam-column connections with a bearing seat allow for quick release of the beam from the crane without the need for temporary propping or fastener installation. The fasteners required for the final connection can then be installed off the critical path of the crane.

Moment Frames Lifted into Place – Beatrice Tinsley Building University of Canterbury.

Sequencing is another key aspect which can lead to the successful construction of a post and beam building. If the site is congested there may be little room for storage and handling of material, and it is therefore important to sequence the delivery of building elements accurately. This is often done by the contractor and manufacturers during the construction phase; however, it should also be thought about earlier in the design process in case there are more complex elements. For instance, large elements such as roof trusses or moment frames may require space to be preassembled on the ground instead of in place. The Beatrice Tinsley moment frames are a good example, for this build the moment frames were assembled and partially tensioned to provide fixity on the ground floor slab prior to being lifted in place.

2.3.2 Transportation

The benefit of prefabrication is immense, however, there are certain practical limits including transportation which often drive the size of prefabricated elements. The New Zealand Transportation Authority (NZTA) outlines the rules and restrictions for the size and weights of vehicles. Typically, the maximum width and overall length of a transport vehicle without requiring a permit or a pilot vehicle are 3.1m and 20m, respectively. This is outlined in NZTA factsheet series 13 and 53.

It is difficult to state the optimum transport strategy for post and beam construction as it is likely that most elements will be within the restrictions of NZ roads. Floor panels should generally be kept within these size limits to keep transportation costs at a minimum. CLT fabricator XLAM, generally suggest a maximum floor panel size for larger projects of 3m wide x 12m long (sometimes up to 16m) as this will not require special transport permits and works well with grid options. Best practice is to engage the contractor and prefabricators early in the project to further understand these constraints as they may also influence the grid layout and strategy of delivery.

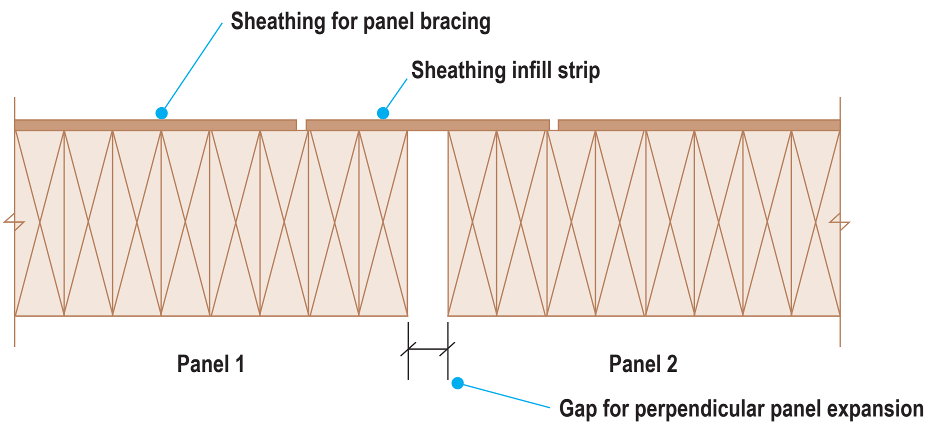
The NZ Wood Design Guide "Designing for Prefabrication" further discusses the topics Transport, Storage and Erection in Section 6.

2.3.3 Tolerance

Due to the precision of today's CNC machining capabilities, structural timber elements can be fabricated very accurately. That said, tolerance for constructability must still be considered. Proper layout is key to ensure everything fits and the structural design intent and aesthetics are maintained. Depending on the type of beam connections, different tolerances may be acceptable. For instance, proprietary pre-designed hangers (see Section 3.8 - Connections) can have as low as a 2mm tolerance, therefore accuracy of the column layout and verticality is key. Building in tolerance in other areas helps to ensure everything goes together well. Regular set-out and verticality surveying is recommended.

It is also very important to account for shrinkage and expansion of wood elements during construction as well as in design. The movement of wood is discussed in detail in the NZ Wood Design Guide – Trees, Timber, Species & Properties. Timber will expand or contract much more perpendicular to grain than parallel to grain (length wise) due to changes in moisture content. Exposed end grains of timber elements are particularly susceptible to moisture movement. Local swelling at the end of a columns while exposed during construction could be enough to cause tolerance issues when placing beams that sit snug between them. In some instances, swelling can even fracture screws installed perpendicular to grain.

Depending on the type of floor panels, tolerance for moisture expansion may be required. For instance, one way spanning mass timber panels such as glulam panels, which consist of many laminations of timber parallel to each other may require a gap between the panels to allow for the panels to expand and contract as swelling occurs perpendicular to grain. CLT has be benefit of being more dimensionally stable as the timber fibres run in both directions.



Tolerance Gap in One-way Spanning Panels.

2.3.4 Weather Protection

Protection of timber elements, whether they are natural timber or engineered wood products, is very important. When mass timber elements leave the prefabrication factory, they are generally at a low moisture content around 12-15%. Ideally these moisture conditions will be maintained throughout construction, however, this can be difficult to achieve unless the construction site is tented which is rarely done. Protection by wrapping timber elements and sealing joints with tape can be effective and is recommended where rain or moisture exposure is expected. Care must still be taken with protected elements, if wrapping is damaged, moisture can enter and potentially cause mould or decay in the right conditions.

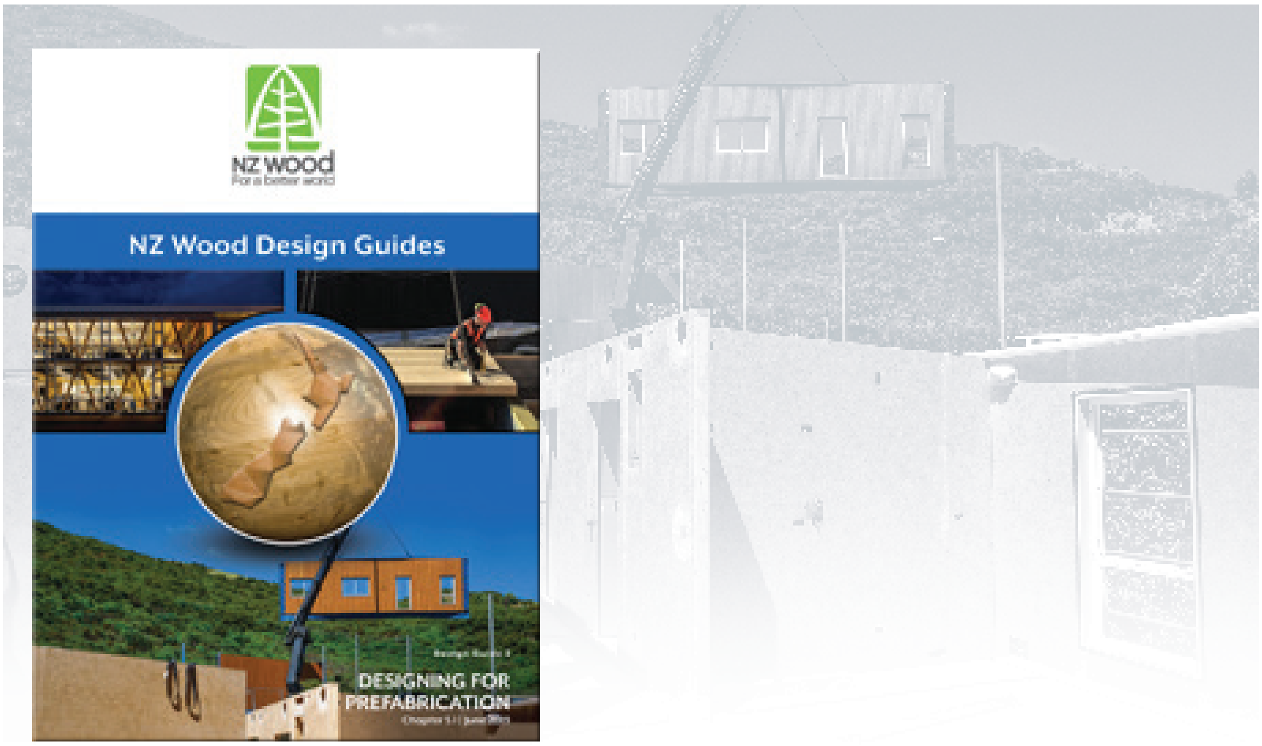
A moisture management plan should be included in the structural specification to ensure the contractor has a good understanding of what is required for timber buildings. Sealers, stain prevention, moisture control and dry out should all be considered. Sealers can be used to protect against moisture intrusion during construction. If timber is to be exposed in its final condition, staining could be an issue. Water movement during construction can penetrate joints and carry other materials such as rust from metal filings or concrete debris both of which can cause staining.

Managing construction materials and activities including site welding near exposed timber elements can prevent or reduce clean-up time and expense. Moisture control should be considered through two basic concepts. First, avoid prolonged water exposure through protection, as mentioned above, and having a strategy to remove water from the structure after rainfall. Secondly, allow moisture to leave timber elements prior to enclosing. Mass timber should not be encapsulated if the moisture content is above 16%, instead it should be given a controlled opportunity to dry out and release moisture (Anderson, 2020). Drying too quickly through the use of manufactured heat can cause cracking and thus a controlled approach to heating the structure should be considered. The moisture content of the various timber elements should be recorded throughout construction by the contractor and engineer performing construction monitoring to ensure quality and performance of the finished structure.

The possible negative effects of moisture should not deter from the use of post and beam or other timber structures. The effects must be managed and planned accordingly to best succeed in this construction type.

2.3.5 Prefabrication

Prefabrication is a huge benefit to post and beam construction and virtually all mass timber projects include a significant portion of it. The benefits including reduced site construction time and a controlled environment for fabrication leading to high precision and a better-quality product. The NZ Wood Design Guide "Designing for Prefabrication" further discusses the components, benefits and considerations of this type of construction in much more detail.



2.3.6 Quality Assurance

Prefabrication in factory conditions often allows for better quality assurance processes, and an easy paper trail. However, quality assurance on site during erection is just as important. Construction monitoring to ensure all connections are installed correctly is important and should be considered during design; for instance, can the connection be accessed and viewed from all sides to ensure the quality and design intent is achieved.

3 STRUCTURAL DESIGN

The information provided in this section is intended to assist Structural Engineers develop concept level designs for mass timber post and beam structures. Advice on material properties, design actions and performance criteria are provided, along with sample calculations for a beam and column. As connection types can influence member sizes and member configuration, an illustrated table of common connection types is also provided.

3.1 DESIGN STEPS

The design of timber post and beam construction is similar to any type of construction and typically involves the following main steps that are in line with the New Zealand Construction Industry Council Design Guidelines.

1. **Design Brief (Project Establishment)**
    - Defining the project criteria, performance requirements, limitations, constraints and budget.
    - Find relevant information associated with the design problems. Site conditions and geotechnical information, material availability (early supplier engagement), and design loads.
    - Determine the drivers for using timber to ensure these aspects are targeted throughout design.
2. **Concept Design**
    - Review/recommend importance levels, seismic requirements, loads, geotechnical issues, etc.
    - Develop and assess possible solutions to the design problem.
    - Determine the structural load paths including options for the lateral resisting systems.
    - Confirm the design loads and determine if any changes can or need to be made.
    - Determine the basic member sizes under a few key load cases, including member deflection and vibration. Also consider the main connection types to be used – note this can typically be done later in the design process of concrete or steel structures.
    - Consider costing, fabrication and material availability again at this stage.
    - Determine whether a structural peer review will be required for the project.
    - Decisions made in this phase will have a significant impact on the cost, appearance and construction method of the structure.
3. **Preliminary Design**
    - Further develops the conceptual design.
    - Determine the difficult areas and scope them out.
    - Consider buildability and consult with contractors if possible.
    - Outline preliminary materials, durability, etc.
    - Solidify member sizing and choice of components. Ensure serviceability limit states particularly vibration will be satisfied.
4. **Developed Design**
    - Further develop design towards final documentation, incorporate with architectural.
    - Confirm all member and element sizes under all load cases. Iterative process as this may be dependent on any of the gravity or lateral design cases, or the connection design.
    - Design of difficult areas of the structure.
    - Key connection design complete.
5. **Detailed Design**
    - All structural members, connections, systems, complete.
    - Structure is integrated with all disciplines.
    - Timber material supplier should be on-board.
    - Finalise erection / construction design of the structure.

