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Domestic Timber Deck Design

Technical Design Guide issued by Forest and Wood Products Australia

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Timber-framed Construction
for Townhouse Buildings
Class 1a

Design and construction guide for BCA compliant sound and fire-rated construction

Technical Design Guide issued by Forest and Wood Products Australia

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Introduction

Scope

This guide outlines key design and construction considerations for light domestic timber decks for both raised and close to or on-ground timber decks that are exposed to the weather.

It covers decks associated with Class 1 structures (such as detached houses, villas and townhouses) and Class 10 structures (such as garages, sheds and swimming pools) according to the National Construction Code (NCC) Volume 2. For the design and construction of decks for commercial, industrial or marine applications, or where a deck has to take heavier loads such as tiles, spas or even vehicles, a structural engineer must be consulted.

Terms used in domestic deck design and construction are illustrated in Figure 1.

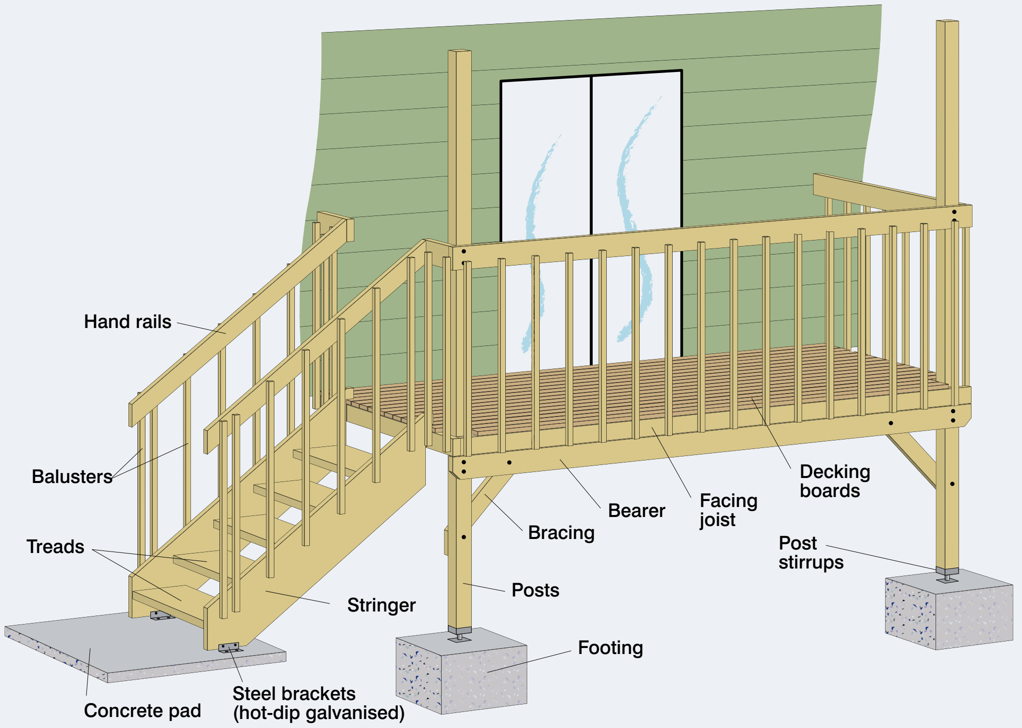

Figure 1: Components used to make up a timber deck.

How to Use This Guide

Section 1 provides general information applicable to all types of light domestic decks. Information relevant to specific types of decks is contained in Section 2.

1

General Information

The following information is applicable to all deck systems.

1.1 Bushfire Construction Requirements

In all parts of Australia prone to bushfires, there are limitations on the use of timber in deck construction. This limit varies depending on the risk of bushfire attack and the elements of the deck under consideration.

Appendix A of this guide contains a list of common timber species used for timber decks and the maximum Bushfire Attack Level (BAL) that the species can be used for in a deck, in accordance with *AS 3959 Construction of buildings in bushfire-prone areas*.

Refer to *WoodSolutions Technical Design Guide #4: Building with Timber in Bushfire-prone Areas* for further information. It also should be noted that South Australia and NSW have some different requirements that need to be followed in those states.

The WoodSolutions website contains a list of timber species and the various properties of each species. Properties for each species include classification as resistant or not resistant to termites.

1.2 Termite Protection

The National Construction Code includes requirements for decks. The decks must be:

- constructed from naturally termite-resistant timbers, in accordance with Appendix C in AS 39660.1, or
- constructed from preservative-treated timber in accordance to Appendix D of AS 3660.1; or
- have a termite barrier to protect the primary building elements installed in accordance with AS 3660.1.

Primary building elements include framing members, floor (decking boards), stairways and ramps, i.e. elements that take part of the building load.

Where the installation of a termite barrier according to AS 3660.1 is chosen as the method to provide protection, AS 3660.1 requires attachments to buildings, such as decks, to be separated at least 25 mm from the building. Where this can't be achieved, the termite barrier must be extended to include the deck.

Termite protection can be achieved by placing all posts that support the deck framing on galvanised metal stirrups that have at least 75 mm clearance above the finished ground level (Figure 2).

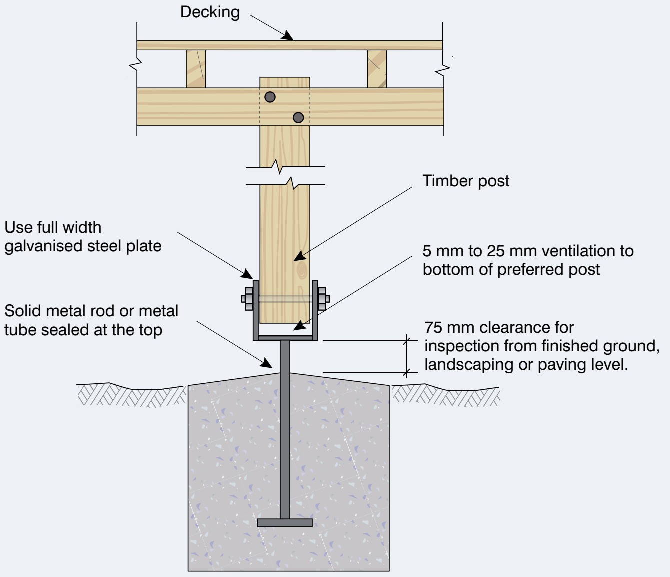

Figure 2: Metal stirrup supporting posts.

Alternative deck supports include metal posts or brick piers. Where they are used, a termite cap can be placed between the pier and the bearer. Refer to Figure 3 for metal posts and brick pier supports.

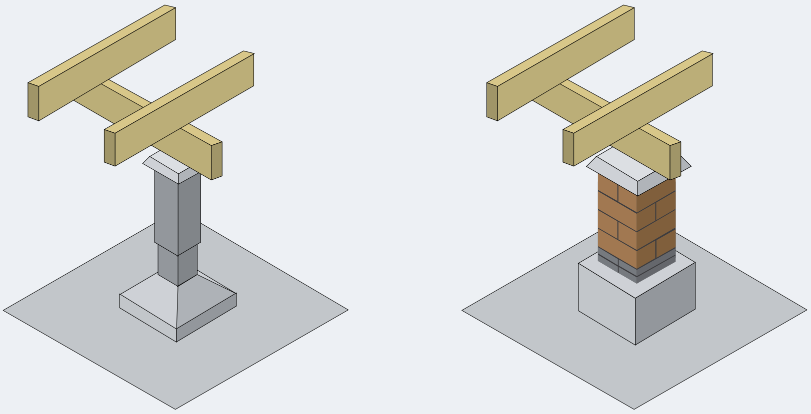

Figure 3: Metal and brick pier supports for timber decks.

Where engaged brick piers to the external wall are used to support bearers in addition to the termite cap, AS 3660.1 requires the bearer and joist of the deck to provide a gap of 25 mm between the wood surface and the building envelope (Figure 4). Again this is to ensure adequate termite inspection can take place.

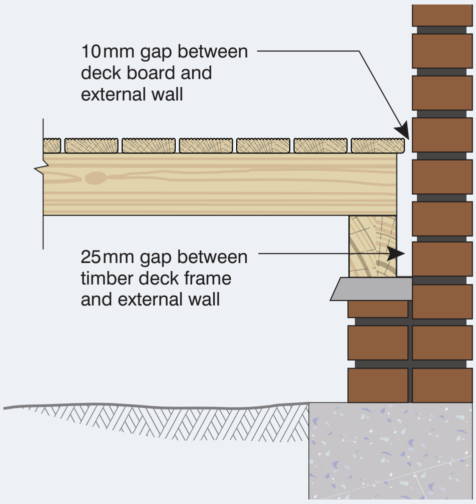

Figure 4: Illustration of a 25 mm gap between timber deck-frame work and brick external wall.

A good design technique is one that makes the inspection for termites easier, irrespective of what termite prevention method is employed to comply with the NCC. One method is having the decking boards that are parallel to the house envelop screwed instead of nailed, which allows easy and regular inspection without causing damage to the decking boards (Figure 5).

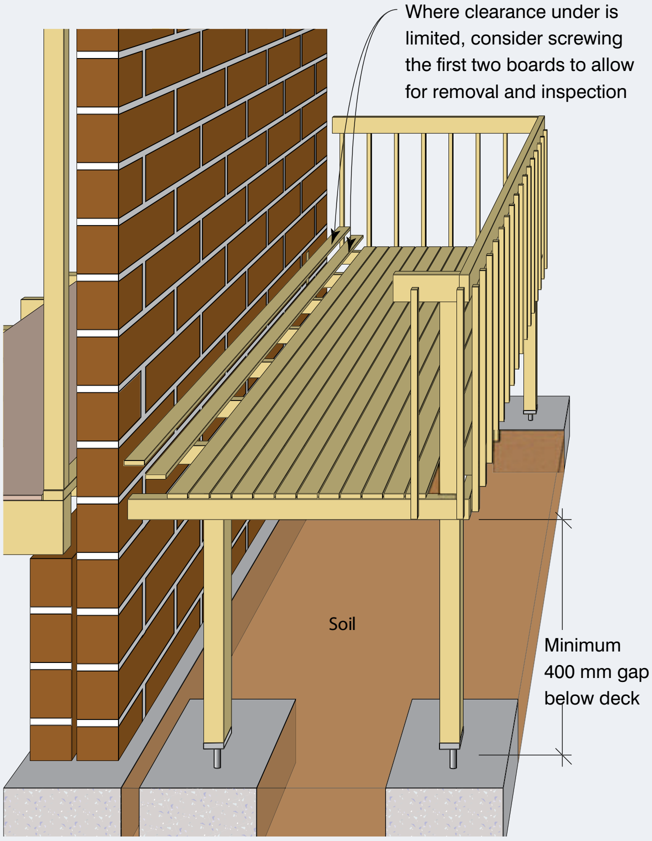

Figure 5: Strategy to improve inspections at the interface of a timber deck and the house envelope.

The* Termite Risk Management Handbook, *which details further strategies to minimise termite risks, is available from the WoodSolutions website.

1.3 Timber Framing

The following requirements for timber framing of a deck are based on the Australian Standard *AS 1684 Residential Timber-framed Construction.*

1.4 Bearers and Joists

Bearers and joists come in a variety of stress grades, timber types and sizes and their availability will vary from one region to the next. Before designing a deck, check availability with local suppliers of timber.

The available stress grades in unseasoned hardwood are usually F11 and F14, while seasoned hardwoods are available in F17 or F27 stress grades. Treated softwoods are predominately available in F7 stress grade; however, F5 and MGP10 are available in some regions.

For deck floors greater than 1,000 mm above the finished ground level, bearer sizes can be found in the span Table 49 in AS 1684. For deck floors less than or equal to 1,000 mm greater than the finished ground level, span Table 5 in AS 1684 can be used. Both these tables assume a minimum end bearing of 50 mm by bearer width, and intermediate bearing of 100 mm by bearer width for continuous bearers.

To avoid splitting when receiving nails or screws from the placement of decking boards, joists that are at least 45 mm wide (seasoned hardwood and treated softwood) or 50 mm wide (unseasoned hardwood) are recommended. This is particularly relevant where decking boards abut over the joist as the fixings can be placed further from the board’s end. For deck floors greater than 1,000 mm above the finished ground level, joist sizes can be found in span Table 50 in AS 1684. For deck floors less than or equal to 1,000 mm greater than the finished ground level, Table 6 in AS 1684 can be used. Joists of 35 mm or 38 mm wide are only suitable where proprietary deck fixings are fixed to the side of joists.

The recommended timber sizes for the bearers and joists are for when timber only decking boards are being used. Where the deck is to be tiled, or a spa or hot tub is built into a deck, the sizes in AS 1684 are not applicable. In these circumstances, advice should be sought from a structural engineer.

Engineered timber products used in exterior applications have a varying degree of performance and are dependent on the type of engineered wood product, level of exposure and projection methods employed. Individual manufacturers of engineered wood products should be consulted prior to considering the use of engineered wood products in deck construction.

Placing a layer of 110 mm malthoid dampcourse or proprietary protection strip on top of a joist will increase its service life (Figure 6).

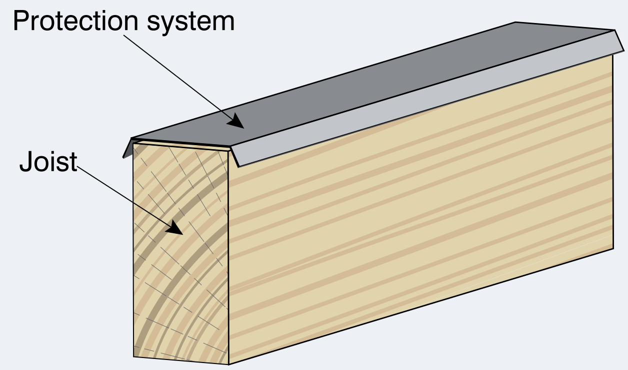

Figure 6: Protection strip over deck joists

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1.4.1 Structural Joints and Connections

The joints between posts, bearers and joists need to be able to transfer load efficiently through the structure – refer to AS 1684 for the design of these elements. Where possible, bearers and joists should be long lengths and continuous, spanning over at least three supports.

Where joints in bearers are required, they must occur over supports and provide an adequate bearing for each bearer. Joints in joists must be made over a bearer and have a minimum of 30 mm of bearing for each joist. Figure 7 illustrates methods to join joists, where they are required to be in line. Scarf or butt joints can be used with a minimum of 30 mm of bearing for each joist.

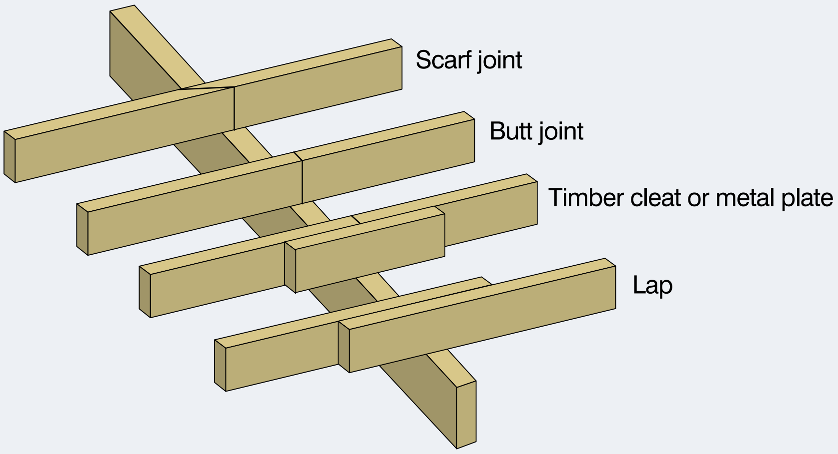


Figure 7: Joints in deck joists.

1.4.2 Connector and Fasteners Durability

All connections should be of sufficient durability. All framing bolts, screws, nails, and other hardware should be hot-dipped galvanised or stainless steel. Electroplated fasteners are not suitable due to early breakdown of the plating. Fixings within the splash zones (minimum 1.0 m from pool edge) of swimming pools or in coastal zones (within 1 km of the coast) must be stainless steel. Fixings for preservative-treated decking boards should be hot-dipped galvanised, stainless steel or with a coating approved for use with treated timber decking.

Refer to *WoodSolutions Design Guide #5: Timber Service Life Design – Design Guide for Durability* for further information on the estimated service life of connectors.

Due to moisture potentially being trapped at the interface of crossing timber members, e.g. bearer and post connections, a timber sealer should be used between the interfacing elements.

Timber washers need to be appropriately sized (Table 1).

Bolt	**Washer Size**		
	Thickness	**Round Washer Minimum diameter (mm)**	**Square Washer Minimum side length (mm)**
M8	2.0	36	36
M10	2.5	45	45
M12	3.0	55	55
M16	4.0	65	65
M20	5.0	75	75

Table 1: Timber washer selection guide coach screws or bolts. *Note: Source: AS1720.1*

1.5 Decking Boards

There are three main types of decking board profiles available: plain, pencil round and ribbed/reeded (Figure 8).

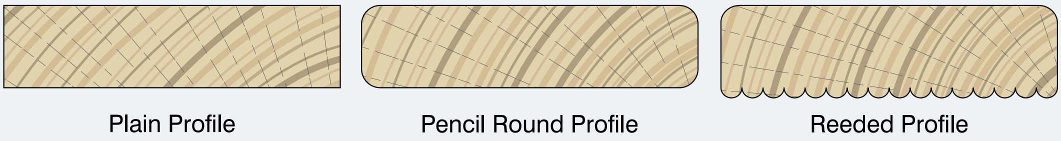


Figure 8: Decking board profiles.

Plain profile decking is not common as the square edges of the boards are more prone to splintering. Pencil Round has significantly less chance of splintering compared to plain boards and is the most common decking board available. Ribbed (or reeded) board profile can be used face up or down. Where ribbed boards are used face up, care should be taken in moist areas that the boards are kept free of mould and moss build-up that can make them slippery.

Decking boards are available in various widths. For 19 mm thick Australian species boards, the widths that are usually available are 64 mm and 86 mm. Imported hardwood decking species are generally available in 70 mm or 90 mm widths. Other widths are available, but consultation with suppliers regarding availability is required before specifying.

In all cases, it is recommended that boards with a narrow width are selected because it is easier for water to drain through the deck. Where wider boards are selected, they will need to be thicker to reduce the possibility of cupping developing.

Tongue and grooved timber, plywood or particleboard sheet flooring products are not recommended for use as decking in weather-exposed situations.

1.5.1 Decking Grades and Span Capacity

Decking boards have no stress grade requirements, unlike joists and bearers and other framing material, that is assigned a stress grade. Instead of this, decking boards have to meet an appearance grade, which are limits on knots, holes, gum pockets, splits, shakes, wane, and want. Hardwood, cypress and softwood have their own appearance grading standard and are listed in Table 2. Generally, a product that is described as Select will have fewer timber features than a product described as Medium Feature Grade or Standard. In all appearance grades, the decking board will have timber features included within.

The Australian Standard AS 1684 provides a relationship between the various thickness of the board, the appearance grade, and the maximum joist spacing (see Table 2).

Decking	Stress grade	Thickness (mm)	Maximum joist spacing (mm)
Hardwood	Medium Feature Grade or Standard Grade (AS 2796)	19	500
Cypress	Grade 1 (AS 1810)	19 21	400 450
Treated Softwood	Standard grade (AS 4785)	19 22	400 450

Table 2: Maximum joist spacing for various decking boards. *Source: AS 1684*

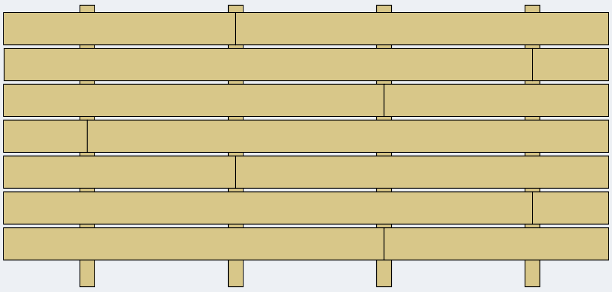


Figure 9: Illustration of staggered decking boards.

Deck boards can be laid in various directions to add style to the project; Figure 10 shows various decking patterns. Care is required to ensure that decking boards that are not perpendicular to the joists do not span further than the maximum joist spacing allowed (see Table 2). For example, 19 mm. Standard grade hardwood decking boards at 45 degrees to the joists will require the joist spaced at 350 mm to maintain the maximum allowable span of 500 mm.

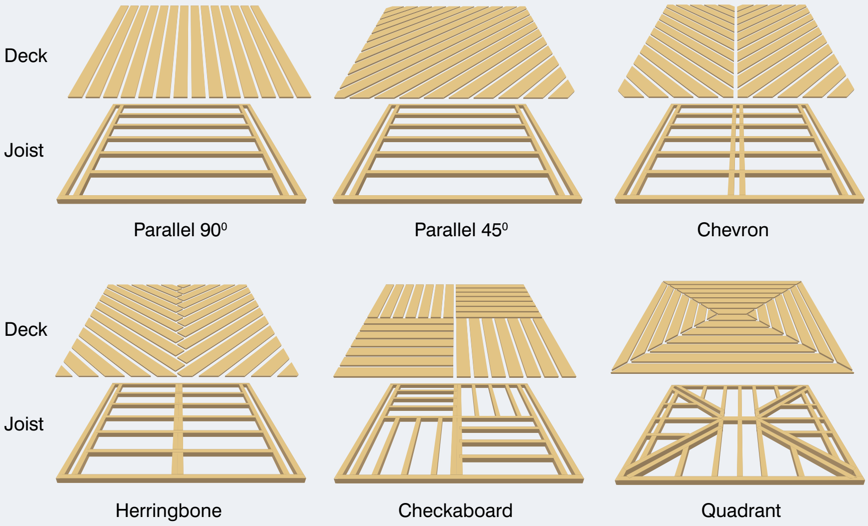


Figure 10: Decking board patterns.

Decking boards should also be kept 10 mm clear of the building wall to allow a drainage gap between the building wall and the boards (Figure 11).

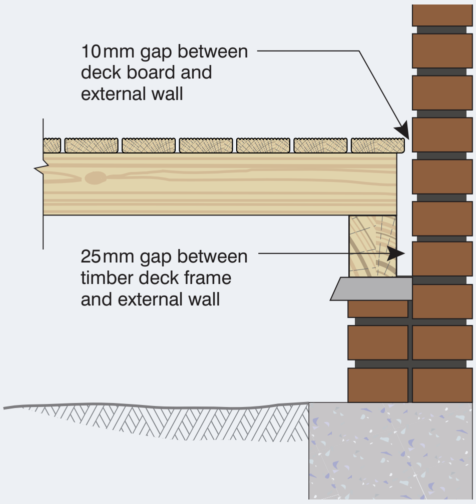


Figure 11: Decking board kept away from walls.

1.5.2 Nail Fixing

Each board must be fixed at each joist with at least two nails, which should be finished flush with the top of the boards (rather than punched) to prevent moisture being trapped. Where the fixing occurs, other than at the ends of the board, nails should be staggered across the joist to avoid the possibility of cracks caused by moisture movement in the decking (Figure 12).

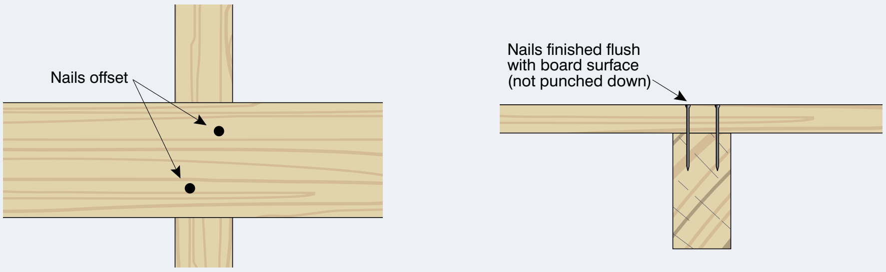


Figure 12: Illustration of nail fixing timber decking.

To obtain a tight fit at joints for abutting boards, a slight under-cut is recommended (Figure 13). To reduce the splitting of the decking board, nails or screws must be kept a minimum of 12 mm from edges and the board's end and holes predrilled. The drilled nail holes should be 80% of the nail diameter.

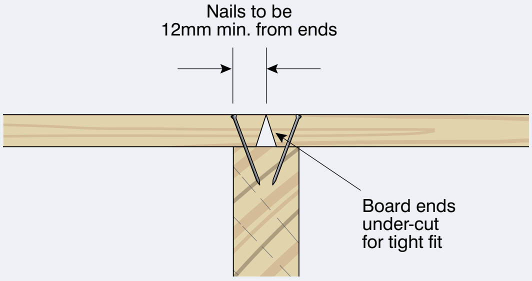


Figure 13: Nailing at board ends.

Table 3 describes the minimum hand-driven nails that can be used for decking up to 22 mm thick and the deck joists.

Decking	**Joists**	**Nailing - 2 nails per board crossing**			
		Machine driven		Hand driven	
		50 x 2.5 flat or dome-head		50 x 2.8 bullet-head	
Hardwood or cypress	Hardwood or cypress	50 x 2.5 flat or dome-head		50 x 2.8 bullet-head	
	Treated softwood	50 x 2.5 flat-head deformed shank	65 x 2.5 flat-head or dome-head	50 x 2.8 bullet-head deformed shank	65 x 2.8 bullet-head
Treated softwood	Hardwood or cypress	50 x 2.5 flat or dome-head		50 x 2.8 flat or dome-head	
	Treated softwood	50 x 2.5 flat-head deformed shank	65 x 2.5 flat-head	50 x 2.8 flat head deformed shank	65 x 2.8 flat-head

Table 3: Minimum hand-driven nail size for various timber species decking and joist combinations.

1.5.3 Machine-Driven Nails

Machine-driven nail properties usually vary between nailing gun manufacturers and are considered proprietary to the manufacture. Machine-driven nails can be used as long as the nail has the same capacity as the hand-driven nails detailed in Table 3. T-nails should not be used. Care is required when using machines to ensure the nail head is not driven below the surface of the board.

1.5.4 Screw Fixing

As is the case for machine-driven nails, screw requirements are not referenced in AS 1684. The principles described above for machine nails should be followed for screws. Types of screws are usually proprietary information and reference to the manufacturer's specification is required.

1.5.5 Fixings to Steel Joists

Screws normally used for fixing timber decks are not suitable for fixing timber decking to steel joists. This is due to the seasonal and differential expansion and contraction of timber decking against the steel substructure that may cause the screws to fail in shear. It is recommended that a timber batten is affixed above or beside the steel joist, so the decking board is nailed or screwed to this timber batten. The size of any timber batten must allow adequate fixing for the decking to batten as well as the batten to the steel joist.

1.5.6 Hidden Fixings

There are a number of proprietary systems available that fix the decking at the side of the board. Figure 14 shows one system. Most systems require a groove into the side of the decking for fixings while some use spikes. In all cases, the fixing systems are proprietary and manufacturers' recommendations must be followed.

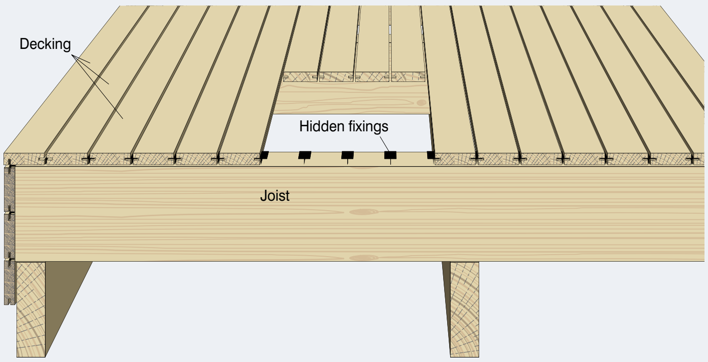


Figure 14: Hidden timber deck fixings.

1.6 Fixing Deck Structure to Existing or New Buildings

A common source of deck failure has been the fixing of decks to an existing or new building. It is recommended that the deck be self-supporting, i.e. on its own posts or piers, and not connected to the building's external wall or subfloor framing.

Where this is not possible, the NCC has specific requirements for fixing decking to existing or new buildings. These requirements are for a particular situation, and if it is not possible to meet the NCC requirements, the design should be carried out by a structural engineer.

Care is also required in the way decks interface with the building's exterior fabric, as water ingress into the house may develop at this crossing point. Flashing is one way to provide a barrier to prevent moisture from entering the house. Also, consideration is required to maintain the appropriate performance of other external wall function such as fire resistance, bushfire protection, external sound insulation and thermal insulation.

1.7 Timber Finishes

It is important that a suitable finish is applied and maintained to protect the surface of the timber from weathering and to maintain an attractive appearance. This protective finish of the timber surface will reduce the effects of weathering of any timber (treated or untreated) in an exposed situation. From a durability perspective, the main function of the finish is to slow down the rate at which the timber will take up or lose moisture. By slowing that rate down, the severity of any checking on the surface of the timber is considerably reduced. The finish should contain a fungicide to prevent mould from growing on any sugars or starches that may be in the finish.

There are two main types of timber finishes:

- ***Film-forming finishes,*** such as paints, clear surface coatings and heavy-bodied stains appear as a layer on the surface of the timber, visually creating a smooth surface and do not penetrate significantly into the surface of the timber.

- ***Penetrating finishes*** such as water repellents, decking oils and decking stains penetrate into the surface of the timber and do not form a significant surface film. Due to the wear expected with foot traffic, penetration finishes are better for decking boards than film-forming finishes.

Translucent coatings and stains are typically a combination of film-forming and penetrating coatings with added preservatives, fungicides and colourants. The degree of film formation and penetration varies with product and manufacturer.

As a minimum, a protective finish should be applied to all surfaces (including any freshly cut ends) of each decking board, preferably before fixing to the joists. A protective finish includes products that penetrate the surface of the timber and products that provide a film or coating to the surface of the timber.

Further information on timber finishes can be found in *WoodSolutions Design Guide #13: Finishing Timber Externally.*

1.7.1 Slip Resistance

Where there is a risk of the deck becoming slippery when wet, especially if it is not kept clean and brushed regularly, the slip resistance of the decking boards can be increased by the choice of finishes or the addition of slip-resistant strips.

Slip-resistant finishes can be achieved by adding a slip-resistant additive to the deck finishing product. Some coating manufactures have products with anti-slip particles already included, while others have particles that can be added to standard coating products. Refer to the coating product manufacture for more information.

The WoodSolutions website contains a list of timber species and, where available, the above-ground and in-ground natural durability ratings for each species according to Australian Standards are given.

1.8 Timber Durability

The recommended durability of the timber for deck sub-structure and decking boards is in Section B of this guide. In all cases, either a recommended natural durability class or preservative-treated timber hazard level is given.

1.8.1 Natural Durability Classes

There are two natural durability classes used in this guide: 'above-ground' (AG) and 'in-ground' (IG) and they refer to the heartwood of the timber only. The sapwood of all timber species is considered non-durable when exposed to the weather. A number of Australian Standards list the above-ground and in-ground natural durability class for various timbers and these Standards are:

- *AS 1684 Parts 2 and 3 Residential timber-framed construction*
- *AS 5604 Timber - Natural durability ratings*

More information on timber durability can be found in:

- Keith Bootle's *Wood in Australia*
- *WoodSolutions Technical Design Guide #5: Timber Service Life Design - Design Guide for Durability*

The natural durability class of many imported timbers can also be found in the Australian Standards referenced above.

Where there is no durability class given for a timber species, an indicator of performance can be found for a number of timber species from the paper; *Natural Durability of Wood: A Worldwide Checklist of Species*, Scheffer and Morrell, 1998. Note, the durability classes quoted in this publication, do not correspond with Australia's timber durability system.

Specifiers in Queensland must also refer to the *Construction Timber in Queensland* guide available from the Queensland Department of Agriculture Fishery and Forestry.

1.8.2 Preservative-Treated Timber Hazard Levels

Australian Standard *AS 1604 Timber – Preservative-treated – Sawn and round* defines the retention rates for various timber preservatives for different exposures and hazard levels.

Handrail or decking boards treated with the preservative Copper Chrome Arsenate (CCA) are not allowed to be used in areas where children could come into frequent or intimate contact with it. CCA-treated timber can be used in other locations of the deck, such as sub-floor framing, roof rafters, and so on. Timber treated with other preservatives such as ACQ (alkaline copper quaternary), copper azole or LOSP (light organic solvent preservatives) can be used as handrails and decking boards.

Timber treated with LOSPs is not suitable for in-ground use (H4 or H5 hazard level) and timber treated for additional resistance to termites (H2f, H2s and H2 hazard level) is not suitable for use in weather-exposed applications.

1.9 Handrails and Balustrades

If the deck is more than one metre off the ground, handrails or balustrades are required. The choice of appropriate handrails and balustrades will depend on the design and application and even location in relation to other structures. For example, balustrades for decks next to a swimming pool vary from balustrades required in the NCC for fall protection. Further information can be found in *WoodSolutions Technical Design Guide #8: Stairs, Balustrades and Handrails Class 1 Buildings – Construction.*

1.10 Maintenance and Wear

Timber is a natural product and, as deck timbers weather, small cracks (or checks) are likely to appear on the surface of the boards. These cracks are caused by the intermittent wetting and drying of the wood. They are part of the character of wood and have no structural effect. This natural ageing process can be slowed by the use of finishes, as discussed above, which reduce moisture movements in timber.

All decks will benefit from regular maintenance, otherwise, the decking boards will discolour, and the surface will become rough and prone to splinters. A poorly maintained deck is also susceptible to mould, which can make the surface slippery or reduce the service life of the decking boards.

The deck should be cleaned regularly. When cleaning the deck, avoid hosing it down; use a broom or a blower instead.

1.10.1 Pot Plants and Other Permanent Placed Items

Pot plants or other items that are not moved regularly should be elevated off the deck. Pot plants should be placed in drip trays. To minimise uneven weathering of the deck, all items should be moved regularly.

1.10.2 Resealing the Deck

At least once a year, or as indicated by the coating manufacturer, the deck should be thoroughly cleaned, and resealed or stained. The process involves the removal of dirt, algae, moss and other organic matter.

Clean the deck by hosing it down with an appropriate deck-cleaning solution. The deck should then be scrubbed and rinsed. During this process, check for loose boards and nails or screws that stick up and make any necessary repairs. Also, examine all areas where deck boards come into contact with any joists or any point that comes into contact with the ground. These areas are particularly susceptible to moisture damage.

Allow the deck to dry and reseal it with the sealer or stain originally applied. Where a different finish is used to the original finish, check with the manufacturer about using different types of sealers or stains, as mixing them may prevent adhesion of the new coating.

1.11 Tannin, Iron Stain and Resin Bleed

1.11.1 Tannin Bleed

Most hardwood timber species contain water-soluble extractives that provide colour and some natural decay resistance to the timber. Water-soluble extractives may be leached to the surface of the timber whenever moisture leaves the timber. Because the discolouration is water-soluble, it can be washed to other surfaces and may leave an unsightly stain that can be difficult to remove from brickwork, concrete or any paving underneath the deck that is not sealed. To lessen the likelihood of such extractives bleeding and staining, use seasoned timber and apply a water-repellent finish to all surfaces, including any freshly cut ends.

1.11.2 Iron Stain

Any iron filings that are not cleaned from the surface are likely to react with moisture and the timber extractives to create unsightly black staining on the timber. Avoid using any power tools on, near or above an uncovered deck that may deposit fine iron filings or dust on the timber surface. Particular care should be taken with cutting metal, masonry, brick or ceramics with an angle grinder. Cutting bricks or tiles with an angle grinder creates iron filings from the metal mesh that forms the base of the cutting disk. Storing or leaving metal on the deck for long periods of time may also cause tannin stain.

1.11.3 Resin Bleed

Some softwood timber species boards such as radiata and slash pine can be prone to resin bleed. Ideally, if a board shows obvious signs of resin bleed, it is preferable not to use that board or to cut out the affected area. If it has to be fixed in the deck, it should be fixed in a position where the resin bleed won’t be a problem. Sometimes it may not be obvious that a board is prone to resin bleed until after the finished deck has been exposed to a period of hot weather. In such circumstances, the resin can be cleaned up or the offending board replaced.

2

Specific Requirements

2.1 Raised Timber Decking

A raised timber deck is any timber deck where the decking boards are more than 400 mm above the finished ground (Figure 15). It is assumed there is appropriate drainage available for water and adequate cross-flow ventilation underneath the deck. Adequate cross-flow ventilation for decks is regarded as the same as the minimum requirement for raised timber floors in houses. For the minimum cross-ventilation requirements, refer to NCC, Volume 2, Part 3.4.1.

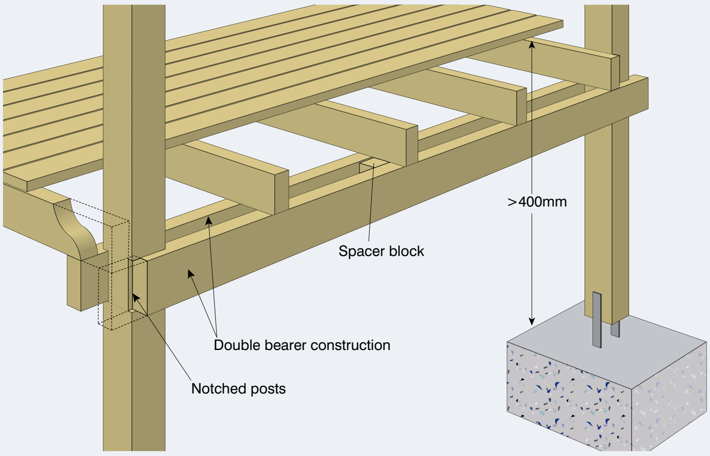


Figure 15: Raised timber deck.

2.1.1 Sub-Deck Supports

The sub-deck supports transfer horizontal and vertical loads into the ground, sometimes including uplift forces, particularly where decks are covered with a roof.

Footings
Footings for supporting posts are usually designed in two ways. The most common method is concrete footings with galvanised stirrups embedded or fixed in the footings to support the posts (Figure 16).

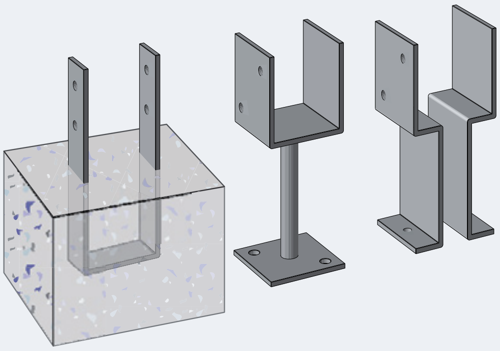


Figure 16: Proprietary metal stirrups.

An alternative method is to support the deck post by embedding the post directly into the concrete footing. When this method is used, use no-fines concrete, have adequate concrete under the post and slope the top of concrete footing away from the post (Figure 17).

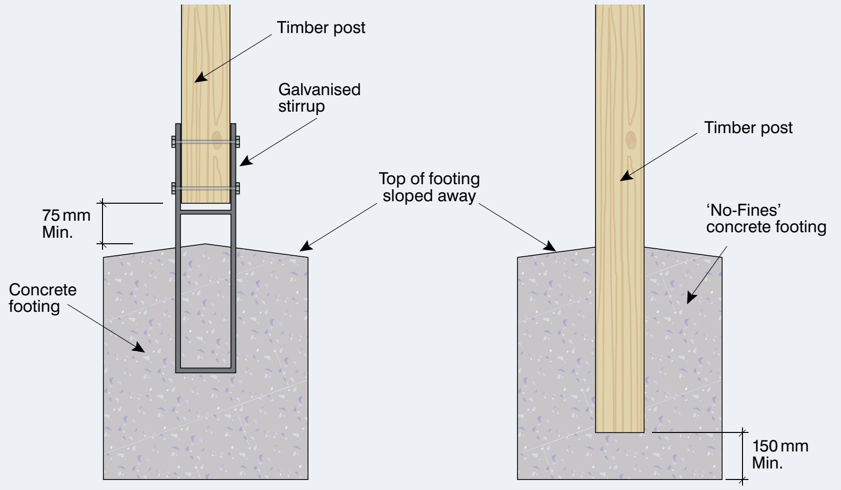


Figure 17: Post embedded into concrete footing.

The design of footings is outlined in AS 2870 or AS 1684. Usually, the soil classification and expected loads on the deck are required to be known. Decks designed to AS 2870 and AS 1684 are for decks used for housing with average loads and ground conditions. If these conditions are not met (e.g. the deck needs to support a spa or the deck is to be tiled), the design needs to be considered by a structural engineer.

2.1.2 Deck Framing and Decking Boards

Timber selection

Unless the deck is entirely protected by a roof, the timber framing and boards will be exposed to the weather, so it is essential that the selected timber can provide a good service life in those conditions.

Timbers used above the ground (framing, boards and posts on stirrups) should be hardwoods rated above-ground natural durability Class 1 or 2 (plus sapwood removed or H3 treated) or if softwood is used, preservative-treated to at least H3 hazard level. Softwood timber that is treated to H2, H2F or H2S hazard level is not suitable for use in the construction of decks. Timber embedded in the ground (embedded posts) should be in-ground natural durability Class 1 or be preservative treated to H5 hazard level. Refer to Appendix A for a list of common timbers and their above-ground and in-ground natural durability ratings. Durability ratings only refer to the heartwood of the timber. Sapwood is not durable when exposed to the weather.