6. Design Documentation

- Building consent documentation.
  - structural and architectural drawings should be as close to full drawings as possible at this stage.
  - Foundation design is complete based on the final geotechnical report.
  - Calculations for main structure and all key elements are complete.
- Construction documentation.
  - Full building documentation.
  - Final architectural and structural specifications complete.
  - Drawings are coordinated with the other disciplines.

3.2 COMMON GRADE AND SIZES OF GLULAM & LVL

For reference, standard glulam and LVL grades and sizes are included in this section as they are the most common materials used for post and beam construction. These values should be verified by the designer and confirmed with the material supplier.

For both Glulam and LVL, when using sections built-up of smaller laminations, it is recommended that a 5mm "efficiency tolerance" is allowed for in structural calculations. This allows the manufacturer to use section sizes best suited to their supply chain.

Glue Laminated Timber (Glulam)

Glulam grades in New Zealand typically include GL8, GL10 and GL12. GL8 or GL10 is commonly available for large volume orders (>50m^3), whereas GL12 is not as readily available – quantities should be confirmed with manufacturers early in the design process to ensure enough stock is available and does not come at a significant cost premium. GL17 is also available from numerous manufacturers in NZ although the width is often only available in small sizes because all laminations must be selected from high grade timber only. Glulam can be made into almost any size with lengths up to 35m (see 2.3.2 for transportation length restrictions). Standard sizes are as follows, while other sizes can generally be made on request:

Glulam Grade	Glulam Characteristic Design Values (MPa)					
	Modulus of Elasticity, E	Modulus of Rigidity, G	Bending, f'_b	Compression Parallel, f'_c	Shear in beams, f'_s	Tension Parallel, f'_t
GL12	11,500	770	25.0	29.0	3.7	12.5
GL10	10,000	670	22.0	26.0	3.7	11.0
GL8	8,000	530	19.0	24.0	3.7	10.0

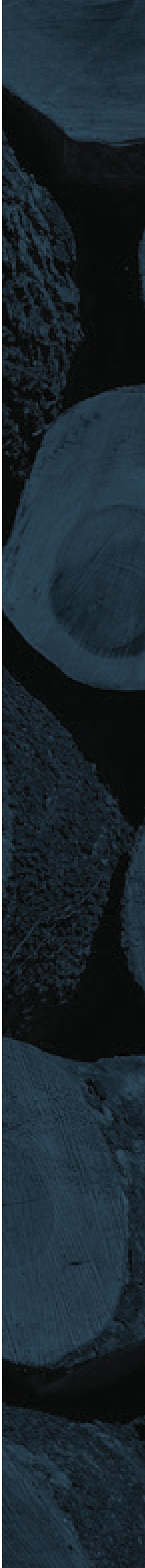
Width: Typically, 42mm, 65mm, 90mm, 115mm, 135mm, 180mm, 230mm, or larger. Manufacturers normally pay a premium for large board widths therefore it is generally more cost efficient to specify 180mm wide beams over 230mm wide. Beyond 230 wide, block glulam is required. To create block glulam, smaller boards are glued together to create a wider board which are then stacked and laminated together adding more cost.

Depth: Typically increasing in 45mm increments – 135mm, 180mm, 225mm, 270mm, etc. The lamination thickness is often thinner for curved members with tight radii.

Characteristic design values can be found in NZS AS 1720.1 (draft at time of writing) or can be found in manufacturers' technical guidance – these values may vary and should be confirmed during design. For reference and comparison to the LVL design values, the above table is included based on Timberlab and Techlam design values (as of May 2020):

Laminated Veneer Lumber (LVL)

LVL can be manufactured in panel sections up to 18.4m long, 1220mm in width and 12-90mm in thickness. LVL billets may be relaminated to form thicker sections usually from 45mm billet thicknesses to achieve 135, 180, 225, 270mm or greater thicknesses x up to 1220mm deep. As beams are cut from a 1220 mm wide panel, it is desirable to choose beam depths that minimise wastage. New Zealand manufacturers' provide different characteristic design values for their respective products. These values may differ from NZS AS 1720.1 and should be confirmed with the manufacturers



during design. For reference and comparison to the glulam design values, the adjacent table is included based on Nelson Pine LVL design values (as of May 2020). Availability of sections and grades should be confirmed with the manufacturer.

LVL Grade	LVL Characteristic Design Values, 'On-Edge' (MPa)						
	Modulus of Elasticity, E	Modulus of Rigidity, G	Bending, f'_b	Compression Parallel, f'_c	Shear in beams, f'_s	Tension Parallel, f'_t	Compression Perp, f'_p
LVL13	13,200	660	48.0	38.0	5.3	33.0	10.0
LVL11	11,000	550	38.0	38.0	5.3	26.0	10.0

LVL13 is common for beams due to the higher bending strength and stiffness. LVL11 can be used for columns as it has the same compression strength as LVL13, however, manufacturers are tending to primarily manufacturer LVL13 therefore there may not be a cost saving. Consult the manufacturer during design for up to date information. Note that modification factors apply for larger section sizes according to NZS AS 1720.1 and the manufacturers' guidance.

3.3 DESIGN ACTIONS

Design actions are defined in AS/NZS 1170 and should be confirmed for each project. This section provides an estimate of typical permanent loadings for post and beam construction and discussion of lateral actions.

3.3.1 Gravity Actions

Timber structures may contain additional permanent actions due to the acoustic and fire linings required. The weights of many materials are defined in AS/NZS 1170.1 Appendix A and can be used to get an accurate estimate of the design loads. The following table may be used as an estimate of permanent design actions on a typical timber project which should be confirmed once the project advances and further information on the architectural build-up is known.

Imposed actions on post and beam structures are the same as other types of structures. These actions can be found in Section 3 of AS/NZS 1170.1, and in AS/NZS 1170.3 for snow and ice actions.

ELEMENT	SYSTEM AND MATERIALS	ESTIMATED PERMANENT ACTION
Floor	Carpet, timber substrate flooring, joists, fire-rated ceiling on resilient mounts	0.75 kPa
Floor	Ceramic tiles, timber substrate flooring, joists, fire-rated ceiling on resilient mounts	0.9 kPa
Floor	Mass timber panels (e.g. CLT panels - species and moisture dependant)	5kN/m3 x panel depth
Floor	Cassette Panels (varies by design)	0.4-0.7kPa
Floor	Additional weight for acoustic mats and extra acoustic layers	+0.4 kPa
Floor or balconies	Additional for 50 mm light-weight concrete topping, acoustic mat	+0.9 kPa
Floor	Additional for services – air conditioning ducting, fire services, plumbing	0.2 kPa
Floor	Extra for false ceilings or floors – extra battens and linings	0.2 kPa
Internal Walls	Double stud fire-rated walls – wall, linings, insulation	0.7 kN/m2*
Internal Walls	Single stud fire-rated walls	0.5 kN/m2*
Internal Walls	Single stud non-load bearing wall, non-fire rated	0.3 kN/m2*
External walls	Lightweight cladding, single stud, fire-rated	0.7 kN/m2*
External walls	Heavy cladding, single stud, fire rated	0.5 kN/m2* + weight of heavy cladding
Roof	Gardens, tanks, building services	by calculation
Supports	Beams and columns to be estimated based on type of material	by calculation

NOTES:
- *Loads are evaluated per square metre of wall and applied to floors as a line load in kN/m.
- Refer to AS/NZS 1170 for all actions.
- This table is modified from Australian Wood Solutions Timber Design Guide 50.

3.3.2 Lateral Actions

Wind actions are defined in AS/NZS 1170.2 and are based on site location, terrain, and building height and shape. Design wind speeds are used to determine the design wind pressure which varies for different parts of the structure. Wind actions are not covered in this guide; the approach is essentially the same as other non-timber buildings, however, serviceable wind drift limits may govern the design of some timber lateral load resisting systems. Seismic actions are further discussed in Section 3.7.

3.4 SERVICEABILITY DESIGN

All structures have the same basic requirements to remain safe through construction and the life of the structure, as well as performing the serviceability requirements. Ultimate limit states include checks for stability and strength and are intended to ensure catastrophic failure, such as collapse, does not occur during the useful life of the structure. Serviceability limit states are focused on the performance of the structure for its components and occupants under service conditions through the design life. These include deflection causing building damage, deflection causing local damage to elements, or visual impacts, and vibration of the structure causing discomfort to the occupants or malfunction of sensitive equipment. The combinations for each limit state are given in AS/NZS 1170.0 with further information provided in NZS AS 1720.1 (Section 1.4 and Appendix B).

Timber elements are often governed by serviceability states and should be checked accordingly. There are several guidelines and code requirements for deflection and vibration. Table C1 of AS/NZS 1170.0 provides suggested limits for serviceability deflection and vibration, however, these limits should be used as a guide and engineering judgement is required. Some building uses may also require more stringent limits defined by the owner.

Deflection

Deflection must be considered from a whole system approach. For instance, the mid span deflection of a beam must also account for movement at the supports particularly where it is supported by another beam or shrinkage is expected. The variation in deflection must also be considered – for example where a beam or joist deflects more significantly compared to a stiff wall or in the line of sight of a soffit.

Beam Deflection.

The deflection of a beam should account for elastic bending deflection, inelastic deflection (creep), shear deflection and deflection due to joint movement. Shear deflections are not normally accounted for in rectangular beams as they are usually less than 10% of elastic bending deflections and are generally accounted for in the modulus of elasticity of graded timber (NZ Wood, 2013). Deflection due to joint movement is prevalent in nailed plywood box beams where the fasteners slip at the web joint but can be overcome by gluing the joint. This can also be an issue in long span roofs where splices are created with fasteners.

Similar to concrete, timber undergoes a time-dependent variation known as creep. Creep is an increase in deformation under prolonged loading and is considered in the long-term serviceability limit state. Creep is dependent on size, material, grade, environmental conditions and coatings. NZS AS 1720.1 provides factors for creep in Table 2.4 for different stresses, moisture contents and duration. In order to calculate the long-term creep deformations of a structure, the portion of the serviceability load that is applied permanently or semi-permanently must first be estimated and then the creep factor is applied to that portion. An example calculation is included in the beam design example below.

When looking at the structure as a whole, the total vertical movement includes settlement, elastic deformation, creep and shrinkage/swelling, the BRANZ Multi-Storey Light Timber-Framed Buildings design guide (Carradine, 2019) covers this in Section 9. A similar approach can also be used for post and beam buildings. This can be more of an issue when part of a timber structure is attached to a concrete core, for instance, and adjacent elements experience differential vertical movements.

Vibration

Floor vibration can often be the governing design factor in timber floor systems, particularly when considering long spans. Vibrations can arise from external sources such as road or rail traffic, or from internal sources such as from walking, impact or mechanical equipment. This section is primarily based on interior sources, of which pedestrian traffic (footfall) is the most common type and can be a significant source of annoyance to occupants.

The concept of vibration can be complex because it means that serviceability requirements can result in higher demands than safety and structural integrity. The client must be involved in the decision for the design target level for vibration response because it can have a significant impact on cost and sizing of elements. Once a floor is constructed it can be very difficult to modify vibrational performance as changes to the mass, stiffness or damping of the floor are the only methods to reduce people's perception of vibration. It is important to note that floor vibrations do not necessarily mean there is a structural safety issue.

Vibration control is a complex topic and for the purpose of this guide only a quick overview with some simple equations to consideration in the early design of a post and beam structure have been included. The Australian WoodSolutions Timber Guide 49 Long-Span Timber Floor Solutions is a more comprehensive source on vibration of cassettes and CLT floors. Both the Steel Construction Institute Publication P354 (Smith, Hicks & Devine 2009) and the Cement and Concrete Industry Publication CCIP-16 (Willford and Young 2006) provide methods for determining sensible targets for acceptable levels of vibration which can be adapted for use with mass timber floors.