A wide variety of engineered wood products are now available on the market, such as glue-laminated timber, finger-jointed timber and LVL products. If these products are being considered, direct reference to specific manufacturer recommendations is required. In most cases, there are additional requirements or limits when these products are used in applications such as decks where they are exposed to the weather. Timber I-beams (treated or untreated) are not suitable for use in the construction of decks.

Posts

As described previously, posts are usually connected to concrete footings via a stirrup. They are generally preservative-treated softwood (H3 hazard level) or natural above-ground durability Class 1 or 2 timber species.

The span tables within AS 1684 have the required timber sizes for posts. These are dependent on the deck area, roof area (if any), post height and stress grade of the timber selected. Common cross-sectional sizes for posts vary, but usually start at 88 mm and upwards. Minimum sizes for posts are also governed by the distance between the ground and the underside of the bearers. The maximum height of a deck above the ground for a given post dimension is 15 times the face width of the post.

Deck posts need to be braced and AS 1684 has various bracing methods. These methods are either cross-bracing between posts (Figure 18) or as a cantilever timber stump (Figure 19).

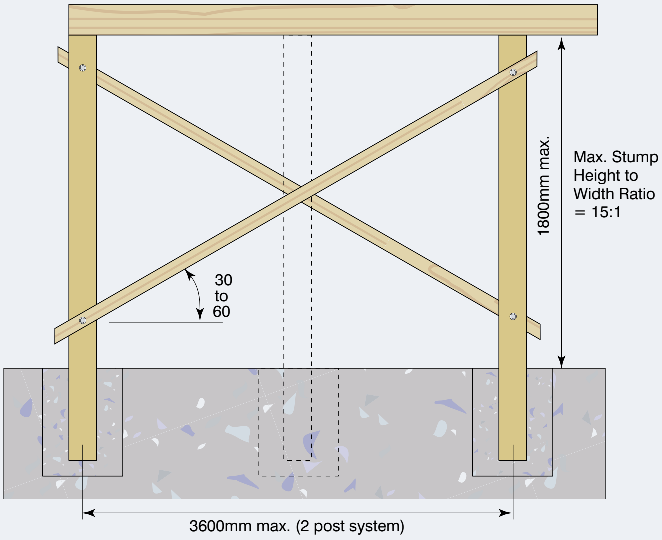


Figure 18: Braced timber posts.

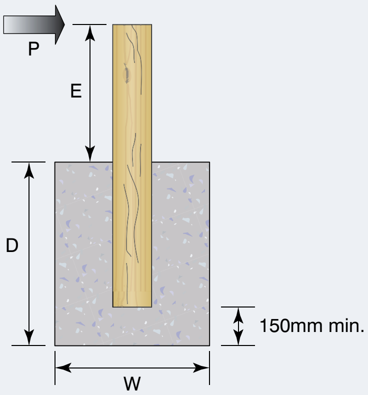


Figure 19: Cantilever timber stump.

Deck board spacing

The purpose of spacing decking boards is to allow seasonal movement of the timber, so a gap is maintained to allow water to drain freely. The gap must not be so far apart that it forms a trip hazard. The size of the gap between the boards depends on:

- whether it is a hardwood or softwood timber species
- the decking board cover width
- the moisture content of the timber during the installation process, i.e. unseasoned decking board requires less of a gap than seasoned decking boards.

A gap of 3 mm to 4 mm is ideal over the long term. Table 4 shows the recommended spacing at the time of decking board installation.

	Decking cover width (mm)	**Seasoned or unseasoned**	**Recommended decking gap**
Hardwood	86 to 90	Seasoned	3 - 4 mm
	91 to 140	Seasoned	4 - 5 mm
	86 to 90	Unseasoned	2 - 3 mm
	91 to 140	Unseasoned	2 – 3 mm
Softwood	70 to 90	Seasoned	3 - 4 mm
	91 to 120	Seasoned	4 - 5 mm

Table 4: Recommended decking gaps at installation.

2.1.3 Attachments of Decks To External Walls

The Building Code of Australian has a new Deemed-to-Satisfy requirement for attaching decks to external walls of buildings. The scope of decks that are required to comply with this DTS is

- The deck is not located in Alpine regions.
- The top of the decking boards are not more than 3.0 m above the top of the footings.
- The deck is not cantilevered from the external wall.
- Imposed loads (live loads) do not exceed 2 kPa.
- The plate used to attach the deck to the external wall (waling plate) supports only one deck, not support the external or other wall type or any roof loads and the joist be perpendicular to the wall and be a maximum span of 3.0 m.
- The external wall is made from timber framing complying with AS 1684 and be continuous from the decking board surface to footings, and with no openings or lintels below the deck. For non-timber systems refer to the BCA Volume 2 Provision 3.10.6.2.
- The decking is to be braced against longitudinal movement.

Decks that don't meet the above requirements, the deck can be built on a separate structure or be design by a structural engineer.

Fixing of the deck to the external wall

The waling plate is to be at least 190 x 45 mm or greater and be of stress grade MGP10 or F5 or higher.

The waling plate is to be fixed to the external wall with fixings placed at a maximum of 300 mm centres. Fixings can be M12 coach screws or 4.6/S M12 bolts with a 3 mm thick and 55 mm diameter washer. The coach screw is to have the screw part of the coach screw embed into the subfloor framing or external wall of the building for at least 96 mm (see Figure 20).

Fixings are to be hot-dipped galvanised or stainless steel if the building is located with 200 m of breaking surf. Fixings into the waling plate or other subfloor timber framing must not be located within 120 mm of the end or 60 mm from the top and bottom edge.

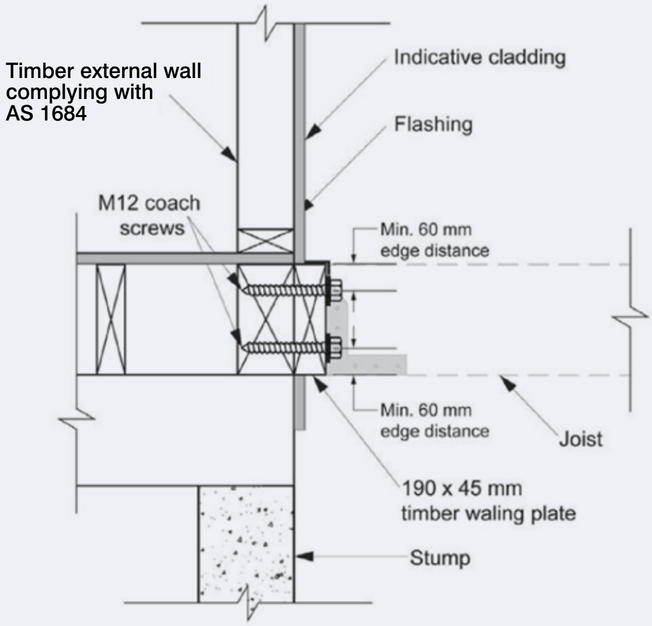


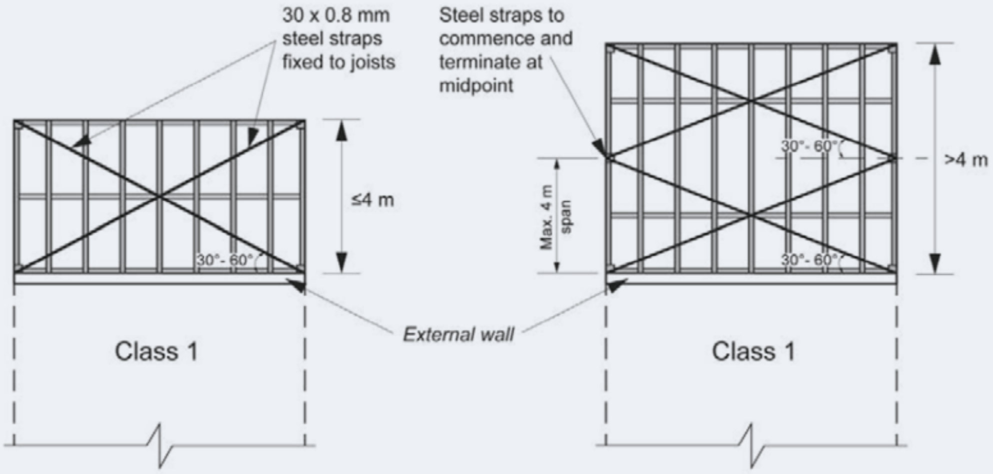
Figure 20: Fixing of waling plate to an external wall.

Where cladding is removed from the external wall, flashing must be provided in accordance with the BCA provision 3.10.6.3. Also, consideration is required to maintain the appropriate performance of other external wall function such as fire resistance, bushfire protection, external sound insulation and thermal insulation.

Deck bracing

Where the decking surface is 1 m or more off the ground, the decking structure is to be braced. Bracing consist of a 30 x 0.8 mm thick steel strap, placed diagonally at an angle between 30 and 60 degrees to the waling plate. The steel strap is to be continuous and not span more than 4.0 m measured at right angles from the external wall (see Figure 21). The steel strap is to be installed either to the top side or the underside of the decking joists.

Fixings for the steel strap must be 50 x 3.15 hot-dipped galvanised flat head ring shank, or flat head deformed nails, fixed at every joist the steel strap crosses.



a) Decks or balconies extending up to 4 m from the external wall

b) Decks or balconies extending more than 4 m from the external wall

Figure 21: Bracing to deck's framing.

2.2 Decks Close to or On-Ground

When decking is less than 400 mm off the ground, additional consideration to ensure adequate performance and service life of the timber is required (Figure 22). This includes increased ventilation, sub-surface drainage, increased timber durability/preservative treatment and access for termite inspection and maintenance.

Where any of the conditions described in the guide cannot be met, performance may be affected and the service life of the deck will be reduced.

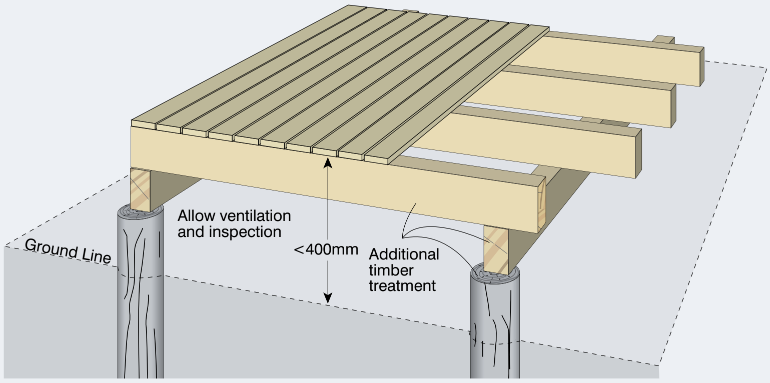


Figure 22: Timber deck close to the ground.

2.2.1 Sub-Deck Area Preparation

It is important that the ground beneath the deck is completely cleared of all building rubbish, garden debris and obstructions to water or air movement. Water must not be able to pool under the deck and the ground must be sloped away from the foundations of the house or other nearby buildings. Agricultural drainage pipes may be required in some instances so water can properly flow away from beneath the deck.

Plastic sheeting acting as a waterproof membrane should be placed on the cleared ground. If timber bearers are to be placed directly on the ground, the plastic sheet should be covered with compacted gravel or sand to provide a solid base.

2.2.2 Footings

There are two main ways these can be arranged:

- Concrete beams, with joists sitting on top, with no need for bearers (Figure 21).
- Bearers placed straight on to the ground or soil (Figure 23).

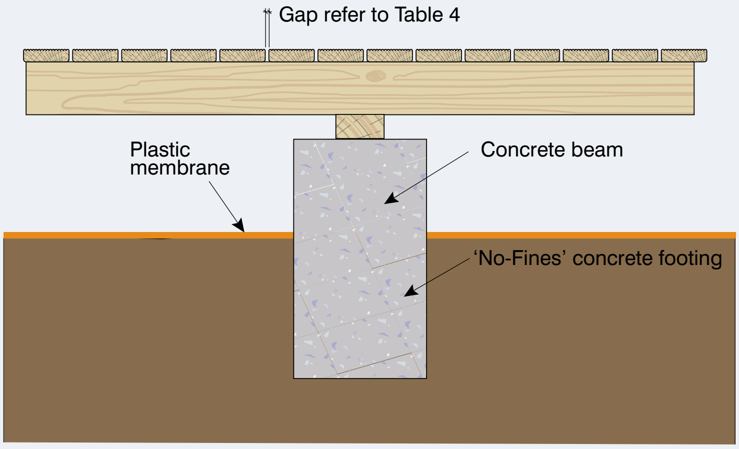


Figure 23: Concrete beam footing.

Concrete foundations and bearers should be placed so they don't restrict the flow or drainage of water. The perimeter of the deck should be kept open to allow for ventilation. Preferably, a decking system should be designed so it is panelised. The panels need to be sized so that they can be easily lifted to allow for easy maintenance and inspection.

2.2.3 Termite Inspection

Only termite-resistant timber should be used (see the section above) and there should be a gap between the house and deck of at least 40 mm to allow for pest inspection and air flow (see Figure 24).

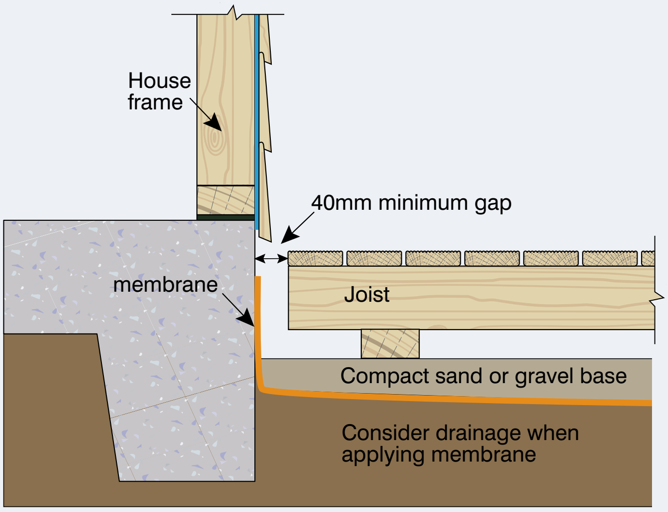


Figure 24: Bearer directly on to ground.

2.2.4 Deck Framing and Decking Boards

Timber selection

Timbers used close to or on the ground require additional durability as well as termite resistance. Framing timbers more than 150 mm above the ground should be termite resistant and above-ground durability Class 1 or 2 (plus sapwood removed or H3 treated) or softwood preservative treated to at least H3 hazard level. Framing timbers on the ground or lower than 150 mm should be termite resistant and in-ground durability Class 1 (plus sapwood removed or H4 treated) or preservative treated to H4 or better. Durability ratings refer to the heartwood only of the timber.

Decking boards should be termite resistant above-ground natural durability Class 1 or 2 (plus sapwood removed or H3 treated) or preservative treated to H3 or better. To reduce the likelihood of excessive movement and allow for more ventilation, the minimum width board should be selected.

Decking board spacing

The decking should be the minimum width available and have a minimum spacing between boards (long term) of 5 to 6 mm to allow water to flow between the boards and ensure adequate ventilation.

3

References

Australian Building Codes Board, National Construction Code Series, Volume Two

Australian Standards
AS 1604.1 Specification for preservative treatments, Part 1: Sawn and round timber
AS 1684.2 Residential timber-framed construction, Part 2: Non-cyclonic Areas
AS 1684.3 Residential timber-framed construction, Part 3: Cyclonic Areas
AS 2870 Residential slabs and footings
AS 1810 Timber - Seasoned cypress pine - Milled products
AS 2796.1 Timber - Hardwood - Sawn and milled products - Product specification
AS 2796.2 Timber - Hardwood - Sawn and milled products - Grade Description
AS 2870 Residential slabs and footings standard
AS 4785.1 Timber - Softwood - Sawn and milled products - Product specification
AS 5604 Timber - Natural durability ratings

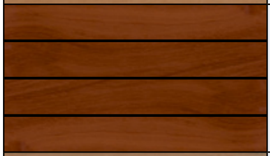
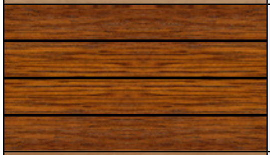
Queensland Department of Agriculture Fishery and Forestry,
Construction Timber in Queensland

WoodSolutions Technical Design Guides:
#04 Building with Timber in Bushfire-prone Areas - BCA Compliant Design and Construction Guide
#05 Timber Service Life Design - Design Guide for Durability
#08 Stairs, Balustrades and Handrails - Class 1 Buildings - Construction
#13 Finishing Timber Externally

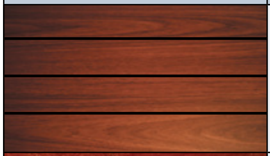
Bootle, Wood in Australia, Second Edition

Scheffer and Morrell, Natural Durability of Wood: A Worldwide Checklist of Species

Appendix A - Common Decking Board Timber Species

	Species	Common size	In-Ground Durability Rating	Above-Ground Durability Rating	Termite Resistant	Bushfire Resistance
	Blackbutt	64 × 19 86 × 19	2	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Red Ironbark	64 × 19 86 × 19	1	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Grey Ironbark	64 × 19 86 × 19	1	1	Yes	Density greater than 750 kg/m3 **BAL 12.5 and 19**
	Spotted Gum	64 × 19 86 × 19 136 × 32	2	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Merbau / Kwila	70 × 19 90 × 19 140 × 25	3	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Northern Box / Pelawan	90 × 19 140 × 25		1	Yes	Density greater than 750 kg/m3 **BAL 12.5 and 19**
	Jarrah*	65 × 19 88 × 19	2	2	Yes	Density greater than 750 kg/m3 **BAL 12.5 and 19**
	Tallowwood	64 × 19 86 × 19	1	1	Yes	Density greater than 750 kg/m3 **BAL 12.5 and 19**
	Turpentine	64 × 19 86 × 19	2	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Treated Pine	70 × 19 90 × 19 120 × 25	H3	H3	Yes	No

*Jarrah can be used in a BAL 29 situation under some circumstances. Refer to WoodSolutions website for more information.

	Species	Common size	In-Ground Durability Rating	Above-Ground Durability Rating	Termite Resistant	Bushfire Resistance
	Red Mahogany	64 × 19 86 × 19	2	1	Yes	Density greater than 750 kg/m3 **BAL 12.5 and 19**
	River Red Gum	64 × 19 86 × 19	2	1	Yes	Bushfire Resisting Timber **BAL12.5, 19 and 29**
	Cypress	90 x 20	2	1	Yes	No

B

Appendix B - Common Deck Problems

Common problems to avoid when designing or building a deck:

1. Deck framing not designed to stand alone or is inadequately connected to the house.
2. Fasteners incorrectly sized or not of sufficient durability.
3. Timber species not sufficiently durable or the right preservative treated hazard class for the intended exposure to weather.
4. Sub-floor frame not adequately braced.
5. AS 1684 timber spans and sizes used when the deck is tiled or includes a hot tub or spa.
6. Deck does not contain adequate termite inspection points.
7. In bushfire-prone areas, bushfire resistant construction methods or timbers are not used.
8. Timbers not all sealed, including cut joints in timber.
9. Stair goings and risers not sized correctly according to NCC requirements.
10. Handrails on stairs and ramps not continuous.

Additionally, if a deck is built close to or on the ground, common problems include:

1. Inadequate or impeded drainage.
2. Inadequate subfloor ventilation.
3. Insufficient easy access termite inspection points next to the house.
4. Timber species not of sufficiently durability or preservative treated hazard class for the closeness to the ground.
5. Inadequate deck board spacing.

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4 Building with timber in bushfire-prone areas
5 Timber service life design - design guide for durability
6 Timber-framed Construction - sacrificial timber construction joint
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24 Thermal Performance for Timber-framed Residential Construction
25 Rethinking Construction - Consider Timber
26 Rethinking Office Construction - Consider Timber
27 Rethinking Apartment Building Construction - Consider Timber
28 Rethinking Aged Care Construction - Consider Timber
29 Rethinking Industrial Shed Construction - Consider Timber
30 Timber Concrete Composite Floors
31 Timber Cassette Floors
32 EXPAN Long Span Roofs - LVL Portal Frames and Trusses
33 EXPAN Quick Connect Moment Connection
34 EXPAN Timber Rivet Connection
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37C Mid-rise Timber Buildings, Commercial and Education Class 5, 6, 7, 8 and 9b (including Class 4 parts)
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Guide 23: Using thermal mass in timber-framed buildings in Australia: Effective use of thermal mass for increased comfort and energy efficiency by Ben Slee and Dr Richard Hyde, University of Sydney.

Guide 24: Thermal performance for timber-framed residential construction: Building comfortable and energy-efficient timber houses, by Dr Mark Dewsbury and Associate Professor Gregory Nolan, University of Tasmania.

Compiled by Scott Willey as a guide to the above publications.

Author: Scott Willey

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Introduction

If thermal mass is used correctly within housing it can moderate daily temperature fluctuations, leading to more comfortable interiors, and reduce the energy used for artificial heating or cooling. If thermal mass is used incorrectly, the opposite occurs.

This Guide gives a simple step-by-step overview of housing design for greater thermal comfort.

The design considerations listed are covered in greater detail in two FWPA publications which focus specifically on the thermal performance of timber framed houses:

Guide 23: Using thermal mass in timber-framed buildings (see page 10)

Guide 24: Thermal performance for timber-framed residential construction (see page 11)

References to these and other useful resources are listed at the base of each design consideration.

It is worth remembering that a house built today might still be providing shelter and comfort in more than 60 years time. Thoughtful design and construction offer benefits over the life of a house:

- The earlier in the design phase decisions are made to improve comfort, the more cost effective they can be.
- Exceeding minimum ‘star’ ratings offers greater comfort for residents.
- Greater comfort means less energy is needed for heating and cooling.
- Careful detailing can avoid maintenance problems with moisture build-up.

Refer to Technical Design Guides under the Resources section of the WoodSolutions website (www.woodsolutions.com.au) for the above publications..

Timber and thermal comfort in housing

Most existing houses in Australia are timber-framed and new homes continue this tradition. Many modern homes perceived to be 'brick' houses are actually timber-framed houses with bricks used only as a cladding.

Modern construction methods mean an increasing number of low-rise apartment buildings, traditionally constructed out of masonry for fire-resistance, are now being built with timber frames as well.

Designing for timber thermally

As construction technology has developed standards of fire-resistance, acoustic separation and thermal comfort in timber buildings have improved. This guide provides design and construction knowledge on how to achieve superior thermal comfort and better thermal performance which delivers:

- more comfort for residents
- less energy use for heating and cooling
- less greenhouse gas emissions

Decreasing emissions - increasing comfort

Timber-framed houses tend to be more responsive to heating and cooling than buildings with higher thermal mass. Keeping occupants comfortable is achieved by moderating internal temperatures to avoid extremes. Comfort and energy efficiency can be maximised by a focus on avoiding unwanted heat loss or gain through the building envelope. This Guide gives solutions for achieving this with:

- fewer greenhouse gas emissions
- well insulated building envelope
- avoiding air infiltration

High performing social housing
Hopkins Street Affordable Housing Project is a multi-residential timber framed building with a 7.3-8.1 Star Rating (Source: Xsquared Architects, Photographer: Ray Joyce)

House design and orientation

1 Designing for Residents' Needs

Successful house design works best when it is tailored for its residents, which is why thermal comfort is important.

When a home is designed to pair comfort to occupant's lifestyles they will want to use less heating and cooling and thus use less energy.

For example, a house designed for retired residents might have a greater focus on daytime living. A younger working family's house design is more likely to focus on comfort in the evening.

If the future residents are not known then design should focus on the needs of the most likely residents.

More information:

- *Your Home: www.yourhome.gov.au/you-begin/preliminary-research*

2 Designing for Climate

To increase both comfort and energy efficiency, a house design should work with the local climate rather than against it.

Seasonal temperature and humidity variations are strong drivers of climate-responsive design.

Daily temperature variation also need to be considered. For example, hot, dry climates often have nights that are significantly cooler than days. Houses can respond by closing down during the heat of the day and opening up in the cool at night.

Alternatively, responsive design in a hot, humid climate opens in the day to take advantage of cooling breezes.

Refer to the National Construction Code for the specific climate zone for your project.

More information:

- *Guide 23: Section 6, Thermal Mass in Australian Climates*
- *Guide 24: Section 3.2, Designing for Climate, 3.4 Considerations for Specific Climates*
- *Your Home: www.yourhome.gov.au/passive-design/design-climate*
- *Bureau of Meteorology: www.bom.gov.au/climate*

3 Orientation - Working with the Sun

For most Australian climates, houses should orientate to the north to maximise daylight, especially in winter.

In cooler climates, capturing the warmth of the winter sun is a priority.

In hot climates, orienting toward cooling breezes and avoiding the sun all year round can determine the best orientation.

It may be that the cooling breezes in warmer months come from a different direction to winter sun.

Views, privacy, road noise and bushfire risk are just some of the other considerations that need to be considered when deciding which direction to face a house and how open it should be.

More information:

- *Guide 24: Section 3.3, Designing for Sun, Section 4.1 Planning and Site Selection*
- *Your Home: www.yourhome.gov.au/passive-design/orientation*

Planning and form

4 Room Zoning

Beyond the other functional needs in planning a house, dividing rooms by occupation type can determine their orientation priority.

Morning sun can be welcome in eastern bedrooms, particularly in colder climates. Northern living areas allow residents to take advantage of the best daylight and the sun's warmth in winter.

Non-occupied spaces such as garages or utility rooms can be placed to the west to block undesirable afternoon summer sun.

Zoning rooms together with similar heating and cooling requirements aids efficiency.

Adding doors to halls and between living areas can prevent unwanted loss of heated or cooled air.

More information:

- *Guide 24: Section 3.3, Designing for Sun*
- *Guide 24: Section 4, Planning Strategies*
- *Your Home: www.yourhome.gov.au/passive-design/orientation*

5 Controlling Surface Area with Form

As the floors, external walls and roof all form part of the building envelope, these surfaces form the primary line of control for heat entering and leaving a building.

The greater the surface area – the greater the potential heat transfer.

Some climates warrant elongated, more lineal floor plans designed to catch warming sun or cooling breezes.

Compact house forms minimise the area of the exposed envelope to external temperatures, and are more appropriate for extreme climates.

More information:

- *Guide 24: Section 4.2, Site Master Planning*
- *Guide 24: Section 5, Envelope Strategies*

Controlling heat gain & loss

6 Capturing the Sun - Glazing Design

Glazed windows and doors allow access to views and natural light and, if openable, allow ventilation as well. Windows become 'thermal holes' in the envelope and their design needs careful consideration.

Direct sun admitted to a building can quickly cause overheating. The area of glazing requires careful consideration of the amount of solar warmth required for a particular orientation.

In most climates, western facing windows admit too much heat in summer, and should be limited.

The poor insulative property of glass leads to high heat loss in cooler weather. In cooler climates, minimise southern glazing, as it loses winter warmth while never gaining warming sun.

More information:

- *Guide 23: Section 4.2.5 Window Size*
- *Guide 24: Section 5.6, Windows*
- *Your Home: www.yourhome.gov.au/ passive-design/passive-solar-heating, yourhome.gov.au/passive-design/glazing*

7 Capturing breezes - Ventilation

Any house needs constant ventilation to exhaust odours and provide fresh air for occupants, though the amount needed for this is small.

When ventilating for cooling, it is important that cross ventilation be well designed to maximise airflow, even in calm conditions. Narrow floor plans allow for greater cross ventilation.

In cooler weather, unwanted air movement equals unwanted loss of heat. In summer, the reverse is true for air-conditioned spaces.

Well-designed ventilation should consider wet weather, flying insects, wind gusts, etc. If security is not considered in window design, residents are less likely to be able to leave windows open when needed, including overnight.

More information:

- *Guide 23: Section 4.2.4, Controlled Ventilation*
- *Guide 24: Section 4.2.7, Natural Ventilation*
- *Your Home: www.yourhome.gov.au/ passive-design/passive-cooling*

8 Controlling Solar Gain with Shading

The sun's heat can be as much as that from a 1000 watt single-bar electric heater on every square metre of the building it contacts. Roof overhangs limit the amount of heat reaching external walls. The hotter the climate, the more important this is.

As winter sun comes at a lower altitude to summer sun, well-designed roof overhangs and awnings can allow winter sun while providing shade in the warmer months. Fortunately, in the higher latitudes where winter sun is more important, this effect is more pronounced. Verandahs, pergolas, trellises and external blinds can all be used to control sun while also adding visual interest.

More information:

- *Guide 24: Section 5.7, Eaves and external shading*
- *Your Home: www.yourhome.gov.au/ passive-design/shading*

- Your Home: Orientation: www.yourhome.gov.au/passive-design/orientation

Penetration design

9 Controlling Heat Conduction with Insulation

As the building envelope is the line at which heat is lost or gained in a building, the ability to control heat movement through it is critical.

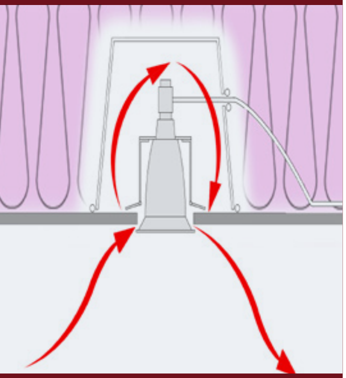
Insulation is valued for its ability to resist heat flow, and thus a higher 'R' value indicates greater insulative ability. Insulation products work to slow heat conduction, and reflect radiant heat.

Insulating roofs, ceilings, walls and under floors has become common practice. It is important however, that the insulation provided is detailed and installed correctly to maximise its value. Beware thermal short-circuiting known as 'thermal bridging'.

Double glazed windows with 'thermally broken' frames prevent heat loss in cold climates, and heat gain for air-conditioned buildings in hot climates.

More information:

- *Guide 24: Section 5.4, Thermal Insulation*
- *Your Home: www.yourhome.gov.au/passive-design/sealing-your-home*



10 Controlling Air Leakage

Uncontrolled air movement brings unwanted heat movement. Creating more airtight construction will give greater comfort and greater energy efficiency – leaving ventilation control to the operation of windows and doors by occupants.

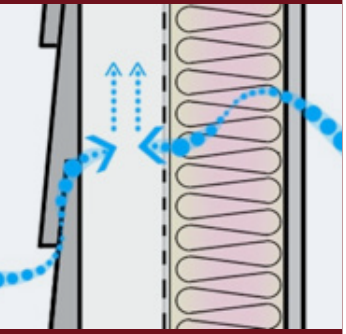
Using sarking in roofs and quality building wrapping over walls inhibits the flow of air through the building fabric.

It is important the building wrap is continuous and that wrap joints and penetrations are well lapped and sealed with tape.

The underside of raised timber floors can also be wrapped, although it is important to ensure timber members are able to breathe, and no moisture is trapped.

More information:

- *Guide 24: Section 5.3, Air-tightness*
- *Your Home: www.yourhome.gov.au/passive-design/shading*



11 Avoiding Moisture Build-up

Air inside and outside buildings contains moisture. Condensation occurs when moist air hits cool surfaces.

In cool weather, when air passing outward from the building interior contacts the back of the external cladding, condensation can form within the building fabric.

Similarly, condensation can form when outside air contacts the back of the internal cladding of an air-conditioned building.

To avoid deterioration of building materials and potential health problems, houses should be detailed and wrapped well to avoid moisture vapour movement through the building envelope. Construction should also allow for any trapped condensation to evaporate.

More information:

- *Guide 24: Section 5.1, Structural moisture control*

Adjusting mass and testing

12 Moderating Temperatures with Thermal Mass

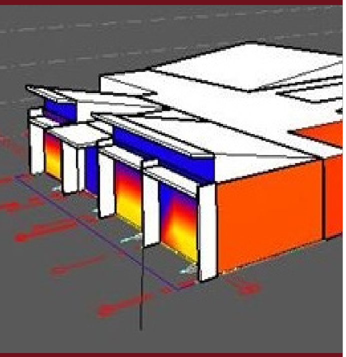
Solid and heavy materials often have an ability to store and release heat. This ability can be utilised to even out daily temperature extremes. This ability is commonly known as 'thermal mass'.

Utilising well-designed thermal mass can provide more comfortable interiors. However, if not designed well, too much mass can create interiors that are hard to keep comfortable.

For any climate there is a point at which adding thermal mass provides little or no benefit. The location of the mass within a room is also important. As heat rises, mass in ceilings can be used to absorb heat for optimal cooling and when used for heating, solar-heated mass in the floor is best.

More information:

- *Guide 23: Section 4, Placing Thermal Mass*
- *Guide 24: Section 5.8, Thermal Mass and Thermal Capacity*
- *Your Home: www.yourhome.gov.au/ passive-design/thermal-mass*



13 Testing the Design

Computer modelling thermal performance allows building designers to test which design changes will be the most effective for enhancing thermal comfort. Allowing for additional experimentation with the building design and testing before the design is locked-in will produce the most effective results.

An optimal design will save money on construction and energy usage.

More information:

- *Guide 24: Section 2.3 Thermal simulation*
- *Nathers: www.nathers.gov.au/accredited-software/how-nathers-software-works/star-ratingscale*

14 Informed Occupants

Like anyone buying a new appliance, new home owners appreciate understanding what they have bought, and how it is designed to operate.

Good passive design and a high energy star rating on a house can be unwittingly over-ridden by a 'one-star occupant'.

Many home owners will presume they will need air-conditioning or ducted heating systems, based on their previous living experiences. As thermal performance standards increase, it can be valuable for future occupants to be made aware of the performance they can expect from their new home, before they commit to heating and cooling systems that are oversized, or not needed at all.

More information:

- *www.yourhome.gov.au/passive-design*

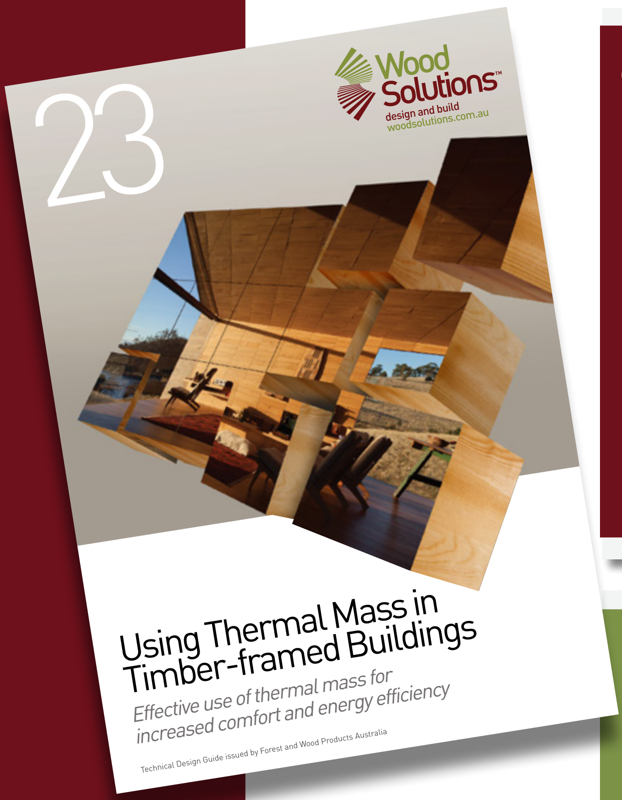
Guide 23 - Using Thermal Mass in Timber-framed Buildings

Effective use of thermal mass for increased comfort and energy efficiency

Traditional cultures have long understood the value of thermal mass in buildings for moderating internal temperatures. However if used in the wrong proportions, too much thermal mass can actually decrease comfort.

Modern Australian homes tend to use the same lighter-weight, brick veneer and timber construction across a wide variety of climatic conditions, yet with remarkably little design variation. In this Guide the authors explain thermal comfort is not only dependant on the proportion of thermal mass but also the size and location of glazing in a building.

Thermal mass can be used to carry the warmth of the day into cool nights, or inversely - the cool of the evening into hot days. A series of simulations demonstrate that the height mass is placed within a space will vary its value in enhancing heating or cooling.



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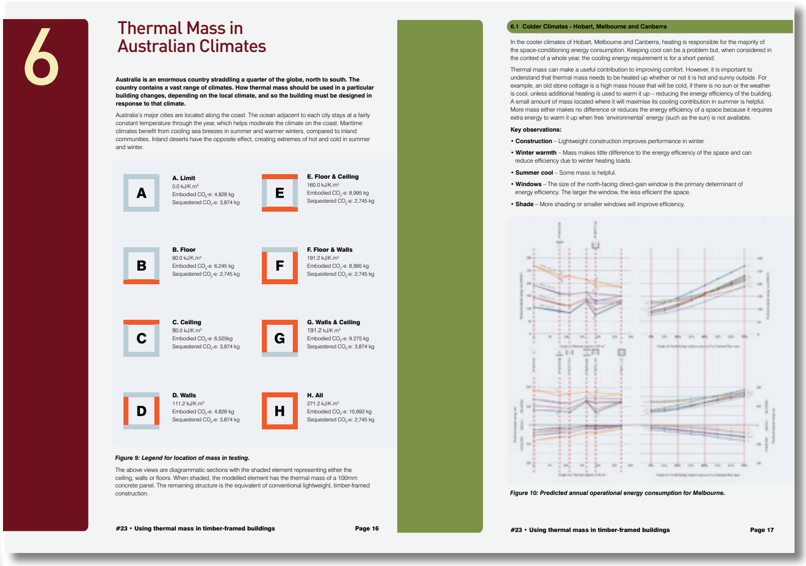
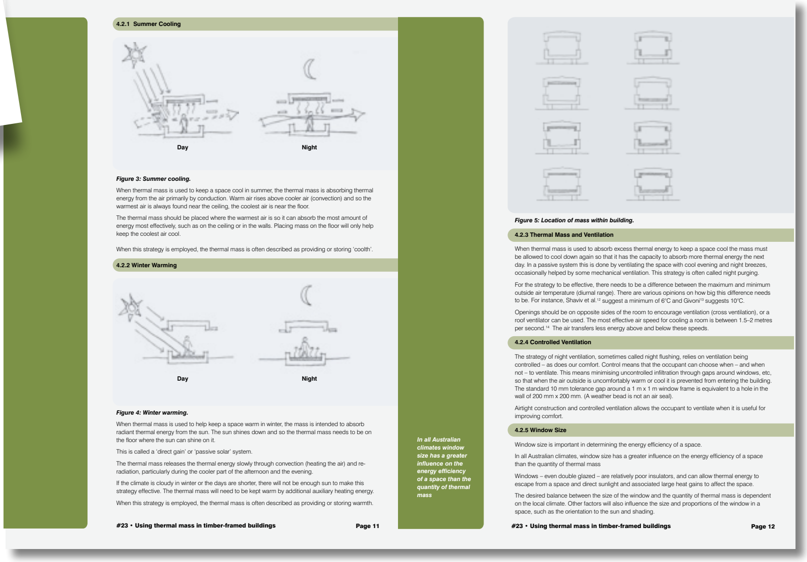
Using Thermal Mass in Timber-framed Buildings

Effective use of thermal mass for increased comfort and energy efficiency

Technical Design Guide issued by Forest and Wood Products Australia



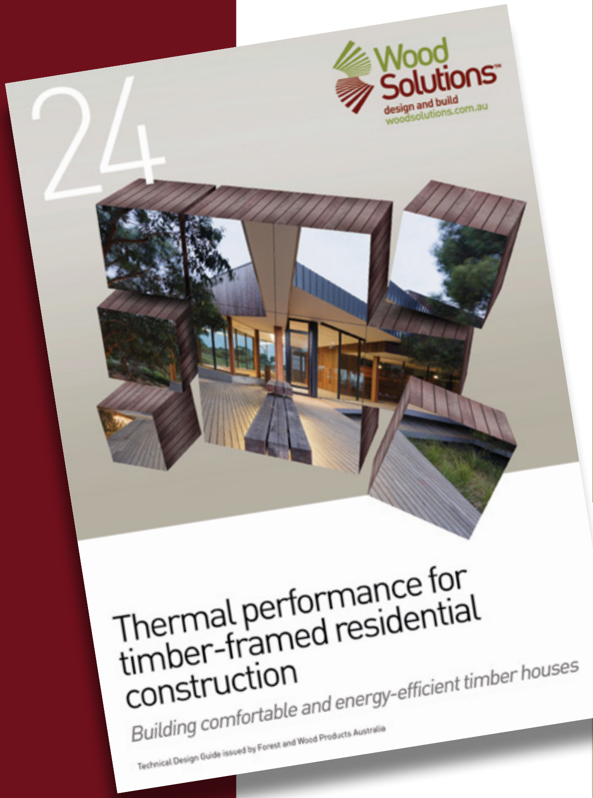


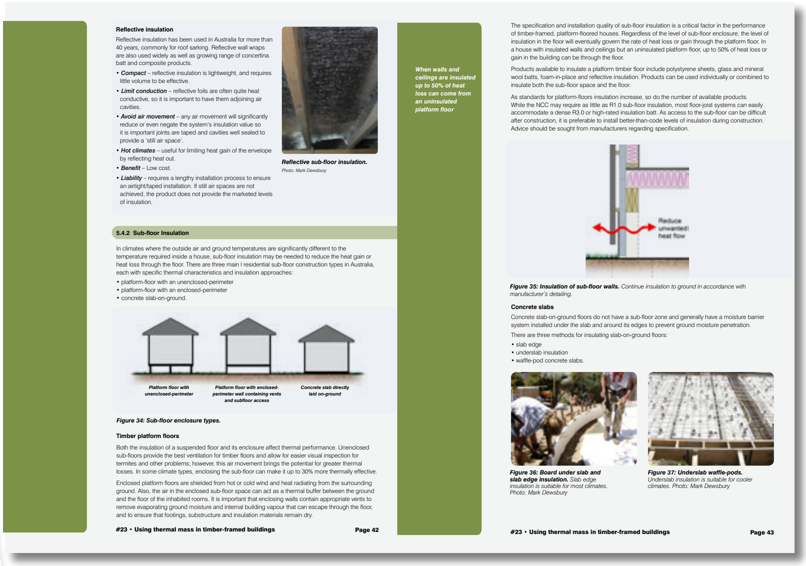
Guide 24 - Thermal performance for timber-framed residential construction

Building comfortable and energy-efficient timber houses

Maximising occupant thermal comfort and therefore increasing energy efficiency is achieved by balancing a combination of design factors. These vary from the basics such as orientation up to more elaborate concepts such as thermal bringing and the control of moisture vapour within building elements. This Guide uses many diagrams and photographs to illustrate in detail how to design for increased energy efficiency.

The authors use the modelled thermal performance of two typical project homes to contrast how minor design variations give significant gains in energy efficiency - especially when customised to climate.





Reflective insulation

Reflective insulation has been used in Australia for more than 40 years, commonly for roof sarking. Reflective wall wraps are also used widely as well as growing range of concertina batt and composite products.

- ***Compact*** – reflective insulation is lightweight, and requires little volume to be effective.
- ***Limit conduction*** – reflective foils are often quite heat conductive, so it is important to have them adjoining air cavities.
- ***Avoid air movement*** – any air movement will significantly reduce or even negate the system's insulation value so it is important joints are taped and cavities well sealed to provide a 'still air space'.
- ***Hot climates*** – useful for limiting heat gain of the envelope by reflecting heat out.
- ***Benefit*** – Low cost.
- ***Liability*** – requires a lengthy installation process to ensure an airtight/taped installation. If still air spaces are not achieved, the product does not provide the marketed levels of insulation.

Reflective sub-floor insulation.
Photo: Mark Dewsbury

5.4.2 Sub-floor Insulation

In climates where the outside air and ground temperatures are significantly different to the temperature required inside a house, sub-floor insulation may be needed to reduce the heat gain or heat loss through the floor. There are three main l residential sub-floor construction types in Australia, each with specific thermal characteristics and insulation approaches:

- platform-floor with an unenclosed-perimeter
- platform-floor with an enclosed-perimeter
- concrete slab-on-ground.

Figure 34: Sub-floor enclosure types.

Timber platform floors

Both the insulation of a suspended floor and its enclosure affect thermal performance. Unenclosed sub-floors provide the best ventilation for timber floors and allow for easier visual inspection for termites and other problems; however, this air movement brings the potential for greater thermal losses. In some climate types, enclosing the sub-floor can make it up to 30% more thermally effective.

Enclosed platform floors are shielded from hot or cold wind and heat radiating from the surrounding ground. Also, the air in the enclosed sub-floor space can act as a thermal buffer between the ground and the floor of the inhabited rooms. It is important that enclosing walls contain appropriate vents to remove evaporating ground moisture and internal building vapour that can escape through the floor, and to ensure that footings, substructure and insulation materials remain dry.

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When walls and ceilings are insulated up to 50% of heat loss can come from an uninsulated platform floor

The specification and installation quality of sub-floor insulation is a critical factor in the performance of timber-framed, platform-floored houses. Regardless of the level of sub-floor enclosure, the level of insulation in the floor will eventually govern the rate of heat loss or gain through the platform floor. In a house with insulated walls and ceilings but an uninsulated platform floor, up to 50% of heat loss or gain in the building can be through the floor.

Products available to insulate a platform timber floor include polystyrene sheets, glass and mineral wool batts, foam-in-place and reflective insulation. Products can be used individually or combined to insulate both the sub-floor space and the floor.

As standards for platform-floors insulation increase, so do the number of available products. While the NCC may require as little as R1.0 sub-floor insulation, most floor-joist systems can easily accommodate a dense R3.0 or high-rated insulation batt. As access to the sub-floor can be difficult after construction, it is preferable to install better-than-code levels of insulation during construction. Advice should be sought from manufacturers regarding specification.

Figure 35: Insulation of sub-floor walls. *Continue insulation to ground in accordance with manufacturer's detailing.*

Concrete slabs

Concrete slab-on-ground floors do not have a sub-floor zone and generally have a moisture barrier system installed under the slab and around its edges to prevent ground moisture penetration.

There are three methods for insulating slab-on-ground floors:

- slab edge
- underslab insulation
- waffle-pod concrete slabs.

Figure 36: Board under slab and slab edge insulation. *Slab edge insulation is suitable for most climates. Photo: Mark Dewsbury*

Figure 37: Underslab waffle-pods. *Underslab insulation is suitable for cooler climates. Photo: Mark Dewsbury*

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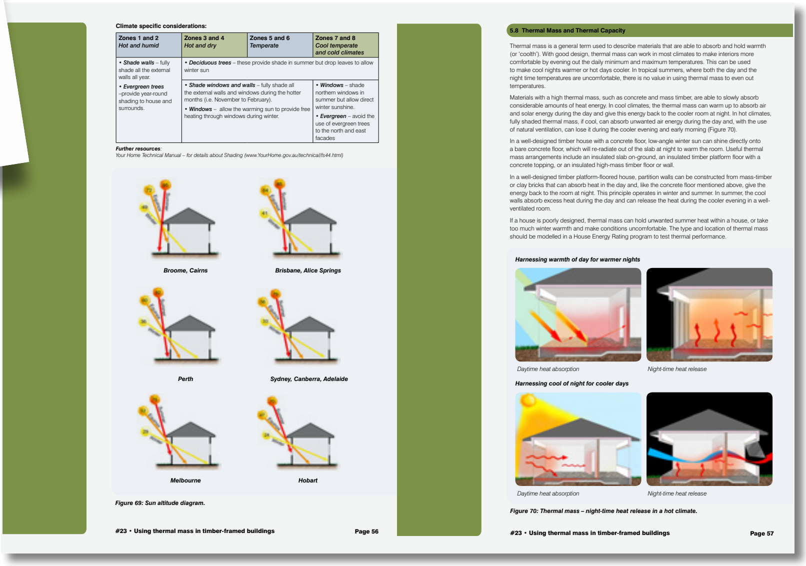

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Shade walls*** – fully shade all the external walls all year. • ***Evergreen trees*** –provide year-round shading to house and surrounds.	• ***Deciduous trees*** – these provide shade in summer but drop leaves to allow winter sun		
	• ***Shade windows and walls*** – fully shade all the external walls and windows during the hotter months (i.e. November to February). • ***Windows*** – allow the warming sun to provide free heating through windows during winter.		• ***Windows*** – shade northern windows in summer but allow direct winter sunshine. • ***Evergreen*** – avoid the use of evergreen trees to the north and east facades

Further resources:
Your Home Technical Manual – for details about Shading (www.YourHome.gov.au/technical/fs44.html)

Figure 69: Sun altitude diagram.

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5.8 Thermal Mass and Thermal Capacity

Thermal mass is a general term used to describe materials that are able to absorb and hold warmth (or 'coolth'). With good design, thermal mass can work in most climates to make interiors more comfortable by evening out the daily minimum and maximum temperatures. This can be used to make cool nights warmer or hot days cooler. In tropical summers, where both the day and the night time temperatures are uncomfortable, there is no value in using thermal mass to even out temperatures.

Materials with a high thermal mass, such as concrete and mass timber, are able to slowly absorb considerable amounts of heat energy. In cool climates, the thermal mass can warm up to absorb air and solar energy during the day and give this energy back to the cooler room at night. In hot climates, fully shaded thermal mass, if cool, can absorb unwanted air energy during the day and, with the use of natural ventilation, can lose it during the cooler evening and early morning (Figure 70).

In a well-designed timber house with a concrete floor, low-angle winter sun can shine directly onto a bare concrete floor, which will re-radiate out of the slab at night to warm the room. Useful thermal mass arrangements include an insulated slab on-ground, an insulated timber platform floor with a concrete topping, or an insulated high-mass timber floor or wall.

In a well-designed timber platform-floored house, partition walls can be constructed from mass-timber or clay bricks that can absorb heat in the day and, like the concrete floor mentioned above, give the energy back to the room at night. This principle operates in winter and summer. In summer, the cool walls absorb excess heat during the day and can release the heat during the cooler evening in a well-ventilated room.

If a house is poorly designed, thermal mass can hold unwanted summer heat within a house, or take too much winter warmth and make conditions uncomfortable. The type and location of thermal mass should be modelled in a House Energy Rating program to test thermal performance.

Figure 70: Thermal mass – night-time heat release in a hot climate.

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Using Thermal Mass in Timber-framed Buildings

Effective use of thermal mass for increased comfort and energy efficiency

Technical Design Guide issued by Forest and Wood Products Australia

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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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- Building with timber in bushfire-prone areas
- Designing for durability
- Timber finishes
- Stairs, balustrades and handrails
- Timber flooring and decking
- Timber windows and doors
- Fire compliance
- Acoustics
- Thermal performance

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Authors: Ben Slee and Richard Hyde

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Contents

Introduction

The view that “thermal mass is good and therefore more thermal mass is better” is incorrect

If thermal mass is used correctly within housing it can moderate daily temperature fluctuations – leading to more comfortable interiors – and reduce the energy used for artificial heating or cooling. If thermal mass is used incorrectly, the opposite occurs.

Thermal mass describes the ability of a material to absorb and release thermal energy with little or no change to the temperature of the material itself relative to a large amount of stored thermal energy. This is sometimes described as the thermal mass effect.

High thermal mass means the material can absorb or release large amounts of thermal energy without changing temperature. Low thermal mass, or a ‘lightweight’ material, describes a material that can only absorb or release a small amount of thermal energy before it changes temperature. Thermal mass can be used to store ‘coolth’ by acting as a heat sink or ‘warmth’ by acting as a heat store.

The use of thermal mass to enhance thermal comfort is well documented in design guides and encouraged in legislation, although there is little or no information to help designers understand how much mass is required. The view that “thermal mass is good and therefore more thermal mass is better” is incorrect. Getting the correct amount of thermal mass in a building is important because:

- too much thermal mass can reduce thermal comfort and increase annual energy use; and
- the manufacture of high thermal mass materials often comes with a high environmental cost.

Many rules of thumb have been developed for calculating the amount of thermal mass needed. Unfortunately, in an attempt to provide a simple answer to a complex system, these do not adequately define the climate or design strategies they were developed for, making their useful application to practice impossible.

The thermal behaviour of buildings is dependent on local climatic conditions. Australian climatic conditions can vary considerably, particularly near the coast, where the majority of the population lives.

This Guide was written following an analysis of existing rules of thumb and existing design guidance. It is based on analysis of both real-world and computer simulations of thermal mass in typical project homes and experimental structures in several Australian climates. The project revealed the following surprising results:

- It is possible to have too much thermal mass.
- Thermal mass is more useful in some climates than in others.
- How much thermal mass to use, and whether to use it in the floor, walls or ceiling, depends on the local climate.
- Thermal mass needs to be in one place to aid cooling and a different place to aid heating.
- The size and location of the windows has as large an influence on the thermal efficiency of a space as the quantity of thermal mass.
- Because the manufacture of many materials with high thermal mass results in high carbon dioxide emissions, the inclusion of thermal mass may actually increase rather than reduce the carbon emissions of a building, when viewed across its entire lifecycle.

The energy that is used and the carbon dioxide that is produced during the extraction and manufacturing of products is said to be ‘embodied’ in the product. Materials commonly used in construction to provide thermal mass also have high embodied energy and high embodied carbon dioxide.

The purpose of this design guide is to help designers understand how to use thermal mass in a building, how to achieve an optimum amount of thermal mass and, as a result, how to reduce the operational energy and embodied energy costs of the buildings.

Related publications are listed under Further Reading at the end of this Guide.

1

Thermal Mass Properties and Materials

Thermal mass is a term used to describe a material's ability to absorb, store and release energy. A material can be said to have good thermal mass if it can absorb a significant amount of heat energy without changing its own temperature. A material needs to be able to absorb and then release heat over a period of several hours to be useful in moderating internal day/night (diurnal) temperature variations. Materials with good thermal mass tend to be heavy, dense and conduct heat sufficiently to be able to absorb heat within their interior.

The two key properties of thermal mass that measure its effectiveness are:

- thermal capacity: heat storage ability; and
- admittance: ability to absorb or release heat.

1.1 Thermal Capacity

Thermal capacity (also called Specific Heat Capacity or Thermal Capacitance) is a measure of the amount of energy needed to raise one kilogram of material by one degree Kelvin. (A temperature difference of one degree Kelvin is the equivalent to one degree Celsius).

- Thermal capacity is expressed in KJ/kg.K

Thermal capacity can also be expressed as a function of the materials volume, i.e. the amount of thermal energy needed to raise one cubic metre of a material one degree Kelvin.

- The volumetric heat capacity is expressed in KJ/m^3.K

1.2 Admittance

The term for a material's ability to absorb or release thermal energy is admittance.[1] Admittance is the quantity of energy absorbed by one square metre of a surface in one second given a temperature difference of one degree Kelvin. This measure is useful because it relates to time (1 W = 1 J/s).

- Admittance is measured in W/m^2.K.

1.3 Construction Materials and Thermal Mass

Materials that possess thermal properties associated with the thermal mass and are commonly used in construction include:

- concrete
- stone
- bricks.

Water is another material that has excellent thermal mass properties and is readily available. Various architects have used water in clear glass columns or metal tanks.

1.4 Insulation

Thermal insulation is different to thermal mass. The most common form of insulation – bulk insulation – is designed to resist the conduction and convection of thermal energy, rather than the radiation of thermal energy, by using the poor conduction and low thermal capacity properties of air trapped in small pockets as bubbles (foam) or between fibres.

Reflective insulation resists radiation but not conduction or convection. In order to work effectively, the reflective surface must be free from dust or dirt and have a clear air space in front of it. For reflective insulation to keep a space warm, the air space adjacent to the reflective surface must be still.

1.5 Thermal Mass and Insulation

Thermal mass and thermal insulation are both very useful, but do different things for different reasons:

- Thermal mass is intended to absorb and store thermal energy and conduct it away from the source.
- Insulation is designed to resist the passage of thermal energy and prevent it leaving the source.
- Lightweight materials are not good at storing energy – they have a low thermal mass (thermal capacity).

1.6 Phase Change Materials

The use of phase change materials in buildings to regulate internal temperature is an expanding area of research and offers many opportunities.

Phase change materials are often referred to as new, although they have been around since at least the 19th century, when the Victorians used them used them in pistons to open and close windows in their greenhouses.

Phase change materials work by changing state. They absorb thermal energy by changing from a solid to a liquid and release energy by changing back to a solid. When a material changes from one state to another it absorbs or releases huge amounts of energy without changing temperature. This is called latent energy.

There are two types of phase change materials:

- paraffin wax
- phase change salts.

Various manufacturers are looking at how they can be incorporated into building materials, such as plasterboard. Phase change materials can be ‘tuned’ or designed to change state at a particular temperature. Below and above this temperature, the material does not absorb large amounts of energy and, once all the material has changed state, it cannot absorb or release more energy.

2

Lifetime Environmental Cost

Legislation concentrates on the environmental impact of a building during its operation. The construction and demolition of the building also has a significant environmental impact. In a lifecycle environmental assessment of a building, the environmental cost – including energy – of the extraction, processing and production of the materials used in the construction of the building and the environmental cost of demolition are added to the operational costs of the building to ascertain a lifetime environmental cost.

2.1 Embodied Energy

Materials that possess the properties of thermal mass are dense and usually require large amounts of energy to extract, transport and process them. This energy is said to be 'embodied' in the material and is often expressed as carbon dioxide equivalent (CO_2-equivalent or CO_2-e). This carbon dioxide equivalent value takes into account the energy and other greenhouse gas emissions that are associated with the extraction, processing and manufacturing of a product, from its beginning as a raw material, such as a tree or quarry, to when it leaves the factory gate.[2,3]

2.2 Carbon Dioxide Equivalent

The carbon dioxide equivalent measure converts the energy used into a quantity of CO_2 based on an assessment of the source of the energy. For electricity in Australia, a figure of 1 kg of CO_2 per 1 kWh of electricity is used.[4] In Australia, 96% of electricity is generated from carbon-based fuels.[5]

Different greenhouse gasses (e.g. methane) create more or less powerful greenhouse effects. The carbon dioxide equivalent model converts a quantity of each greenhouse gas into a quantity of CO_2 that has an equivalent greenhouse effect.[3]

AccuRate Sustainability software (AccuRate_Sustainability, 2012)[4] includes a calculation engine for calculating the embodied energy in the building being assessed. The tables that this calculation is based on can be found in the FWPA report *Development of an Embodied CO_2 Emissions Module for AccuRate.*[3]

2.3 Concrete – Chemical Reactions During Manufacture

Some materials are created through a chemical reaction that produces CO_2 or other greenhouse gasses. The most obvious of these in construction is concrete. Concrete is produced by roasting limestone and clay. The chemical reaction that turns limestone into cement emits large quantities of CO_2.

2.4 Sequestered or Stored Carbon Dioxide

Materials that are grown, such as timber, absorb CO_2 from the atmosphere while the trees are growing. When timber is used in buildings, this carbon dioxide is stored in the building fabric. This carbon dioxide is said to be sequestered. When the building is demolished, the carbon dioxide may be released back into the atmosphere either by burning or decomposition, unless the timber is reused. Because the sequestration is not permanent, there is some debate as to whether or not the sequestered carbon should be set against the emitted carbon dioxide over the longer term.[2]

As the global population of trees is in decline, it is important to ensure that the timber used in the construction of a building comes from sustainably managed forests that replace the felled trees.

2.5 Thermal Mass and Saving Energy – Achieving a Balance

Thermal mass materials may require large amounts of energy to produce but, when used appropriately, they also help us save energy and improve comfort in our buildings. So it is important to understand the balance between the energy (or carbon dioxide equivalent) invested in the construction of the building and the energy this will potentially save over the lifetime of the building by making it more efficient. If the building's life is short it is possible that the energy saved during the life of the building is less than the energy invested in the thermal mass used to make it more efficient. In this case, other efficiency strategies should be investigated.

3

Amount of Thermal Mass

You can have too much thermal mass in a space.[7]

The internal temperature of a lightweight building tends to follow the external temperature variation. Adding some thermal mass to the inside of a lightweight building reduces the internal diurnal temperature variation (the difference between the highest and lowest temperature in a calendar day). Increasing the amount of thermal mass in the space further reduces the internal temperature variation until a point is reached when adding further mass has no influence on the diurnal temperature variation.

This may appear to be counterintuitive, because so much design guidance suggests that thermal mass is good and therefore more mass must be better. However, if we consider what thermal mass does, the assertion that it is possible to have too much mass makes sense.

Thermal mass absorbs and stores thermal energy. In any building there will be an average and maximum quantity of thermal energy that enters a particular space and needs to be stored to avoid overheating, or to provide additional warmth in the evening. Therefore, if there is more thermal mass or thermal storage capacity than needed to store the thermal energy, this additional capacity will not be used and will not influence the temperature in the space. In certain circumstances, the additional mass may need to be heated up using the building's heating system so that it does not make the space too cool.

You can have too much thermal mass in a space

The quantity of mass that is useful in a building will depend on the local climate, the size and occupation patterns of the building and the environmental design strategy employed (see Section 4).

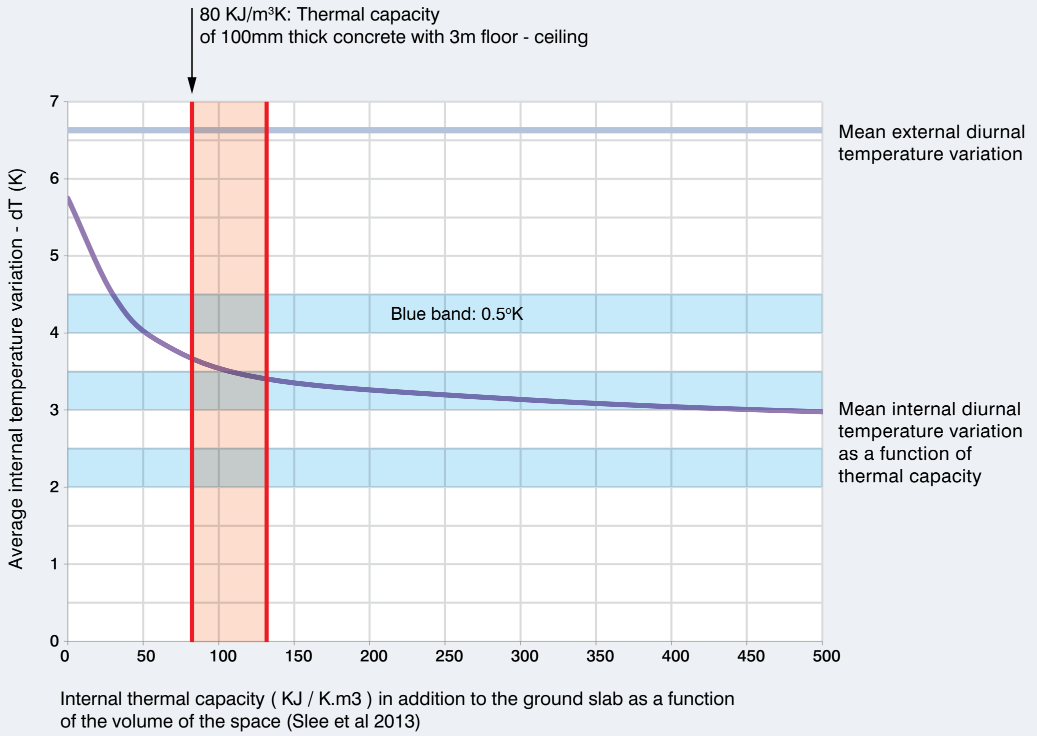


Figure 1: Thermal mass graph. As the thermal mass is increased, the effect on the temperature variation is shown to reduce. (Adapted from Slee et al.)[7,15]

4 Placing of Thermal Mass

4.1 Comfort

Understanding how humans perceive and interact with the thermal environment and how thermal energy is transferred in this environment helps explain how thermal mass, ventilation, shade and sunshine can be used to enhance comfort with the greatest effect.

Appreciation of the thermal environment – thermal comfort – is derived from the rate and direction of the heat energy transfer between the human body and the surrounding environment. Almost half the body's exchange of heat with the surrounding environment occurs through radiation:

- 47.5% through radiation;
- 27.5% though convection and conduction; and
- 25% through other means, including perspiration (evaporation) and respiration (breathing).

The human body continuously produces heat, although the rate of production varies. When lying quietly, the body produces about 83 watts, but it can produce 585 watts when performing heavy work. To maintain a comfortable equilibrium, the body's loss of heat (through radiation, convection, conduction and other means) must equal the amount of heat that it generates.

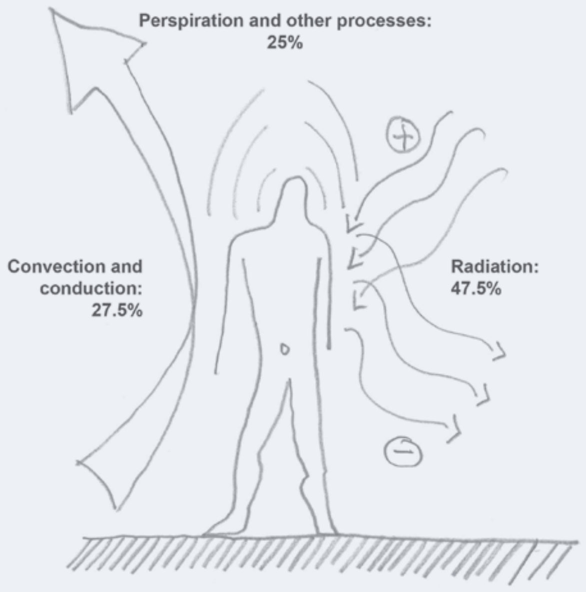


Figure 2: Human Comfort. Thermal perception: Sources of thermal sensation with approximate perceptual weighting.

4.1.1 Radiation

Interior surfaces such as floor, walls, windows and ceilings can radiate heat and absorb heat. These elements exchange thermal energy with people and other surfaces, including the sun, by radiation. If the surface is at a higher temperature than the surface of the body, radiant energy is received from it giving the sensation of warmth. Conversely, if it is at a lower temperature the body will lose radiant energy to it, giving a cool sensation. Since a large part of our perception of comfort is derived from radiation, the relative temperature of those surfaces is important.

4.1.2 Convection and Ventilation

Convection and ventilation are related but slightly different concepts. Convection is the movement of thermal energy by air (or a fluid) as a result of the cooling or heating of the fluid.

Ventilation is the movement and exchange of air in a space involving air from outside that space. Ventilation can result from opening windows (natural ventilation) or be forced through by a mechanical system such as a fan (mechanical ventilation).

Convection

Surfaces that are in contact with the air in the room are constantly exchanging thermal energy with the air through convection. If the air is warmer than the surface of the thermal mass, the thermal mass will absorb thermal energy from the air, cooling the air down. Occupants will experience a lower ambient temperature. If the surface temperature of the mass is higher than the air, for example in the evening, then the mass will warm the air, which will circulate via convection air currents and so the ambient temperature will be increased.

Ventilation

Air movement has a significant influence on the human perception of comfort. Ventilation or breezes are important to aid evaporation in the form of perspiration. The stronger the breeze, the greater the cooling effect, to a point. Indoor breezes stronger than 1.5 metres per second are considered uncomfortable,[8,9] although the same breeze outside would generally be considered comfortable. Natural breezes are considered more comfortable and are more effective at creating a cooling sensation than continuous monotonous mechanical air flow, due to the random variability in the natural breeze.[10,11]

<table>
<tr><th>Air Speed</th><td>0.6 m/s</td><td>0.9 m/s</td><td>1.2 m/s</td></tr>
<tr><th>dT_{op} (°C)</th><td>1.2</td><td>1.8</td><td>2.2</td></tr>
<tr><td colspan="4">dT-op is the change in acceptable Operative Temperature as a result of the air flow. T-op is a good approximation of our perception of temperature. It is normally taken as the mean of the ambient air temperature and the radiant or globe temperature.[9]</td></tr>
</table>

Table 1: Increases in acceptable Operative Temperature (T_{op}) resulting from increasing air speed above 0.3 m/s when T_{op} > 25°C.

4.1.3 Conduction

Conduction occurs through direct contact between materials.

When the human body is in contact with a surface that is cooler than the body's skin, thermal energy will be conducted away from the skin into the surface, particularly if the material is a good conductor (as dense materials are). This causes the part of the body in contact with the cool surface to feel cool. If the temperature difference is reversed, we will feel warm. However, if the material is a poor conductor – such as timber – heat energy will not be conducted away very effectively, so the material will feel relatively warm. Such materials are often considered 'warm' materials.

4.2 Design Strategies

Thermal mass can be used by designers to achieve two different objectives:

- help keep buildings cool in summer; and
- help keep buildings warm in winter.

How and where the thermal mass needs to be used to achieve these two objectives differs. In both cases, thermal mass is used to absorb and store thermal energy so that it can be released later. The higher the temperature difference between surfaces, the faster the heat transfer. It is important to place the thermal mass in a location where it can absorb the thermal energy most effectively.

4.2.1 Summer Cooling

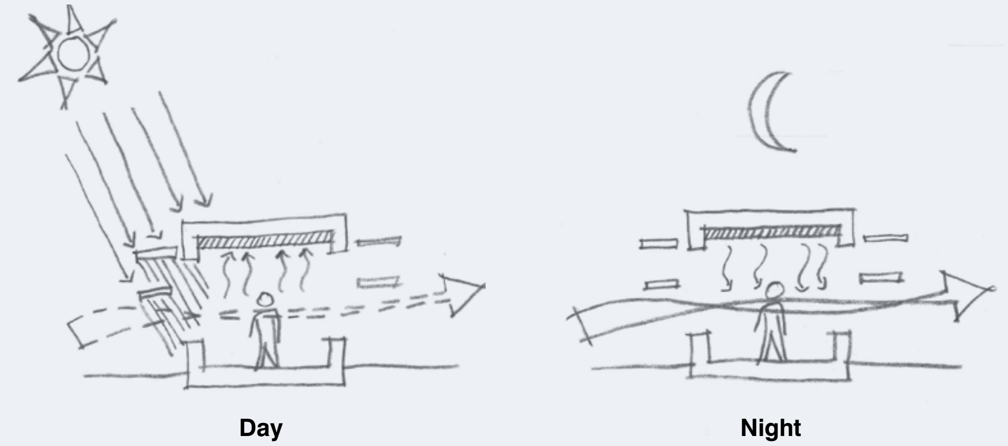


Figure 3: Summer cooling.

When thermal mass is used to keep a space cool in summer, the thermal mass is absorbing thermal energy from the air primarily by conduction. Warm air rises above cooler air (convection) and so the warmest air is always found near the ceiling, the coolest air is near the floor.

The thermal mass should be placed where the warmest air is so it can absorb the most amount of energy most effectively, such as on the ceiling or in the walls. Placing mass on the floor will only help keep the coolest air cool.

When this strategy is employed, the thermal mass is often described as providing or storing 'coolth'.

4.2.2 Winter Warming

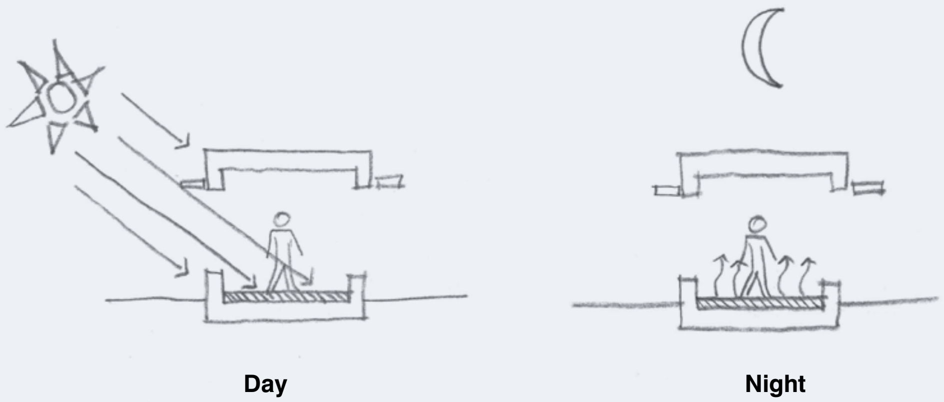


Figure 4: Winter warming.

When thermal mass is used to help keep a space warm in winter, the mass is intended to absorb radiant thermal energy from the sun. The sun shines down and so the thermal mass needs to be on the floor where the sun can shine on it.

This is called a 'direct gain' or 'passive solar' system.

The thermal mass releases the thermal energy slowly through convection (heating the air) and re-radiation, particularly during the cooler part of the afternoon and the evening.

If the climate is cloudy in winter or the days are shorter, there will not be enough sun to make this strategy effective. The thermal mass will need to be kept warm by additional auxiliary heating energy.

When this strategy is employed, the thermal mass is often described as providing or storing warmth.

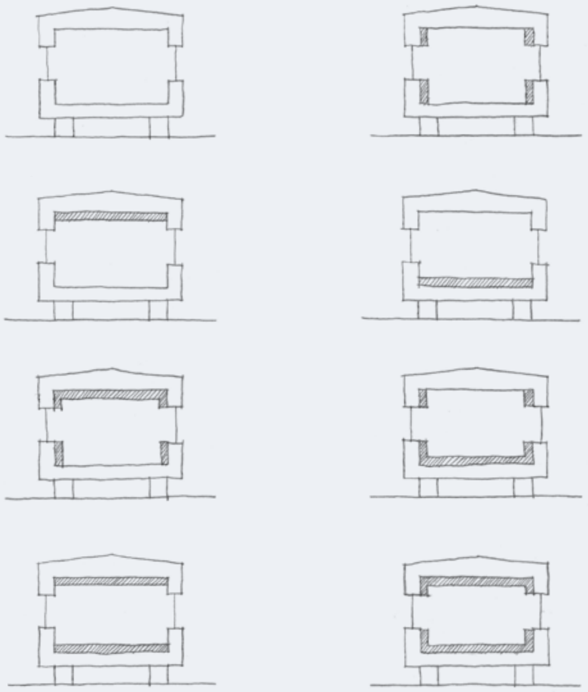


Figure 5: Location of mass within building.

4.2.3 Thermal Mass and Ventilation

When thermal mass is used to absorb excess thermal energy to keep a space cool the mass must be allowed to cool down again so that it has the capacity to absorb more thermal energy the next day. In a passive system this is done by ventilating the space with cool evening and night breezes, occasionally helped by some mechanical ventilation. This strategy is often called night purging.

For the strategy to be effective, there needs to be a difference between the maximum and minimum outside air temperature (diurnal range). There are various opinions on how big this difference needs to be. For instance, Shaviv et al.[12] suggest a minimum of 6°C and Givoni[13] suggests 10°C.

Openings should be on opposite sides of the room to encourage ventilation (cross ventilation), or a roof ventilator can be used. The most effective air speed for cooling a room is between 1.5–2 metres per second.[14] The air transfers less energy above and below these speeds.

4.2.4 Controlled Ventilation

The strategy of night ventilation, sometimes called night flushing, relies on ventilation being controlled – as does our comfort. Control means that the occupant can choose when – and when not – to ventilate. This means minimising uncontrolled infiltration through gaps around windows, etc, so that when the air outside is uncomfortably warm or cool it is prevented from entering the building. The standard 10 mm tolerance gap around a 1 m x 1 m window frame is equivalent to a hole in the wall of 200 mm x 200 mm. (A weather bead is not an air seal).

Airtight construction and controlled ventilation allows the occupant to ventilate when it is useful for improving comfort.

4.2.5 Window Size

Window size is important in determining the energy efficiency of a space.

In all Australian climates, window size has a greater influence on the energy efficiency of a space than the quantity of thermal mass

In all Australian climates window size has a greater influence on the energy efficiency of a space than the quantity of thermal mass

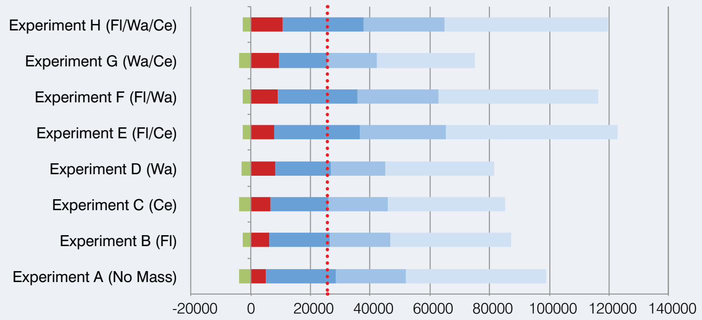
Windows – even double glazed – are relatively poor insulators, and can allow thermal energy to escape from a space and direct sunlight and associated large heat gains to affect the space.

The desired balance between the size of the window and the quantity of thermal mass is dependent on the local climate. Other factors will also influence the size and proportions of the window in a space, such as the orientation to the sun and shading.

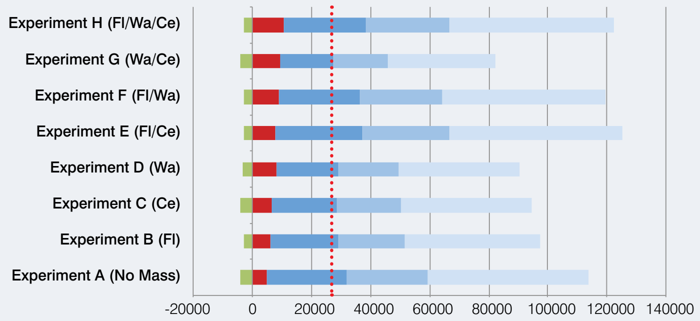
5

Reduction of Lifetime Carbon Dioxide Emissions

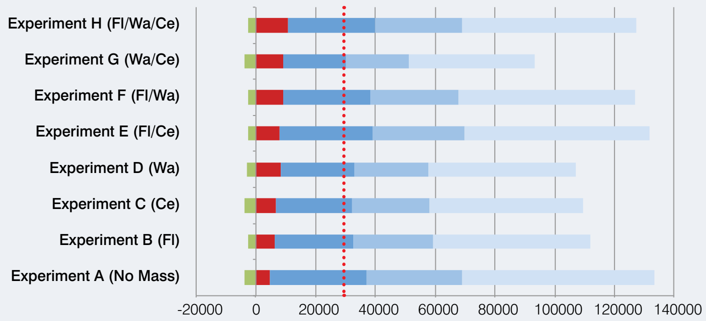
Buildings require more energy to construct than they use each year. A masonry building will involve considerably more energy to build than a lightweight building. Over 25, 50 or 100 years the operational energy adds up and may account for an equal or larger proportion of the building's lifetime CO_2 emissions. How the proportions between embodied and total operational energy change over time depends on the construction method and the local climate.



Predicted net CO_2-e emissions (kg) over time Window 5% of floor area



Predicted net CO_2-e emissions (kg) over time Window 15% of floor area



Predicted net CO_2-e emissions (kg) over time Window 25% of floor area

🟩 **Sequested CO_2-e**

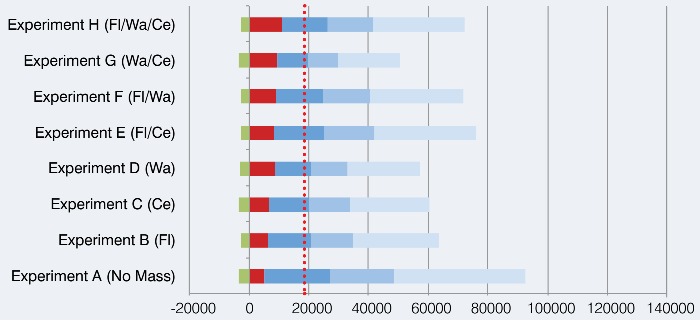
🟥 **Embodied CO_2-e**

🟦 **Operational CO_2-e - 25 Years**

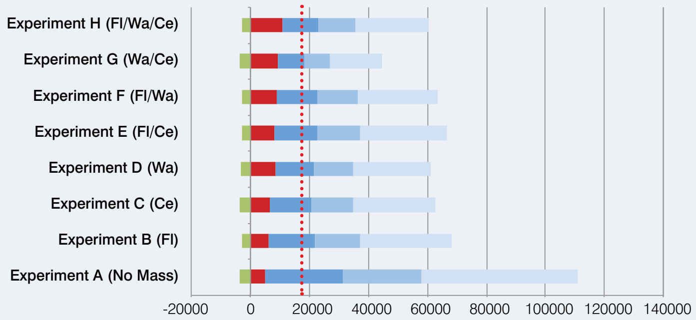
▨ **Operational CO_2-e - 25-50 Years**

□ **Operational CO_2-e - 50-100 Years**

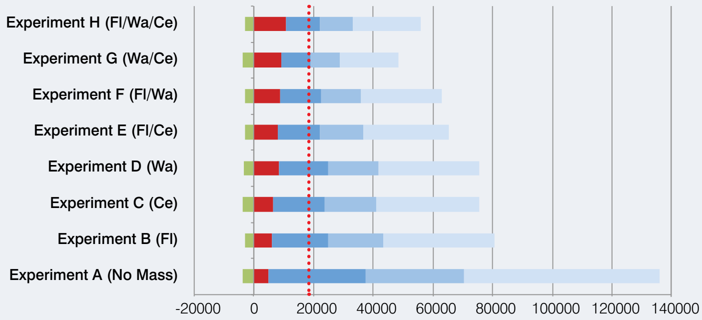
Figure 6: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Melbourne.