Eurocode 5 states that for floors with a fundamental frequency less than 8Hz a special investigation should be made, and for frequencies greater than 8Hz certain criteria should be satisfied regarding deflection and velocity response. The fundamental frequency of a rectangular floor can be calculated as:

$$frequency\ (Hz) = \frac{\pi}{2L^2} \times \sqrt{\frac{(EI)_l}{m}}$$

where:

L = floor span (m)

m = mass per unit area of floor (kg/m^2)

$(EI)_l$ = effective bending stiffness of the floor (Nm^2/m)

AS/NZS 1170.0, Table C1 states the static mid-span deflection of floors under a 1.0kN point load should not exceed 1-2mm. Note this is given only as a guide to whether vibration concerns may be an issue, and states further investigation may be required. The second limit for deflection provided below is from the National Building Code of Canada and is sometimes a preferred deflection limit by engineers (APA, 2004).

$$\delta = \frac{P \times L^3}{48\ (EI)_{eff}} \leq 1 \text{ to } 2mm \ \ (AS/NZS\ 1170.0) \qquad or \qquad \delta \leq \frac{2.55}{L^{0.63}} \ \ (NBCC)$$

where:

L = span (m)

EI_{eff} = effective bending stiffness (1m wide panel for CLT panel)

Canadian CLT Handbook 2019 – FPInnovations have done testing on the behaviour of various floor systems which have shown that CLT vibration behaves differently to lightweight joist floor systems. The Canadian CLT Handbook 2019 provides a detailed design procedure for controlling vibrations in CLT floors which has been implemented into the Canadian Timber Code – CSA 086. The Handbook recognises that vibration performance of floors is dependent on the support conditions. Manufacturer span tables and design procedures often assume a rigid support condition because even if the floor has enough stiffness and mass, the performance may not be adequate if the supports are too flexible. For the purpose of this guide, only the design equation for CLT vibration span and the Supporting Beam Stiffness Requirement from Section 7.3 of the CLT Handbook 2019 are included for reference (FPInnovations 2019). The engineer should confirm the use of these equations in the design process.

CLT Vibration-controlled span:

$$L \leq 0.11 \frac{\left(\frac{(EI)eff}{10^6}\right)^{0.29}}{m^{0.12}}$$

where:

L = vibration-controlled span limit (m), clear span

m = linear mass of 1m wide CLT panel (kg/m)

EI_{eff} = effective bending stiffness of 1m wide CLT panel (N-mm^2)

Stiffness Requirement of Supporting Beams:

$$(EI)_{beam} \geq F_{span} \times 132.17 \times l_{beam}^{6.55}$$

where:

EI_{beam} = supporting beam apparent bending stiffness (N-m^2), per manufacturer or

= MOE x b x h3/12, MOE = modulus of elasticity (N/m^2)

F_{span} = 1.0 for simple span, ≈ 0.7 for multi-span continuous beam

l_{beam} = clear span of supporting beam (m)

3.5 BEAM DESIGN

Beams in mass timber buildings often resist a combination of distributed and concentrated loads. They must be designed to have enough strength to resist these loads and have adequate stiffness to prevent excessive deflection or vibration. Beam design in post and beam structures will generally be governed by bending strength or deflection, however, shear can govern for shorter beams or built up beams such as box or post-tensioned beams.

Gravity Design

The design of timber structural members should be carried out according to NZS AS 1720.1 and AS/NZS 1170.0. The gravity design must consider the environmental and loading conditions over the lifetime of the element. The modification factors (k factors) are covered in NZS AS 1720.1. Section 2.4 covers the general factors: duration of load (strength and creep), moisture condition, temperature, bearing, strength-sharing and stability factor.

Deflection

The deflection of beams should be checked for serviceability limits to avoid damage, visual impacts or vibration. Refer to the previous section Serviceability Design for more information.

Camber

Camber or pre camber is an upward curve that is manufactured into beam elements to counteract the effect of deflection. Including camber does not increase the strength or stiffness of the element but instead acts to reduce the visual effect of deflection. A typical camber is around span/400 at the mid-span of beams.

An advantage of glulam is that camber can manufactured into the beam during the lamination process. There is normally a maximum limit of camber before the element becomes a curved beam where extra costs may be enquired. It is worth discussing with the supplier during the design phase if larger camber is desired. LVL can also incorporate camber in the beams, however, this is done by cutting the beam in a slight curve after the lamination process is done.

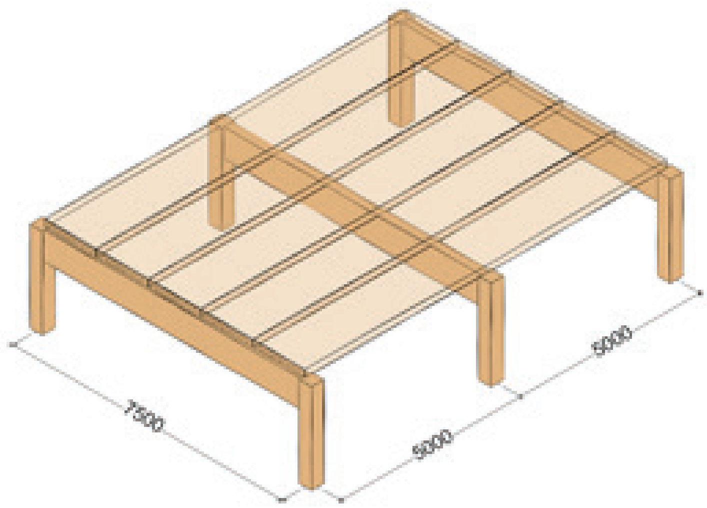
Fire Design

Fire design or protection of the element must be considered. The reduced section strength after charring, as shown in the example calculation and discussed in Performance Requirements, can be used as one method for verifying the fire resistance of a member.

Beam Design Example

To illustrate the design of a simply supported beam in a glulam post and beam structure, a design example has been included. The beam under consideration is an internal simply supported glulam beam in an office building. The beam spans 7.5 m and is spaced at 5.0m with parallel beams. The floor comprises of 5-layer (225mm) CLT that is continuous over the beam. The CLT has a 50mm light weight concrete topping and acoustic mat and is exposed on the underside. The CL5/225 has a 30/30/30 fire rating with associated span of 4.95m based on Q=3kPa and SDL=1.5kPa (per XLam Design Guide 2017).

Reference codes: NZS 1720.1, AS/NZS 1170.0 & 1170.1



Internal Beam used for Design Example.

LOADING & ELEMENT INFO

CLT panel weight, ρ		$5\ kN/m^3$ (XLam)	
Panel depth		225mm	
Beam spacing, S		5m	
Trib width = S x 1.25		6.25m (accounts for continuous decking)	
Beam length, L		7.5m (full beam length assumed in calculations)	
Beam width, b		230mm	
Beam depth, d		765mm	
Beam weight, ρ		$5.4\ kN/m^3$ (Glulam)	
Material grade		GL10	
Elastic Modulus, E		10000 MPa	(AS/NZS 1720.1 - Table 7.1)
Live load reduction, ψ_a		0.79	(AS/NZS 1170.1 - 3.4.2)
			Line Load on Beam (incl. continuous factor)
Permanent Load	Deck	1.13 kPa	7.03 kN/m
	SDL	1.5 kPa	9.38 kN/m (conc. top, partitions, etc.)
Imposed Load	Office, gen.	3 kPa	18.75 kN/m
G =			16.41 kN/m
Q = ψ_a * Imposed Load			14.81 kN/m

LOAD COMBINATIONS (AS/NZS 1170.0)

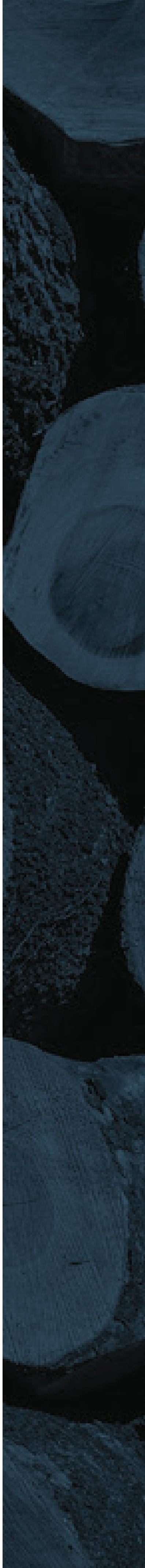
Strength Limit State (4.2.2)				
	1.35G	22.1 kN/m	(long term)	
	1.2G+1.5Q	41.9 kN/m	(medium term)	
	$1.2G+1.5\psi_l Q$	28.6 kN/m	(long term - $\psi_l = 0.4$)	(Table 4.1)
Serviceability Limit State (4.3)				
	$G+\psi_s Q$	26.8 kN/m	Short term - $\psi_s = 0.7$	(Table 4.1)
	$G+\psi_l Q$	22.3 kN/m	Long term - $\psi_l = 0.4$	(Table 4.1)

ELEMENT DEMAND

M* (1.2G+1.5Q)	$= wL^2/8$	294.6 kNm	(1.2G+1.5Q - medium term)
M* ($1.2G+1.5\psi_l Q$)		200.9 kNm	($1.2G+1.5\psi_l Q$ - long term governing case)
V* (1.2G+1.5Q)	= w*(L/2-1.5d)	109.1 kN	(taken at 1.5d from support - see 3.2.5)
V* ($1.2G+1.5\psi_l Q$)		74.4 kN	

CAPACITY

Bending Strength		$M_d \geq M^*$,	$M_d = \varphi\, k_1\, k_4\, k_6\, k_9\, k_{12}\, f_b'\, Z$		3.2(1), (2)
φ =	0.8	Z2.3 (DZ NZS 1720.1)	k_4 =	1	7.4.2 (EMC≤15)
k_1 (medium) =	0.8	2.4.1.1 / Table G1	k_6 =	1	2.4.3
k_1 (long) =	0.57	2.4.1.1 / Table G1	k_9 =	1	7.4.3
L_{ay}		1500mm (lateral restraint assuming panel fixed at 500 crs)			
r (0.4 imposed load/total load)		0.25 (worse case r = 0.25 per E2)			E2
ρ_b	0.85 (material constant)				E2(1) / Table 7.2(A)
Restraint check	Continuous (if $L_{ay}/d \leq 64(b/\rho_b\, d)^2$, $S_1 = 0$				3.2(6)
S_1		0.0			3.2(4), 3.2(6)
$\rho_b S_1$		0.0			
k_{12}		1			3.2.4
f_b'	GL10	22 MPa			7.3.1
$Z = bd^2/6$		$22433625mm^3$			
$M_{d,\ medium\ term}$ =	**315.9 kNm**	**>**	**M* =**	**294.6 kN**	**OK**
$M_{d,\ long\ term}$ =	**225.1 kNm**	**>**	**M* =**	**200.9 kN**	**OK**
Shear Strength					
$V_d \geq V^*$	$V_d = \varphi\, k_1\, k_4\, k_6\, f_s'\, A_s$				3.2(13), (14)
f_s'	GL10	3.7 MPa			NZ Manufacturer
A_s = 2/3*b*d	$117300mm^2$	3.2.5			
$V_{d,\ medium\ term}$ =	**277.8 kN**	**>**	**V* =**	**109.1 kN**	**OK**
$V_{d,\ long\ term}$ =	**197.9 kN**	**>**	**V* =**	**74.4 kN**	**OK**



DEFLECTION CHECKS

Elastic Modulus, E		10000 MPa	(AS/NZS 1720.1 - Table 7.1)	
Moment of Inertia, $I = bd^3/12$		8580861563mm⁴		
Load Factor for Creep, j_2		2	(≤15% EMC; ≥1year)	2.4.1.2
$\Delta = (5wL^4)/384EI$	$\Delta(G)$ =	7.9mm		
	$\Delta(Q)$ =	7.1mm		
	$j_2\Delta(G+\psi_1 Q)$	21.4mm	Max L/250 30.0	**OK**

Note: only the long term deflection check is shown and compared to a deflection limit of L/250 for a 'beam where line of sight is across soffit' (AS/NZS 1170.0 Table C1)

FIRE CHECK (AS/NZS 1720.4)

Charring, $c = 0.4+(280/\delta)$ — 0.65 mm/min (same rate as NZS3603 - WPMA guide 1.2)
Notional density, δ = — 550 kg/m³ (radiata pine at 12% M.C.)
Effective depth of charring, $d_c = c*t+7.0$
- t — 30 min
- d_c — 26.5mm

Effective Residual Section
- $b = 230 - (d_c *2)$ — 177mm
- $d = 765 - d_c$ — 739mm
- $Z = bd^2/6$ — 16088776mm³
- $A_s = 2/3*b*d$ — 87143mm²

Design Load
- $W = G+\psi_l Q$ (SLS above) — **22.3 kN/m** (no thermal effect on remaining, 1170.0 - 4.2.4)
- $M^* = WL2/8$ — **157.0 kNm**
- $V^* = W(L/^2-1.5d)$ — **59.0 kN**

Capacity
- $M_d \geq M^*$ — $M_d = \varphi\, k_1\, k_4\, k_6\, k_9\, k_{12}\, f_b'\, Z$
- φ — 1 Z2.3 (DZ NZS 1720.1)
- k_1 (fire) — 0.94 (5 days duration per 2.4.1.1h) 2.4.1.1 / Table G1
- Other factors same as above

Fire M_d =	**332.7 kNm**	**>**	**M* =**	**157.0 kN**	**OK**
Fire V_d =	**303.1 kN**	**>**	**V* =**	**59.0 kN**	**OK**

VIBRATION CHECK

In order to avoid vibration issues in the floor, the support beams must have adequate stiffness. A vibration analysis of the floor plate may be required. The following preliminary stiffness check is based on the Canadian CLT Handbook 2019 edition - section
7.3. Refer to Serviceability Design for more information.

$$(EI)_{beam} \geq F_{span} \times 132.17 \times l_{beam}^{6.55}$$

EI (Nm²)	**>**	**F_{span} x 132.17 x $L_{beam}^{6.55}$**	**OK**
85808616	>	71249885	

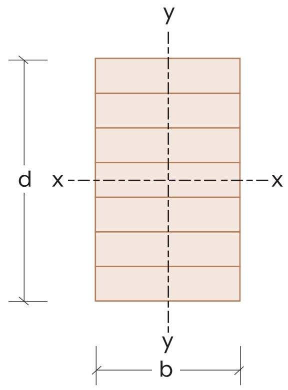
where F_{span} = 1 (1.0 for simple beam, 0.7 for multi-span continuous beam)
L_{beam} = 7.5m (full beam length assumed)

3.6 COLUMN DESIGN

Gravity columns in post and beam structures are usually vertical members which primarily carry axial loads. Columns must be designed to resist compressive loads and to resist bending due to eccentric loads, uneven loading or horizontal loads such as from façade systems. Columns in timber post and beam structures are normally made of LVL or glulam in solid rectangular sections but can also consist of sawn timber, box columns or hybrid (steel or concrete) solutions. The design of timber columns is prescribed in NZS AS 1720.1.

Slenderness

The capacity of compressive members is usually limited by lateral buckling of the section. The more slender the member, the greater the possibility of buckling. Buckling must be considered about both the X (major) and Y (minor) axis of the member. Under pure axial compressive loads, square columns are most efficient, as the buckling length of the unrestrained members is dependent on the smallest cross-sectional dimension. Where bending in one direction contributes significantly to the demand of the column or notching a column for a beam connection is required, a rectangular section may be more appropriate.

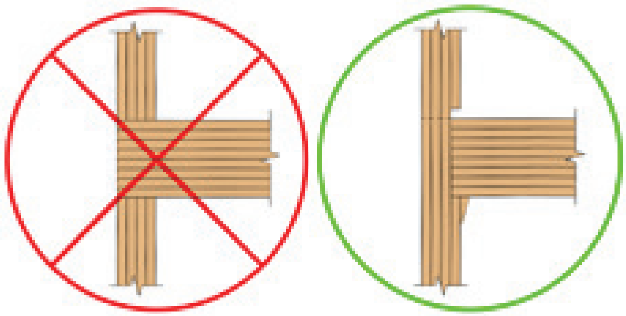


Column Cross Section.

Note for short columns, where buckling does not occur, the compressive capacity depends on the crushing strength of the wood. This is not normally the case in post and beam structures; however, the bearing does need to be considered, especially if the column section is reduced at connections.

Detailing and Continuity

Columns are stiffest and strongest along the grain of the member with compressive values in the same range as concrete. Because timber is much stiffer and stronger parallel to grain, it is best practice in post and beam structures for columns not to bear on perpendicular to grain timber without a specifically designed connection or reinforcement. This differs from timber framed walls where studs often perpendicular to wall top and bottom plates. This becomes relevant in the build-up and connection of columns, beams and floors.


Instances where columns bear on the perpendicular grain of a beam or floor should be avoided.

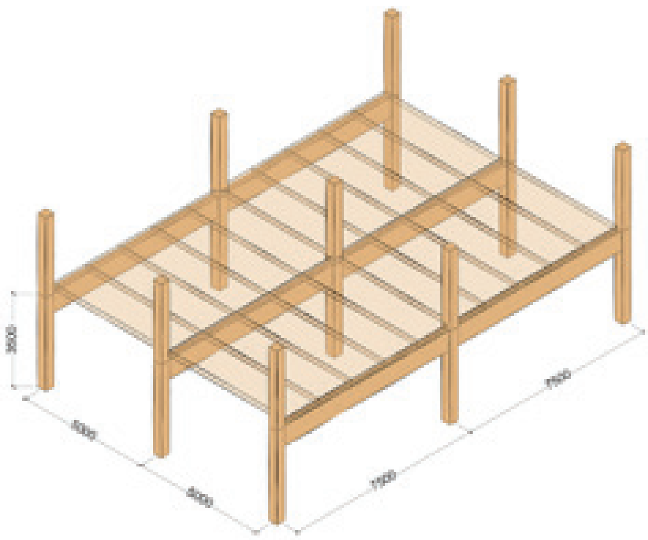
Continuous columns can be advantageous from an installation and design perspective as there are fewer elements and potentially less congested connections at nodes. Continuous columns have a different behaviour to single storey pinned columns. For instance, continuous columns may experience bending moments through the section at the beam intersection. If the section is reduced for notching of a beam seat and high moments are induced, this could impact the design.

Moisture Effect

As previously discussed, moisture effects are more pronounced perpendicular to grain (radial and tangential), therefore post and beams structures do not experience as much shrinkage when columns are supporting each level with a continuous parallel to grain load path. Refer to deflection in the Serviceability Design section for more on building shrinkage.

Column Design Example

The column under consideration is an internal gravity column at the ground level of a 4 storey office building. The column has a height of 3.5m and a tributary area of 5x7.5=37.5m^2 multipled by 4 levels. The floor comprises of a single span 5 layer (225mm) CLT panel, with a 50mm light weight concrete topping and acoustic mat. A superimposed dead load of 1.5kPa and Imposed Load of 3kPa. The Imposed action area reduction factor, ψ_a = 0.54, as per AS/NZS 1170.1 is used. Reference codes: NZS AS 1720.1, AS/NZS 1170.0 and 1170.1.


Internal Column used for Design Example.

ELEMENT INFORMATION

Size (b x d)	315mm x 315mm
Height, L	3.5m
Material grade	GL10
E =	10000 MPa

FIRE CHECK (AS/NZS 1720.4)

Case		
Medium Term	N* =	1086 kN
1.2G+1.5Q	Mx* =	10 kNm
Long Term	N* =	865 kN
1.2G+1.5ψlQ	Mx* =	4 kNm

The demand of the column has been determined based on the variables below with a tributary area of 5x7.5m2 x 4 levels (same loading on each level). The bending moment is based on partial imposed loading on one level and an eccentricity of d/2. Column assumed pinned at each level.

G = 1.5kPa (SDL) + Self-weight (beams, columns, CLT deck)

Q = 3.0kPa

FIRE CHECK (AS/NZS 1720.4)

Compression Strength		**Clause (AS1720.1 u.n.o)**
$N_{d,c} \geq N_c^*$ $N_{d,c} = \varphi\, k_1\, k_4\, k_6\, k_{12}\, f_c'\, A_c$		3.3(1), (2)
φ	0.8	Z2.3 (DZ NZS 1720.1)
k_1 (medium term)	0.8	2.4.1.1 / G2 - Table G1
k_1 (long term)	0.57	2.4.1.1 / G2 - Table G2
k_4 (EMC≤15)	1	7.4.3
k_6	1	2.4.3
g_{13}		1 Table 3.2 - pinned
$L_{ax,\,ay}$	3500mm (full height assumed)	
r (0.4 live load/total load)	0.25 (worse case r = 0.25 per E2)	E2
ρ_c	1.11 (material constant)	E2(3)
f_c' **GL10**	26 MPa	NZ Manufacturer value
A_c = bd	99225mm³	

Major Axis		**Minor Axis**		
$S_3 = \min(L_{ax}/d,\ g_{13}L/d)$	11.11	$S4 = \min(L_{ay}/b,\ g_{13}L/b)$	11.11	(3.3.2.2)
$\rho_c S_3$	12.36	$\rho_c S_4$	12.36	
k_{12}	0.882	k_{12}	0.882	(3.3.3)
$N_{d,cx}$ Medium Term =	**1456.0 kN**	**$N_{d,cy}$ Medium Term =**	**1456.0 kN**	
$N_{d,cx}$ Long Term =	**1037.4 kN**	**$N_{d,cy}$ Long Term =**	**1037.4 kN**	

Compression Check Axial only - Min (Nd,cx , Nd,cy)

$N_{d,c}$ Medium Term =	1456.0 kN	>	N* = 1086.0 kN	**OK**
$N_{d,c}$ Long Term =	1037.4 kN	>	N* = 865.3 kN	**OK**

Bending Capacity about Strong Axis

$M_{d,x} \geq M^*$ $M_d = \varphi\, k_1\, k_4\, k_6\, k_9\, k_{12}\, f_b'\, Z$				3.2(1), (2)
k_9	1			7.4.3
ρ_b	0.85 (material constant)			E2(1) / Table 7.2(A)
Restraint check	Continuous (if $L_{ay}/d \leq 64(b/\rho_b d)^2$, $S_1 = 0$			3.2(6)
S_1	0.0	3.2(4), 3.2(6)		
$\rho_{3b}S_1$	0.0			
k_{12}	1	3.2.4		
f_b'	GL10	22 MPa		7.3.1
$Z = bd^2/6$		5209313mm³		
Md,x Medium Term =	**73.3 kNm**	**>**	**M* = 10.5 kN**	**OK**
Md,x Long Term =	**52.3 kNm**	**>**	**M* = 4.2 kN**	**OK**

Combined Axial and Bending

Medium Term	$(M_x^*/M_{d,x})^2 + N_c^*/N_{d,cy} \leq 1$	**0.77**	**<**	**1**	**OK, 3.5 (1)**
	$(M_x^*/M_{d,x}) + N_c^*/N_{d,cy} \leq 1$	**0.89**	**<**	**1**	**OK, 3.5 (2)**
Long Term	$(M_x^*/M_{d,x})^2 + N_c^*/N_{d,cy} \leq 1$	**0.84**	**<**	**1**	**OK, 3.5 (1)**
	$((M_x^*/M_{d,x}) + N_c^*/N_{d,cy} \leq 1$	**0.91**	**<**	**1**	**OK, 3.5 (2)**

LONG TERM SHORTENING (AXIAL ONLY) BETWEEN GROUND AND LEVEL 1

Load Factor for Creep, j_2		2	(≤15% EMC; ≥1year)	2.4.1.2
Δ = PL/AE	G =	598.5 kN	Δ(G)	2.1 mm
	Q =	245.2 kN	Δ(Q) =	0.9 mm
			j_2Δ(G+ψlQ) =	4.9 mm

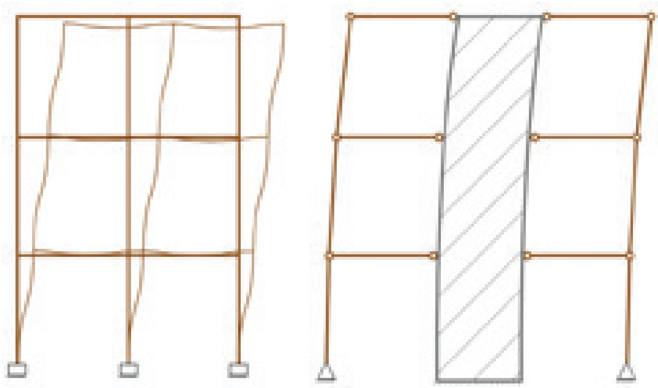
3.7 LATERAL DESIGN

The lateral design of any structure is integral to its function – the structure must be able to resist the wind and seismic forces it encounters to remain safe and function as intended. Seismic forces are proportional to the weight of the structure; therefore, the relatively light weight of timber is beneficial compared to other heavier materials. Lateral design in New Zealand is based on the standards AS/NZS1170.2 for wind actions and NZS1170.5 for earthquake actions. The new standard for timber design, NZS AS 1720.1, provides further guidance on the seismic design of timber structures in Section 9. This section of the guide gives a high-level overview of considerations for lateral design of timber post and beam structures. The NZ Wood Design Guide "Seismic Design" covers this topic in more detail.