Predicted net CO_2-e emissions (kg) over time
Window 5% of floor area



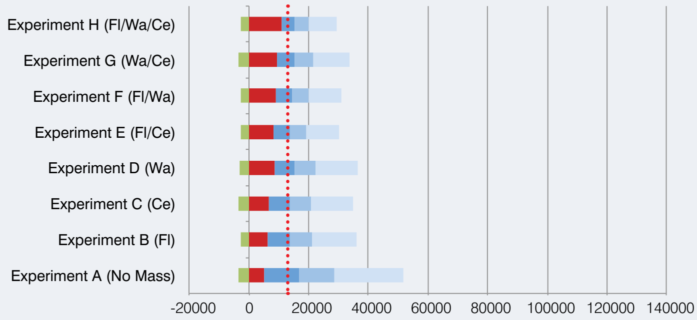
Predicted net CO_2-e emissions (kg) over time
Window 15% of floor area



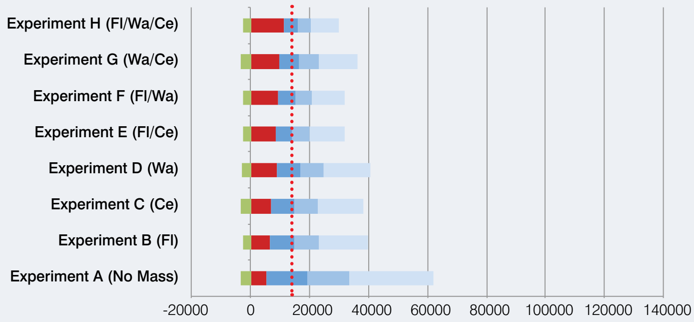
Predicted net CO_2-e emissions (kg) over time
Window 25% of floor area

- 🟩 **Sequested CO_2-e**
- 🟥 **Embodied CO_2-e**
- 🟦 **Operational CO_2-e - 25 Years**
- 🟦 **Operational CO_2-e - 25-50 Years**
- ⬜ **Operational CO_2-e - 50-100 Years**

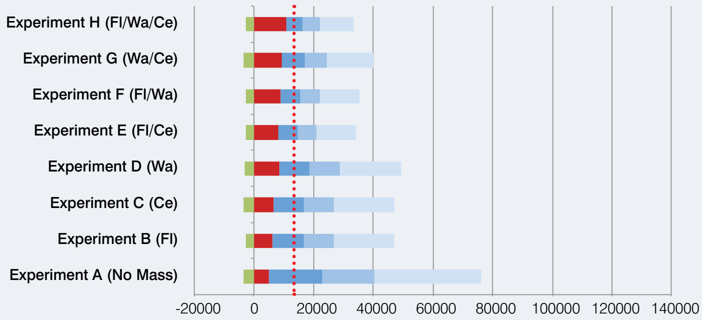
Figure 7: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Sydney (Penrith).



Predicted net CO_2-e emissions (kg) over time
Window 5% of floor area



Predicted net CO_2-e emissions (kg) over time
Window 15% of floor area



Predicted net CO_2-e emissions (kg) over time
Window 25% of floor area

🟩 **Sequested CO_2-e**
🟥 **Embodied CO_2-e**
🟦 **Operational CO_2-e - 25 Years**
🟦 **Operational CO_2-e - 25-50 Years**
🟦 **Operational CO_2-e - 50-100 Years**

Figure 8: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Brisbane.

For all Australian climates researched by the authors, it appears that a modest amount of thermal mass may help to reduce the total lifetime CO_2 emissions if the building lasts for more than 50 years. However, high mass, high embodied-energy buildings are unlikely to be more efficient overall than lighter-weight buildings – even after 100 years.

Currently, 96% of Australia's energy is produced from non-renewable carbon based sources.[6] How this will change over the next 25, 50 or 100 years is impossible to predict. Regardless of generation, buildings that have a lower embodied and operational environmental cost must be better than buildings that use resources inefficiently.

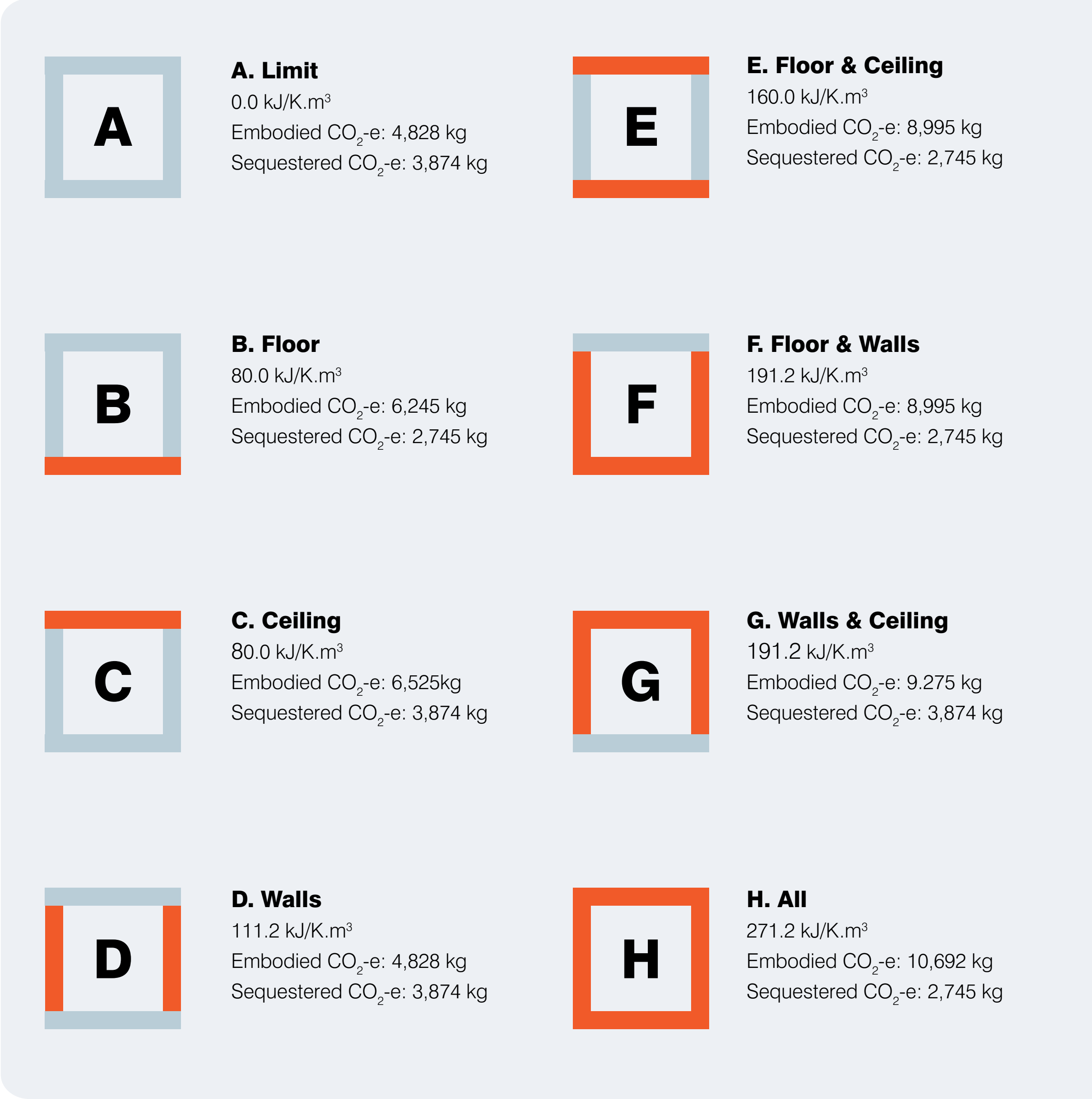
The research suggests that lightweight timber buildings that incorporate thermal mass strategically, together with controlled ventilation and shading, are better than the status quo.

6

Thermal Mass in Australian Climates

Australia is an enormous country straddling a quarter of the globe, north to south. The country contains a vast range of climates. How thermal mass should be used in a particular building changes, depending on the local climate, and so the building must be designed in response to that climate.

Australia's major cities are located along the coast. The ocean adjacent to each city stays at a fairly constant temperature through the year, which helps moderate the climate on the coast. Maritime climates benefit from cooling sea breezes in summer and warmer winters, compared to inland communities. Inland deserts have the opposite effect, creating extremes of hot and cold in summer and winter.



A. Limit
0.0 kJ/K.m^3
Embodied CO_2-e: 4,828 kg
Sequestered CO_2-e: 3,874 kg

E. Floor & Ceiling
160.0 kJ/K.m^3
Embodied CO_2-e: 8,995 kg
Sequestered CO_2-e: 2,745 kg

B. Floor
80.0 kJ/K.m^3
Embodied CO_2-e: 6,245 kg
Sequestered CO_2-e: 2,745 kg

F. Floor & Walls
191.2 kJ/K.m^3
Embodied CO_2-e: 8,995 kg
Sequestered CO_2-e: 2,745 kg

C. Ceiling
80.0 kJ/K.m^3
Embodied CO_2-e: 6,525kg
Sequestered CO_2-e: 3,874 kg

G. Walls & Ceiling
191.2 kJ/K.m^3
Embodied CO_2-e: 9.275 kg
Sequestered CO_2-e: 3,874 kg

D. Walls
111.2 kJ/K.m^3
Embodied CO_2-e: 4,828 kg
Sequestered CO_2-e: 3,874 kg

H. All
271.2 kJ/K.m^3
Embodied CO_2-e: 10,692 kg
Sequestered CO_2-e: 2,745 kg

Figure 9: Legend for location of mass in testing.

The above views are diagrammatic sections with the shaded element representing either the ceiling, walls or floors. When shaded, the modelled element has the thermal mass of a 100mm concrete panel. The remaining structure is the equivalent of conventional lightweight, timber-framed construction.

6.1 Colder Climates - Hobart, Melbourne and Canberra

In the cooler climates of Hobart, Melbourne and Canberra, heating is responsible for the majority of the space-conditioning energy consumption. Keeping cool can be a problem but, when considered in the context of a whole year, the cooling energy requirement is for a short period.

Thermal mass can make a useful contribution to improving comfort. However, it is important to understand that thermal mass needs to be heated up whether or not it is hot and sunny outside. For example, an old stone cottage is a high mass house that will be cold, if there is no sun or the weather is cool, unless additional heating is used to warm it up – reducing the energy efficiency of the building. A small amount of mass located where it will maximise its cooling contribution in summer is helpful. More mass either makes no difference or reduces the energy efficiency of a space because it requires extra energy to warm it up when free ‘environmental’ energy (such as the sun) is not available.

Key observations:

- **Construction** – Lightweight construction improves performance in winter.
- **Winter warmth** – Mass makes little difference to the energy efficiency of the space and can reduce efficiency due to winter heating loads.
- **Summer cool** – Some mass is helpful.
- **Windows** – The size of the north-facing direct-gain window is the primary determinant of energy efficiency. The larger the window, the less efficient the space.
- **Shade** – More shading or smaller windows will improve efficiency.

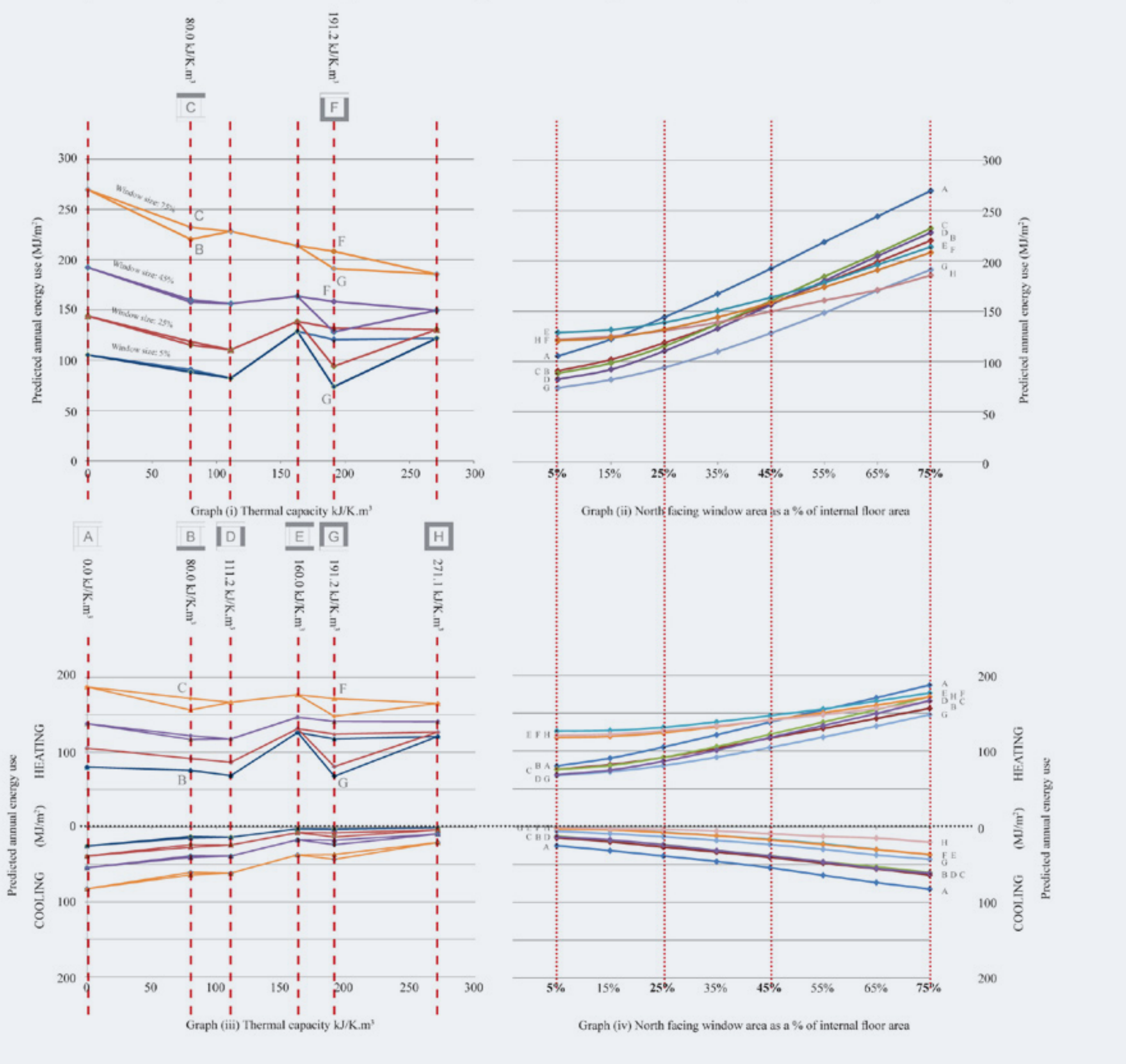


Figure 10: Predicted annual operational energy consumption for Melbourne.

6.2 Warm Temperate Climates - Sydney and Perth

The climate of Sydney becomes more extreme as it moves inland from the coast to the edge of the mountains to its west. The opportunities to save energy and the benefits of modifications to a design increase proportionately.

The climate in Perth has similarities to both the eastern and western Sydney climates.

In these warm temperate climates, some mass helps moderate the extreme climates. High levels of mass can help to keep a building cool during a heat wave. However, the same mass can then take several days to cool down – creating discomfort when the heat wave passes and the air temperature returns to something more pleasant. The same problem can happen on a daily cycle where the house stays warmer than desired in the evening because there is too much heat stored in the mass.

In winter, the mass must then be heated, and more mass means more heating to achieve the desired temperature. Given the right site and careful design, the sun can be used in winter to heat the mass. Beware of warmer winter days when it is easy to overheat the space.

Key observations:

- **Construction** – A lightweight structure that avoids direct solar gain can be efficient
- **Position of mass** – A ground slab plus mass in the walls or the ceiling is very helpful.
- **Amount of mass** – Lots of mass is no more efficient than some mass. The limit of useful thermal capacity is 160KJ/K.m^3 (including ground slab).
- **Direct sun** – If there is no direct gain, higher mass reduces efficiency. Passive solar design (direct gain) can be helpful in this climate provided the window is not too large and the mass is on the floor.
- **Windows** – The size of the windows facing the northern sun is important. Windows larger than 30% of floor area receiving direct sun, and which are fully shaded between the spring and autumn equinoxes, reduce efficiency.
- **Design iteration** – Using a simulation tool such as AccuRate or BERS to model slightly different versions of the building will help find the best balance between window size and thermal capacity and will improve the performance of the building.

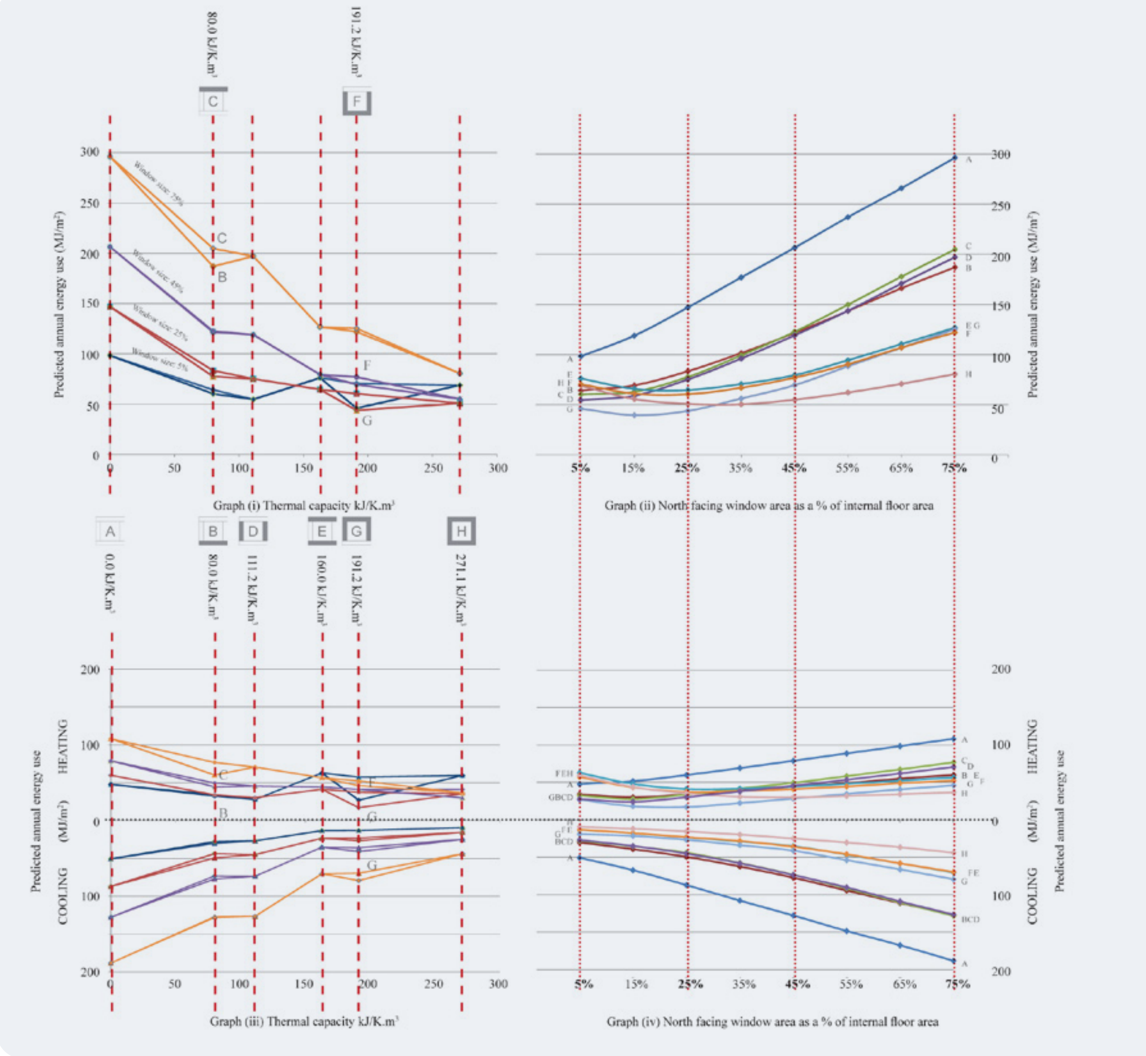


Figure: 11 Predicted annual operational energy consumption for Sydney (Penrith).

6.3 Hot, and Hot and Humid Climates - Brisbane and Darwin

Two distinct design strategies emerge from research looking at these climates:

- the high mass, sealed, conditioned space
- the lightweight, flexible naturally ventilated space.

When the energy embodied in the structure of the building (embodied carbon dioxide equivalent); the physiological factors influencing our perception of comfort; and the desire for a relaxed, free-flowing lifestyle are all taken into account, the well-shaded, lightweight approach appears to be preferable for this climate.

- **Vernacular** – the lightweight construction of ‘the Queenslander’ is the traditional design and construction system for northern Australia. It uses verandahs and awnings to avoid direct solar gain and lightweight construction with little or no thermal mass.
- **Windows** – to improve thermal comfort, it is important to avoid larger windows that allow direct solar gain.
- **Amount of mass** – Some mass may be helpful in the floor or walls or ceiling.

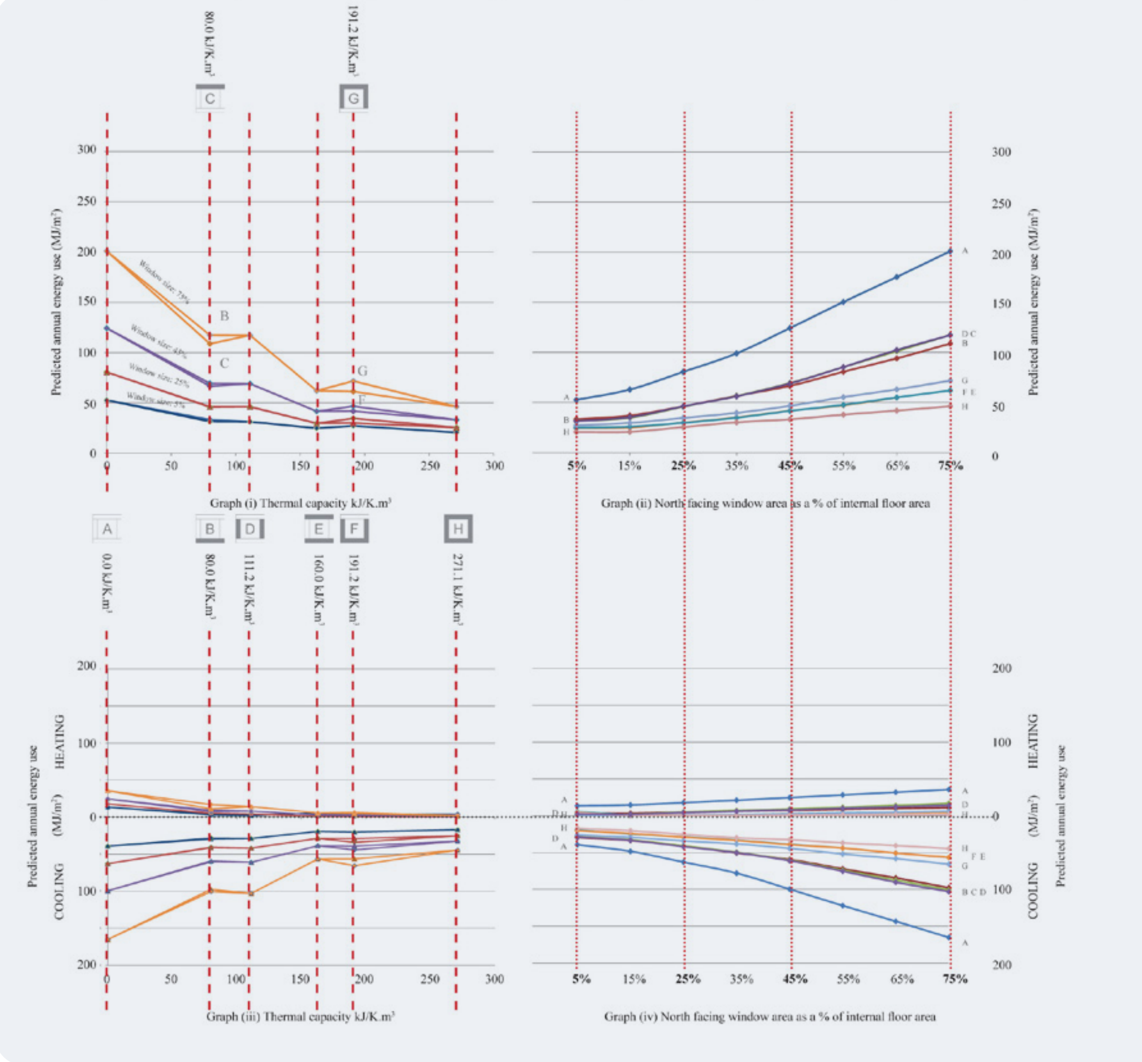


Figure 12: Predicted annual operational energy consumption for Brisbane.

6.4 Five Design Considerations

1. Design for your climate Passive solar design might work in Sydney but not in Darwin, Brisbane or Melbourne.15 Different climates will have different heating or cooling priorities. In some climates, keeping cool in summer is the biggest problem while keeping warm in winter is the bigger problem in other climates. If thermal mass is used to help keep the house warm in winter, the climate needs to provide very consistent clear sunny days. If the thermal mass is to be used to keep the house cool in summer then the evenings need to be consistently cooler than the day, with a diurnal range of about 10°C or more.

2. Orientation Consider the local factors affecting the site including shadows, wind patterns and solar orientation.

3. Natural ventilation Natural ventilation does not mean draughty or leaky buildings. Good natural ventilation should be controllable. A well-sealed building avoids wasting actively heated or cooled air.

4. Thermal mass and insulation Thermal mass is not thermal insulation. Insulation does not provide thermal mass. Both mass and insulation have an important role to play in improving comfort and energy efficiency. They must be used together and in the right place for the particular climate.

5. Window size Large windows can provide wonderful views and light, but they can also significantly reduce the thermal comfort and energy efficiency of a space.

In every climate, larger windows that allow direct solar gain reduce the efficiency of a space. If larger windows are used, direct solar gain should be carefully controlled with solar shading throughout the year.

7

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8

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Thermal performance for timber-framed residential construction

Building comfortable and energy-efficient timber houses

Technical Design Guide issued by Forest and Wood Products Australia

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Contents

Introduction

Timber and thermal comfort in housing

Most existing houses in Australia have timber frames and new homes continue this tradition. Modern construction methods mean an increasing number of low-rise apartment buildings, traditionally constructed from masonry for fire-resistance, are also now being built with timber frames.

Designing for timber thermally

As construction technology has developed, standards of fire-resistance, acoustic separation and thermal comfort in timber buildings have improved. This Guide provides design and construction information for superior thermal comfort. Better thermal performance results in:

- more comfortable residents
- less energy use for heating and cooling
- reduced greenhouse gas emissions.

Increasing comfort

Timber-framed houses tend to be more responsive to heating and cooling than buildings with higher thermal mass. Occupants are kept comfortable by moderating internal temperatures to avoid extremes.

Comfort and energy efficiency can be maximised by avoiding unwanted heat loss or gain through the building envelope. This Guide gives solutions for achieving this with:

- appropriate building orientation and design
- insulating the building envelope well
- avoiding air infiltration

Useful information

The Guide includes:

- general and climate specific considerations
- useful references for further reading
- modelled house case studies
- principles for thermal comfort

1

Background

A house's thermal performance is its ability to provide a naturally comfortable environment all year round. To slow unwanted heat gain or loss, and so minimise the need for artificial heating or cooling, consider:

- **Insulation** - used to retard heat flows through the envelope
- **Sealing** – used to close gaps and limit air infiltration/exfiltration that would otherwise leak heat in or out of the interiors
- **Ventilation** – used to avoid heat build-up.

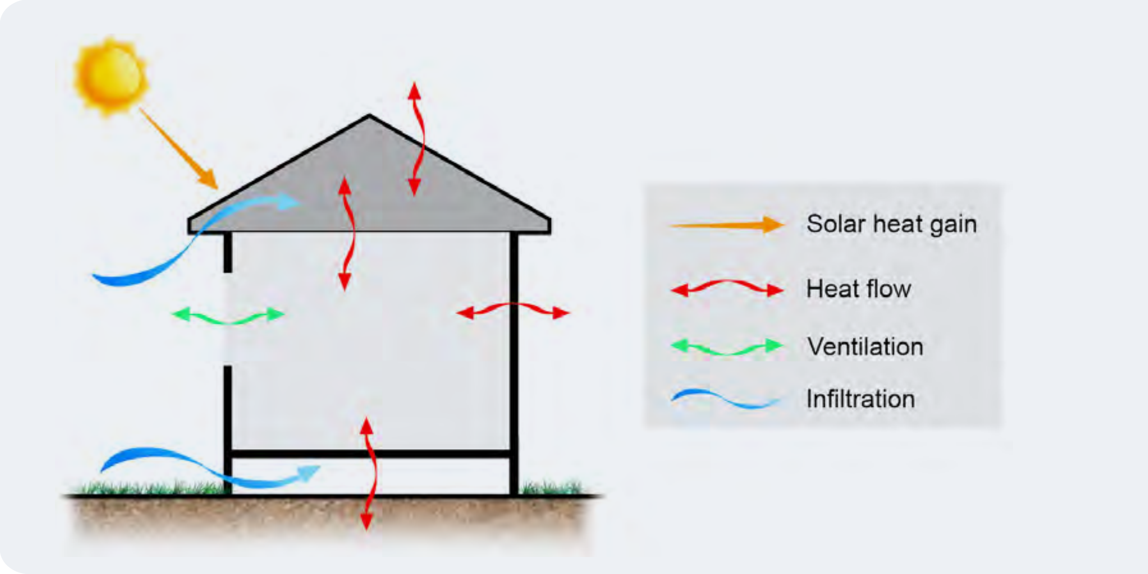


Figure 1: Energy flow in a residential building

1.1 Increasing Thermal Standards

Australia's Building Code has incrementally added controls designed to reduce energy use and greenhouse gas emissions. The National Construction Code (NCC) regulations apply to residential and most non-residential types of buildings and focus on:

- improving the thermal performance of the building envelope to reduce the amount of energy needed to heat or cool the building
- increasing the energy efficiency of fixed appliances within the building.

1.2 Purpose of this Guide

This Guide explains the principles of thermal performance and focuses on ways to enhance the performance of residential timber-framed buildings. It:

- explains principles of thermal performance for timber-framed construction
- provides strategies to optimise performance for each climate zone
- presents tips for increasing thermal performance efficiently.

The Guide focuses on detached or semi-detached dwellings but many of these principles are useful for larger timber-rich commercial and multi-residential buildings.

1.3 Designing Better Houses

To be effective, design strategies for efficient and economic thermal performance in new or renovated timber buildings must accommodate a complex interplay of factors. These include:

- **site location** - characteristics of the project's location and site, particularly its climate
- **building fit to site** - general arrangement of the building on that site
- **building planning** – planning interiors to work with natural site features such as desirable sun, shade and breezes
- **building design** - detailed design and construction of the building envelope.

These factors interact at different scales: at a site scale (e.g. climate and building orientation); at a functional scale (e.g. positioning of bedrooms and living spaces); and at an elemental scale (e.g. performance of windows, walls and floor elements).

Both general and climate specific considerations are listed a discussion of various building design elements.

Given the innate complexity of thermal performance for buildings in Australia's eight climate zones, it is difficult to provide concise design guidance. To obtain the best design results with timber-framed construction:

- use the principles and guidance in this Guide to improve both design choices and on-site construction practice
- model new house designs with thermal analysis software from an early stage in the design process
- model a number of variations to establish the most effective design features.

1.4 Using this Guide

The guide is divided into sections that address these and other key aspects of design for thermal performance:

Section 1. Background

Section 2. Codes and Standards
Includes the regulatory framework of the NCC and the various state variations, the broad working of the NCC-mandated energy rating software, and the relevant Australian Standards.

Section 3. Design Strategies
Provides general strategies for well-performing timber buildings, with suggested improvements for tuning the building's performance to match the climatic conditions of the site. Site factors are critical for the thermal performance of all forms of buildings, especially lightweight timber-rich structures.

Section 4. Planning Strategies
Outlines broad planning recommendations and discusses the potential for outdoor areas to contribute to thermal comfort and energy efficiency.

Section 5. Envelope Strategies
Discusses envelope strategies for timber-framed houses in detail. While site level factors are critical to overall performance, quality envelope performance provides the most immediate and effective means of ensuring ongoing thermal comfort. This section includes information on the control of structural moisture, the management of air infiltration and vapour movement, the requirements of insulation practice, window design, shading of the building and the potential and problems of thermal mass.

Section 6. Learning from Case Studies
Uses the lessons learnt from the computer modelling of two houses to illustrate the concepts discussed in this Guide. A range of building variations are modelled across a range of climates illustrating the how different climates require different design responses.

Section 7. Thermal Comfort and Technical Principles
Outlines key definitions and concepts of the thermal performance of lightweight buildings. These include aspects of the thermal comfort of occupants and performance of materials.

1.5 Continually Increasing Standards

Unlike more established areas of building practice, most aspects of the thermal performance of building are changing and are likely to continue to change over coming years. These include:

- **Regulatory aspects** - Thermal performance requirements have regularly increased since they were introduced in 2004. While requirements vary between Australian states, the national trend is for a continued increase in the regulated thermal performance of buildings.
- **Market expectation** - The building regulations impose accepted minimum requirements for thermal performance. The market is either accepting these minimums or requiring better-than-code performance. Given the difficulty of improving thermal performance after completion, the most cost-effective improvements are made during the design and construction process.
- **Construction practice** – New construction practices are evolving to meet increasing regulatory and market expectations.

1.6 Thermal Basics Refresher

The technical concepts involved in thermal principles are explained at the end of this Guide. Here is a summary of some basic thermal terms:

Comfort
Human thermal comfort is governed by the temperature of the surfaces that enclose us, the temperature of air within a room and the rate of airflow through a room.

Air
Buildings need to be vented to avoid a build-up of moisture, odours and carbon dioxide, and to provide fresh air for breathing. Air movement is also used to reduce heat build-up.

Moisture
In hot climates, humid air inhibits humans' ability to cool through perspiration. In hot and cold climates, condensation can lead to mould, which is hazardous to humans, and can lead to the decay of building materials.

Heat flow
Heat flows in one of three ways: radiation, conduction or convection.

Heat gain
Apart from body heat from humans and heat from equipment, the heat gain within a home can be from direct solar radiation, heat flow through the building fabric or unwanted hot air leaking into the building through gaps in the building fabric.

Solar radiation can be received through direct sunlight or indirectly through being radiated off hot surfaces around a building, such as adjacent walls or paving.

Heat loss
Heat loss in cool conditions occurs through mass conduction of the building envelope to the cooler outside air. In addition, air gaps – no matter how small – will lead to a loss of warm air.

Climate
Each climate has specific patterns of temperature, humidity and wind that need specific design responses. Exposed sites can experience magnified sun and wind effects, and sheltered sites can have microclimates that change conditions for a building. The Bureau of Meteorology website (bom.gov.au) provides local climate data on breeze direction and temperatures.

Passive vs active systems
Working with natural 'eco-services' such as the sun, wind and external air and ground temperature can maximise comfort and minimise energy use.

Passive systems work without using artificial energy and their use should be maximised. Active systems allow for a back-up when passive systems cannot maintain comfortable temperatures. A combination of passive and active technologies often creates the most effective compromise between control and energy efficiency use (such as prioritising ceiling fans over air-conditioning).

'Energy Rating'
Energy efficiency in houses can be measured in many ways, from home appliances to whole buildings. 'Energy ratings' for Australian dwellings are measured under a national system that computer models how well a building envelope will perform to keep a home's interior thermally comfortable.

2

Codes and Standards

Whether it is a design for a new house or an addition or retrofit for an existing house, the proposed building needs to comply with the minimum requirements detailed in each of the following codes or referenced standards:

- National Construction Code (NCC)
- State/jurisdictional variations
- Nationwide House Energy Rating Scheme (NatHERS)
- Australian Standards (when referenced in the above documents).

2.1 National Construction Code

The NCC specifies the minimum thermal performance requirements for buildings in Australia.

Thermal performance requirements for residential construction were introduced into Australia's building regulations in 2004, with a minimum 4-star requirement on a scale of 10 stars. The minimum requirements have continued to rise since then to a 6-star requirement in most states/territories in 2012. This increased requirement for energy efficiency has been expanded to include equipment such as lighting, hot water systems and heating and cooling systems.

Meeting NCC Standards

There are two ways to meet the NCC performance requirement:

complying with the 'Deemed to Satisfy' (DTS) provisions

OR

provide an acceptable 'Alternative Solution'

While many timber houses in Australia are built to the prescribed DTS construction, house designs from bespoke designers and builders who seek alternative formats need to be assessed for compliance with the NCC. A House Energy Rating Assessor uses approved software to simulate the building's thermal performance in the local climate, and produces a comprehensive report and a house energy star rating. An example of this report is shown in Figure 2.

A number of modelling software tools are accredited under the Nationwide House Energy Rating Scheme (NatHERS) that is mandated by the NCC. See Table 1.

Energy intensity (per square metre per year)							
Location	**5.0 Stars**	**6.0 Stars**	**% Improvement**	**7.0 Stars**	**% Improvement**	**8.0 Stars**	**% Improvement**
Broome	335 MJ/m^2	285 MJ/m^2	15%	234 MJ/m^2	18%	182 MJ/m^2	22%
Brisbane	55 MJ/m^2	43 MJ/m^2	22%	34 MJ/m^2	21%	25 MJ/m^2	26%
Perth	89 MJ/m^2	70 MJ/m^2	21%	52 MJ/m^2	26%	34 MJ/m^2	35%
Hobart	202 MJ/m^2	155 MJ/m^2	23%	113 MJ/m^2	27%	71 MJ/m^2	37%

Table 1: Energy efficiency improvement per star rating
This table shows the relative Improvement per star rating for given climates.

Allowing for climate variances

Although there are 69 climate classifications used for Australia in the NatHERS software, the NCC uses eight that are based on vapour pressure, air temperature and annual heating degree days. The description for each climate type follows internationally accepted definitions.

The average 3 pm *water vapour measure* is a key factor in determining the amount of moisture in the air and whether the climate is hot and dry or hot and humid. *Heating degree days* indicates the degree to which heating would be required to be comfortable for a given climate or building. The value is calculated on the number of days in a calendar year when the day's average temperature is below 18°C.

Generally, hot climates require cooling, temperate climates require cooling and heating, and cool climates require heating. Climates 1 to 4 have a nil heating degree days, whereas climates 5 to 7 have increasing values for heating degree days.

Climate Zone	**Description**	**Average 3pm January water vapour pressure**	**Average January maximum temperature**	**Average July mean temperature**	**Average annual heating degree days**
1	High humidity summer, warm winter	≥ 2.1kPa	≥ 30°C		
2	Warm humid summer, mild winter	≥ 2.1kPa	≥ 30°C		
3	Hot dry summer, warm winter	< 2.1kPa	< 30°C	≥ 14°C	
4	Hot dry summer, cool winter	< 2.1kPa	≥ 30°C	< 14°C	
5	Warm temperate	< 2.1kPa	< 30°C		≤1,000
6	Mild temperate	< 2.1kPa	< 30°C		1,000 to 1,999
7	Cool temperate	< 2.1kPa	< 30°C		≥ 2,000 Other than Alpine areas
8	Alpine areas are: (a) likely to be subject to significant snowfalls (b) in New South Wales, ACT or Victoria, more than 1200 m above the Australian Height Datum; and (c) in Tasmania, more than 900 m above the Australian Height Datum				

Table 2: NCC Climate Zone Definitions.

2.2 State/Jurisdictional Variations

Many state and local government agencies have additional legislation that applies to developments within their jurisdiction, which includes requirements for solar access and other aspects of amenity.

Developers and designers must be familiar with the federal, state and local government legislation that applies to their site and the desired development. This includes jurisdictional-based variations to the NCC.

NCC implementation varies at state/territory level in response to industry, economic and energy policy. NCC Section 3.12 requirements on energy efficiency variance per jurisdiction are set out in Table 3.

As thermal performance requirements are being continually reviewed and improved, consulting the local authority for a given project to confirm current regulatory requirements is recommended.

Victoria, Western Australia, and Australian Capital Territory
• Section 3.12 is generally adopted and a 6-Star requirement exists
Tasmania and Northern Territory
• BCA 2009 is adopted (5-star) but it is expected that 6-star provisions will soon apply.
Queensland
• Section 3.12 is generally adopted and a 6-star requirement exists. • There are options for outdoor living rooms and solar power to provide optional credits toward achieving a 6-star house. • Consult the local authority to establish the minimum star rating and optional credits that are available.
New South Wales
• The web-based BASIX building sustainability index is used in conjunction with section 3.12 of the NCC, but with broader scope, which includes water efficiency measures. • For energy efficiency, the BASIX system requires consideration of lighting, hot water system, and minimum insulation and glazing levels similar to those in the NCC, but the NCC should still be consulted to ensure compliance. • Designs that do not comply with BASIX energy efficiency requirements can use a house energy star rating to illustrate compliance with heating and cooling values designated per given postcode. • A lower star rating for timber platform floors is allowed with a concession that requires efficient heating and cooling equipment.
South Australia
• Section 3.12 is generally adopted and a 6-star requirement exists, however, some concessions apply for ratings less than this (refer to local authority). • Subject to house size and location, concessions exist for elevated timber-floor houses with a minimum 5-star rating, but these must include prescribed household solar power.

Table 3: Variations in state/territory thermal requirements.

2.3 Thermal Simulation

In the building design and approval process, the likely or theoretical passive thermal performance of the house is categorised using a star rating on a scale of 1 to 10 stars. The energy star rating results from a computer simulation of the thermal performance of the building's envelope under assumed occupancy and climatic patterns.

The simulation uses Home Energy Rating Software (HERS) to calculate the quantity of energy in megajoules per square metre that could be used to maintain thermal comfort within a house for a calendar year.

These tools are concerned with measuring heating and cooling energy loads; they do not currently assess domestic hot water, lighting or any other fixed or unfixed appliances.

The energy used to condition a home may primarily be for cooling (for example, in Broome), a combination of heating and cooling (Sydney) or primarily heating (Hobart), with milder climates generally requiring less energy for a given star rating. A rating of 10 signifying no heating or cooling should be required, see Table 4.

Star Rating	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	(MJ/m²/year conditioned floor area										
Launceston	895	740	513	366	272	208	160	117	74	33	1
Sydney	286	230	148	98	68	50	39	30	22	13	6
Broome	732	652	531	448	387	335	285	234	182	134	99

Table 4: Star bands for Launceston, Sydney and Broome

When designing a house or renovation, the most efficient way to compare the likely thermal performance of the design is to have varying designs evaluated by a trained assessor using Home Energy Rating Software (HERS). The HERS assessor should visit the site and model both the site and the house. The site model may include objects that provide shading, act as wind breaks and otherwise affect the house simulation.

To achieve a more practical and economic thermal performance for the house, a HERS professional should be engaged in the early stages of design, along with the architect or building designer. This will allow informed decisions to be made based on thermal efficiency and relative cost. Selecting a HERS assessor is similar to selecting any professional consultant – ensure that you are confident and at ease with their experience and communication skills prior to engagement.

2.4 Nationwide House Energy Rating Scheme (NatHERS)

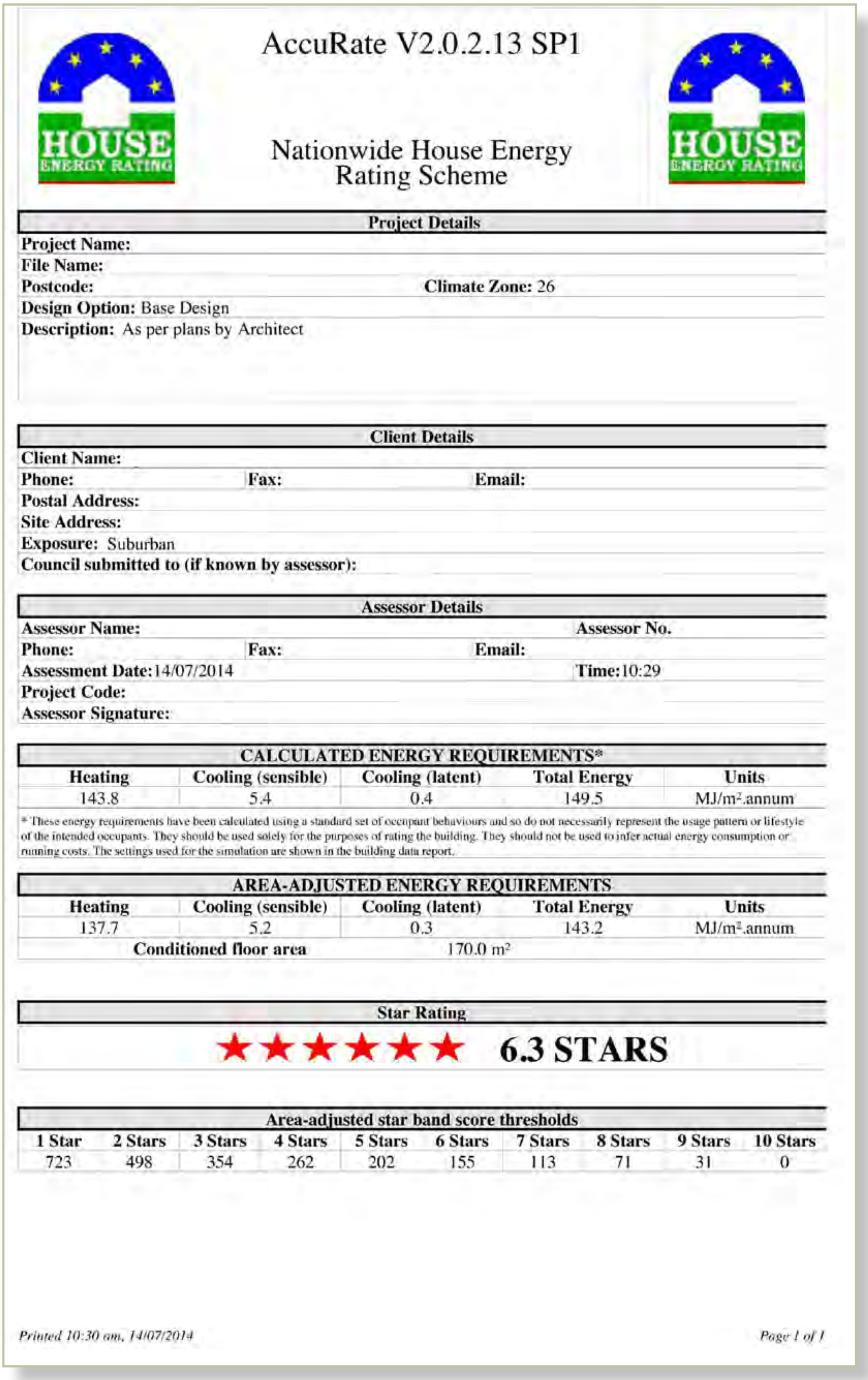
NatHERS was established by the Federal Government in 1993 to develop a mechanism to measure the relative thermal performance of new housing.

The scheme is constantly under review and is periodically recalibrated, based on industry and government research activities. The Federal Government and industry use the information gained by NatHERS to inform the improvement of minimum thermal performance requirements in the NCC.

There are three accredited NatHERS software tools for completing a house energy star rating assessment (Figure 2). These provide a comprehensive report and universal certificate. All three use the same CSIRO-developed building simulation software but have distinctly different user interfaces and levels of flexibility. The three tools are:

- **AccuRate** - The AccuRate tool has been developed by CSIRO and is the most complex, as it allows for the greatest flexibility in modelling a house, but it therefore takes longer to perform a house energy rating.
- **BERS** - The BERS tool has been developed in Queensland and has a more graphical user interface than AccuRate, enabling quicker simulation times.
- **FirstRate** - is the simplest of the three tools; it was developed in Victoria with a focus on standard residential building systems and volume builders.

The NatHERS approved software tools allow a deeper exploration of non-DTS designs and use 69 postcode-based climate zones, allowing a specific climate of the house location to be considered.



AccuRate V2.0.2.13 SP1

Nationwide House Energy Rating Scheme

Project Details

Project Name:
File Name:
Postcode: **Climate Zone:** 26
Design Option: Base Design
Description: As per plans by Architect

Client Details

Client Name:
Phone: **Fax:** **Email:**
Postal Address:
Site Address:
Exposure: Suburban
Council submitted to (if known by assessor):

Assessor Details

Assessor Name: **Assessor No.**
Phone: **Fax:** **Email:**
Assessment Date: 14/07/2014 **Time:** 10:29
Project Code:
Assessor Signature:

CALCULATED ENERGY REQUIREMENTS*

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
143.8	5.4	0.4	149.5	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
137.7	5.2	0.3	143.2	MJ/m².annum
Conditioned floor area		170.0 m²		

Star Rating

★★★★★★ **6.3 STARS**

Area-adjusted star band score thresholds

1 Star	2 Stars	3 Stars	4 Stars	5 Stars	6 Stars	7 Stars	8 Stars	9 Stars	10 Stars
723	498	354	262	202	155	113	71	31	0

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Figure 2: Sample of a house energy star rating report.

2.4.1 Heating and Cooling

The NatHERS-accredited software simulates the envelope of the house in a given climate and provides temperatures for each room for each hour of a full year. The simulated room data is used by the software to calculate the quantity of energy that may be required to condition rooms based on their usage type and accepted occupancy patterns. The temperature data will reveal rooms that may get too hot or too cold, and enable timely design intervention to improve the thermal comfort. This may include changing the windows, levels of insulation or room shading or an incorrect use of thermal mass. Each of these approaches can be tested in the house energy rating software.

Table 5 lists the standard room types in most houses and the times they are used. It also identifies which rooms are normally conditioned to make them thermally comfortable.

Room Type	Common Usage Patterns	Conditioned
Kitchen	6.00am to midnight	Yes
Dining Room	6.00am to midnight	Yes
Lounge Room	6.00am to midnight	Yes
Family Room	6.00am to midnight	Yes
Home Office	6.00am to midnight	Yes
Home Theatre	6.00am to midnight	Yes
Bedrooms	7 am to 9 am 6 pm to Midnight midnight to 7 am	Yes – Daytime thermostat temp. Yes – Daytime thermostat temp. Yes – Sleeping thermostat temp.
Bathroom	Random	No
Toilet	Random	No
Laundry	Random	No
Hallway	Random	No
Garage	Random	No

Table 5: NatHERS room conditioning patterns

2.4.2 Building Size

Australian houses have grown to be the biggest in the world, yet the number of people per household has either decreased, or not increased correspondingly. The size of a new house, regardless of its star rating, will play a significant role in the cost of construction, the amount of energy used for heating and cooling and lifetime maintenance and operational costs. Table 6 shows how house size affects heating and cooling energy costs.

	Conditioned Area (m^2)	Simulated Energy Use (MJ per year) and Cost					
		Launceston	Energy cost ($0.22/kWhr)	Sydney East	Energy cost ($0.22/kWhr)	Broome	Energy cost ($0.22/kWhr)
House 1	80.0	12,800	$2,816	3,120	$686.40	22,800	$5,016
House 2	150.0	24,000	$5,280	5,850	$1,287	42,750	$9,405
House 3	300.0	48,000	$10,560	11,700	$2,574	85,500	$18,810

Table 6: Energy use and building size
Possible conditioning energy use in a 6-star home relative to building scale.

Area Adjustment Factor

The Nationwide House Energy Rating Scheme encourages smaller houses through a star rating improvement via an Area Adjustment Factor (Table 7).

Location	50 m^2	150 m^2	250 m^2	350 m^2
Hobart	1.2 stars	0.3 stars	-0.4 stars	-0.8 stars
Perth	1.2	0.3	-0.3	-0.8
Brisbane	1.5	0.3	-0.4	-0.8
Darwin	1.7	0.3	-0.4	-0.8

***Table 7: Encouraging smaller houses** (from NatHERS)*
Impact of house size Area Adjustment Factor on final star ratings.

Larger houses may contain more volume with fewer walls, but overall will use more energy to heat or cool than smaller houses. To create incentive for smaller houses, the NatHERS and BASIX tools provide an adjustment factor for houses smaller than 200m2.

2.5 Australian Standards

Standards establish acceptable levels of performance for many aspects of industry, manufacturing, construction and services practice. Through government guidance, Standards Australia develops and revises standards with contributions from relevant industry groups and government agencies. The NCC references many standards relevant to the construction and thermal performance of housing. Some Standards relevant to this Guide are:

• AS 1288	Glass in buildings - Selection and installation
• AS/NZS 1680	Interior lighting
• AS 1684	Residential timber-framed construction
• AS 2047	Windows in buildings – selection and installation
• AS 3660	Protection of buildings from subterranean termites
• AS 3959	Construction of buildings in bushfire-prone areas
• AS 3999	Thermal insulation of dwellings – bulk insulation – installation requirements
• AS/NZS 4859	Materials for the thermal insulation of buildings

Other relevant standards of practice include the Australian Building Codes Board's Protocol for House Energy rating Software.

Figure 3: High performing social housing
Hopkins Street Affordable Housing Project is a multi-residential timber framed building with a 7.3-8.1 star rating. Source: Xsquared Architects, Photographer: Ray Joyce

3

Design Strategies

Strategies for the efficient design for thermal performance in timber-rich buildings must address the:

- characteristics of the site

Strategies for the efficient design for thermal performance in timber-rich buildings must address the:

- characteristics of the site

- general arrangement of the building and its surrounding landscape
- detailed design and construction of the building envelope

3.1 Establishing Performance Level

The star rating required under the NCC has increased over time, and is currently at 6 stars for most states/territories, although this varies from state to state as noted in Section 2. While the NCC provides a minimum standard, some owners may want higher performance. Any improvements in thermal performance will:

- give greater comfort for occupants
- save energy, as less will be required for heating and cooling
- deliver savings for the life of the house (50 years on average)
- be cheaper if designed in before construction, rather than added later.

Establishing best value

Better thermal performance offers residents significant energy savings for the life of the building, but improvements need to be balanced between insulation, infiltration control, glazing and thermal mass to gain the best value. Generally, it is easier and more economical to invest in:

- higher levels of insulation
- better-quality building wrapping (building paper, sarking, etc)
- better-performing windows
- more-efficient heating/cooling equipment.

The cost effectiveness of better-than-code enhancements will vary according to climate and also by builder – depending on how experienced they are with the chosen construction technologies. House Energy Rating simulation should be used to assess the thermal impact of each improvement. Research has found that increasing the thermal resistance value to the amounts shown in Table 8 can provide a significant benefit. However, the value of increasing insulation will vary subject to climate.

Location of Insulation	R-Value
Sub-floor – Platform floors	Up to R4.0
Sub-floor – Concrete Slab-on-ground	Up to R3.0
Walls	Up to R6.0
Ceiling	Up to R8.0

Table 8: Potential increased levels of thermal insulation.

3.2 Designing for Climate

A dwelling designed to respond well to climate can produce more comfort and liveability, and minimise the energy needed for additional comfort control.

Balancing internal and external conditions

Buildings tend to be warmer than their surrounding environment, due to their intrinsic enclosure and the heat generated by occupants and equipment. Designing for efficient thermal performance of most buildings requires limiting the amount of unwanted heat loss/gain through the building envelope (the floor, external walls and roof structure).

Timber buildings are more responsive

Conventional timber-clad and timber-framed buildings generally have lower thermal capacity than masonry buildings and, as a result, are more responsive to changes in external temperature. Compared to 'heavier' buildings, lightweight buildings:

- tend to cool down and heat up faster
- can be easier to heat and cool down
- can be less reliant on orientation for adequate performance.

Working with climate

To optimise comfort, it is important to control how much external temperature, solar radiation, breeze and humidity enters the building. This will need to be specific for a given climate. It means controlling:

- ***Solar heat*** – catching sun for heating and shading from the sun to keep cool.
- ***Air movement*** – opening up for cooling in non-conditioned space and closing down to contain heat.
- ***Heat gain/loss through envelope*** – using insulation to slow heat transfer and high quality, climate-specific building wrap to stop unwanted air leakage.
- ***Windows size and orientation*** – to control heat loss in winter and overheating in summer, as well as ventilation.

General strategic approaches for lightweight building are summarised in the sections below.

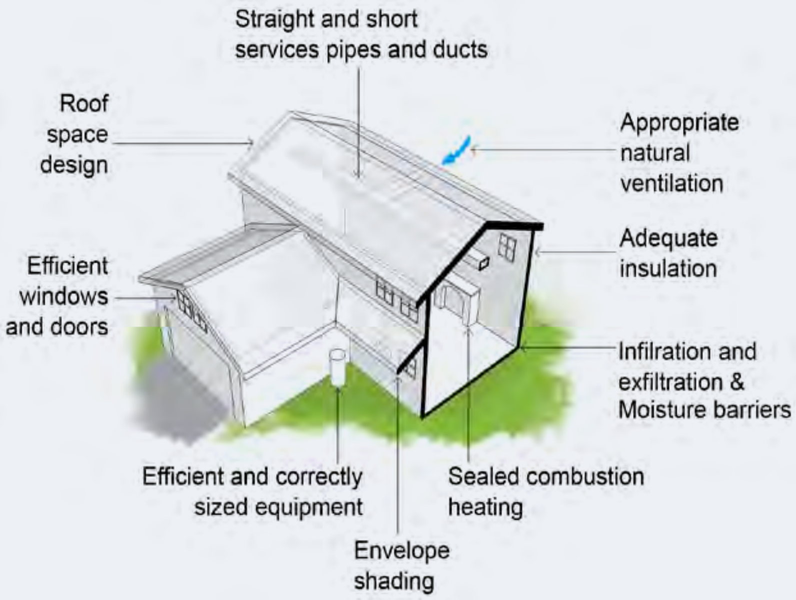


Figure 4: Key strategies in design and construction.

3.3 Designing for Sun

Passive solar gain is radiant energy from the sun that enters a building directly through glazed openings or indirectly by conduction through the envelope. Once inside, the energy heats up the air and thermal mass within a house. This can be exploited where artificial heating would otherwise be needed, although interiors can overheat in warm weather or with too much glazing.

Solar heat gain can be controlled with careful use of room planning, appropriate placement of glazing and shading. Eaves and other shading on the north can be designed to allow welcome lower altitude winter sun while cutting out unwanted higher summer sun.

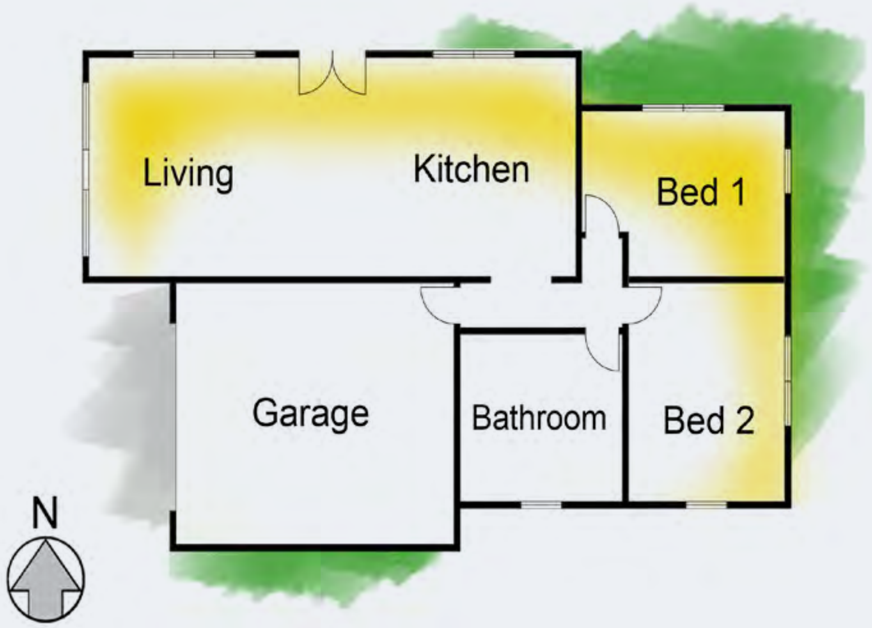


Figure 5: Plan for solar warmth.
Use room orientation, as well as window size and location to utilise sun in a cool climate.

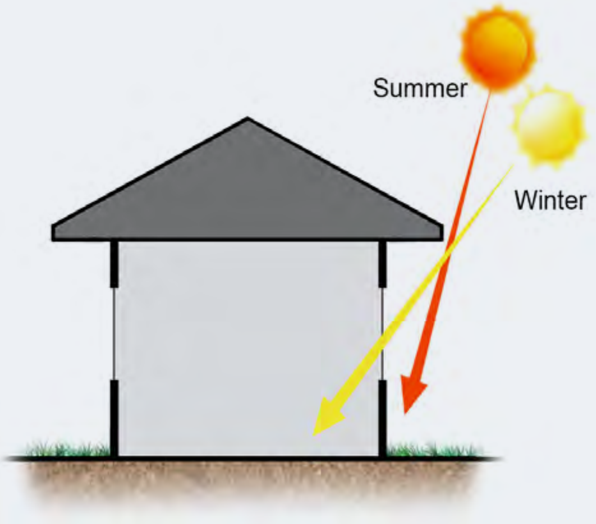


Figure 6: Control solar radiation.
Eaves and overhangs offer seasonal control of sun.

3.4 Considerations for Specific Climates

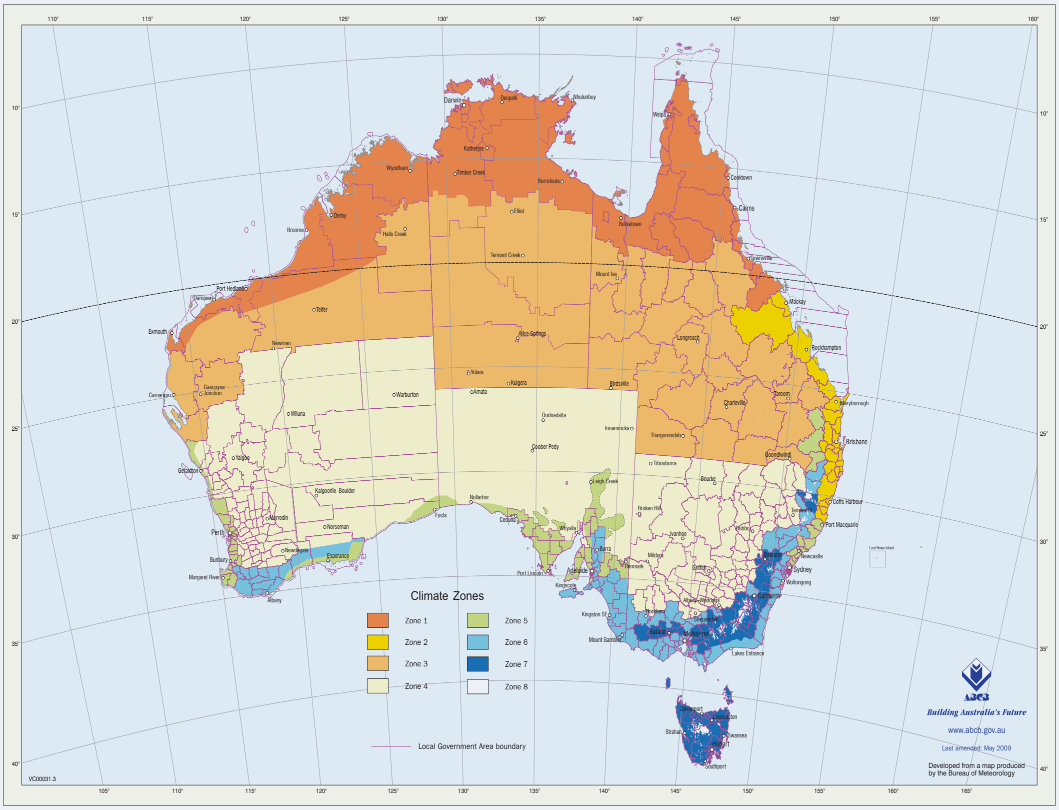


Figure 7: NCC climate map 2009.
Source: Australian Building Codes Board (ABCB) www.abcb.gov.au

3.4.1 Hot and Humid (NCC Climate Zone 1 and 2)

In hot and humid climates – focus on shading and maximising natural ventilation to non-conditioned spaces – both day and night.

Hot and humid climates have intense solar radiation and high rainfall. The intense direct and reflected energy in these climates places considerable thermal load on buildings. Shading the building envelope is very important. The consistently high temperatures create the need for cooling, while the high humidity limits the human body's ability to cool itself by perspiration.

The main focus of building for comfort in hot and humid climates is providing the capacity to open up the building to maximise ventilation, when the air temperature is suitable, while also maximising shading to limit solar gain.

Generally, designing a house for hot and humid climates should:

- limit unwanted heat gain (solar, conduction and infiltration)
- capture available cooling breezes day and night in a secure and weatherproof way
- provide internal spaces that can be efficiently conditioned
- allow good flow from internal to more comfortable outdoor spaces (day and night)
- avoid moisture build-up which can be a hazard to humans and the building.

3.4.2 Hot and Dry (NCC Climate Zone 3 and 4)

In hot and dry climates – focus on good shading to limit sun, and insulate for both hot days and cooler nights.

Hot and dry climates have intense solar radiation and low rainfall. In contrast to more humid climates, nights in hot and dry climates can be very cool. These extremes in day-to-night temperature place considerable thermal loads on a building.

There is little rain in this climate type but it can be brief and intense when it does occur.

Generally, designing a house for hot and dry climates should:

- limit unwanted heat gain (from direct sunlight, conduction through the envelope and air infiltration)
- capture available cooling breezes
- provide internal living spaces that can be efficiently conditioned
- allow good flow from internal to more comfortable outdoor spaces (day and night)
- provide water and moisture barriers to protect the building fabric and insulation.

3.4.3 Temperate (NCC Climate Zones 5 and 6)

In temperate climates – focus on capturing winter sun and insulate to keep winter warmth in, and summer heat out.

Temperate climates experience more moderate aspects of the conditions in hot and cool climates. The aim is to keep the heat in the building during winter and out of the building during summer.

Generally, designing a house for temperate climates should:

- capture winter sun
- limit unwanted heat gain/loss (sunlight, conduction and infiltration)
- shade to exclude unwanted summer solar radiation
- use natural ventilation to remove unwanted hot air.

3.4.4 Cool Temperate and Cold Climates (NCC Climate Zone 7 and 8)

In cooler climates – focus on capturing winter sun and keeping warmth in.

Timber houses in cool temperate and cool climates can require heating 8-12 months of the year. Summers are often mild and, if the house is adequately shaded and insulated, natural ventilation should provide most of the required cooling.

Due to high levels of heat, moisture vapour from house interiors can be forced into the building envelope by vapour pressure. This can be mitigated by correct and careful selection of sub-floor, external wall and roof space building wraps.

Generally, designing a house for cool temperate and cold climates should:

- exploit solar gain during colder months
- provide internal spaces that can be efficiently conditioned
- limit avoidable heat losses particularly through infiltration and exfiltration
- have access to wind-shielded sunny outdoor spaces
- pay special attention to avoiding moisture problems in the structure by using vapour breathable building wraps.

4

Planning Strategies

The thermal performance of new timber houses is influenced by the site's characteristics, the general arrangement of the building and its surrounding landscape and the detailed design and construction of the building envelope. This section deals with the larger-scale aspects of site and building orientation.

Section 5 deals with more detailed aspects of envelope detail and arrangement.

Design and planning strategies discussed in this section are:

- planning and site selection
- building orientation
- room and zone planning
- natural ventilation
- outdoor spaces and landscaping.

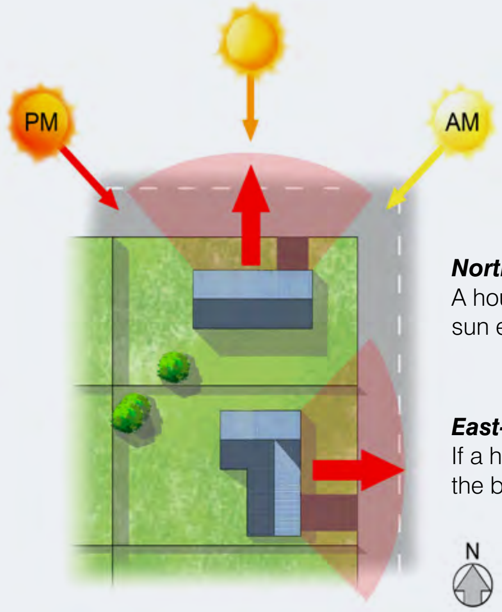
4.1 Planning and Site Selection

Selecting the right site for a house project can have a significant impact on the quality of living and thermal performance of the house.

A house's thermal performance needs to be considered when deciding on the land, the position of the house on the land, and the position and type of landscaping around the house. Each will affect the house's thermal performance and durability for its entire lifetime. In Australia, this is 50 years or more on average.

Consider the following in site selection:

- ***Solar radiation*** – access to direct solar radiation, especially in temperate and cooler climates.
- ***Breeze*** – access to prevailing breezes (especially in warm and hot climates) that can come from different directions in the morning and evening.
- ***Adjacent landscape*** – topography, vegetation and adjoining buildings can block sun and breezes which could bring benefits or be a hindrance, depending on the climate. These factors can also create a microclimate that can affect comfort.
- ***Site shape and orientation*** – house planning can be limited by the way a block sits relevant to the street and the northern sun.



North-south running block.
A house design running east-west allows good northern sun exposure to half the house.

East-west running block.
If a house is to face the street rather than run the length of the block, maximising solar control can be more difficult.

Figure 8: maximising solar control.

4.2 Site Master Planning

Before a house can be designed or planned in detail, a master plan for the site has to be developed. A master plan should balance the major functional and architectural requirements of the house, including characteristics that influence thermal performance. These include:

- ***Orientation*** – orientate the house to capture beneficial sun and breezes.
- ***Landscaping*** – add landscaping to improve the site's microclimate.

4.2.1 House Location and Orientation

Siting a house is inevitably influenced by the views, and location of street frontages and neighbouring buildings. However, a house's orientation with respect to solar radiation, shading, breezes and room-usage patterns has significant impact on its thermal performance. Research has shown that correct house orientation can save up to 60% of lifetime heating and cooling costs.

General considerations:

- ***Siting*** - locate the house to capture available cooling breezes, especially in warmer climates.
- ***Layout*** - position living spaces where they will benefit from solar heat gain when heating is needed and where solar gain can be minimised when cooling is required.
- ***Maximise daylight*** - use natural daylight to limit the need for energy-consuming electrical lighting. In some countries, regulations mandate no place within a room is to be more than 6 metres from an opening window.
- ***Passive solar heating*** - use solar heat for warmth wherever possible.
- ***Natural shade*** - use natural shade wherever possible and avoid exposure to the afternoon sun.
- ***Indoor-outdoor living*** - couple living areas with shaded outdoor spaces for summer.
- ***Capturing cooling breezes*** - allow the capture of breezes to provide an efficient and natural way to cool buildings and occupants in all climates.
- ***Eastern morning sun*** - use for warmth on cold mornings when appropriate.
- ***Northern sun*** - control exposure to the northern sun for the best orientation for solar heating.
- ***Western afternoon sun*** - limit this exposure; it is undesirable in most climate zones.
- ***Controlled shade*** - carefully design shading to allow warming sun in cooler months while excluding it during warmer months.

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Orientation*** - position the house to make the most of cooling breezes and shade it from unwanted solar radiation. • ***Breeze*** - focus on capturing breeze for living spaces in the afternoon and evening. • ***Western sun*** - limit exposure to western sunlight. It is difficult to control throughout the year due to its low altitude and overheating of western facades can render the house uncomfortably hot well into the night. • ***Southern aspect*** - use the southern aspect to create well-ventilated internal or external spaces on the south side of the building. These can make useful cool refuges.		• ***Orientation*** - position the house to promote use of solar passive design principles. • ***Layout*** - position living spaces to the north for winter sun. • ***Cold winds*** - block cold winds that will generate drafts inside the house. These drafts are a problem for efficient thermal performance in temperate and cool climates. Protection from cold winds by vegetation or built screens is desirable. • ***Eastern sun*** - use morning sun to provide warmth and physiological benefits. • ***Southern aspect*** - avoid using this aspect for habitable spaces as it generally gets no exposure to sunlight.	
• ***Eastern sun*** – give thought to this exposure – early summer sun can cause overheating.	• ***Solar passive design*** –orientate the house to assist solar passive design principles. • ***Eastern sun*** – consider making use of the eastern sun – it may be wanted on winter mornings.	• ***Northern sun*** – position living spaces to the north but with access to cooling breezes, especially in summer.	• ***Northern sun*** – position living spaces to the north and spaces likely to be used in the morning to the north or east. •***Avoid cold winds*** – limit exposure to cold winter winds.

Further resources: *Window Energy Rating System (WERS) - for details about How To Select Windows (www.wers.net/werscontent/how-to-select-windows)*

Your Home Technical Manual - for details about Passive Cooling (www.YourHome.gov.au/technical/fs46.html)

4.2.2 Landscaping

Plants, screens and other landscaping items are a key component of the site master plan as they improve the thermal performance, privacy and comfort of a house.

General considerations:

- ***Visual amenity*** - landscaping can be used to balance views with privacy.
- ***Shade*** - trees and shrubs can be used to limit direct sun on the building.
- ***Wind control*** - trees can direct wind and breezes.
- ***Foliage*** - as well as shade, plants can provide cooler microclimates through evapotranspiration from leaves.
- ***Seasonal sun*** -careful location, spacing and selection of deciduous and non-deciduous plants allow the timing and extent of shading and wind moderation to be controlled.
- ***Targeted shade*** - small, contained trees and landscape screens with or without associated climbing plants can provide focused shade on specific openings, elements or areas.
- ***Trellises*** - climbing plants over timber or wire screens are effective in controlling exposure to the western sun.
- ***Risk*** - having landscape elements close to the house for amenity reasons needs to be balanced with risk from bushfire, high winds or cyclonic conditions.

Climate specific considerations:

<table>
<tr><th>Zones 1 and 2
<i>Hot and humid</i></th><th>Zones 3 and 4
<i>Hot and dry</i></th><th>Zones 5 and 6
<i>Temperate</i></th><th>Zones 7 and 8
<i>Cool temperate and cold climates</i></th></tr>
<tr><td colspan="2">• <i>Tall trees</i> - can be used to block solar radiation from the walls, windows, roof and surrounding ground and still allow breezes.
• <i>Lower trees</i> - shaded ground and paving radiate less heat into the house and can provide a more comfortable microclimate around the perimeter of the house.
• <i>Screens</i> - shrubs grown close to the house provide additional shading and privacy.
• <i>Vines</i> - climbing plants over timber or wire screens are effective in controlling exposure to the western sun.</td><td colspan="2" rowspan="2">• <i>Cold winds</i> - use trees or built screens to block undesirable cold winds that can cause drafts inside the house.
• <i>Winter courtyards</i> - shrubs can be used to provide outdoor spaces that are sheltered from cool breezes.
• <i>Seasonal sun</i> - deciduous trees can provide shade in summer but permit additional solar gain when the leaves fall in colder months.
• <i>Winter sun</i> - ensure winter solar access is maintained</td></tr>
<tr><td>• <i>Breeze</i> – note morning and afternoon cooling breezes can come from different directions.</td><td>• <i>Increasing humidity -</i> vegetation can improve comfort by increasing humidity.</td></tr>
</table>

Further resources*: Your Home Technical Manual – for details about Shading (www.yourhome.gov.au/passive-design/shading)*

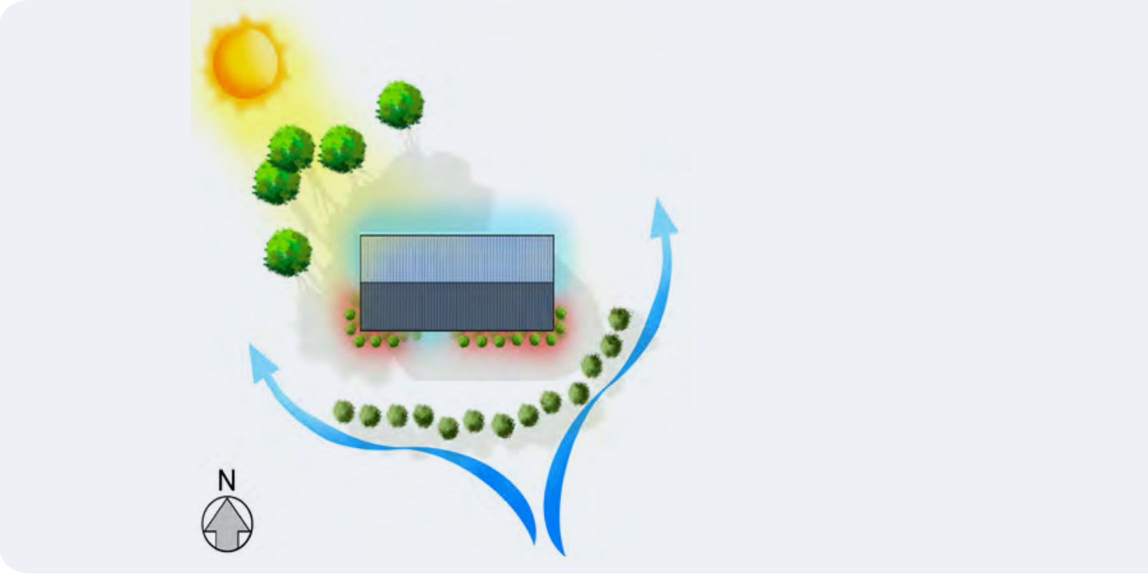


Figure 9: Divert cold winds. *Trees can divert unwanted hot and cold winds*

Figure 10: Blocking western summer sun. *Trellises with climbing plants can be used to shield western façades. (Photo: Gregory Nolan)*

Figure 11: Creating cooler microclimates. *Plants integrated into decks and screens. (Courtesy of CplusC Architectural Workshop)*

4.2.3 Internal Conditioned Spaces

Internal spaces in the house can be grouped into zones based on their function, common usage pattern and the likelihood that they will be conditioned. Zoning rooms helps clarify which ones need to be thermally comfortable and at what time of day. Prioritising the thermal comfort of rooms in this way allows planning that will incorporate the site sun and breezes – maximising comfort, while minimising the energy usage.

Although individual families will live differently, NatHERS provides assumptions for how rooms are used. These assumptions provide a good guide to design.

Maximise passive systems to minimise energy use

4.2.4 Passive vs Active Systems

Buildings can be heated or cooled by passive or active means, or a mixture of the two. Using well-placed windows to bring in winter sun for warmth or summer breezes for cooling are considered passive methods. The use of mechanised equipment to provide heating and/or cooling is considered an active system.

4.2.5 Containing Conditioned Spaces

Modern houses tend to have living, dining and kitchen spaces effectively joined together into one open-plan space. The increased volume of these combined spaces and connected hallways can significantly increase the volume of air requiring conditioning to expected levels of thermal comfort. There are two cautionary aspects to room volumes. In hotter climates, having a larger volume can keep the warmer surfaces of the walls and ceiling further away from the room occupants, making the room feel cooler. In temperate and cool climates, where the inside walls should not be as warm, smaller volumes significantly affect the energy needed to heat and cool a home.

Dividing spaces with doors that control air movement can increase comfort and save energy. Common room and zone concepts include:

- ***Living space*** - are critical thermal comfort areas and need maximum comfort so they should be contained with separation from entries, halls and other spaces.
- ***Dining rooms*** - often connect to living rooms and kitchens for function but are often used for short periods.
- ***Kitchens*** - need more venting to exhaust odours and heat from cooking and so can remove conditioned air from interiors as well.
- ***Hallways***- can be used as breezeways in summer, but there is generally little need for conditioning.
- ***Bedrooms*** - avoid overheating in bedrooms from western summer sun, although in cooler climates an eastern aspect can provide welcome morning warmth. The conditioning focus is afternoons and overnight, with acoustic and visual privacy being a high concern. Note that most people sleep with bedroom doors closed, which can prevent cross ventilation if there are not multiple windows.
- ***Bathrooms*** - the use period is short and ventilation needs to be high to remove excess moisture from the house. Heat loss through bathrooms is exacerbated through the common practice of leaving doors to bedrooms or hallways open.
- ***Home office*** - positioning these areas to the north in most climates can maximise daytime comfort and light.
- ***Auxiliary spaces*** - comfort in non-habitable rooms such as laundries, pantries and other storage spaces is less of a concern, so these spaces are frequently placed to the south.
- ***Garages*** - as these are not considered habitable, they can be positioned to block undesirable aspects such as the summer afternoon sun.

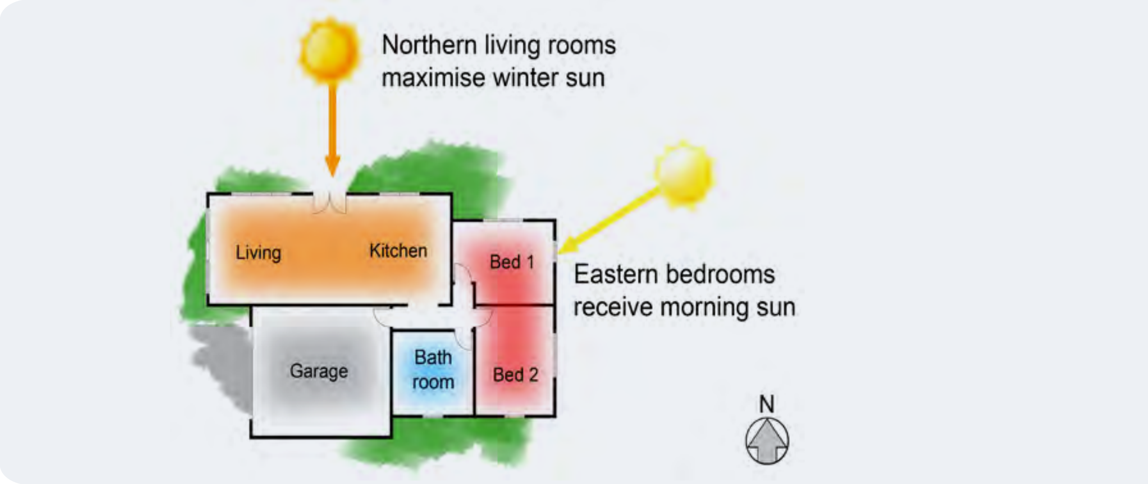


Figure 12: Orientation for non-tropical dwellings. *Appropriately orientated and zoned timber house south of the Tropic of Capricorn.*

4.2.6 Outdoor Spaces

Australia's climates are generally mild, which promotes outdoor activities. Well-designed outdoor spaces can extend living areas and provide relief from thermally uncomfortable houses. Multiple outdoor spaces can be positioned to suit different seasons and can include living rooms, decks, verandas, pergolas or garden areas for eating and relaxing.