Often the timber post and beam components of the structure are considered as "gravity only" elements; however, their design is still influenced by the lateral design of the building. The gravity only components must be able to withstand the likely displacements imposed on them by the lateral system and the beams may also form chords or drag members in the floor diaphragms and be needed to transfer loads into the lateral load resisting system.

Lateral Displacement Compatibility

The whole system must be checked for the likely displacement demands under lateral loading. The connections between beams and columns must be able to transfer the moments generated by the displaced shape, or if the connections are designed as pinned and are not intended to take moment, they must allow for rotation during lateral displacement. Columns should also remain stable under lateral drift demands which can be higher for timber buildings compared to other construction materials.

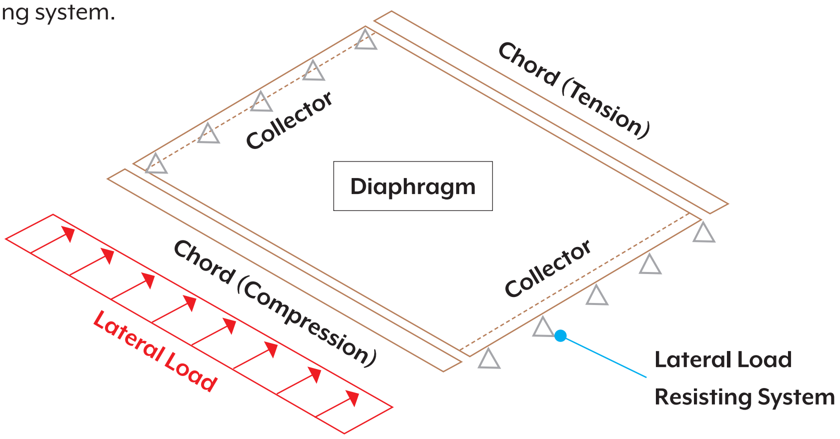


Idealised displaced shape of Fixed Beam Connections vs. Pinned Connections under Lateral Displacement.

Diaphragms

All structures require a diaphragm at each floor level and roof in order to transfer the horizontal lateral forces to the vertical lateral resisting elements. In post and beam structures, the diaphragm is often a gravity resisting element i.e. the floor panels or sheathing above the timber framing. The diaphragm panels must be connected to transfer the shear force through the elements. If a concrete topping is part of the design this could also act as the diaphragm, but careful detailing is required to ensure transfer of forces.

A simple rectangular diaphragm consists of the basic components shown in the below figure. The chords in post and beam structures can be the floor panels themselves or gravity beams. The chords must be designed for both tension and compression meaning specific detailing of connecting the beam or floor elements for this load path must be considered. Collectors are generally beams that are part of the lateral load resisting system in brace or moment frame designs, or in timber or concrete shear walls another element which collects the load and transfers it to the lateral load resisting system.



Diaphragm Components.

NZS 1170.5 defines two types of diaphragms: flexible and rigid. A diaphragm that allows for the maximum lateral deformation to be twice the average inter-storey deflection at that level is defined as flexible, whereas a diaphragm may be considered rigid if the diaphragm deformation is less than half the average inter-storey drift of the level below (FPInnovations, 2013). The load distribution into the vertical lateral resisting elements can be determined by tributary area for flexible diaphragms. For rigid diaphragms the distribution is proportionate to the stiffness of the vertical elements, and accidental torsion must be considered. A timber diaphragm without irregularities often falls somewhere between flexible and rigid. For example, a plywood or OSB based diaphragm may be considered flexible with a stiff vertical LLRS such as concrete shearwalls. On the other hand, a CLT panel diaphragm with a CLT or hybrid LLRS is recommended to be considered rigid. If the designer is unsure of which category the diaphragm should be considered, it is recommended that an envelope approach be taken in which the diaphragm is analysed assuming a flexible diaphragm and then assuming a rigid diaphragm, taking the worst case scenario for the design (FPInnovations, 2013).

Timber diaphragms are important to the performance of the structure. This section has only provided a high-level discussion of considerations for diaphragms in timber post and beam structures. Further information can be found in the WoodSolutions Guide 35 – Floor Diaphragms in Timber Buildings (Moroder, Pampanin, Buchanan, 2016) and the BRANZ Multi-Storey Light Timber-Framed Buildings in New Zealand (Carradine, 2019).

3.8 CONNECTIONS

There are numerous methods for connecting timber elements in post and beam structures and the design of connections is a vast topic. Research and development of connectors is continually changing and there is always the possibility of new designs for timber connections. This section of the guide is intended to give a high-level overview of different methods and considerations for connections that are commonly used in timber post and beam structures. The specific design of timber connections is covered in NZS AS 1720.1.

Timber connections can generally be classified as bearing connections, adhesive-based or mechanical-based. Bearing type connections are the most economical and involve timber resting on timber or another material. Adhesive-based approaches are stiff connections which use glue to attach timber elements with a chemical bond. This approach is not common in post and beam connections but is used in the fabrication of engineered wood products such as between the web and flanges of I-beams, or in glued knee joints. Specific conditions are required for the application of adhesives which are often impossible to achieve on site, therefore gluing on site should be avoided unless strictly necessary and completed by a certified professional.

Mechanical-based connections are more typical than adhesive-based connections in post and beam structures. This approach uses fasteners and connectors to transfer load between elements. The strength of the connections is based on the material properties of the fastener and the timber (moisture, duration, etc.), number and quality of fasteners, and spacings of fasteners relative to each other and the boundaries of the timber elements. Mechanical type fasteners include:

- **Nails** – commonly used in light timber construction, generally for timber-timber or thin-plate to timber applications, economical fastener, various size and lengths.
- **Screws** – various types available. Small wood screws commonly used with light timber, coach screws (normally threaded section, shank and hexagonal head similar to a bolt) and modern self-tapping structural screws which have had significant technical development in recent years. Self-tapping screws vary greatly in range, diameter and purpose. Diameters of 12mm, with lengths over 450mm, are not uncommon in timber connections (pilot holes are required for large screws). Screws can be used for direct timber to timber connections (shear and withdrawal), or for steel to timber connectors. Screws can also be used to reinforce timber around other connections.
- **Bolts** – metal fastener installed into pre-drilled holes. Various sizes available. Could be hexagonal head, cup head or threaded rod with nuts on both ends. Split-rings, shear-plates or toothed-plate connectors can be added to strengthen bolted connections but are seldom used. Larger diameter bolts can have a high capacity but are often limited by brittle timber failure.

- **Dowels** – similar to bolts but without nut and washers. Dowels are generally metal but can be wood (pegs in traditional timber framing). Self-tapping dowels are also available. High capacity connections when used in double or triple shear. More small dowels are often better practice than fewer large bolts. Fully threaded screws of bolts can be combined with dowels to resist timber splitting.
- **Epoxied Rods** – often used for high strength connections where steel rods are inserted into the end grain of glulam or LVL and fixed in place using epoxy resin.

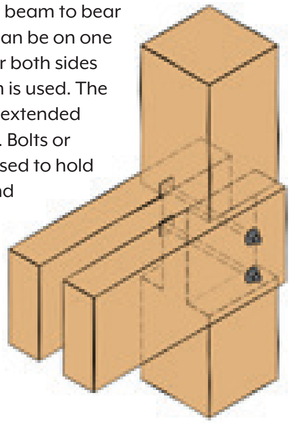
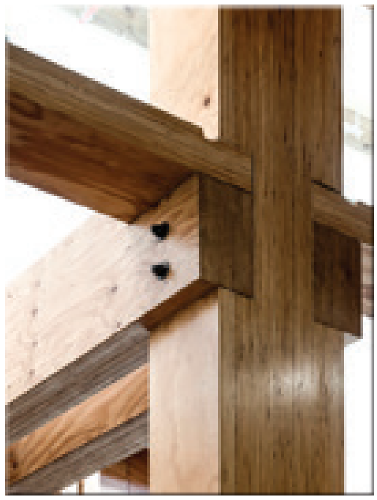
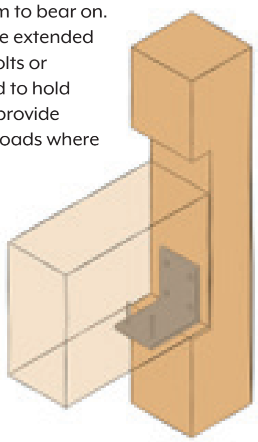
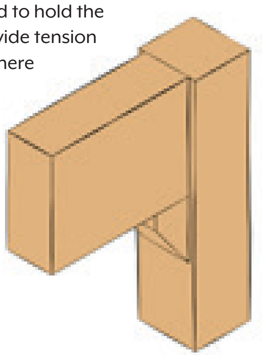
When installing fasteners in any timber connection, the moisture content of the timber should be as near to service moisture content as possible to avoid dimensional changes of the element. The expansion of timber due to swelling can put significant stresses on a connection even causing fasteners to snap. Likewise, shrinkage can cause splitting of timber or leave gaps between beams and columns or bearing seats. It is important that this is considered when designing timber connections.

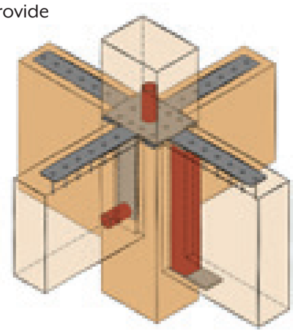
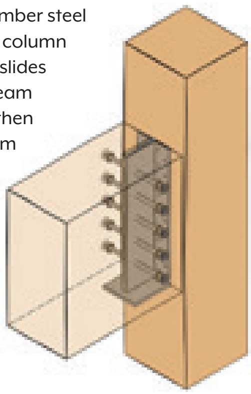
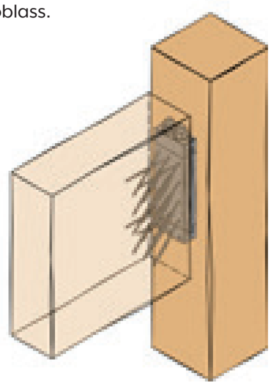
The following tables present example connection types for timber beams, columns and floors. The examples included are simplified representations of possible connections which can be incorporated into timber post and beam structures. The examples are not exhaustive.