General considerations:

- ***For hot weather*** - focus on maximising shade and capturing predominant breezes.
- ***For cooler weather*** - focus on capturing sun while sheltering from cool breezes.
- ***Rain protection*** - aside from protecting furniture, rain protection is unlikely to be required in cooler weather when spaces won't be used if there is no sun, as opposed to hotter climates, where outdoor spaces might be used in wet or dry weather.
- ***Fans*** - some climates will benefit from adding fans to outdoor living spaces.
- ***Protection*** - consider security and protection from insects, dust and wind-blown rain when designing for outdoor living.

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Shaded spaces*** – consider providing in hot climates for summer. • ***Separate sunny spaces*** – can provide options during winter.		• ***Catch sun –*** in cooler climates, a sheltered space to capture the sun is invaluable. • ***Wind shelter*** – winter spaces need to be in the sun and protected from cold winds or drafts.	
• ***Warm-nights*** – Consider extended night-time use of outdoor spaces.	•***Cooler nights*** – nights tend to be noticeably cooler in drier climates.	• ***Shade*** – daytime summer temperatures can still be extreme and require shade.	• ***Limited shade*** – the need for shade might be limited during a short summer.

Further resources: *Your Home Technical Manual – for details about Passive Cooling (www.YourHome.gov.au/technical/fs46.html)*

Figure 13: Screened outdoor space. *If rain protected, these spaces can function as outdoor rooms in warmer climates. (Courtesy of CplusC Architectural Workshop)*

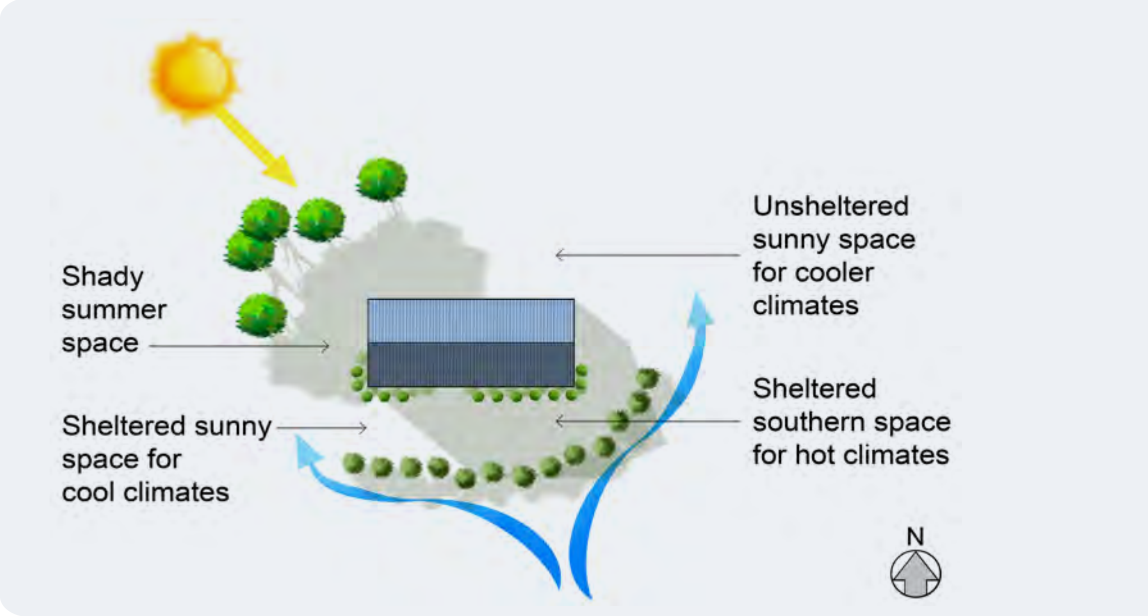


Figure 14: Design for outdoor living.

4.2.7 Natural Ventilation

All houses require ventilation to remove stale, polluted and oxygen-depleted air. Natural ventilation can be used to provide passive cooling. Additional active systems such as fans can be used to enhance this natural effect at low cost. Air movement is generated by a change of air pressure, which can be generated by wind pressure, or rising hot air as it expands.

Ventilation rates

There are minimum levels of ventilation required to maintain a healthy internal environment. Internationally, it is accepted that a house should have 0.25 air changes per hour (ACH). To provide the potential for natural ventilation, the NCC establishes a minimum requirement for openings in habitable room of not less than 5% (1/20) of the room's floor area. Although such openings may allow for convection to exhaust warm and polluted air, minimal openings do little to guarantee comfort.

For natural ventilation to work effectively without active means, a building's external openings need to be exposed to differential air pressures. Openings on the windward face of a building are subject to a positive air pressure; openings on the leeward side of the building will be subject to a negative air pressure. If the building's depth does not provide too much resistance, airflow will be generated between windows exposed to differential air pressures.

General considerations:

- ***Natural ventilation*** - encourages physiological cooling, removes unwanted stale and hot air and gets rid of heat that may have built up in the internal building fabric.
- ***Stack ventilation*** - paired low and high openings allow fresh air to be drawn in at a low height and hotter stale air to rise and flow out higher openings (Figure 17).
- ***Cross-ventilation*** - even slight breezes can create airflow through a building when it has opposing openings of adequate size, but this doesn't work when multiple windows are placed in the same wall (Figure 18).
- ***Single-loaded corridors*** - plans with rooms only to one side of a hallway provide greater potential for cross ventilation than 'double loaded' hallways.
- ***Double-loaded corridors*** - plans with rooms both sides of a corridor provide more compact planning, although free air movement is more inhibited, especially when opposing rooms rely on their doors as well as windows being open to gain cross ventilation (see Figure 16).
- ***Windows type*** - different types of windows allow different opening areas and each offers additional benefits: double-hung windows can aid stack ventilation, awning windows can be left open during rain, and casement windows 'catch' the breeze, even if it is moving parallel to the wall surface.
- ***Privacy and security*** - most people sleep with bedroom doors shut – restricting the possibility for cross ventilation unless alternate air paths have been allowed for.

Climate specific considerations:

Zones 1 and 2 *Hot and humid*	**Zones 3 and 4** *Hot and dry*	**Zones 5 and 6** *Temperate*	**Zones 7 and 8** *Cool temperate and cold climates*
• ***Stack ventilation*** – high-level windows can provide more secure venting of heat, particularly overnight. • ***Air-tightness*** – Air-tight construction is important to minimise unwanted heat gain.		• ***Air-tightness*** – Air-tight construction is important to minimise heat-loss.	
• ***Evening ventilation*** - continued ventilation is required for comfort in evening. • ***Low windows*** - Ensure low-level openings to promote the entry of cooler outdoor air.	• ***Evening ventilation*** - evening temperatures can be much cooler and thus less ventilation is required.	• ***Warm breezes*** - warm breezes in winter can help remove the chill from cool rooms.	• ***Avoid drafts*** – consider providing for ventilation but avoiding drafts.

Further resources*: Window Energy Rating System (WERS) – for details about How To Select Windows (www.wers.net/werscontent/how-to-select-windows)*

Your Home Technical Manual – for details about Passive Cooling (www.YourHome.gov.au/technical/fs46.html)

Ventilation of buildings

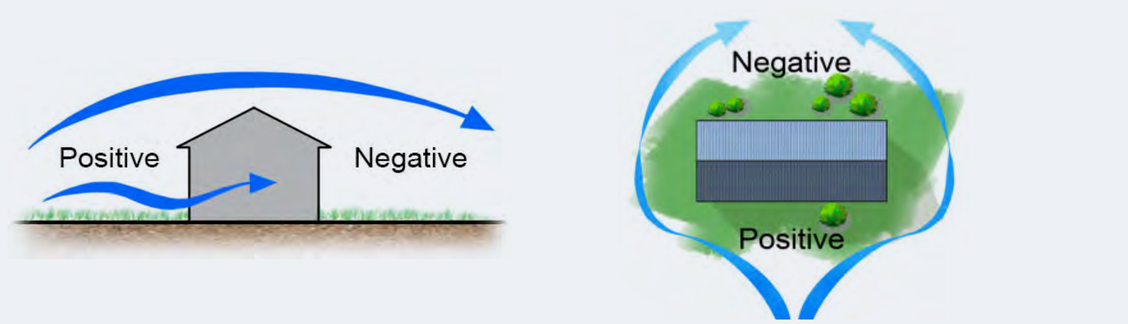
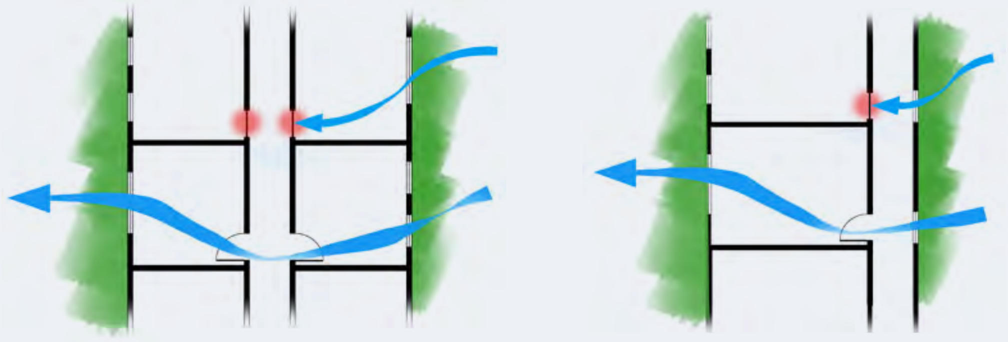


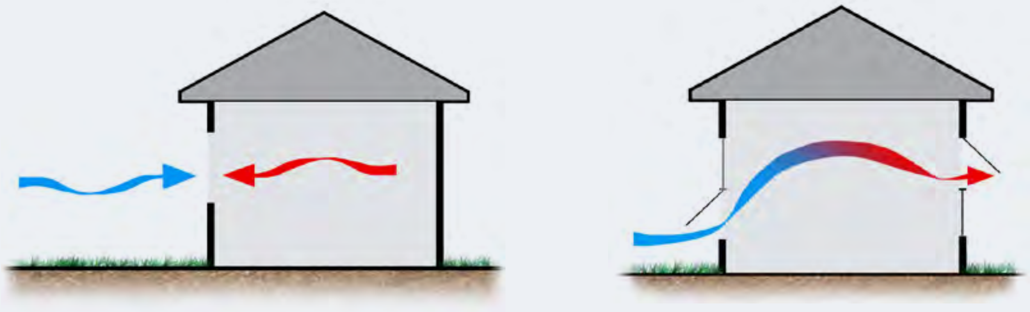
Figure 15: Wind pressures on buildings.
Wind creates differential air pressures on the windward and leeward sides of the house.



Double-loaded hallways limit cross ventilation - consider roof windows.

Single-loaded hallways increase the potential for cross ventilation.

Figure 16: Narrow buildings allow greater ventilation.



Single openings don't benefit from cross ventilation.

Combine stack and cross ventilation.

Figure 17: Number of openings.

Adjacent openings don't promote cross ventilation.

Opposing openings promote cross ventilation.

Figure 18: Location of openings.

5

Envelope Strategies

The thermal performance of a building is determined by the amount of moisture, air and heat passing through the envelope. The envelope of a house consists of its floor, walls, windows, ceiling and roof. This section covers the critical control of moisture, air and heat through the envelope. It discusses:

- structural moisture control
- control of infiltration, exfiltration and vapour through the wall systems
- thermal insulation
- the performance of window and doors
- eaves and external shading
- thermal mass
- conditioning and other equipment and services.

Balancing insulation

The thermal performance of the envelope involves the balance between the levels of insulation, the area of glazing and the amount of thermal mass. The simplest way to determine an economic balance of these elements is to test variations through thermal modelling.

Heat and moisture control

The external and internal climatic variables that affect the thermal performance of the house envelope include:

- ***Solar radiation*** - including direct radiation from the sun and indirect radiation from surrounding objects and the ground heated by the sun.
- ***Conductive heat gain*** - the conductive effect from internal and external air and material temperatures and the temperature of external surfaces such as adjacent ground temperature.
- ***Convected heat gain*** - the convective effect from internal and external air movement.
- ***Air movement*** - unwanted heat loss or gain from uncontrolled air infiltration and exfiltration.

A natural material such as timber needs to breathe

Roofs play a key role in protecting buildings from the penetration of rain and heat. Depending on thermal insulation, they can protect ceilings from significant heat gain but, just as importantly, they can shade walls to limit solar heat gain from direct sun.

5.1 Structural moisture control

The control and management of moisture within the built fabric must be considered for all climates, based on two principles:

- ***Moisture exclusion*** - the capacity for the envelope to prevent unwanted moisture entering the building from the rain and ground.
- ***Moisture vapour*** - the capacity for the envelope materials to allow or block the flow of water vapour through the building envelope, subject to climate and heating and cooling systems.

The roof and walls must resist moisture from rain, snow and other precipitation; the walls or the sub-floor structure must resist moisture from the ground. The NCC lists minimum performance standards.

General considerations for ground and storm water

- ***Site falls*** - the site should be graded away from the building for a minimum of 1 m (ideally 3 m) and landscaped to direct surface and sub-surface moisture away from the building.
- ***Drains*** - drains should be provided on the uphill side of the building to minimise ground water near the building.
- ***Under floors*** - the ground beneath platform floors should be above adjacent ground and graded to prevent ponding.

General considerations for sub-floors, walls and roof

- ***Flashings*** - breaks in external wall cladding systems caused by joins, windows, doors and other penetrations should have lapped flashings to direct water to the exterior surface.
- ***Moisture control*** - high quality moisture barriers that stop moisture moving from behind the cladding system to the inner structure should be applied to walls and roofs. A high quality of wall wrap installation will also minimise air infiltration and exfiltration.
- ***Cladding*** -pre-primed timber cladding should be installed with an air space between the cladding boards/panels and the wall wrap.

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Moisture and vapour protection*** - a high quality building wrap that is water and vapour impermeable.	• ***Moisture protection*** - a high quality building wrap that is water impermeable but may be vapour permeable.		
• ***Drafts*** - a high-quality installation of a good building wrap system will also help in vapour management and provide a significant control of unwanted hot and cold drafts within the home.			

Further resources:

Your Home Technical Manual – for details about Insulation (www.YourHome.gov.au/technical/fs48.html)

Insulation Council of Australia and New Zealand Insulation Handbook (www.icanz.org.au/wp-content/uploads/import/pdf/17132_ICANZ_HANDBOOK.pdf)

Australian Standards – As NZS 4200.1-1994 Pliable Building Membranes and Underlays Materials

General considerations for roofs

- ***Sarking*** – install high-quality reflective sarking to help control inward-bound moisture and reduce unwanted heat radiation from the roofing material.
- ***Ventilation*** – ensure the roof space is well ventilated to remove unwanted heat and moisture.
- ***Ducting vents through roof*** – do not duct bathroom and kitchen ventilation into the roof space.
- ***Gutters*** – roofs should be guttered, and any run-off from un-guttered roofs should be at directed at least 1 m away from walls.
- ***Shading*** – a well-designed roof can also provide shading to the walls and rooms below

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Ventilate roof space*** – provide high levels of ventilation to allow unwanted hot air and moisture to leave. • ***Bushfire*** – consult your local authority about the type of meshes that can be used to allow roof space ventilation but stop ashes and cinders from entering.			

Further resources:

Your Home Technical Manual – for details about Insulation (www.YourHome.gov.au/technical/fs48.html)

Insulation Council of Australia and New Zealand Insulation Handbook (www.icanz.org.au/wp-content/uploads/import/pdf/17132_ICANZ_HANDBOOK.pdf)

5.2 Vapour management

Controlling the movement of vapour through the external skin of the home is an important function of the building envelope. Significant damage can occur to the built fabric if the movement of vapour is not managed. In this context, the problem is called 'vapour pressure'. Good construction will have three opportunities to manage vapour pressure and the subsequent movement of vapour into and through building elements. These are:

- ***External cladding system*** – The cladding system should not touch the building wrap. Ideally, the cladding system is fixed to battens, which provide a vapour zone between the cladding and the building wrap. This type of construction can also reduce the chances of damaging the building wrap and is suitable for all climate types.
- ***Building wrap systems*** – Building wrap systems vary depending on climate type. In a hot and humid climate, vapour wants to migrate into the house, while in a cool climate the water vapour generally wants to migrate out of the house. The temperate and hot and dry climates can provide a more complex situation as the water vapour will want to migrate inward in hotter periods and outward during cooler periods. This can be a daily or seasonal pattern. In some climates, an additional building wrap on the inside of the timber framing may be advantageous.
- ***Internal linings*** – All lining materials have intrinsic vapour permeability properties. Most timber products, plasterboard and some paints are vapour permeable, allowing vapour to penetrate the internal skin and allowing it to pass through to the permeable insulation and timber framing.

Special notes on building wraps:

- Building wraps come with a wide range of properties, from a non-permeable moisture barrier to a permeable moisture barrier.
- Generally, a permeable (breathable) system should be used for houses in a climate where heating is used.
- Additionally, the building wrap can provide significant infiltration control. In this case there must be no holes in the product.
- A good-quality product that is resistant to external moisture and provides good infiltration control can be vapour permeable, even if it has no visible holes.
- Manufacturers provide a range of products and they should be consulted to establish the minimum and best product for a particular house relative to its climate and the heating and/or cooling systems intended to be installed.

Vapour impermeable	Vapour semi-impermeable	Vapour semi-permeable	Vapour permeable
Polyethylene Vinyl Glass Aluminium foil Sheet metal Foil-faced insulation	Oil-based paints Some vinyl wall coverings Extruded polystyrene Paper-faced bulk insulation	Plywood Particleboard Expanded polystyrene Most plastic paints	Unpainted paper-faced plasterboard Unpainted plaster Bulk insulation such as rock-wool, glass-wool and polyester Cellulose insulation Timber Clay bricks Concrete blocks

Table 5: Building materials and vapour permeability.

Climate specific considerations – showing vapour travel direction:

Zones 1 and 2 *Hot and humid*	**Zones 3 and 4** *Hot and dry*	**Zones 5 and 6** *Temperate*	**Zones 7 and 8** *Cool temperate and cold climates*
• ***Refrigerated A/C*** – this creates dryer internal conditions, therefore adopt impermeable wrap to avoid moister ingress	• ***Cooling system*** – if evaporative cooling is used adopt a vapour permeable system	• ***Vapour reversal*** – adopt a vapour permeable system in this climate due to frequent reversal of vapour pressure	• ***Walls*** – generally can be permeable • ***Ceilings*** – constant vapour migration into roof spaces can cause rapid decay of structure. Application-specific permeability requirements should be confirmed with wrap manufacturers
General direction of vapour flow			
• inward	• both directions	• both directions	• both directions
When heating is in use			
• N/A	• outward	• outward	• outward
Refrigerated air-conditioning			
• inward	• inward	• inward	• inward
Evaporative cooler			
• N/A	• outward	• outward	• outward
Be sure to consult a suitable manufacturer about the building wrap system for your house in your climate with your heating and/or cooling system.			

Further resources*:*
ABCB Condensation in Buildings: www.abcb.gov.au/en/education-events-resources/publications/abcb-handbooks

5.3 Air-tightness

Air movement through the building envelope reduces the thermal performance of all buildings and is particularly important in lightweight timber-framed buildings. Unwanted infiltration of hot or cold air can lead to more pollutants, dust, moisture and noise within the house and an increased need to use heating and cooling equipment to maintain thermal comfort. Similarly, points of unwanted air exfiltration can become locations for excessive condensation and diminish thermal comfort and energy efficiency. While other countries have regulations and tools that mandate a level of airtight construction for buildings, Australian jurisdictions currently do not. The NatHERS-accredited House Energy Rating Software programs currently use the default infiltration rates specified within NatHERS, and therefore cannot show the benefits of tighter construction.

Wrap well:
more air gaps =
more energy loss

Increasing air-tightness to save energy

Good airtight construction avoids uncontrolled infiltration and exfiltration. When paired with well-designed controlled ventilation, this will provide a healthier home in most climates.

Although the air-tightness of most buildings is never known, tests conducted on typical Australian houses suggest they are not very airtight with a rating on average at 1.72 air changes per hour (ACH), varying from 0.4 to 3.67 ACH. Generally, Europe and the UK have a stronger focus on energy conservation and have standards on air-tightness. By comparison, the voluntary Passivhaus standard for Europe is producing construction that is about six times more airtight at 0.25 to 0.3 ACH.

Air-tightness and internal lining

Air leaking from a building interior into a wall or ceiling structure not only loses heating or cooling energy from the interior, but can also carry moisture as discussed above. To limit this, the internal linings can be constructed to provide a secondary airtight skin to retard air movement leakage. Well-installed floor, wall and ceiling lining will further reduce air leakage. Take care in lining detailing and construction at the ceiling-to-wall and wall-to-floor junctions, which are common points for leakage in Australian homes.

Measuring air-tightness

The infiltration and exfiltration in a house can be measured by a blower door test. This test, which has been in use internationally for the past decade, has become an economical method of testing houses for unwanted air leakage (Figure 28). It consists of a fan temporarily sealed into an external doorway. The fan depressurises and pressurises the house to pre-set levels – mimicking the pressure differential that a house experiences from wind.

This test allows easy location of areas with unwanted air leakage during construction. With the blower door operating, a small smoke-producing device can clearly indicate significant leakage points. If this test occurs before the external cladding is installed, leaks can be easily repaired. If it is delayed until the commissioning of the building, repairs – if possible – will be much more difficult and expensive.

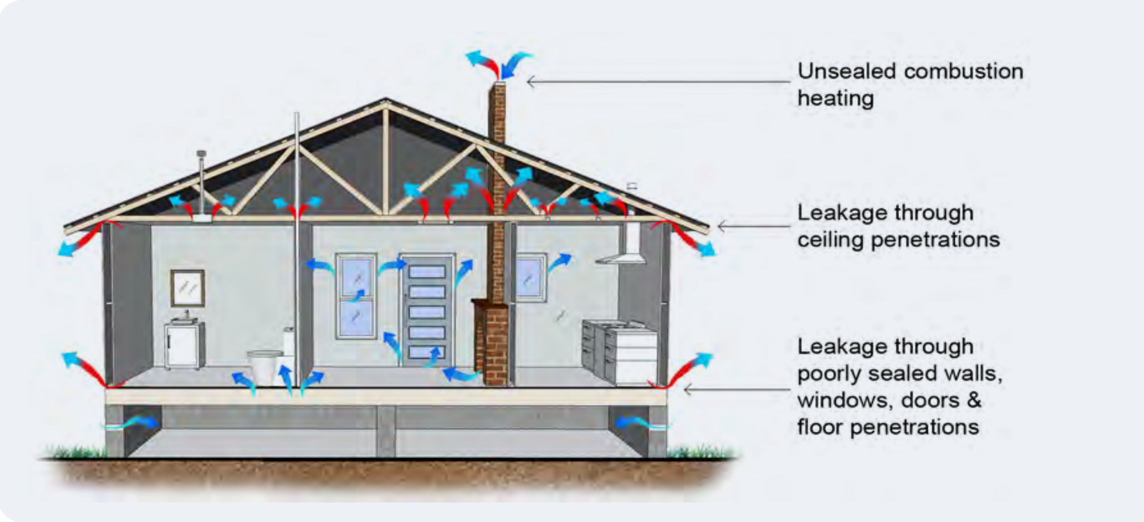


Figure 19: Air leakage. *Common locations of air leakage in house construction.*

General considerations:

- ***Continuous linings*** - provide continuous sheet wall, floor and ceiling linings that are appropriately installed and sealed at corners and joints.
- ***Tapped joints*** - install high quality building wraps to walls, floors and ceilings with lapped and taped joints (Figure 21).
- ***Wrap extent*** - extend the building paper without breaks between the sub-floor and the ceiling space (Figures 26 and 27).
- ***Seal wall framing to floor*** - apply weatherproof sealant between bottom plate of the external wall frames and the floor they sit on.
- ***Downlights*** - reduce downlight penetrations through the ceiling where possible and use proprietary hoods with low wattage fittings to reduce heat build-up and allow insulation to safely abut fitting. Each downlight can ‘leak’ 1 litre per second of warmed or cooled air out of the room, and has the potential for wind pressure to force 1 litre per second of hot air from the roof space into the rooms below.
- ***Service penetrations*** - carefully seal all plumbing and electrical service penetrations with caulk, wrap or tape where they penetrate the floor, wall and ceiling lining. This includes pipes, conduits, waste water pipes, bathtubs, showers, electrical fittings and electrical circuit boards.
- ***Conditioned spaces*** - wrap and fully insulate the walls and roofs between unconditioned and conditioned spaces.
- ***Seal window and doors*** - wrap, tape, seal and weatherproof door and window penetrations in the external envelope and those to conditioned spaces (Figure 25 and WoodSolutions Design Guide 10: Timber Windows and Doors).
- ***Lining to frame joints*** - internal lining material must be sealed to the timber framing at the top and bottom plates, corners, junctions with the ceiling and at all openings and penetrations.

- ***Internal lining joints*** – all corners and joints in plasterboard sheet should be taped before finishing and painting; if timber lining is used, joints should be taped and sealed behind trims.
- ***Additional wall wrap*** – for wallboards or cladding that is not in a sheet form, additional building wrap can be installed on the internal side of the timber frame before lining (Figure 27).
- ***Floor lining*** – floorboards should be installed over a particleboard substrate or, alternatively, a fitted floor can be used, with wrap installed over the bearers and under the floor joists. If the wrap is installed under the floor joists, it must be fully taped and sealed on all sides to the external wall wrap.
- ***Sealants*** – spray-in foam insulation products can also act as an air sealer, providing extra infiltration and exfiltration control. Fibreglass, polyester, cellulose and wool insulation products do provide good bulk insulation but do not have useful air-sealing properties. However, timber products like plywood, strand-board and high-density fibreboard can be used in conjunction with these products to provide excellent air sealing assemblies.

Advanced practice

- ***Above ceilings*** – Consider installing a vapour-permeable building wrap between ceiling battens and the roof trusses, particularly if the selected ceiling is not a sheet material that can be well sealed (Figure 26).

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Inward heat*** – seal to avoid heat gain.	• ***Daily variable heat*** – seal to avoid day/night heat loss and gain cycle.	• ***Seasonal variable heat*** – seal to avoid seasonal heat loss / heat gain cycle.	• ***Outward heat*** – seal to avoid heat loss.

Further resources:
Window Energy Rating System (WERS) – for details about How To Select Windows (www.wers.net/werscontent/how-to-select-windows)

Your Home Technical Manual – for details about Passive Cooling (www.YourHome.gov.au/technical/fs46.html)

Avoiding air leakage.

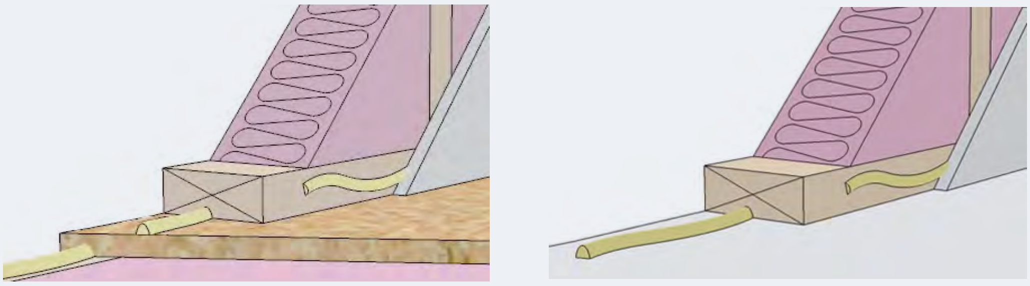


Figure 20: Sealing wall to floor. *Apply weatherproof sealant between the bottom plate and flooring.*

Figure 21: Tape joints. *Building wrap covers all walls and is overlapped and taped. Photo: Mark Dewsbury*

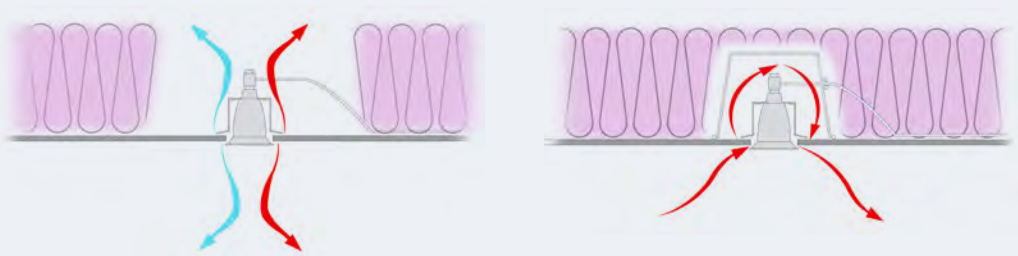


Figure 22: Seal downlights. *Beware unwanted air movement through vented downlights.*

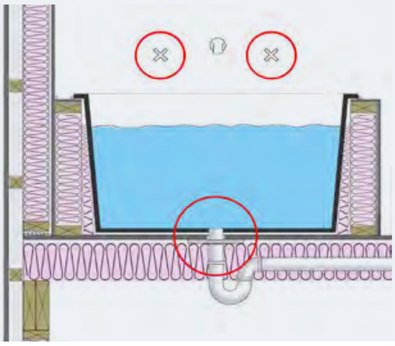


Figure 23: Seal penetrations.
Carefully seal all services penetrations.

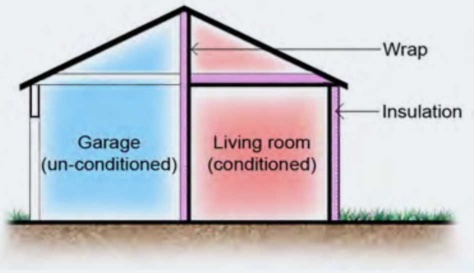
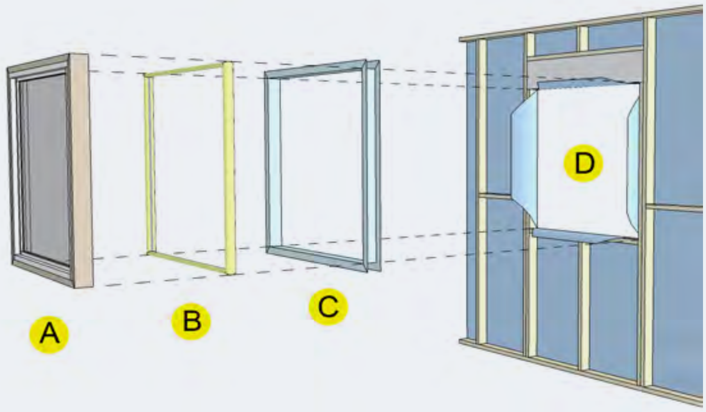


Figure 24: Separate conditioned zones.
Use wrap and insulation between conditioned and unconditioned spaces.

Wrap used to seal envelope.



A: Window unit

B: Sealant between window and frame

C: Reinforcing to protect wrap at openings

D: wrap folded around and fixed to inside of frame.

Figure 25: Seal wall openings. *Installation of doors and windows into a well-wrapped wall*

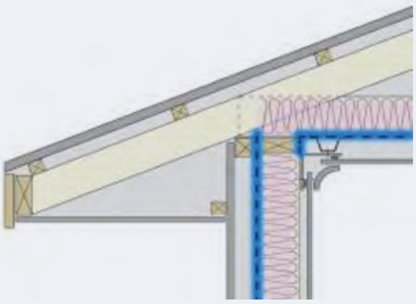


Figure 26: Seal ceilings to walls.
Continuous seal created by fixing to wall plate.

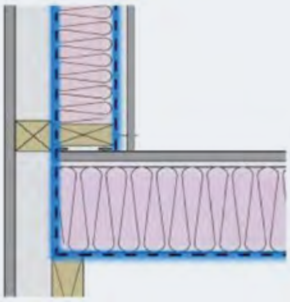


Figure 27: Seal walls to floors.
Continuous seal created by fixing to wall plate.

Figure 28: Blower door testing. *A fan temporarily sealed in an external door allows for airtightness to be measured. Photo: Mark Dewsbury*

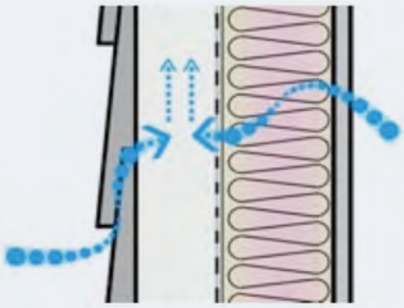


Figure 29: Cavity behind external cladding. *Battening cladding off of studwork promotes vapour diffusion.*

5.3.1 Moisture and Vapour Management inside the Cladding

Venting moisture from walls

In all climate types, it is desirable to establish an air cavity between the exterior cladding system and the building wrap (as shown in Figure 23). This gap provides a zone for moisture moving from the exterior inwards to evaporate and for vapour moving from the interior outwards to diffuse. It also limits 'thermal bridging' or conduction of heat between the cladding and the wall frame and insulation.

Venting moisture from roof spaces

Reflective sarking is usually installed under sheet metal and tile roofing systems to reflect unwanted heat away from the roof space and to prevent any moisture that comes through the roofing material from entering the roof space. Sarking is generally installed in continuous, overlapped and/or taped lengths and is impermeable to moisture vapour.

Any vapour that enters the roof space from the house or other sources can become trapped and condense on the underside of the sarking or other cooler surfaces such as metal ductwork. If this moisture is allowed to build up, it will be retained by the materials in the roof structure (such as timber, plasterboard and insulation) and will eventually lead to their decay.

To counteract this possible problem, it is important to adequately ventilate the roof space and avoid extra vapour loads from bathroom or kitchen ceiling exhausts. Simple actions such as keeping the ridgeline unwrapped or providing vents in gables in combination with eave vents will, in most cases, provide adequate ventilation to remove this excessively hot and at times very moist air.

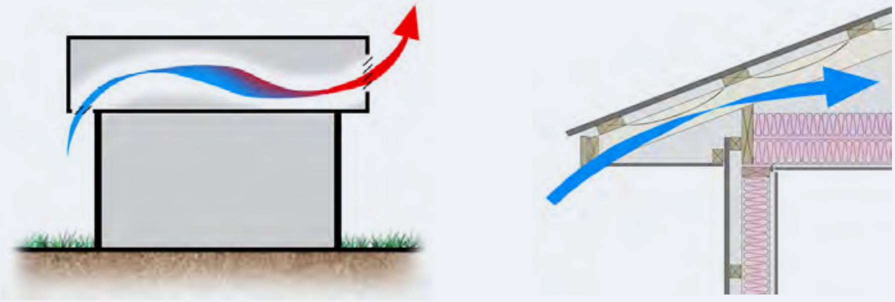


Figure 30: Ventilate roof spaces. *Ensure the attic or cathedral roof space is ventilated.*

Moisture management on service ducts and units

In most climate types, condensation can form in or on surfaces –such as ductwork and pipes for centralised heating and cooling equipment and hot water services – when moisture-laden air comes into contact with these significantly cooler surfaces. Insulating ducts and pipes will deter this.

General considerations:

- ***Sarking*** - install high-quality reflective sarking to help control inward-bound moisture and reduce unwanted radiant heat from the roofing material.
- ***Vent roof space*** - place sufficient vents in both eaves and gables to allow a cross-flow of air through the roof space.
- ***Insulate ceilings*** - use ceiling batts to provide a thermal barrier between the ventilated roof space and the house interior.
- ***Vent exhausts to exterior*** - vent bathroom and kitchen exhausts to the building exterior rather than into the roof space to avoid adding unnecessary moisture.

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Non-breathable vapour barriers*** – control inward-bound vapour pressure.	• ***Breathable vapour barriers*** – control inward or outward-bound vapour pressure.	• ***Breathable vapour barriers*** – control inward or outward-bound vapour pressure.	

Further resources:

Your Home Technical Manual – for details about Insulation (www.YourHome.gov.au/technical/fs48.html)

Insulation Council of Australia and New Zealand Insulation Handbook (www.icanz.org.au/wp-content/uploads/import/pdf/17132_ICANZ_HANDBOOK.pdf)

ABCB Condensation in Buildings: www.abcb.gov.au/en/education-events-resources/publications/abcb-handbooks

Australian Standards – As NZS 4200.1-1994 Pliable Building Membranes and Underlays Materials

Wood Solutions: R-values for Timber-framed Building Elements R-values for Timber-framed Building Elements

5.4 Thermal Insulation

The air temperature of the interior of a building will tend toward equalising with that of the outside. A building's envelope provides the most obvious line to resist this flow of heat energy by installing thermal insulation.

Although many common building materials resist the flow of heat, materials are termed 'insulation' when they are designed to resist heat flow.

Gaps in insulation installation create what are effectively holes in the thermal envelope. Beyond the obvious thermal holes created by glazing, insulation of the building envelope and across a building element should be continuous, without breaks at edges, corners and junctions.

5.4.1 Common Insulation Products

Formats

Thermal insulation comes in a variety of materials and formats that are often designed to work in specific locations. Various formats include:

- ***Blown-in*** - blown-in fibrous elements.
- ***Foam-in-place*** - spray-on expanding foams.
- ***Rigid*** - extruded polystyrene foam board.
- ***Bulk*** - matted fibrous known as 'blanket' when in continuous rolls or 'batts' if cut into individual panels designed to fit within timber framing.
- ***Reflective*** - foil blankets or individual panels.
- ***Composites*** - reflective materials bonded onto fibrous or cellular materials.

Bulk insulation for ceilings is often quite flexible while bulk wall insulation products are stiffened so that they don't settle over time. Insulation for sub-floors may also be stiffened to avoid sagging. As some products are designed for specific applications, they may not be interchangeable. For example, if a roof insulation product is used in a wall, it may eventually compress and settle into the bottom of the wall frame, leaving uninsulated areas at the top of the wall.

Size

Most insulation products offer sizes that relate to traditional timber construction.

- ***Individual batts*** – 430 mm or 580 mm widths to fit between 450 mm or 600 mm wall stud framing.
- ***Roll-out blanket*** – 900 mm or 1200 mm to fit timber truss common rafter or truss spacing.

Function

There is a range of bulk and reflective insulation products to reduce the heat flow through the building fabric. Of the three types of heat transfer, insulation can resist two:

- ***Conduction:***
  - bulk insulation products slow the flow of heat through the fabric
  - often resisted by materials of low conductivity, and can abut surfaces
  - frequently containing air pockets which slow heat transfer.
- ***Radiation:***
  - reflective insulation reflects radiant heat back in the direction it came from
  - generally can be quite conductive so, to work effectively, an unvented air gap between building elements and the reflective surface is required
  - if an air cavity is vented, air movement across the gap can transfer heat and compromise insulation (Figure 32).

Gaps and ill-fitting insulation = thermal holes

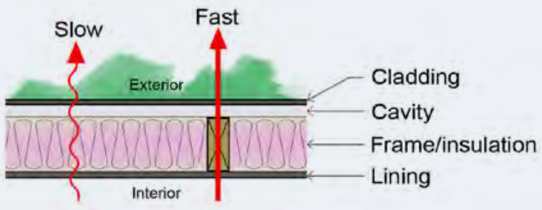


Figure 31: Avoiding conducted heat loss.
Bulk insulation reduces heat flow significantly over that of timber framing elements.

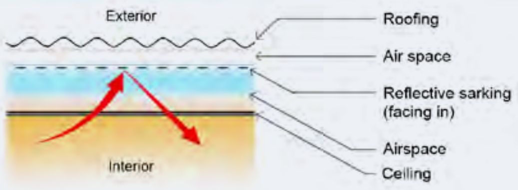
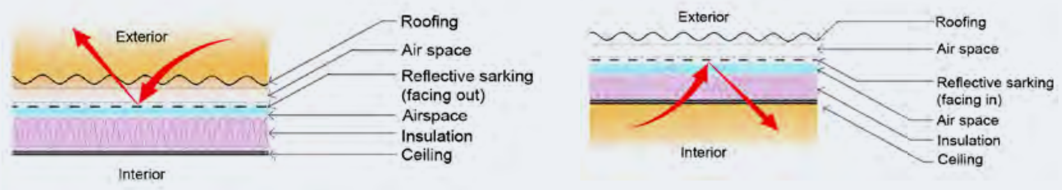


Figure 32: Avoiding radiant heat loss.
Isolate materials to create still air cavity and utilise reflective foil to control heat.



Reflecting heat up

Reflecting heat down

Figure 33: Diagram of reflective insulation.

Rating insulation performance

As the purpose of insulation is to resist the flow of heat, it is the product's thermal resistance or 'R-value' that is used to rate its effectiveness as an insulation product. When selecting an insulation product, be sure that the quoted R-value is for the product only and not that of a typical construction system. This can confuse designers, builders and retailers into thinking that the product has a higher R-value than it physically does.

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Useful insulation values

Material	Thermal Resistance R-value (m2.k)/W
Glass-wool (7 kg/m^3)	R 1.754
Glass-wool (12 kg/m^3)	R 2.273
Mineral-wool (37 kg/m^3)	R 2.500
Polyester (8 kg/m^3)	R 1.587
Polyester (16 kg/m^3)	R 2.222
Lamb's wool (16 kg/m^3)	R 2.222
Expanded polystyrene	R 2.564
Extruded polystyrene	R 3.571
Spray-in-place foam	R 3.571

Table 9: Thermal resistance values (R-value) for 100 mm of insulation products.