Timber connections are complex but interesting design challenges, the following considerations should form part of the design and selection process:

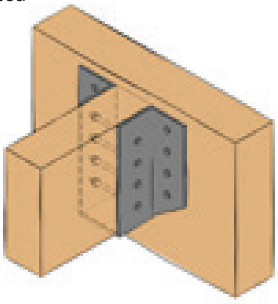
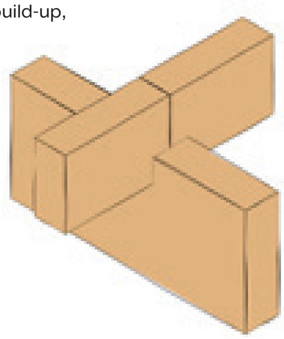
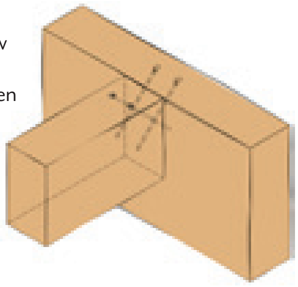
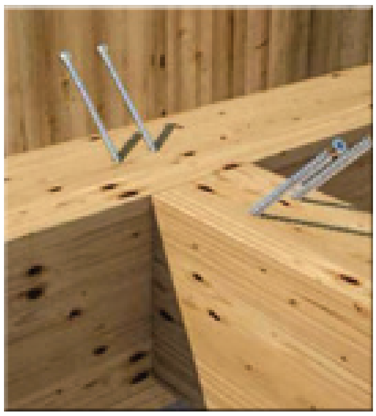
- **Function** – pinned or fixed, transferring shear, axial load, moment, restraining other members.
- **Performance** – strength, stiffness, ductility.
- **Geometry** – complexity, number of fasteners, influence on member size.
- **Moisture effects** – swelling, shrinkage.
- **Durability** – long-term, fastener corrosion, coatings, treatment level and bi-metallic corrosion.
- **Fire performance** – fire rating, exposed or protected.
- **Aesthetics** – visible or hidden.
- **Cost** – part cost, complexity, manufacturing/pre-assembly, installation on site.
- **Installation** – speed/ease of installation, access, safety, crane time, tolerance.
- **Seismic compatibility** – lateral load path, chords, collectors, drift requirements.
- **Quality assurance** – ensuring constructed as designed, complexity.

3.8.1 Beam to Column Connections

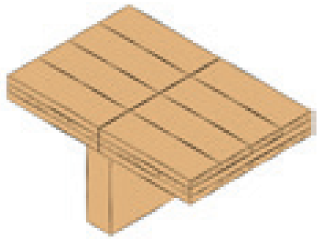
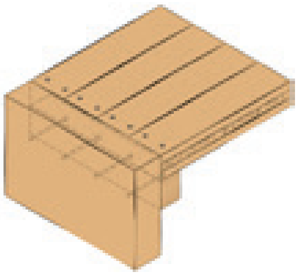
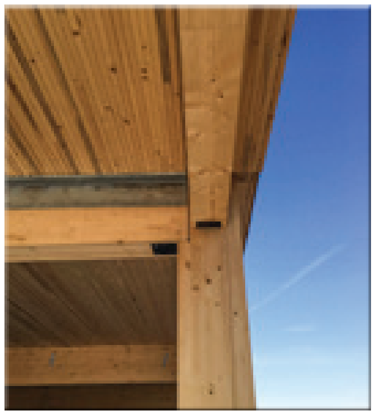
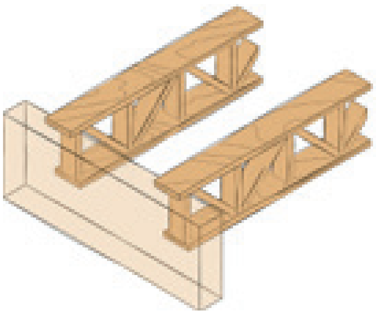
CONNECTION TYPE	FEATURES	EXAMPLES
BEARING CONNECTION INTO SIDE OF COLUMN Created by forming a notch into the side of the column for the beam to bear on. The connection can be on one side of the column, or both sides when a double beam is used. The bearing area can be extended using a steel bracket. Bolts or other fasteners are used to hold the beam in place and provide tension and horizontal loads where needed. 	✓ Robust load path. ✓ Can be protected from fire if steel components covered. ✓ Minimal crane time as bearing connection. ✓ Can be designed to allow for construction tolerance. ✓ Allows for continuous beam. ✓ Economic as utilises commonly available components. ✓ Easy access for installing bolts and QA checks. ✗ Requires machining of column section. ✗ Notch needs verification under displacement and moment demand. ✗ Creates a notch in the column for out-of-plane shear loading. ✗ Reduced section may govern size. ✗ Often limited by perpendicular to grain bearing area.	NMIT (Nelson) 
BEARING ON COLUMN NOTCH Created by forming a notch into the face of the column for the beam to bear on. The bearing area can be extended using a steel bracket. Bolts or other fasteners are used to hold the beam in place and provide tension and horizontal loads where needed. 	✓ Robust load path. ✓ Can be protected from fire if steel components covered. ✓ Minimal crane time as bearing connection. ✓ Can be designed to allow for construction tolerance. ✓ Economic as utilises commonly available components. ✓ Easy access for installing bolts and QA checks. ✗ Requires machining of column section. ✗ Reduced section may govern size. ✗ Notch needs verification under displacement and moment demand. ✗ Often limited by perpendicular to grain bearing area. ✗ Exposed steel requires fire protection.	Lucas House (Nelson)  T3 (Minneapolis) 
BEARING CONNECTION WITH TIMBER CORBEL Created by attaching a timber corbel to the face of the column for the beam to bear on. The bearing area can be extended using a steel bracket. Bolts or other fasteners are used to hold the beam in place and provide tension and horizontal loads where needed. 	✓ Can be protected from fire if steel components covered. ✓ Minimal crane time as bearing connection. ✓ Can be designed to allow for construction tolerance. ✓ Easy access for installing bolts and QA checks. ✓ Efficient use of material. ✗ Fixing of corbel to column can be challenging and costly. ✗ Bearing needs to be maintained under seismic loading and charring. ✗ Requires machining of column section and corbel. ✗ Eccentricity of support to column centre line. ✗ Permanent tension on “tie” at top of corbel.	Scion (Rotorua)  Kaikoura District Council 

CONNECTION TYPE	FEATURES	EXAMPLES
CUSTOM STEEL BEARING BRACKET Created by attaching a timber steel bracket to the face of the column for the beam to bear on. Bolts or other fasteners are used to hold the bracket to the column and provide a tension or horizontal load path to the beam. Complex brackets as shown here can be developed for more complicated joints. 	✓ Minimal crane time as bearing connection. ✓ Can be designed to allow for construction tolerance. ✓ Easy access for installing bolts and QA checks. ✓ Can be designed so column area not reduced by connection. ✗ Exposed steel requires protection from fire. ✗ Fabrication of steel bracket can be costly. ✗ Care needs to be taken with tolerance and shrinkage/swelling of timber. ✗ Eccentricity of support to column centre line.	Albina Yard (Portland) 
STEEL CLEAT WITH BOLTS OR DOWELS Created by attaching a timber steel bracket to the face of the column with a cleat (or two) that slides into pre-cut slots in the beam end. Bolts or dowels are then installed through the beam and cleats to provide the connection. A bottom plate can be included for bearing. Generally, holes through the beam and cleats must be pre-drilled, or self-tapping dowels can be used. 	✓ Can be protected from fire if steel components covered. ✓ Easy access for installing bolts and QA checks. ✓ Connection can be hidden to create “clean” aesthetic. ✓ Bearing plate can be incorporated for easy installation of beam. ✗ Eccentricity of support to column centre line. ✗ May need temporary propping or extended crane time during installation. ✗ Tight tolerance to install bolts or dowels.	 
PROPRIETARY HANGER There are a number of different proprietary connectors available. Typically, a machined aluminium or steel plate is pre-fixed with screws to each side of the interface. On site, the two sides slip together and are locked into place. Suppliers: KNAPP, Rothoblass. 	✓ Concealed connection provides nice aesthetic. ✓ Protected from fire. ✓ Tested technology. ✓ Most connectors installed off-site or on the ground. ✓ Dismountable. ✓ Supplier design advice and approvals. ✗ Little tolerance, this may result in difficult install and more crane time. ✗ Time to install all screws. ✗ Not many proprietary connections have seismic rating. ✗ Difficult to access final placement bolts. ✗ Cost of machining recesses. ✗ Expensive componentry. ✗ Cannot reinstall on same element if misaligned.	International House (Sydney)  

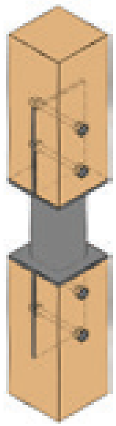
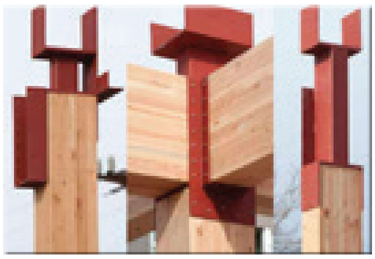
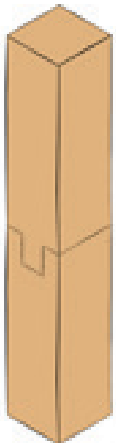
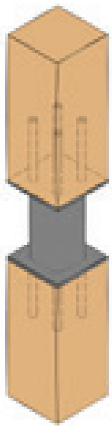
3.8.2 Beam to Beam Connections

CONNECTION TYPE	FEATURES	EXAMPLES
PROPRIETARY OR CUSTOM CONNECTIONS/BRACKETS Concealed proprietary connections (similar to those described above in beam to column connections) can be used for beam to beam connections. There are also a number of exposed large proprietary “joist hanger” type connections available. Custom steel cleats with or without bearing seats can also be used similar to beam-column connections. 	✓ Minimal crane time if bearing connection in bracket. ✓ Easy access for installing bolts and QA checks. ✗ Steel requires protection for fire rating. ✗ Cost of proprietary element. ✗ Eccentricity of support to beam centre line. ✗ Care needs to be taken to allow shrinkage/swelling of timber. ✗ Can be time consuming to install screws/bolts on site.	
BEARING CONNECTION Secondary beams can be positioned to bear on top of primary beams. To reduce the overall depth of the floor build-up, it may be possible to notch the secondary beam. 	✓ Minimal crane time as bearing connection. ✓ Robust load path. ✓ No steel elements to protect from fire. ✓ Services can be reticulated through voids reducing need for beam penetrations. ✓ Secondary beams can be continuous over more than one span. ✓ Timber elements require little machining. ✓ Deconstructable, with long timber lengths re-usable. ✗ Floor build-up depth. ✗ Notch reinforcement may be required.	
SCREW CONNECTION Secondary beams can be connected simply by structural screws. Long self-tapping screws have significant capacity and various testing has been done on screw configurations. Screw suppliers often publish strengths for tested connection configurations. 	✓ Economical. ✓ Minimal hardware required. ✗ Beams must be propped or held in place while connecting. ✗ Limited capacity. ✗ Permanent load on screws.	