Material Depth/Thickness	R-value
57 mm	1.0
114 mm	2.0
171 mm	3.0
228 mm	4.0
285 mm	5.0
342 mm	6.0
399 mm	7.0
456 mm	8.0

Table 10: Glass-wool insulation thickness (these can vary between products).

Material	Thickness mm	Thermal Conductivity W/(m K) – 1m	Thermal Resistance R-value (m.k)/W
General fabric materials			
Aluminium	90	221.000	0.000
Steel	90	45.300	0.002
Glass	4	1.000	0.004
Paper Faced Plasterboard	10	0.160	0.063
Clay Brick Extruded	110	0.614	0.179
Timber – Hardwood	90	0.176	0.523
Timber – Softwood	90	0.110	0.818
Insulation products			
Glass Wool Insulation	90	0.044	2.045
Expanded Polystyrene	90	0.039	2.308

Installation

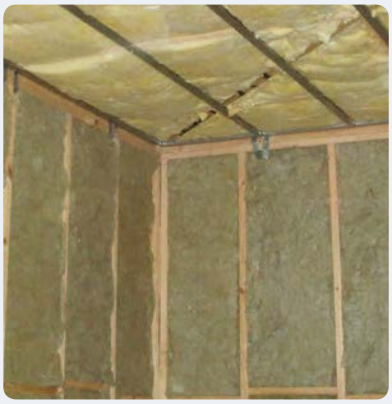
- ***Make continuous*** – if a rigid or foil product is used, all joints should be lapped and/or tapped.
- ***Full cove*r** – coverage should be consistent and well fitted into corners and around penetrations.
- ***Avoid bridging*** – avoid thermal bridging where possible by avoiding the amount or the extent of non-insulation materials which are able to conduct heat through the envelope – see the discussion on 'framing factor' below.
- ***Don't compress*** – while insulation needs to fit snugly, compressing bulk insulation removes the air pockets that provide its insulation property and diminishing its R-value.
- ***Moisture*** – cold surfaces can lead to condensation wherever they are, so insulation type and its ability to transfer vapour are important considerations to confirm with product manufacturers.

Insulation types.

Bulk (batts and blankets)

Bulk insulation in batts and blankets is the most common form of insulation in the sub-floors, walls and ceilings of Australian houses. The batts are made of glass wool, mineral wool, lamb's wool or polyester fibres. Considerations:

- ***Flexile*** – batts and blankets systems are flexible and sized to fit snugly between framing.
- ***High density*** – for best results, use high-density unfaced batts.
- ***Innovation*** – newer products are becoming available that are denser and manufactured from recycled or more sustainable materials.



Glass-wool bulk insulation batts.

Photo: Mark Dewsbury

Unstiffened

- ***Benefit*** – low cost, most common product with the strongest installation knowledge base. Skill level required to install is low. Quick to install.
- ***Liability*** – does not prevent air leakage, requires appropriately sized cavities for installation, and is not suitable for vertical installation (e.g. in walls).

Stiffened

- ***Benefit*** – relatively low cost, ideal for walls and sub-floors, and easy to install.
- ***Liability*** – does not prevent air leakage, and is only available in a limited range of sizes targeted for use in walls and ceilings.

Blow-in

Insulation products can also be blown into place. Common blown-in or loose-fill products include glass wool, mineral wool, lamb's wool and cellulose insulation. These products are generally not acceptable for new buildings as the quality of installation and possible settling of material will significantly affect the thermal resistance value. Considerations:

- ***Retrofits*** – useful in retrofit projects where access is restricted.
- ***Spray*** – some products can be sprayed into existing framed walls, where it dries and sets within the wall. To be effective, these systems require wall frames with minimal cross and diagonal members.
- ***Resist air movement*** – some blown-in products offer resistance to air movement.
- ***Benefit*** – good for top-up and retrofitting.
- ***Liability*** – consistency of application hard to control, therefore not supported by codes.

Blow-in insulation.

Photo: Joe Timi, CSR Bradford

Foamed-in-place

Foam-in-place insulation products are common overseas and of growing availability in Australia. Installed by a certified applicator, they generally provide very high insulation performance.

- ***Tight-spaces*** – ideal for spaces that are small or have limited access (like sub-floors and cathedral ceilings), which are often not insulated correctly.
- ***Seal gaps well*** – by expanding into small voids this form offers excellent infiltration control.
- ***Benefit*** – expanding foams are very flexible, very good insulators and stop airflow well.
- ***Liability*** – generally the most expensive option.

Sprayed-in-place wall insulation

Photo: Mark Dewsbury

Sprayed-in-place wall insulation

Photo: Mark Dewsbury

Rigid insulation

Extruded and expanded polystyrene products are a lightweight rigid insulation most commonly available in sheet form. Other natural fibrous board products are also available. Rigid insulation may be used in conjunction with other insulation types to further improve sub-floor, wall, ceiling and roof insulation. As this product comes as a rigid panel, it is better to apply it to outside of a timber frame (sub-floor, walls and roof), rather than trying to fit it between timber members.

- ***Acoustic*** – provide good thermal and acoustic insulation.
- ***Foil options*** –some products are faced with a reflective wrap (foil-board).
- ***Applied finishes*** – available with surface ready for the application of external render.
- ***Over-laid*** – may be laid across framing and in addition to other insulation types.
- ***Beware vapour*** – foil-surfaced board is vapour impermeable and if used on external wall can trap moisture in the wall.
- ***Termites*** – sheets in contact with the ground should be treated for termite resistance.
- ***Benefit*** – Good insulator, easily screw fixed to the structure and if overlaid and taped – reduces infiltration.
- ***Liability*** – difficult to install between framing due to variability of framing members and all joins require taping.

Extruded polystyrene over-cladding a timber-framed wall before external cladding is fixed.

Photo: Mark Dewsbury

Reflective sub-floor insulation

Reflective insulation has been used in Australia for more than 40 years, commonly for roof sarking. Reflective wall wraps are also used widely as well as growing range of concertina batt and composite products.

- ***Compact*** – reflective insulation is lightweight, and requires little volume to be effective.
- ***Limit conduction*** – reflective foils are often quite heat conductive, so it is important to have them adjoining air cavities.
- ***Avoid air movement*** – any air movement will significantly reduce or even negate the system's insulation value so it is important joints are taped and cavities well sealed to provide a 'still air space'.
- ***Hot climates*** – useful for limiting heat gain of the envelope by reflecting heat out.
- ***Benefit*** – Low cost.
- ***Liability*** – requires a lengthy installation process to ensure an airtight/taped installation. If still air spaces are not achieved, the product does not provide the marketed levels of insulation.

Reflective sub-floor insulation.

Photo: Mark Dewsbury

5.4.2 Sub-floor Insulation

In climates where the outside air and ground temperatures are significantly different to the temperature required inside a house, sub-floor insulation may be needed to reduce the heat gain or heat loss through the floor. There are three main residential sub-floor construction types in Australia, each with specific thermal characteristics and insulation approaches:

- platform-floor with an unenclosed-perimeter
- platform-floor with an enclosed-perimeter
- concrete slab-on-ground.

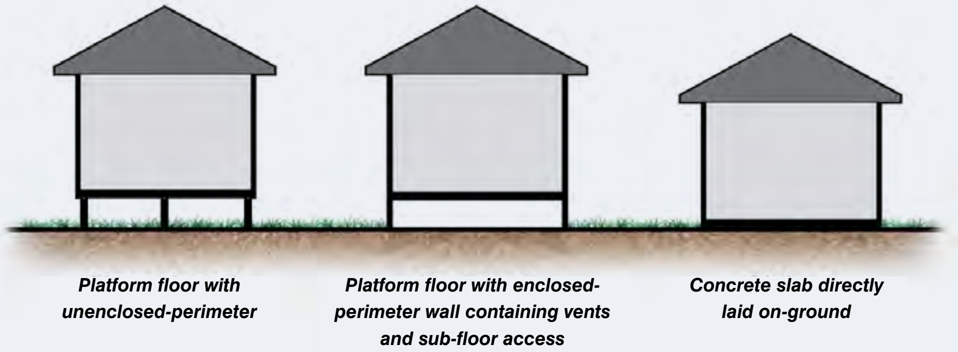


Figure 34: Sub-floor enclosure types.

Timber platform floors

Both the insulation of a suspended floor and its enclosure affect thermal performance. Unenclosed sub-floors provide the best ventilation for timber floors and allow for easier visual inspection for termites and other problems; however, this air movement brings the potential for greater thermal losses. In some climate types, enclosing the sub-floor can make it up to 30% more thermally effective.

Enclosed platform floors are shielded from hot or cold wind and heat radiating from the surrounding ground. Also, the air in the enclosed sub-floor space can act as a thermal buffer between the ground and the floor of the inhabited rooms. It is important that enclosing walls contain appropriate vents to remove evaporating ground moisture and internal building vapour that can escape through the floor, and to ensure that footings, substructure and insulation materials remain dry.

When walls and ceilings are insulated up to 50% of heat loss can come from an uninsulated platform floor

The specification and installation quality of sub-floor insulation is a critical factor in the performance of timber-framed, platform-floored houses. Regardless of the level of sub-floor enclosure, the level of insulation in the floor will eventually govern the rate of heat loss or gain through the platform floor. In a house with insulated walls and ceilings but an uninsulated platform floor, up to 50% of heat loss or gain in the building can be through the floor.

Products available to insulate a platform timber floor include polystyrene sheets, glass and mineral wool batts, foam-in-place and reflective insulation. Products can be used individually or combined to insulate both the sub-floor space and the floor.

As standards for platform-floors insulation increase, so do the number of available products. While the NCC may require as little as R1.0 sub-floor insulation, most floor-joist systems can easily accommodate a dense R3.0 or high-rated insulation batt. As access to the sub-floor can be difficult after construction, it is preferable to install better-than-code levels of insulation during construction. Advice should be sought from manufacturers regarding specification.

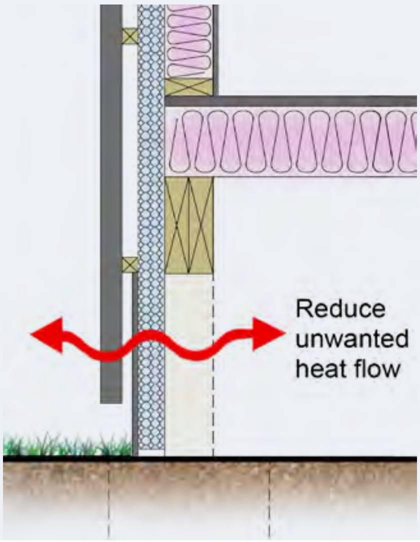


Figure 35: Insulation of sub-floor walls. *Continue insulation to ground in accordance with manufacturer's detailing.*

Concrete slabs

Concrete slab-on-ground floors do not have a sub-floor zone and generally have a moisture barrier system installed under the slab and around its edges to prevent ground moisture penetration.

There are three methods for insulating slab-on-ground floors:

- slab edge
- underslab insulation
- waffle-pod concrete slabs.

Figure 36: Board under slab and slab edge insulation. *Slab edge insulation is suitable for most climates. Photo: Mark Dewsbury*

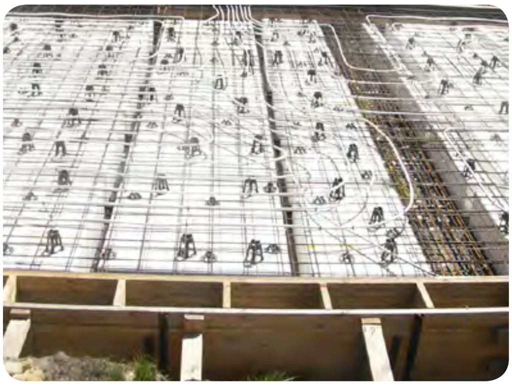


Figure 37: Underslab waffle-pods. *Underslab insulation is suitable for cooler climates. Photo: Mark Dewsbury*

In both concrete slab-on-ground types, the solid polystyrene products provide the thermal insulation. While providing underslab insulation, a polystyrene waffle-pod is largely designed as a void form or sacrificial formwork with as little as 20 mm of solid polystyrene in the top surface.

Overseas research has found that underslab insulation up to R3.0 is cost effective (approximately equivalent of 120 mm thick expanded polystyrene). When Australian house designs were subjected to thermal simulations, 6-star designs that included 50 mm to 75 mm of expanded polystyrene as sub-floor insulation achieved an increased energy ratings of up to 8.0 stars.

However, the use of sub-floor insulation on a concrete slab-on-ground floor in temperate climates needs to be carefully considered in the context of the house design, its heating and cooling requirements and the temperature of the ground. The sub-floor insulation may provide a significant benefit in winter but may allow the house to overheat in summer. By having the design modelled by a House Energy Rating assessor, the heating and cooling requirements can be evaluated and used to inform the right approach to concrete slab-on-ground sub-floor insulation.

5.4.3 Wall Insulation

The external walls of a house are the second most critical area of potential heat loss or gain after the glazed opening in the envelope. A range of factors can significantly improve the effectiveness of wall insulation. These include:

- correct installation
- separating unconditioned and conditioned rooms.
- reducing the external wall 'framing factor' (discussed below)
- over-cladding the wall frame with insulation.

Installation

Most wall insulation products are designed to fit between the wall framing of 450 mm and 600 mm standard wall-framing systems, the most common being bulk insulation batts. As mentioned above, when selecting a bulk batt product look for 'stiffened' batts, as these products have a stiffened face to reduce the chance of the batt crumpling and compressing within the wall. Before cladding, insulation in walls should be inspected to ensure there should be no gaps in the insulation (Figures 38 to 41).

Figure 38: Correctly installed wall batts insulation. *Photo: Mark Dewsbury*

Figure 39: Lack of insulation in corners. *Photo: Mark Dewsbury*

Figure 40: Batt insulation removed for installation of services. *Photo: Mark Dewsbury*

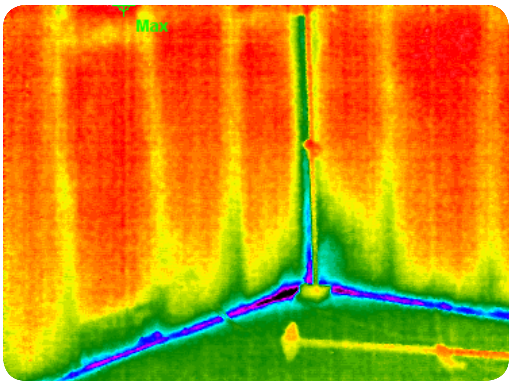


Figure 41: Heat leakage. *This infra-red image of a wall-floor junction with blue tones indicating heat-leakage from this warmed space. Photo: Mark Dewsbury*

Separating unconditioned and conditioned rooms

Most houses limit heating and cooling to 'habitable' rooms with garages and utility rooms wisely excluded. Installing insulation in walls between unconditioned and conditioned rooms can significantly improve the thermal performance of a house.

Figure 42: Separate conditioned rooms. *Insulate internal as well as external walls to contain heating and cooling.*

5.5 Thermal Bridging

Areas or components with lower thermal insulation value break the insulation continuity and are known as thermal bridges; these areas will suffer the most unwanted heat loss or heat gain. For example, gaps in the installation of insulation or a highly conductive member within a wall such as a steel lintel will provide this. The installation of services is common source of thermal bridging.

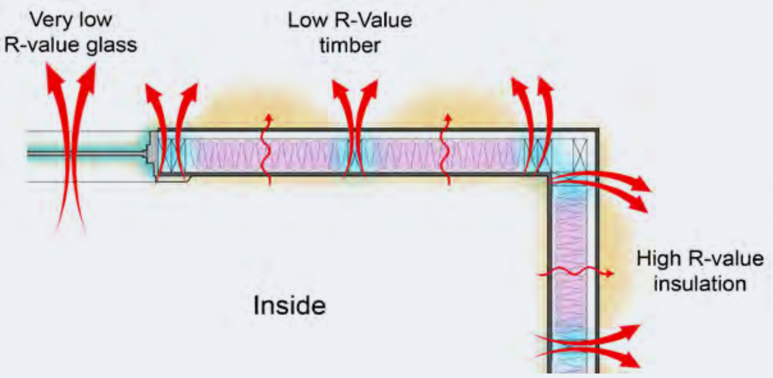


Figure 43: Timber-framed wall. *Conventional timber framing with insulated cavities will still give some thermal bridging.*

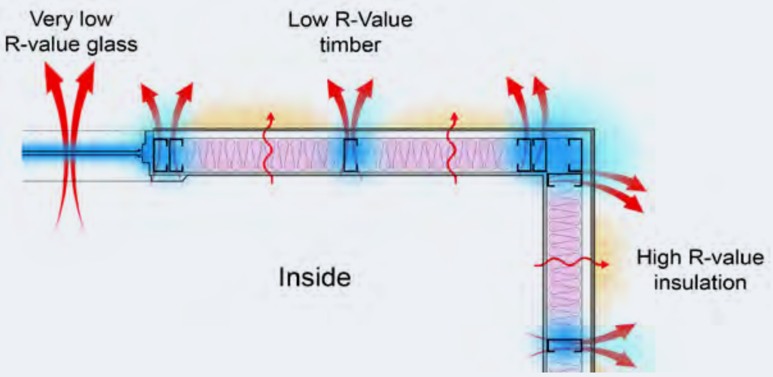


Figure 44: Steel-framed wall. *Due to the substantively higher conductivity of steel thermal 'breaks' are now required in some jurisdictions.*

Reducing the framing factor in wall framing

As the timber frame has less thermal resistance than the surrounding insulation, each framing element in the external envelope conducts more heat than the surrounding insulation. The R-value of softwood timber wall framing (R0.818) and that of wall insulation (R2.0) are significantly different. These weak points in the insulation layers are called thermal bridges and their effect is shown in the infrared images in Figure 41.

In framed systems, such as a timber-frame wall, the area of timber in the frame relative to the area of insulation is called the 'framing factor'. Generally, if the amount of insulation in wall is the same, a wall with a high framing factor will have a lower average thermal resistance than a wall with a low framing factor.

In Australia, framing factors range from 25% to as high as 40%, limiting the portion of the wall area that can contain insulation. At both the design and construction stages, a framing factor of 20 to 25% should be aimed for. Providing timber framing with studs at 600 mm centres as opposed to 450 mm centres will give a lower framing factor, and allow for increased area of insulation. Additional non-required framing elements should be limited wherever possible.

Practices that limit thermal bridging through the wall frame:

- ***Limit noggings*** – to one row where possible, and in a flat rather than vertical format.
- ***Avoid double top plates*** – by aligning roof and wall framing.
- ***Reduce corner studs*** – where permitted by standards by using plaster fixing cleats.
- ***Cover steel beams*** – avoid high levels of thermal bridging by allowing lintels, etc., to be fully encased in insulation.
- ***Insulate face of beams*** – keep lintels to the outside face of the wall frame and maximise the internal wall space that can be insulated.

Reducing thermal bridging.

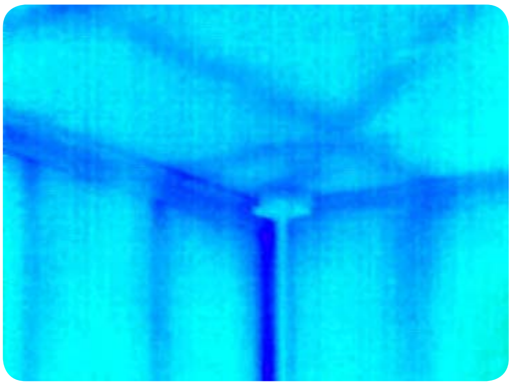


Figure 45: Thermal bridging.
Infra-red image of wall-ceiling junction with darker tones indicating thermal bridging created by timber framing. Photo: Mark Dewsbury

Figure 46: Thermal bridging.
Beware high conducting elements that breach wall insulation. Photo: Mark Dewsbury

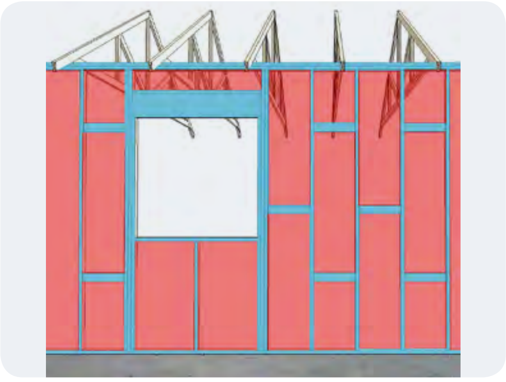


Figure 47: Excessive framing.
Wall with multiple noggings and a high framing factor. Unaligned wall and roof structure as requires a double top plate.

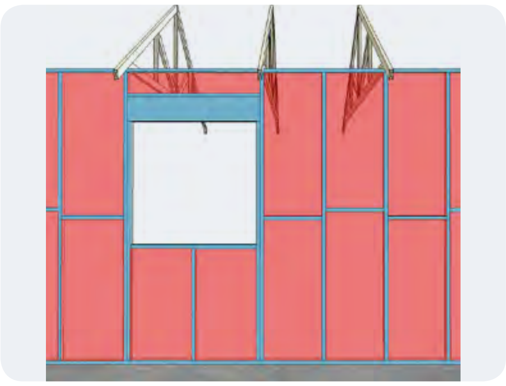


Figure 48: Efficient framing.
Aligned wall and roof structure requiring a single top plate and combined with single on-edge noggins result in a much lower framing factor.

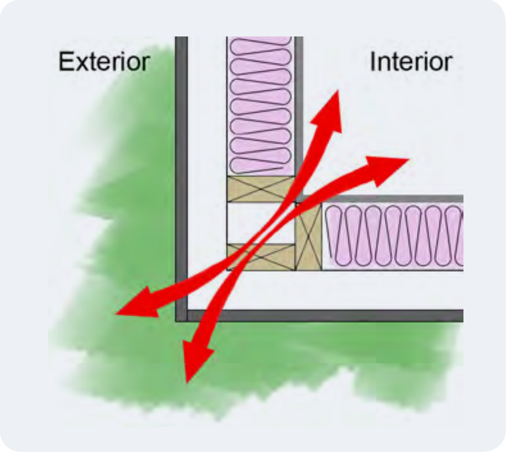


Figure 49: Standard corner framing
Conventional framing often results in uninsulated corners.

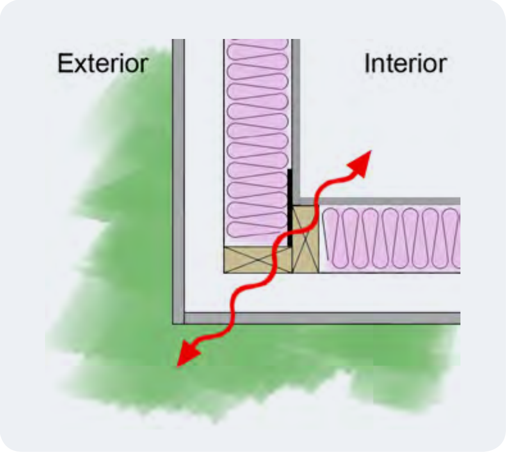


Figure 50: Minimised corner framing
Proprietary fixings minimise studwork and promote effective insulation.

Advanced framing

Advanced framing methods can reduce the framing factor to 9%; their details are available from the US Department of Energy and various European research groups, including the Passivhaus Institute. Advanced framing methods are beyond the standard forms of timber-framed construction detailed in the NCC and AS1684 Residential Timber-framed Construction and their use in design in Australia needs separate engineering certification.

Over-cladding the wall frame to increase insulation levels

To create more space for in-wall insulation, some builders and designers are moving to wider timber frames. However, the increased cost of this may not produce the results sought as it does not eliminate thermal bridging nor reduce the framing factor. It is much more thermally efficient to use standard studs, over-clad the frame with a sheet insulation product and install batt insulation between the studs in the frame. This method has several benefits as it:

- ***reduces thermal bridging*** – by providing insulation between the wall framing and cladding
- ***improves infiltration control*** – by adding an additional barrier and with few joints
- ***increases insulation*** – by allowing levels significantly above current code requirements.

Insulation products such as polystyrene sheets can be applied continuously to the face of timber-framed wall to significantly reduce thermal bridging from the frame. This can be done by including the insulation as a layer within the wall assembly or using the insulating element as the external cladding. With either method, it is critical that the construction detail allows for any moisture to be drained from walls, without creating ventilated cavities.

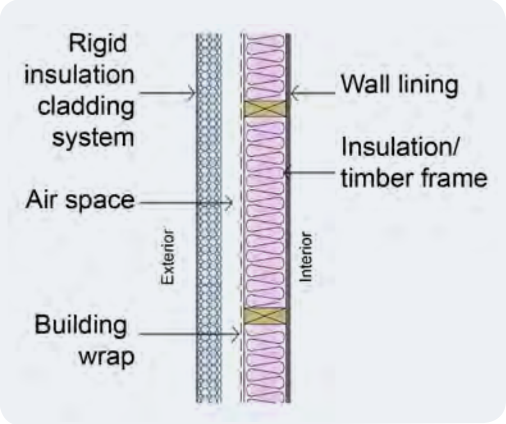


Figure 51: Over-cladding as external cladding.
A still air cavity and wall wrap between the over-cladding and frame enhance insulation.

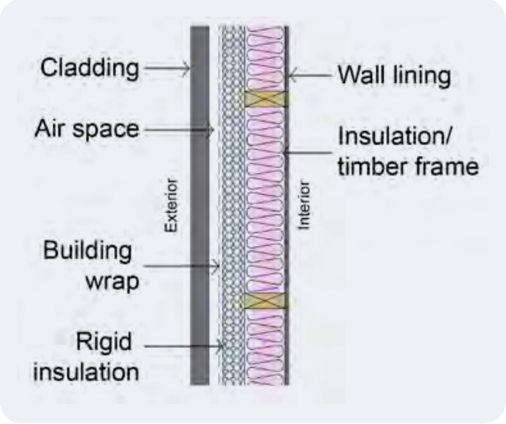


Figure 52: Over-cladding as a layer in the wall assembly.
Battening conventional cladding off of over-clad insulation board enhances insulation.

Figure 53: Rigid insulations as external cladding.
Solid insulated panel with sheet-metal faces and polystyrene core. Photo: Mark Dewsbury

Figure 54: Traditional cladding over rigid board insulation.
Timber ship-lapped boards over polystyrene board. Photo: Mark Dewsbury

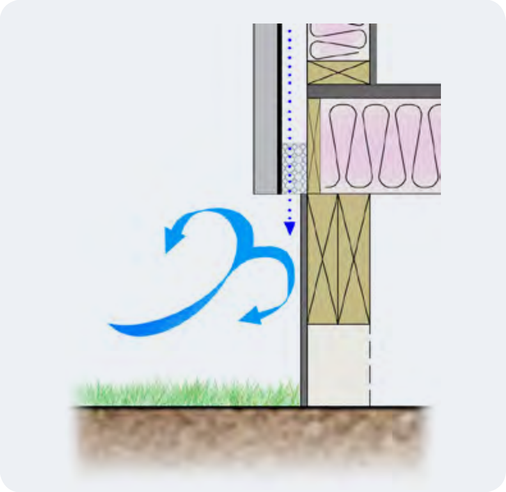


Figure 55: Closed cavity drainage.
Cavity with a closed cell foam product that stops airflow but allows moisture to drain.

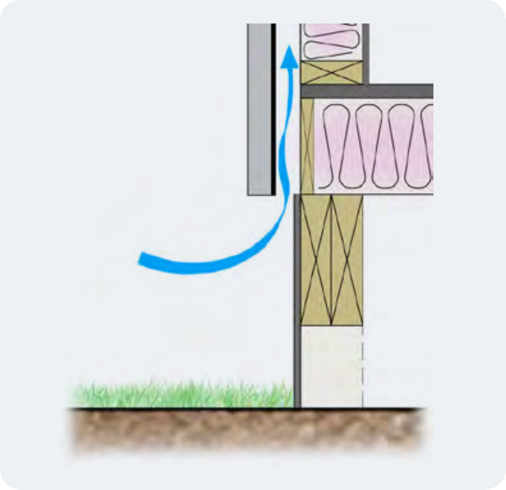


Figure 56: Beware 'chimney' effect.
Open cavities can allow air-movement that compromises thermal performance.

5.5.1 Ceiling Insulation

As hot air rises, ceilings can be the most important element to insulate. While convection can allow heat to rise into the roof space in cool weather, in hot weather, hot ceilings can radiate heat down into building interiors.

Like wall framing, ceiling framing allows some thermal bridging. This can be overcome by applying a second layer of bulk insulation. This is a method of covering the top of exposed framing (Figure 58).

- ***Limit and seal penetrations*** – skylights, ceiling vents and manholes to the roof space can act as flues to bring heat through ceilings. (The NCC includes strict limits on skylight use.)
- ***Manholes*** – access points between the house and the roof space should be weather-stripped and have insulation attached (Figure 60).
- ***Better lighting*** – many common downlights are vented and generate so much heat as to require insulation to be setback from fittings. Using unvented fittings that generate less heat (such as LED) can allow for uninterrupted coverage by ceiling insulation.
- ***Edge treatment*** – provide adequate depth for ceiling insulation to be installed where roofs meet ceilings and provide edge baffles to protect the outer perimeter of the ceiling insulation.

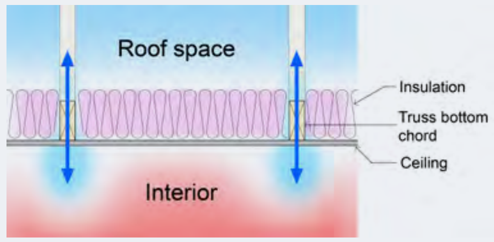


Figure 57: Typical thermal bridging at ceiling.
With ceiling joists exposed to roof space.

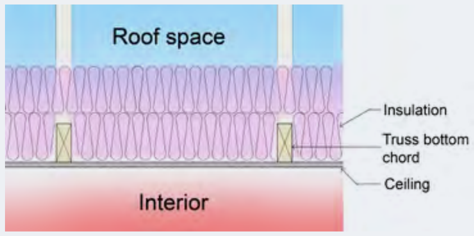


Figure 58: Overcoming thermal bridging.
Insulation applied in a second layer to over joists.

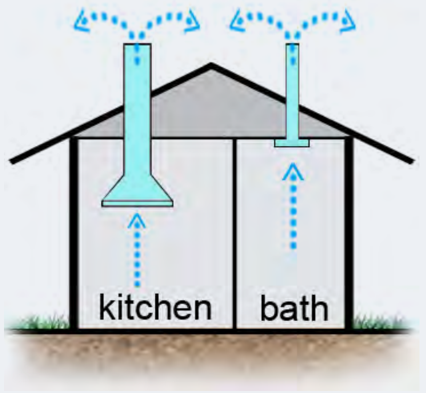


Figure 59: Bathroom and kitchen exhaust.
These must be vented outside the roof space.

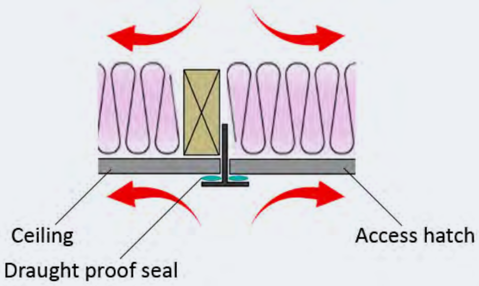


Figure 60: Access hatch.
High-density foam seal between a prefabricated insert and the ceiling.

5.5.2 Roof Insulation

The roof encloses a complex thermal zone of the house that offers a buffer between the atmosphere and solar radiation and a building's interior. It requires both adequate ventilation and careful detailing to control heat flow into and out of the space.

- ***Adequately ventilate*** - use vents in eaves and higher up in the roof to allow heat and any build-up of moisture to escape.
- ***Reflective sarking*** - reflect solar radiation back into the atmosphere limiting overheating of the roof space.
- ***Cathedral ceiling*** - as these allow no roof space to be vented, adopt a detail that allows for a ventilated cavity between the insulation and sarking and another between the sarking and roof covering.

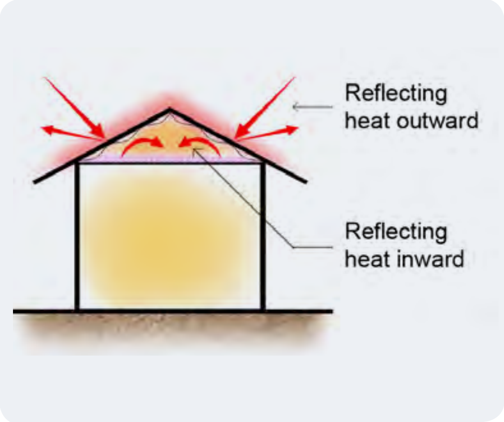


Figure 61: Reflective insulation in the roof
Reflecting internal and external heat.

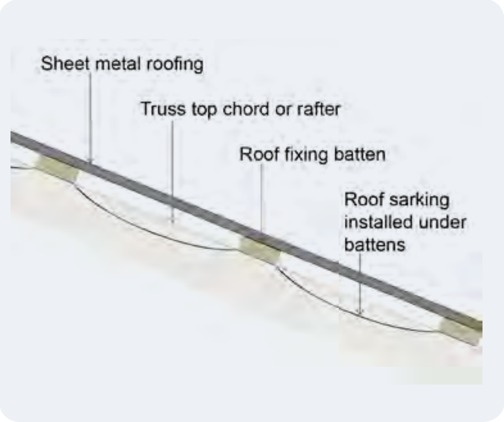


Figure 62: Alternate roof sarking detail.
Sarking under rather over battens allows condensation to form outside the roof space rather than inside it.

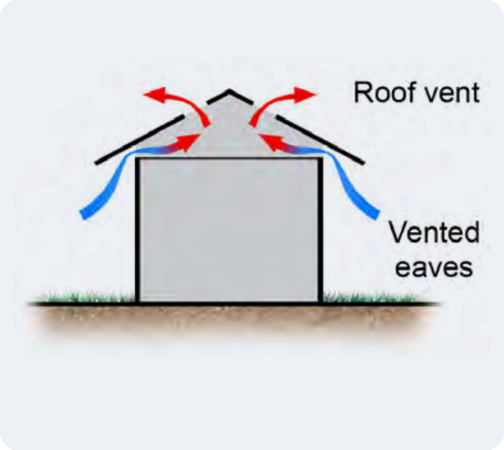


Figure 63: Vent attic roofs.
Having multiple vents to roof space allows airflow.

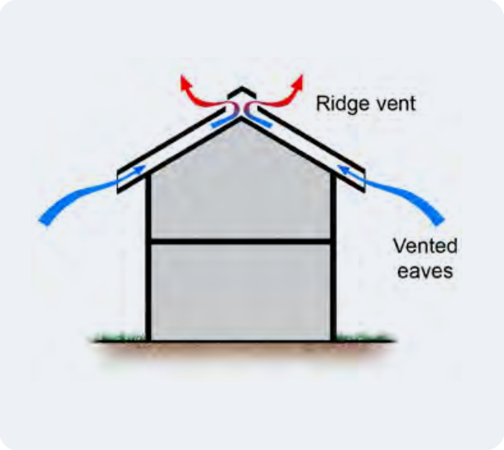


Figure 64: Vent cathedral roofs.
Special detailing is needed to allow vapour to escape.

5.5.3 Tips for Thermal Insulation per Climate Zone

General considerations:

- ***Floors*** – in conditioned rooms use sub-floor insulation to reduce heat gain or loss through the floor.
- ***Walls*** – high levels of wall insulation reduce heat flow through external walls, especially for spaces likely to be conditioned.
- ***Ceilings*** – high levels of bulk ceiling insulation reduce heat flow down from hot roof spaces into the habitable zones and keep conditioned air cool, and the reverse is achieved in cooler weather.
- ***Conditioned spaces*** – consider additional insulation for conditioned spaces.

Climate specific considerations:

<table>
<tr><th>Zones 1 and 2
<i>Hot and humid</i></th><th>Zones 3 and 4
<i>Hot and dry</i></th><th>Zones 5 and 6
<i>Temperate</i></th><th>Zones 7 and 8
<i>Cool temperate and cold climates</i></th></tr>
<tr><td colspan="4">• <i>Vent roof</i> – a well-ventilated roof space can dump the hot air out of the building zone, reducing conductive gain through the insulation and ceiling into the room below.
• <i>Increased insulation</i> –installing R6.0 ceiling insulation will provide significant benefit in all climates.</td></tr>
<tr><td colspan="2">• <i>Reflect heat out</i> – well-installed reflective sarking will significantly reduce the temperature in the roof space.</td><td colspan="2">• <i>Reflect heat in</i> – well-installed reflective sarking will reflect unwanted summer heat up and wanted winter heat back down toward the ceiling.</td></tr>
<tr><td>• <i>If unshaded</i> – if walls are un-shaded, install greater than code wall insulation to reduce conductive gains.
• <i>Sub-floor</i> – subject to the outside air and ground temperatures, sub-floor insulation can reduce heat gain through the floor.</td><td colspan="2">• <i>Low mass cladding</i> – good lightweight, low mass external cladding with a good level of wall insulation will reduce heat flow in on hot days and heat flow out on cool nights.
• <i>Platform floors</i> – good quality sub-floor insulation to reduce heat flow inward during summer and heat flow outward during winter.</td><td>• <i>More insulation</i> – In cool climates, installing greater-than-code floor, wall and ceiling insulation will provide long-term benefit.
• <i>Sub-floor insulation</i> – use to reduce heat loss to the sub-floor space or ground.
• <i>Unenclosed sub-floor</i> – increase the insulation level in the floor to achieve at least the same performance as an enclosed insulated sub-floor.</td></tr>
</table>

Further resources:

Your Home Technical Manual – for details about Insulation (www.YourHome.gov.au/technical/fs48.html)

Insulation Council of Australia and New Zealand Insulation Handbook (www.icanz.org.au/wp-content/uploads/import/pdf/17132_ICANZ_HANDBOOK.pdf)

ABCB Condensation in Buildings: www.abcb.gov.au/en/education-events-resources/publications/abcb-handbooks

Australian Standards – As NZS 4200.1-1994 Pliable Building Membranes and Underlays Materials

Wood Solutions: R-values for Timber-framed Building Elements R-values for Timber-framed Building Elements

5.6 Windows

While glazed doors and windows are key components in the design of houses, they are often the parts of the external envelope that allow the greatest heat loss and gain. Careful window selection and detailing is essential if the target thermal performance is to be attained. Key thermal performance factors include:

- ***size*** – the larger the window, the bigger the impact
- ***thermal conductivity*** – of both the glass and frame
- ***solar heat*** – the Solar Heat Gain Co-efficient (SHGC) or degree of solar heat admitted
- ***air tightness*** – the air infiltration rate.

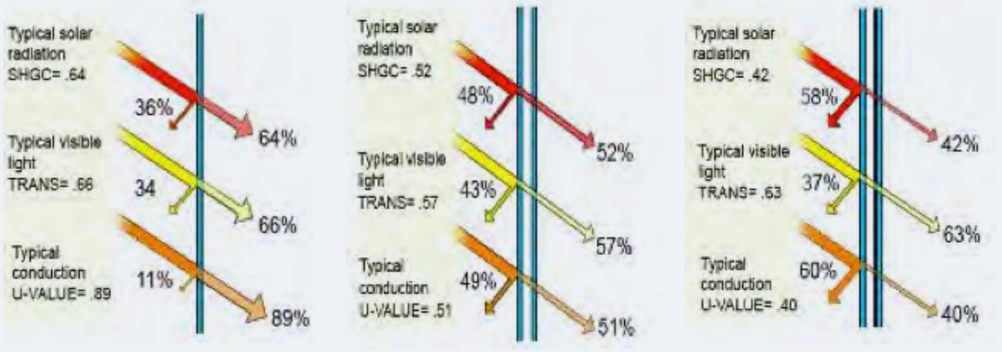
Research has shown that glazing has a significant impact on thermal performance of housing once it exceeds about 12% of floor area. More glazing can mean more heat load from admitted sun, and its low R-value offers poor resistance to heat transfer.

Thermal conductivity

Heat flows through windows by radiant, conductive and convective means. Conducted heat loss/gain comes from both the conductivity of the frame and the glazing. The aim in design is to reduce heat flow by selecting windows with lower conductivity.

Figures 65, 66 and 67 show the differential heat flows through various window components. Double glazing cavities are sometimes filled with argon or other gases, as they are less conductive than air.

Heat flow through windows.



Clear Single Glazed *Clear Double Glazed* *Low E Double Glazed (low-emissivity emits less heat)*

Figure 65: Heat flow through glazing.

Frame Type	Conductivity Value
Aluminium	8.0 – 12.0
Thermally broken aluminium	1.9- 3.5
UPVC	2.0 – 4.0
Timber – aluminium composite	2.5 – 10.0
Timber	2.0 – 3.0

Figure 66: Conductivity values for different frame types

Window Part	Material	Conductivity Value	SHGC	% of window
Window Frame	Meranti (35 mm thick)	2.23	n/a	18
Glazing	4 Clear / 12 Argon gas/ 4 Clear	2.56	0.74	82
Glazed Unit Total Values		2.50	0.62	

Figure 67: Thermal performance calculations for a double-glazed timber window

WoodSolutions Design Guide 10: Timber Windows and Doors provides additional detail on thermal performance, durability and maintenance requirements for timber windows.