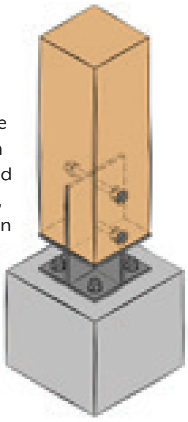
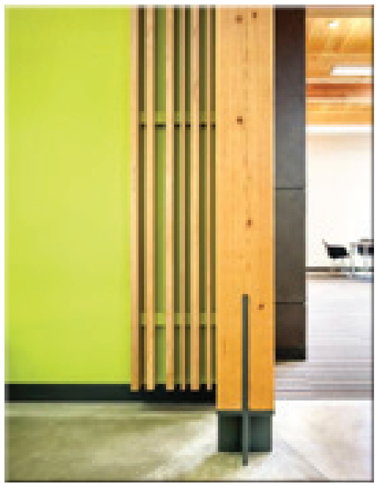
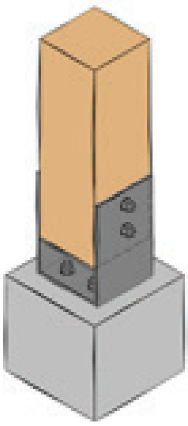
3.8.3 Floor to Beam Connections

CONNECTION TYPE	FEATURES	EXAMPLES
BEARING ON BEAM Floors can span directly on to the top of the beam creating a bearing connection. This is the most common form of floor to beam connections in post and beam construction. 	✓ Economic as utilises commonly available components. ✓ Easy to install, can be released from crane quickly. ✓ Concentric load path. ✗ Deeper floor build-up. ✗ Edge distance can be an issue if panels are used as diaphragm chords or to provide stability to the frame under out-of-plane displacement demand.	 
BEARING ON LEDGER Floors can span into the side of a beam and bear on a ledger made of wood or steel. 	✓ Minimised floor build-up. ✓ Quick to install on site. ✗ Extra material and fasteners required. ✗ More labour intensive. ✗ Eccentric load path could induce beam torsion. ✗ Edge distance can be an issue if panels are used to provide stability to the frame under out-of-plane displacement demand.	
FLANGE HUNG Cassette panels are often hung by the top flange in order to reduce the floor build up above the beam. 	✓ Minimised floor build-up. ✓ Quick to install on site. ✗ Eccentric load path could induce beam torsion. ✗ Permanent tension on top flange screws. ✗ Will not provide out-of-plane stability to the frame under out of plane displacement demand.	

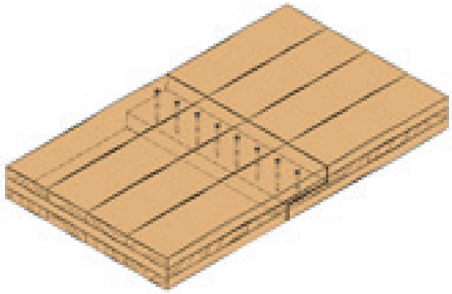
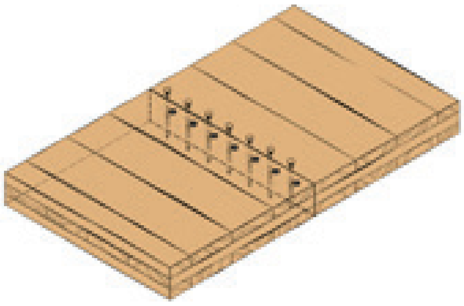
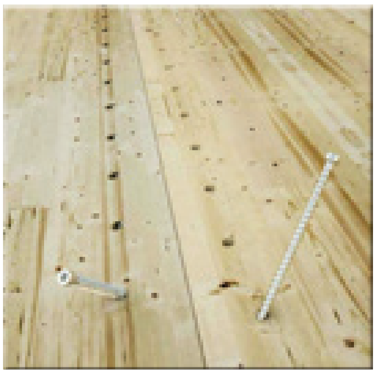
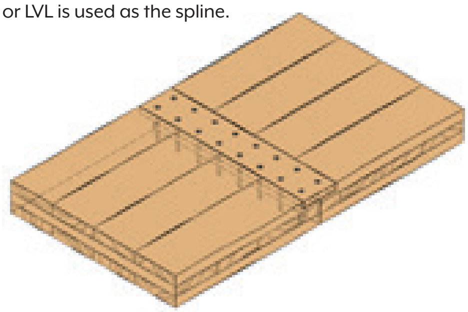
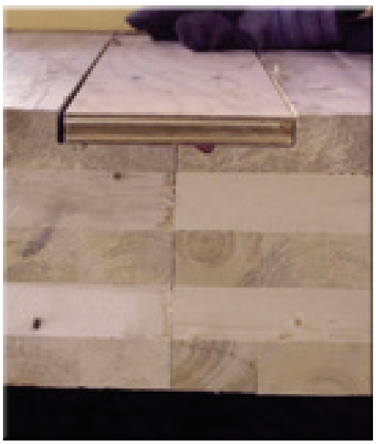
3.8.4 Column to Column Connections

CONNECTION TYPE	FEATURES	EXAMPLES
STEEL BRACKET BEARING Steel brackets can be used for bearing purposes in such a way that the column section is not reduced, keeping the full section strength. These can be incorporated into the prefabrication / assembly of the timber elements. The steel plates could be connected to the beam and column both internally and externally. 	✓ Easy installation. ✓ Pre-assembly. ✓ Robust load path. ✓ Parallel to grain bearing. ✓ Can incorporate into beam connection. ✗ Fire protection may be required. ✗ Complex fabrication. ✗ Could be costly due to amount of steel. ✗ Careful consideration of shrinkage/ swelling required especially during assembly.	
TIMBER-TIMBER BEARING Columns can be connected through direct timber bearing. Typically achieved through a large tongue and groove. 	✓ Material efficient – no extra componentry. ✓ Cost effective. ✗ Screws or other fasteners required for stability and robustness. ✗ Potential for settlement as the end grains crush into each other.	 
EPOXY ROD CONNECTIONS Epoxied rods can be used in both timber-timber connections and timber-steel-timber connections for a robust load path. 	✓ Robust load path. ✓ High tensile capacity in end grain. ✓ Rods could be preinstalled into the upper column. ✗ Machining of holes required in prefabrication. ✗ Injection of epoxy should be done in the factory.	

3.8.5 Column Base Connections

CONNECTION TYPE	FEATURES	EXAMPLES
INTERNAL CLEAT/KNIFE PLATE OR EPOXY DOWELS The base of columns can be connected to the ground or foundation with a bracket that is preinstalled to the column or embedded into the concrete. The bracket could be connected with an internal steel knife plate bolted or dowelled through the column, or epoxied rods into the end grain can be used. Screws into end grain are not recommended. These connections typically lift the column clear of the floor slab to avoid moisture ingress through the end grain of the column. 	✓ Fast installation. ✓ Aesthetics - hidden connection. ✗ Little tolerance. ✗ May require additional fire protection.	
EXTERNAL BRACKETS Numerous manufacturers offer external bracket connections for columns or posts. These are common in small construction but custom brackets can also be fabricated for mass timber columns. 	✓ Install out of critical path of crane. ✓ Can be cheap, proprietary product. ✗ Visible connection. ✗ Limited capacity. ✗ May require additional fire protection.	

3.8.6 Floor to Floor Connections

CONNECTION TYPE	FEATURES	EXAMPLES
HALF LAP CONNECTION A half lap connection involves machining the panel to create an overlap of two adjacent panels that can be vertically screwed together. 	✓ No extra material (spline) required on site. ✓ Screws can be installed vertically (easier to install). ✓ Easy to rate for fire. ✗ Machining required. ✗ Waste of some panel material. ✗ Panel sequencing for install is required to be planned to ensure panels can be lowered vertically into place.	
BUTT JOINT CONNECTION Angled screws are used to connect the adjoining panels. 	✓ No extra machining to the panels. ✓ High stiffness connection through angled screws can be achieved. ✓ No extra material (spline) required on site. ✓ Panels can be lowered vertically into place. ✗ Tight tolerance between panels. ✗ Double inclined screw installation can be time consuming. ✗ Can create ridges in panels as inclined screws are less effective in pulling panels falt.	
SPLINE CONNECTION A spline connection is created by connecting adjacent panels with a thin strip of material. Normally a sheathing product such as plywood, OSB or LVL is used as the spline. 	✓ Panels can be lowered vertically into place. ✓ Screws or nails installed vertically (quick to install). ✓ Double surface spline (top and bottom) can be used for higher shear capacity. ✗ Extra material on site. ✗ Reinforcing of parallel laminations may be required for NLT type panels to achieve higher shear capacity.	

4 BUILDING CASE STUDIES

BEATRICE TINSLEY BUILDING

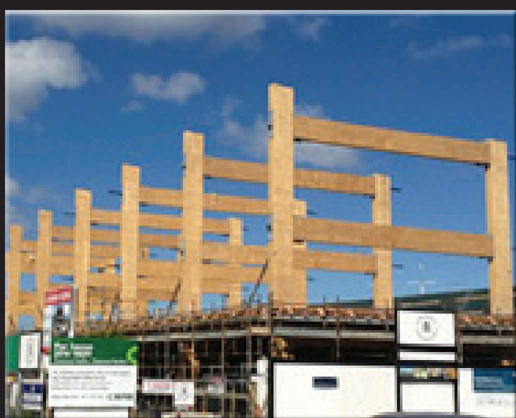
CHRISTCHURCH, NEW ZEALAND

Year: Construction Started March 2017, Opened October 2019
Use: Education
Size: 4 storeys | 3430 m^2
Client: University of Canterbury
Design team: Jasmax (arch) | BECA, PTL (eng)
Construction: Dominion Constructors | NelsonPine (fabricator)
Floor: Potius Double T Cassette | 7m span
Beams: LVL 13 | 1000 x 266 with internal post-tensioning (Pres-Lam direction), 800 x 266 (braced direction), 400 x 266 (braces) | 10.3m max span
Columns: LVL 11 | 1000 x 300, 800 x 356 | 3.9m floor height
Connections: Dowelled/bolted joints through steel knife plates, with steel dissipaters (pictured). Intumescent paint on exposed steel to achieve fire rating
Lateral system: LVL post-tensioned (Pres-Lam) frames in short direction, LVL braced frames in long direction
Feature: First multi-storey building using timber moment frames and timber cross braces in New Zealand, Acceleration Displacement Response Spectrum design methodology
Source: www.constructors.co.nz/beatrice-tinsley-building/

YOUNG HUNTER HOUSE

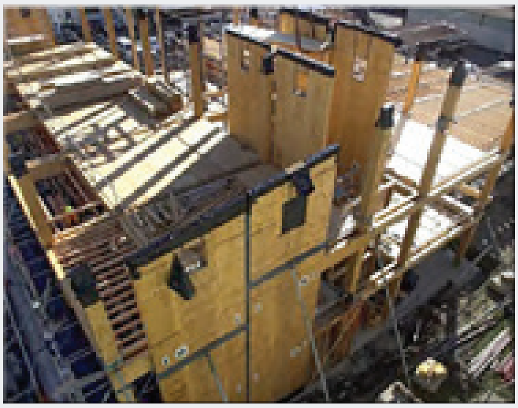
CHRISTCHURCH, NEW ZEALAND

Year: Construction Started Feb 2013, Opened Feb 2014
Use: Office & Retail
Size: 3 storeys | 1850 m^2
Client: Tony Merritt
Design team: Sheppard & Rout (arch) | Kirk Roberts Consulting Engineers
Construction: Contract Construction | TimberLab Solutions
Floor: Timber-Concrete Composite floors
Beams: Hollow LVL13 with internal post-tensioning
Columns: LVL13
Connections: Replaceable Steel Dissipators and post-tensioning form connections as part of Pres-Lam system. Concrete cladding required for fire protection on two walls (not pictured)
Lateral system: Pres-Lam Post-tensioned LVL frames, concrete wall
Feature: One of the first 'true' Pres-Lam buildings in the world, one of the first to be erected after the 2011 Christchurch Earthquakes
Source: www.contract-construction.co.nz/project/young-hunter-house/ | http://pres-lam.com/projects/young-hunter-



NELSON MARLBOROUGH INSTITUTE OF TECHNOLOGY

NELSON, NEW ZEALAND



Year: Construction Started Feb 2010, Opened Jan 2011
Use: Education
Size: 3 storeys | 2900m^2
Client: NMIT
Design team: Irving Smith Jack Architects (arch) | Aurecon (eng)
Construction: Arrow International (contractor) | Hunter Laminates (fabricator)
Floor: Potius panels with 75mm concrete topping | 6m span
Beams: LVL11 | 660 x 189 | 6m
Columns: LVL11 | 400 x 405 | 4m floor heights
Connections: Bolted connections typically throughout post-and-beam system, steel knife plates painted with intumescent paint to achieve fire rating
Lateral system: LVL post-tensioned (Pres-Lam) shear walls with sacrificial steel U dissipators (UFPs) between the walls
Feature: 'NMIT represents a "world first" in terms of innovative timber technology and seismic design', DBB design methodology
Source: http://pres-lam.com/projects/nmit/ | www.archdaily.com/230288/nmit-arts-media-irving-smith-jack-architects

SCION INNOVATION HUB

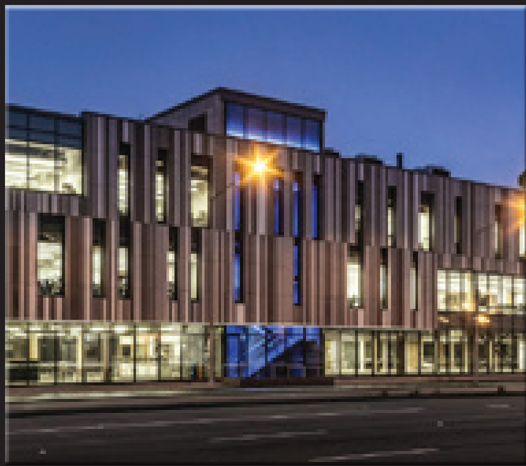
ROTORUA, NEW ZEALAND

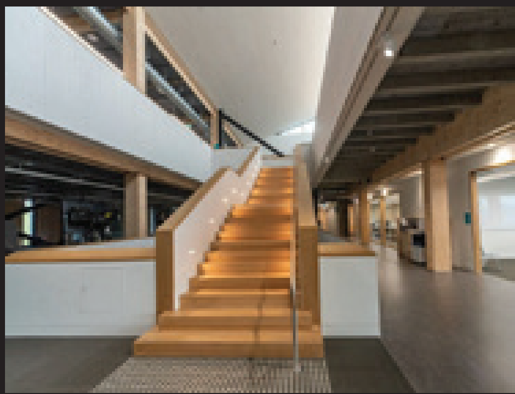
Year: Construction Started in June 2019, Opening Expected mid-2020
Use: Office & Education/Research
Size: 3 storeys | 2000 m^2
Client: SCION
Design team: Irving Smith Architects & RTA Studio (arch) | Dunning Thornton Consultants (eng)
Construction: Watts & Hughes Construction (contractor) | TimberLab Solutions (fabricator)
Floor: 3-ply CLT Floors | 3m span
Beams: LVL 11 | 600 x 126, 450 x 63 at top storey | 8m span, ~3m trib
Columns: LVL 11 | 300 x 135 (diagrid), 300 x 90 at top storey | 3.6m floor heights
Connections: Finger Jointed Timber Elements to Pre-fabricated Diagrid 'Nodes' – UFP dissipators separating adjacent diagrids
Lateral system: Timber braced frames (diagrid) in each direction
Feature: Timber Diagrid Structure, one of the first in NZ
Source: www.scionresearch.com/about-us/news-and-events/news/2019/scions-new-innovation-hub-is-taking-shape

KAHUKURA – CPIT

CHRISTCHURCH, NEW ZEALAND

Year: Construction Started April 2015, Opened August 2017
Use: Education
Size: 3 storeys | 6500m^2
Client: Ara Institute
Design team: Jasmax (arch) | Powell Fenwick (eng)
Construction: Hawkins (contractor) | NelsonPine (fabricator)
Floor: Concrete Interspan rib | 10m
Beams: LVL13 | 900 x 135 | 7.1m (5m trib)
Columns: LVL 11 | 400 x 450 | 4.2m floor heights
Connections: Column-beam bearing connections, exposed timber and steel plates
Lateral system: Concrete diaphragm, concrete shear walls and steel braced frames (separate from timber gravity system)
Feature: "One of the greenest buildings in the Canterbury reconstruction programme"
Source: hawkins.co.nz/projects/ara-institutes-kahukura-building





HUTT VALLEY HEALTH HUB

WELLINGTON, NEW ZEALAND

Year: Construction Started August 2018, Opened Jan 2020
Use: Health
Size: 3 storeys | 3600 m^2
Client: Private Developer
Design team: Medispace (arch) | CGW Consulting Engineers (eng)
Construction: Treadstone Construction | Techlam NZ | NelsonPine | Potius
Floor: Potius cassette panels | 7.5m
Beams: LVL | 800 x 225 | 7.2m
Columns: Glulam | 270 x 270 | 3.8m floor heights
Connections: Bolted beam to column joints using steel knife plates as splices and steel cylinder crucifixes to transfer drag loads. Tectonus RSFJ Dampers on braces/shear walls to provide damping and reduce base shear.
Lateral system: Glulam braced frames with RSFJ / Concrete Shear Walls with RSFJ
Feature: Significant use of Tectonus slip friction joint dampers throughout, IL4 timber building.
Source: www.tectonus.com/hutt-valley-health-hub | techlam.nz/hutt-valley-health-hub-lower-hutt-nz/

WYNN WILLIAMS HOUSE

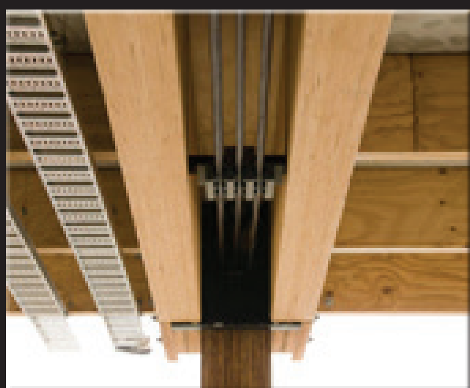
CHRISTCHURCH, NEW ZEALAND

Year: Construction Started August 2012, Opened July 2014
Use: Offices
Size: 6 storeys | 6000 m^2
Client: Richard Owen
Design team: Richard Proko Ltd (arch) | Ruamoko (eng)
Construction: C. Lund & Son (Contractor) | TimberBuilt (AUS)
Floor: Steel deck comflor with concrete topping
Beams: Fabricated Hollow LVL13 Sections | 8.7m span
Columns: Reinforced concrete
Connections: Horizontal post tensioning
Lateral system: Pre-fabricated timber post tensioned beams with concrete columns, base-isolated
Feature: Hybrid timber-concrete post tensioned structure
Source: https://www.wynnwilliams.co.nz/Documents/Wynn-Williams-House-Info-Sheet.aspx

COLLEGE OF CREATIVE ARTS (COCA) – MASSEY

WELLINGTON, NEW ZEALAND

Year: Construction Started September 2011, Opened June 2012
Use: Education
Size: 3 storeys | 3000 m^2
Client: Massey University
Design team: Athfield Architects (arch) | Dunning Thornton Consultants (eng)
Construction: Arrow International (contractor) | Hunter Laminates (fabricator)
Floor: Precast concrete units on LVL beams | 7.2m span
Beams: Double LVL | 600 x 126 | 6m span. Draped post-tensioning cables.
Columns: LVL | 600 x 315 | 3.6m floor heights. Internal post-tensioning.
Connections: Bolted beam-column joints typ.
Lateral system: Post tensioned timber frames, post tensioned concrete walls
Feature: First Pres-Lam building to use draped tendons, uses post tensioning to hold down columns to foundations. Cantilevers achieved with double beams either side of single columns.
Source: http://pres-lam.com/projects/coca/



T3 MINNEAPOLIS

MINNEAPOLIS, USA

Year: 2016
Use: Commercial, office
Size: 6 storeys | 16700m^2 (timber)
Client: Hines
Design team: Michael Green Architecture, DRL Group (arch) | MKA (Eng record), StructureCraft Builders (Design-Assist+Build Eng)
Construction: StructureCraft Builders (Timber) | Kraus Anderson
Floor: Nail Laminated Timber (NLT) | 6m typical span
Beams: Glulam | 7.5m typ. span
Columns: Glulam | 4.2m floor to floor
Connections: Column-beam bearing connections and custom steel hangers, exposed timber and steel plates
Lateral system: Concrete shear wall core
Feature: LEED Gold, timber construction completed at average 9 days per floor
Source: https://structurecraft.com/projects/t3-minneapolis, http://mg-architecture.ca/work/t3-minneapolis/

MJØSTÅRNET

BRUMUNDAL, NORWAY

Year: 2018
Use: Office, hotel, residential
Size: 85.4m | 18 storey | 10500m^2
Client: AB Invest AS
Design team: Voll Arkitekter (arch) | Moelven (eng)
Construction: HENT AS
Floor: Glulam and LVL prefabricated decks with concrete topping, and concrete decks at upper 7 levels for added mass. | 7.5m max span
Beams: Glulam| 395 x 675 | ~7.2m
Columns: Glulam | Typ. interior up to 725 x 810 | corner columns 1485 x 625
Connections: Internal knife plate connections, 120 minute fire rating for primary elements and plate connections embedded for fire protection
Lateral system: Glulam braces around building perimeter with maximum cross-section of 625 x 990, wind load governed
Feature: World's tallest timber structure at time of completion
Source: mjostarnet---18-storey-timber-building-completed.pdf, mjostarnet---construction-of-an-81-m-tall-timber-building.pdf vollark.no/portfolio_page/mjostarnet/

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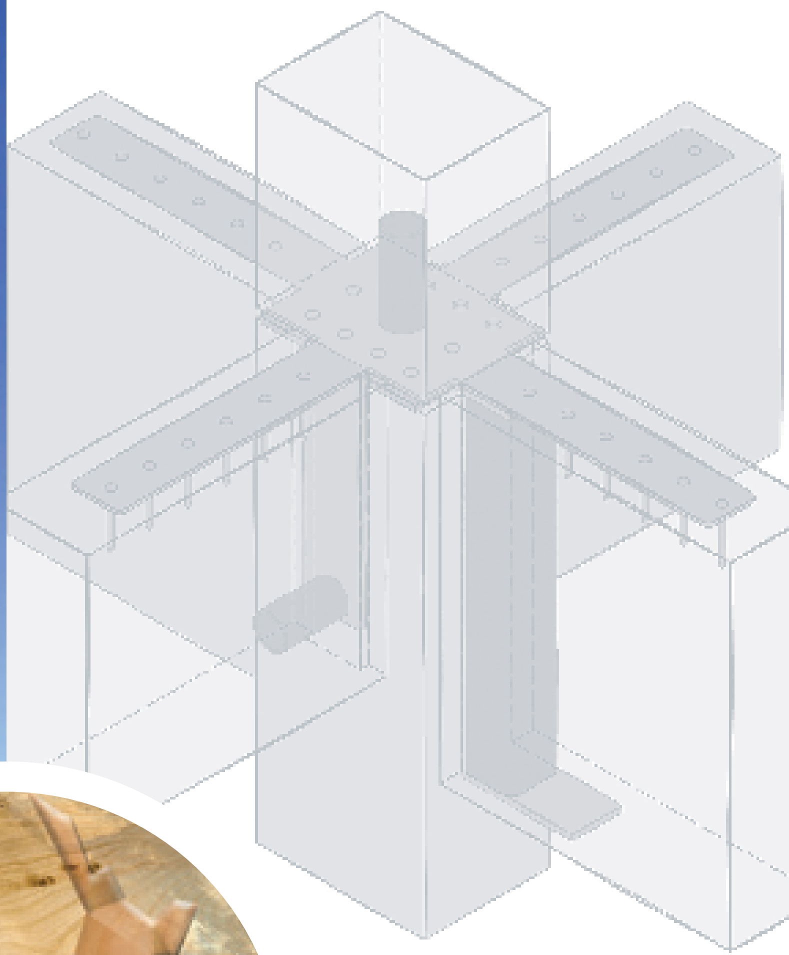
Ben White is a Structural Engineer with Holmes Consulting LP. He attained a Bachelor of Civil Engineering from the University of British Columbia, followed by a master's degree in structural and earthquake engineering. Prior to working for Holmes Consulting, Ben worked for a timber engineering and construction company in Canada where he designed various mass timber projects in Canada and the USA. Currently based in Christchurch, Ben is continually developing his New Zealand design experience through a mixture of projects at Holmes Consulting.



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