Solar heat gain co-efficient

The Solar Heat Gain Co-efficient (SHGC) is the value given to the amount of solar radiation that passes through a glazing system, which will heat-up the building interior. A SHGC of 1.0 indicates that 100% of the solar radiation will travel through to the inside of the glass, dependent on the type of glass, and any films that may be applied to the glass to reduce glare or the R-Value. Where the sun's warmth is sought, a window with a high SHGC and a low U-Value is needed. Where solar heat gain is undesirable a window with a low SHGC and a low U-value is needed.

Window airtightness

Air infiltration for windows is a measure of the amount of air that may leak through a window assembly, between the frame and sashes when the window is closed. To limit unwanted heat transfer through infiltration and exfiltration, windows with a low infiltration rate should be selected.

Historically, windows and other glazed units that slide tended to have a higher infiltration rate than units that are hinged. However, many manufacturers have significantly improved the infiltration properties of their window systems.

Window performance

The national Window Energy Rating Scheme (WERS) lists the thermal properties of a wide range of windows. The WERS website, www.wers.net, provides an extensive report on the relative thermal performance of windows and doors, listed by frame type, glazing type and their particular manufacturers.

Use this information when choosing windows for a new building or renovation and model the impact on thermal performance for a given climate and shading in House Energy Rating software. Some examples of double-glazed units from the WERS website are shown below. Each manufacturer must list a description on their window assessment information for any acronyms and letters that are used to describe the glass and air-gap types. The stars illustrate the window system's relative benefit for climates that require cooling or heating. Other key information includes the amount of daylight that passes through a window (Tvw).

Under the WERS window rating scheme mentioned below, air infiltration ratings are measured up to a maximum rate of 5 litres per second. Untested windows or windows which exceed this are rated at 5.0 litre per second.

Double-glazed, timber-framed casement unit					**Total Window**			
Glazing	Cooling stars	Heating star	Cool %	Heat %	Uw	SHGC	Tvw	Al L/s.m^2
4Gry/6/4Clr	★★★★	★★★★★★	59%	64%	2.9	0.38	0.34	0.12
4Gry/12Ar/4Clr	★★★★	★★★★★★☆	59%	70%	2.5	0.41	0.39	0.12
4Clr/6/4Clr	★★★	★★★★★★☆	49%	71%	2.9	0.51	0.55	0.12
3Clr/8/3Clr	★★★	★★★★★★★	49%	73%	2.8	0.53	0.56	0.12
4Gry/12Ar/4EA	★★★★☆	★★★★★★★	64%	74%	2.0	0.37	0.36	0.12
4Clr/6/4EA	★★★☆	★★★★★★★	54%	74%	2.5	0.47	0.51	0.12
4Clr/12Ar/4Clr	★★★☆	★★★★★★★	51%	75%	2.5	0.51	0.55	0.12
4Clr/12Ar/4EA	★★★★	★★★★★★★☆	56%	80%	2.0	0.48	0.51	0.12

Table 11: Thermal performance window example from www.wers.net

Uw	*whole-window U-value*
SHGCw	*whole-window solar heat gain coefficient*
Tvis	*whole-window visible transmittance*
Uw	*whole-window U-value*
Al	*air infiltration rate at positive inward pressure difference of 75 Pa*

The glazing description 4Gry/6/4clr is a descriptor for the glazing system. In this case, it refers to a 4 mm glass panel with a grey film applied, a 6 mm air-gap and a sheet of 4 mm clear glass.

The 4Clr/6/4Clr and 4Gry/6/4Clr glass types have a SHGC of 0.51 and 0.38 respectively. This indicates that the 4Gry/6/4Clr window stops 13% more radiant heat flow through the glass, making this glazed unit good for un-shaded windows in hot and temperate climates. But this same glazing type is less suitable for climates that require heating. It has a heating stars value of 6 stars while the 4Clr has a heating stars rating of 6.5 stars.

General considerations:

- ***Thermal holes*** – windows and glazed doors allow heat through as they create virtual holes in the thermal envelope of a house.
- ***Size and orientation*** – maximise size for breeze and light penetration and minimise to limit unwanted heat loss/gain.
- ***Position*** – windows placed well can bring ventilation, cooling cross ventilation and warming winter sun. Poorly placed, they can cause heat gain/loss and other issues with noise, dust, security, etc.
- ***Window type*** – consider the best style of window for the application (casement windows catch breezes better, awning windows protect from rain, etc.
- ***Frame conductivity*** – select frames with a low conductivity
- ***Glazing conductivity*** – select glazing with a low conductivity such as laminated glass or double-glazed units to reduce unwanted heat gain or loss in all climate zones.
- ***Daylight*** – consider the light transmittance level of glazing to avoid overly dark interiors.
- ***Solar heat*** – for unshaded windows in hot climates, select low SHGC glazing to reduce unwanted solar heat gain.
- ***Seals*** – high-quality seals limit air, dust and moisture penetration.

Climate specific considerations:

<table>
<tr><th>Zones 1 and 2
<i>Hot and humid</i></th><th>Zones 3 and 4
<i>Hot and dry</i></th><th>Zones 5 and 6
<i>Temperate</i></th><th>Zones 7 and 8
<i>Cool temperate and cold climates</i></th></tr>
<tr><td colspan="3">• <i>Un-shaded</i> – un-shaded windows require a low SHGC to reduce unwanted solar heat gain and maybe a lower visible light transmission to reduce glare.
• <i>Open area</i> – select windows with a high opening percentage to promote natural ventilation and passive house operation.</td><td>• <i>Seasonally shaded glazing</i> – select high SHGC to maximise winter solar heat gain.</td></tr>
<tr><td>• <i>Ventilation</i> – select windows and doors that allow maximum quantity and control of ventilation.</td><td colspan="3">• <i>Conductivity</i> – select windows with a low U-value to reduce heat flow inward and outward as seasons change.</td></tr>
<tr><td>• <i>Better sealing windows</i> – will help limit unwanted hot drafts</td><td>• <i>Shade</i> – ensure windows are seasonally shaded to maximise passive solar opportunities.</td><td colspan="2">• <i>Better sealing windows</i> – will help limit unwanted cold drafts.</td></tr>
</table>

***Further resources**:*

Window Energy Rating System (WERS) – for details about How To Select Windows (www.wers.net/werscontent/how-to-select-windows)

Your Home Technical Manual – for details about Passive Cooling (www.YourHome.gov.au/technical/fs46.html)

Wood Solutions Guide: 10 Timber windows and doors – a comprehensive guide to designing and specifying timber windows and doors

5.7 Eaves and External Shading

Direct midday sun gives the equivalent of about 1000 Watts of heat, which is similar to a single-bar electric radiant heater every square metre. In cold weather, gaining this heat through windows and on external walls is welcome but, otherwise, shade is important to a building's thermal performance for all climate types and building orientations. Shading walls is critical in hotter climates for most – if not all – times of the year.

External devices such as roof eaves, awnings, verandas, pergolas and established trees can all be used for shade; however, internal shading devices do little to reduce heat gain. Blinds and curtains can be used to block light and glare, but as they block the sun inside of the glass line, solar heat is already within the room's interior.

Working with seasonal sun

Below the Tropic of Capricorn, the sun's angle to the ground (altitude) is lower on a winter's midday than midday in summer, and it is possible to design roof overhangs and awnings to allow winter sun to penetrate northern windows and yet block northern summer sun. Correspondingly, during the longer days of summer, the sun rises south of east and sets south of west (Figure 68).

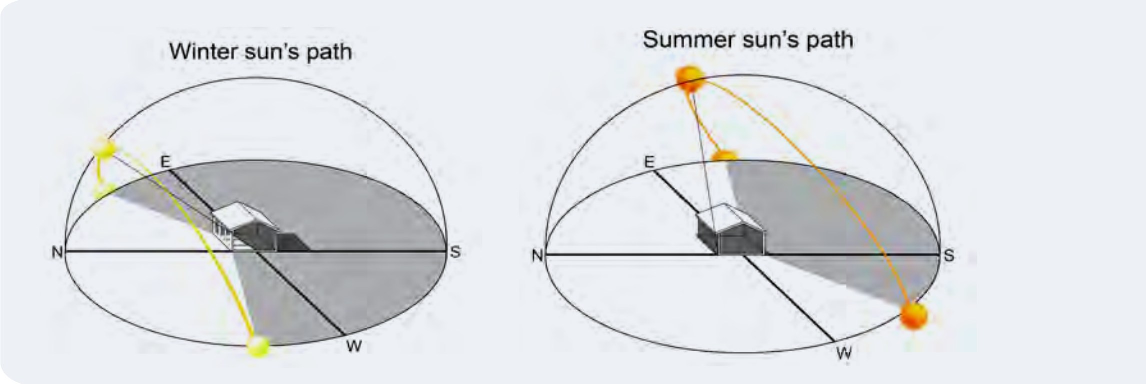


Figure 68: Seasonal sun paths. *Warm House Cool House 1995*

A simple rule of thumb to calculate the midday sun altitude angle for the winter and summer solstices in your location is:

Summer: 90 + 23 – given Latitude, e.g. Sydney: summer 90 + 23 – 34 = 79°

Winter: 90 – 23 – given Latitude e.g. Sydney: winter 90 – 23 – 34 = 33°

The angle of the sun to north is called 'azimuth'. For a given location it is possible to calculate the sun azimuth at any time of the year. However, there are many websites and apps that provide sun angle calculators and most computer-aided drafting software packages now allow buildings to be modelled showing sun paths and shading patterns. Using these tools, the shading of a house can be designed specifically for its climate and location. Figure 73 illustrates how sun angles vary from season to season in the cities listed.

5.7.1 Tips for Envelope Shading per Climate Zone

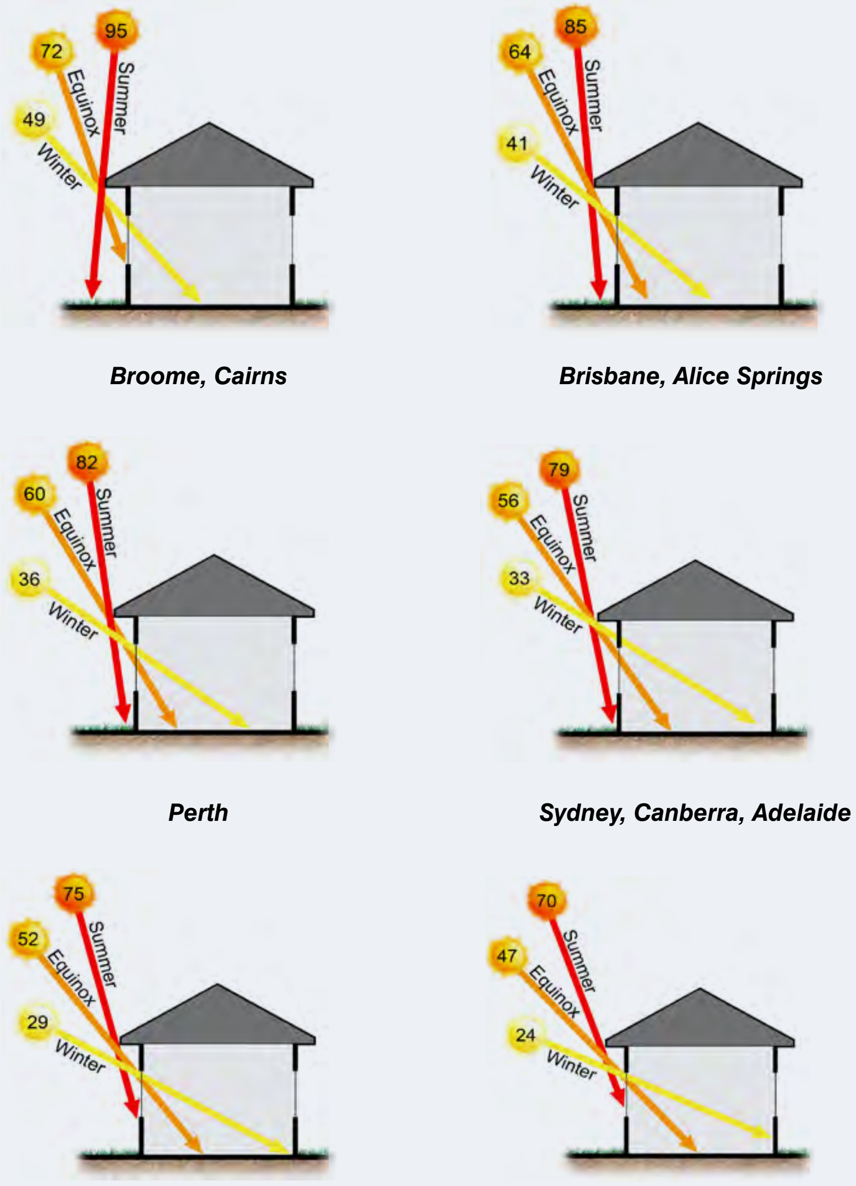
General considerations:

- ***Customise per site*** – shade the house to suit the climate type and orientation using fixed and operable shading as well as deciduous trees.
- ***Customise per facade*** – consider each facade individually and shade to exclude unwanted solar heat gain.
- ***Wanted sun*** – the welcome winter midday sun in the higher latitudes comes at a lower altitude than that of summer.
- ***Unwanted sun*** – the later afternoon summer sun comes from the west at low altitudes, which allows it to come in below eaves and awnings.
- ***Devices*** – provide large eaves, exterior window shades, verandas and pergolas, especially to the west façade.
- ***Seasonal*** – all external walls and windows should be shaded during the hotter months of the year but the shading should allow for passive solar gain during cooler months.
- ***Trees*** – plant deciduous or open evergreen trees to improve natural shading of the site, house, and outdoor spaces.

Climate specific considerations:

Zones 1 and 2 *Hot and humid*	**Zones 3 and 4** *Hot and dry*	**Zones 5 and 6** *Temperate*	**Zones 7 and 8** *Cool temperate and cold climates*
• ***Shade walls*** – fully shade all the external walls all year. • ***Evergreen trees*** –provide year-round shading to house and surrounds.	• ***Deciduous trees*** – these provide shade in summer but drop leaves to allow winter sun		
	• ***Shade windows and walls*** – fully shade all the external walls and windows during the hotter months (i.e. November to February). • ***Windows*** – allow the warming sun to provide free heating through windows during winter.		• ***Windows*** – shade northern windows in summer but allow direct winter sunshine. • ***Evergreen*** – avoid the use of evergreen trees to the north and east facades

Further resources:
Your Home Technical Manual – for details about Shading (www.YourHome.gov.au/technical/fs44.html)



Broome, Cairns

Brisbane, Alice Springs

Perth

Sydney, Canberra, Adelaide

Melbourne

Hobart

Figure 69: Sun altitude diagram.

5.8 Thermal Mass and Thermal Capacity

Thermal mass is a general term used to describe materials that are able to absorb and hold warmth (or ‘coolth’). With good design, thermal mass can work in most climates to make interiors more comfortable by evening out the daily minimum and maximum temperatures. This can be used to make cool nights warmer or hot days cooler. In tropical summers, where both the day and the night time temperatures are uncomfortable, there is no value in using thermal mass to even out temperatures.

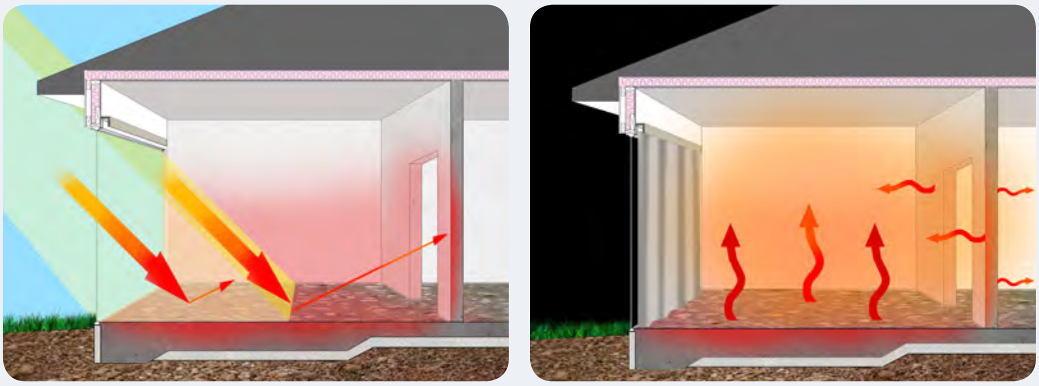
Materials with a high thermal mass, such as concrete and mass timber, are able to slowly absorb considerable amounts of heat energy. In cool climates, the thermal mass can warm up to absorb air and solar energy during the day and give this energy back to the cooler room at night. In hot climates, fully shaded thermal mass, if cool, can absorb unwanted air energy during the day and, with the use of natural ventilation, can lose it during the cooler evening and early morning (Figure 70).

In a well-designed timber house with a concrete floor, low-angle winter sun can shine directly onto a bare concrete floor, which will re-radiate out of the slab at night to warm the room. Useful thermal mass arrangements include an insulated slab on-ground, an insulated timber platform floor with a concrete topping, or an insulated high-mass timber floor or wall.

In a well-designed timber platform-floored house, partition walls can be constructed from mass-timber or clay bricks that can absorb heat in the day and, like the concrete floor mentioned above, give the energy back to the room at night. This principle operates in winter and summer. In summer, the cool walls absorb excess heat during the day and can release the heat during the cooler evening in a well-ventilated room.

If a house is poorly designed, thermal mass can hold unwanted summer heat within a house, or take too much winter warmth and make conditions uncomfortable. The type and location of thermal mass should be modelled in a House Energy Rating program to test thermal performance.

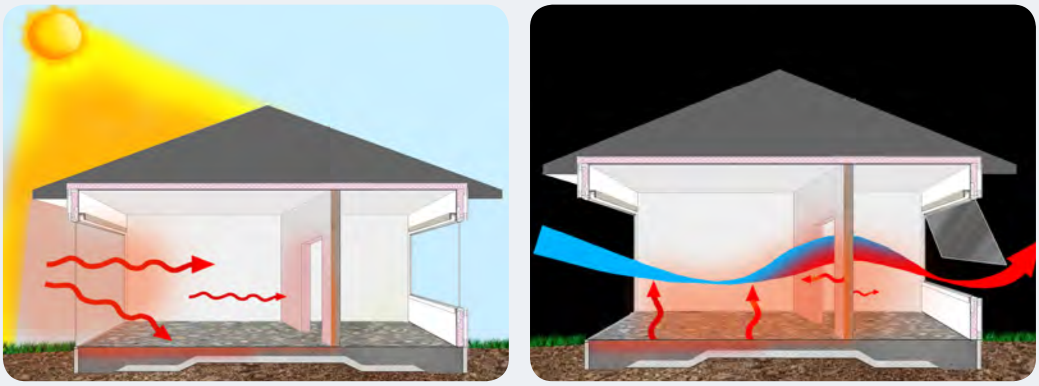
Harnessing warmth of day for warmer nights



Daytime heat absorption

Night-time heat release

Harnessing cool of night for cooler days



Daytime heat absorption

Night-time heat release

Figure 70: Thermal mass – night-time heat release in a hot climate.

5.8.1 Tips for Thermal Mass per Climate Zone

General considerations:

- ***Expose internally*** - expose thermal mass to room interiors so that it can moderate interior temperatures.
- ***Insulate externally*** - in all climates, fully insulate or isolate the thermal mass from the exterior such as locating it in internal walls, platform floors or an insulated concrete floor.
- ***Formats*** - useful thermal mass arrangements include an insulated slab on-ground, an insulated timber platform floor with a concrete topping, or an insulated mass-timber floor or wall.

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
• ***Shade*** - the thermal mass should be shaded at all times as it needs to be cooler than the outside daytime air temperature to be effective.		• ***Thermal mass*** - can be applied to northern and southern rooms in most temperate climates.	• ***Summer use*** – external shading should exclude direct solar gain in summer. • ***Winter use*** – only include thermal mass in rooms with direct winter sun or the mass might make then too cool.
• ***Thermal mass*** – is generally not helpful due to the high night-time air temperatures.	• ***Close-up*** – on hot days, strictly limit ventilation to keep interiors cool. • ***Night-purge*** – ventilate the interior well in the cool of the night to release heat stored from hot days.		

***Further resources**:*
Your Home Technical Manual – for details about Thermal Mass (www.yourhome.gov.au/technical/fs49.html)
Wood Solutions Guide: Using thermal mass in timber framed buildings in Australia

5.9 Equipment and Services

A house with a House Energy Rating of 10 stars should require no heating or cooling; however, most new 6-star houses will require some form of supplementary heating and cooling.

Heating equipment suppliers may still use 'rules of thumb' principles developed when houses and other building types were uninsulated, leading to oversized – and often less efficient – equipment. House thermal performance software should be used to estimate the house's heating and cooling requirements.

Equipment efficiency

As energy efficiency regulation increases, these systems may need to be selected before a planning and building permit is issued. The efficiency of heating and cooling equipment is often referred to as its Coefficient of Performance (COP). A COP of 2.7 indicates that one unit of electricity will be used to give off 2.7 units of heat or 'coolth'. Energy star ratings simplify this process further. For more information see the Federal Government's website: energyrating.gov.au.

5.9.1 Forms of Home Heating and Cooling

Common forms of heating and cooling use either one or a mixture of radiant, conductive and convective methods:

- ***Radiant*** - radiant heaters do not require air-movement or contact as the heat 'shines' through the air, as does the heat of the sun.
- ***Conductive***-– this method heats via contact, which is often contact with air, and the heated air is then circulated around the room through convection.
- ***Convective*** - this is movement of heat carried by air, such as a common fan heater.

Heaters are commonly fuelled by electricity, gas, solar energy or wood, and cooling equipment is usually fuelled by electricity.

In most climate types, reverse cycle air-conditioners provide the most efficient form of mechanised heating and cooling. They are also the most common form of heating and cooling in Australian residential building. Air-conditioners range from units for a single room through to whole-of-house ducted systems. Common COP values range from 2.0 to 4.3. Because of how an air conditioner operates with refrigerant gases, they are often more efficient at heating air than cooling air. This results in units having different star ratings for heating and cooling operation on energy use labels. A correctly sized air-conditioner can be of great benefit in most climate types.

In hot and humid climates, a reverse cycle air-conditioner will remove moisture from the air, making the conditioned room more comfortable. However, if the system is 'wrong sized', and not enough moisture is removed from the air, condensation can form on cold surfaces inside the house and within the building fabric. In these climate types, a supplementary dehumidification system can be incorporated with the air-conditioner to reduce thermal discomfort and save operational energy. This can be very advantageous in an energy-efficient house design as there should be less need for house cooling, and removing humidity from the air may provide a house's cooling requirements.

The reverse cycle air-conditioner's action of removing moisture from the air in both the cooling and heating processes makes this method suitable for cool and temperate climates. However, in hot and dry climates, the additional removal of moisture from the air can make the room feel unpleasant.

In hot and dry climates, an evaporative cooler is the most efficient form of cooling. Moisture is added to the air, lowering its temperature, and the increased humidity significantly improves thermal comfort. Evaporative coolers have a higher COP value than reverse cycle air-conditioners.

Hydronic heating and cooling systems circulate heated or cooling liquids through floors, ceilings, ceiling mounted radiators known as 'chilled beams' and floor or wall-mounted radiators in a reticulation system. The source of energy to heat or cool the liquid may be solar, ground-sourced, a heat-pump, a fire box or a gas boiler. Each of these energy sources has differing COP values and costs of operation. The advantage of a hydronic system is that it allows for the choice of energy source and the capacity to change the energy source when prices, efficiency or technology change.

More detailed information and specifications on heaters and coolers are available from product manufacturers or installers.

Ducts in heating and cooling systems

Reverse cycle air-conditioners, hydronic systems and evaporative coolers can use ducts to circulate the conditioned air. Good duct installation requires that ducts be:

- installed straight, without unnecessary bend of joins as each bend reduces system efficiency (Figure 71)
- fully insulated to maximise the use of conditioned air, and ideally ducts should travel through insulated roof and sub-floor spaces (Figure 72)
- well sealed at each connection and join to reduce system leakage.

Systems with poorly insulated and leaky ducts can generate condensation and increase the moisture load in the roof or sub-floor spaces.

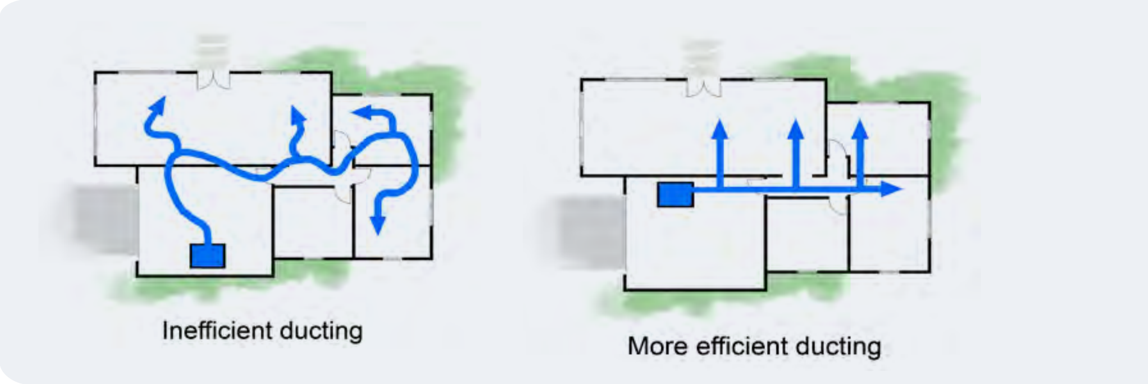


Figure 71: Duct runs. *Straight duct runs improve efficiency.*

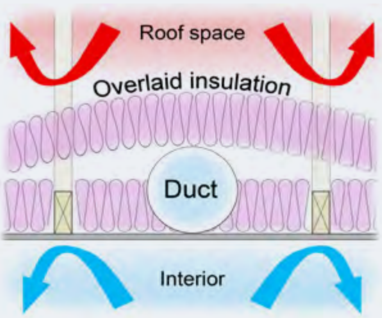


Figure 72: Duct Insulation.
Insulate ducts from the temperature extremes in the roof space.

5.9.2 Tips for Heating and Cooling per Climate Zone

Limiting artificial heating and cooling

General considerations:

- ***Good passive design*** – correct orientation, good planning for windows, shading, etc, will limit the need for artificial heating and cooling.
- ***Insulation*** – contain heat/cool and also limit the need for heating and cooling.
- ***Zoning*** – doors to separate living areas from bedrooms or other areas that do not need conditioning, such as hallways, can allow zoned conditioning and much improved energy efficiency.
- ***Sealed combustion heating*** – if wood or gas heating is installed, units should be free-standing to limit heat loss through walls, and sealed and externally flued to maximise efficiency.
- ***Efficient and correctly sized equipment*** – the design and sizing of the cooling and heating system should include a careful thermal simulation of the house to avoid under or oversized systems that cost more to operate.
- ***Straight and short services pipes and ducts*** – 30 to 50% of operational energy can be saved if ducts are carefully designed and installed. All duct runs should be short, straight, well-sealed and well-insulated without bends and 'S' shapes.

Climate specific considerations:

Zones 1 and 2 ***Hot and humid***	**Zones 3 and 4** ***Hot and dry***	**Zones 5 and 6** ***Temperate***	**Zones 7 and 8** ***Cool temperate and cold climates***
Heating Patterns			
• Intermittent in winter	• Often in winter	• Mostly in winter	• Most of the year
Heating Methods			
• Heat pump • Radiant heating • Solar thermal	• Heat pump • Radiant heating • Solar thermal	• Reverse cycle air-conditioning • Solar thermal	• Reverse-cycle air-conditioning (heat pump) • Radiant heating • Solar thermal
Cooling Patterns			
• Most of the time	• Mostly in spring, summer and autumn	• Mostly in spring, summer and autumn	• Intermittent in summer
Cooling Methods			
• Natural ventilation • Ceiling fans • Air-conditioning • Solar-thermal with absorption chiller	• Natural ventilation • Ceiling fans • Evaporative cooling • Solar-thermal with absorption chiller	• Natural ventilation • Ceiling fans • Reverse cycle air-conditioning • Solar thermal with absorption chiller	• Natural ventilation • Ceiling fans • Reverse cycle air-conditioning (heat pump)

***Further resources**:*
Your Home Technical Manual – for details about Heating and Cooling (www.yourhome.gov.au/technical/fs62.html)
Living Greener – for details about Heating and Cooling (www.livinggreener.gov.au/energy/heating-cooling)
Equipment Energy Efficiency – www.energyrating.gov.au

6

Learning from Case Studies

6.1 Introduction

To explore the principles discussed in this Guide, the thermal performance of two generic house designs were modelled for a range of Australian climates using the NatHERS accredited AccuRate software.

Modifications tested against the base model included: building orientation, eave size, increased levels of insulation, glazing types and the addition or removal of walls.

General simulation notes

- The base design followed passive solar design practices, but shading and the addition of thermal mass were not considered.
- Some modifications had only a small impact compared to the base model. This did not indicate they were not worthwhile pursuing; however, it did illustrate that the house is a living building subject to the climate of its location.
- The importance of balancing approaches was demonstrated. For example, the simulations clearly showed that increasing floor, wall, or ceiling insulation yielded little benefit unless there was a corresponding improvement to glazing.
- The simulations showed that a lightweight house requires careful design tuning to suit the climate and location. Aspects that work well in a cool climate may be detrimental to thermal performance in a hot climate; concepts that work well in a hot and dry climate may not work well in hot and humid climates.

Key simulation results

The simulations demonstrated some distinctive and climate-specific results. These included:

- ***Downlights*** - there was a significant benefit, in all climate types, if the recessed downlights were removed.
- ***Eaves*** - for the hotter climates, the increase from no eaves to 450 mm, 600 mm and 1800 mm eaves all showed an increased thermal performance as the walls and windows were shaded.
- ***Insulation area*** - Increasing floor, wall, or ceiling insulation yielded little benefit unless there was a corresponding improvement to glazing. The increase in wall insulation was affected by the glazing area and had a more significant impact in the cooler climates.
- ***Tiled floors*** - the use of tiles in the northern dining and living area showed a positive result, as this small element added effective thermal mass to the rooms.
- ***Thermal mass*** - replacing internal stud-framed walls with mass timber walling improved thermal performance; however, once this house design approached 6 stars, the additional mass in hotter climates could hinder the effect of further improvements.
- ***Double glazing*** - the shift from single to double glazing had a significant impact.

Description	**House 1** **3 bedroom**	**House 2** **4 bedroom**
Summary	single-storey detached house higher glazing ration	single-storey detached house higher thermal mass (concrete slab)
Size	smaller (182 m^2)	larger (203 m^2)
Floor	suspended particleboard floor R1 insulation batts under finished with carpet on underlay and tiles	concrete slab-on-ground finished with carpet on underlay, and tiles
External walls	brick veneer (timber frame) reflective building wrap R1.0 glass wool batt R1.5 insulation	brick veneer (timber frame) reflective building wrap R1.0 glass wool batt R1 insulation
Ceiling	plasterboard R4.0 glass wool batt	
Roof	sheet metal roofing with no eaves reflective sarking	
Windows	aluminium frames single-glazed, clear glass	
Glazing	11.37% (20.7 m^2) high glazing ration	10.11% (20.5 m^2) single-glazed, clear glass

6.2 Case Study House 1

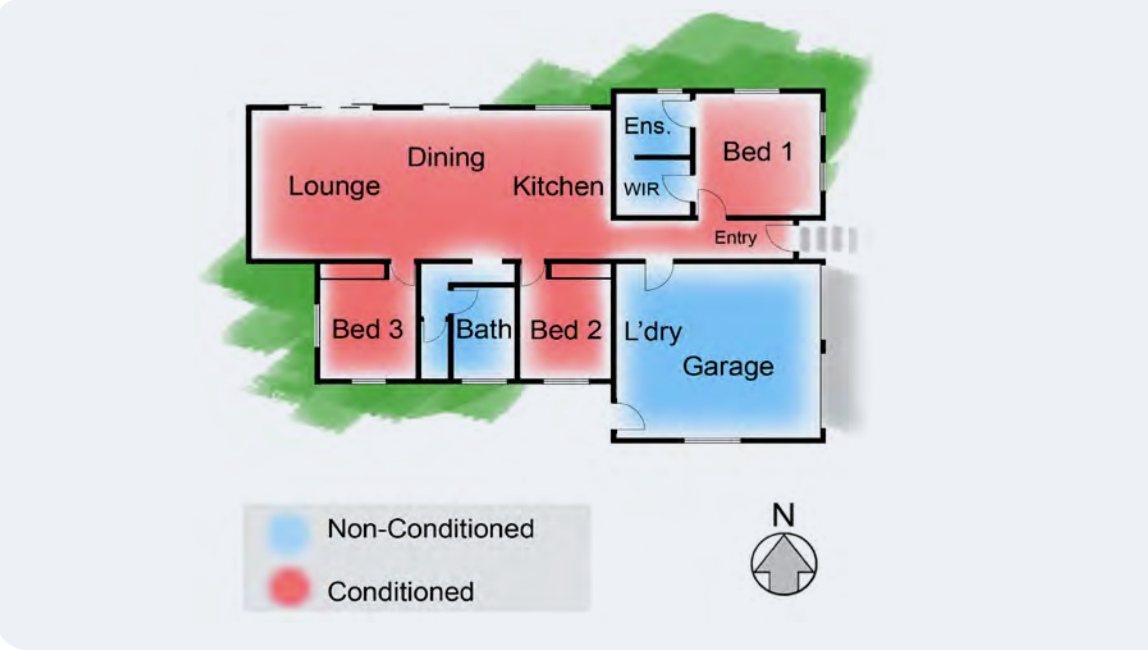


Figure 73: Plan of House 1.
Sixteen design variations were tested for House 1. The comparative impact on thermal performance has been modelled and the results recorded in Table 12.

Table 12: House 1 simulation results.

Platform Floored Case Study House	Hobart 7000				Melbourne 3053				Adelaide 5000				Alice Springs 870				Brisbane 4000				Broome 6725			
	MJ/m².annum				MJ/m².annum				MJ/m².annum				MJ/m².annum				MJ/m².annum				MJ/m².annum			
	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total
Base Design, carpet, R1.0 subfloor insulation, no eaves	5.4	167.5	13.8	181.3	5.1	106.0	40.7	146.7	4.7	62.9	74.7	137.6	4.1	33.0	158.8	191.8	3.2	14.8	76.2	91.0	3.9	0.1	390.4	390.5
Base Design + 90deg change of orientation to West	5.0	185.5	15.0	200.5	4.8	117.7	42.2	159.9	4.4	69.5	77.8	147.3	3.6	40.7	182.3	223.0	2.9	18.3	84.2	102.5	3.6	0.4	410.5	410.9
Base Design + 270deg change of orientation to East	5.2	180.7	9.0	189.7	4.8	113.0	45.0	158.0	4.4	66.0	82.2	148.2	3.6	32.7	186.6	219.3	2.7	15.4	91.2	106.6	3.5	0.1	413.5	413.6
Base Design + 450 Eaves	5.3	181.8	6.5	188.3	5.1	116.2	30.1	146.3	4.9	69.4	59.0	128.4	4.6	36.3	130.3	166.6	3.9	16.8	57.0	73.8	4.8	0.1	345.4	345.5
Base Design + 600 Eaves	5.2	186.8	4.8	191.6	5.1	119.5	27.1	146.6	4.9	71.7	54.5	126.2	4.7	37.5	123.0	160.5	4.1	17.5	51.1	68.6	5.0	0.1	334.2	334.3
Base Design + 1800 Shade	4.6	219.0	1.9	220.9	4.7	141.6	19.7	161.3	4.9	87.3	41.3	128.6	4.9	48.1	100.3	148.4	4.5	22.9	38.6	61.5	5.9	0.2	288.6	288.8
Base Design no recessed down lights	5.7	152.6	14.1	166.7	5.4	96.1	40.1	136.2	4.9	56.1	73.7	129.8	4.2	28.9	157.8	186.7	3.4	12.8	74.0	86.8	4.5	0.1	358.6	358.7
Base Design + R2.5 Insulation to entire floor	5.7	154.2	15.0	169.2	5.2	98.8	43.8	142.6	4.7	59.6	77.5	137.1	4.0	32.7	163.3	196.0	3.1	14.4	80.5	94.9	3.9	0.1	391.2	391.3
Base Design + R 2.5 wall insulation	5.6	160.6	13.3	173.9	5.2	101.5	40.1	141.6	4.8	59.9	73.2	133.1	4.2	31.4	155.4	186.8	3.3	14.1	75.6	89.7	4.0	0.1	386.4	386.5
Base Design + R8 ceiling insulation	5.7	156.6	13.3	169.9	5.3	98.4	39.0	137.4	4.9	57.4	70.2	127.6	4.3	29.0	149.2	178.2	3.3	12.8	75.8	88.6	4.1	0.0	382.4	382.4
Base Design + door to air lock	5.4	167.4	13.8	181.2	5.1	106.0	40.4	146.4	4.7	62.8	74.5	137.3	4.1	32.9	158.9	191.8	3.2	14.8	76.7	91.5	3.9	0.1	391.5	391.6
Base Design + Tiles to dining, lounge and hall floors	5.3	176.3	10.8	187.1	5.0	112.2	36.0	148.2	4.8	66.3	67.1	133.4	4.4	34.4	142.4	176.8	3.5	15.6	67.1	82.7	4.2	0.1	375.3	375.4
Base Design + additional windows for cross ventilation (up to 16% floor area)	4.7	187.3	30.0	217.3	4.3	119.1	61.1	180.2	3.7	72.9	108.2	181.1	3.1	39.1	225.3	264.4	1.9	17.7	122.3	140.0	2.6	0.2	480.1	480.3
Base Design + additional windows for cross ventilation (up to 16% floor area) + 1800 Shade	4.3	237.3	3.5	240.8	4.3	154.2	26.1	180.3	4.3	96.3	54.2	150.5	4.2	53.6	130.8	184.4	3.9	25.4	46.5	71.9	5.1	0.3	329.3	329.6
Base Design + double glazing to living, dining and kitchen	5.8	155.6	10.2	165.8	5.4	97.6	34.7	132.3	5.1	57.5	64.3	121.8	4.5	30.5	138.5	169.0	3.7	13.4	65.2	78.6	4.4	0.1	361.8	361.9
Base Design + double glazing to all rooms	5.9	147.1	10.1	157.2	5.6	92.3	33.8	126.1	5.3	53.9	62.2	116.1	4.7	27.8	132.1	159.9	3.7	12.3	65.5	77.8	4.6	0.1	356.4	356.5
Base Design + added thermal mass to internal walls of northern rooms	5.6	160.9	9.9	170.8	5.4	101.1	32.8	133.9	5.2	55.4	63.8	119.2	4.9	23.6	125.4	149.0	3.7	9.9	67.4	77.3	4.2	0.0	376.9	376.9
Base Design + added thermal mass to internal walls of all rooms	5.4	169.3	9.9	179.2	5.3	106.4	31.5	137.9	5.2	58.2	61.4	119.6	5.1	23.7	119.4	143.1	3.4	10.2	74.0	84.2	4.1	0.0	383.3	383.3
Base Design + added thermal mass to Floor (mass timber)	5.8	151.4	12.0	163.4	5.5	93.9	35.9	129.8	5.2	52.7	67.2	119.9	4.5	24.3	143.9	168.2	3.6	10.1	70.1	80.2	4.2	0.0	376.0	376.0

The most significant improvements, House 1

Cool Temperate Climates (Hobart)	Temperate Climates (Melbourne)	Hot and Dry Climates (Alice Springs)	Hot and Humid Climates (Broome)
1. The change from single glazing to double glazing provided the most significant benefit by reducing outward heat flow in this cooler climate. 2. The removal of recessed downlights provided the second-greatest thermal benefit. 3. The third most significant improvement was equally shared by increasing sub-floor insulation to R2.5, increasing ceiling insulation to R8.0 and the inclusion of carefully placed thermal mass within the home.	1. The change from single glazing to double glazing provided the most significant benefit by reducing heat flow in on hot days and heat flow out on cold nights. 2. The introduction of carefully placed thermal mass provided the second most significant benefit. 3. The removal of recessed downlights and the increase of ceiling insulation up to R8.0 provided very similar thermal performance improvements	1. The most significant improvement resulted from the inclusion of thermal mass in internal partition walls. 2. The addition of 600 mm eaves and a veranda around the entire perimeter of the house to shade the house from direct solar radiation provided the second most significant benefit. 3. The change from single glazing to double glazing provided the third-greatest benefit by reducing heat flow in on hot days and heat flow out on cold nights.	1. The addition of significantly sized eaves (+600 mm) or a 1800 mm veranda around the entire perimeter of the house to shade the walls from direct solar radiation provided the greatest benefit. 2. The design and placement of operable windows to promote cross ventilation provided the second most significant benefit. 3. The removal of vented downlights and the use of double glazing provided a very similar thermal improvement.
Having a veranda around the house or increasing window area to 16% of floor area provided the most thermally uncomfortable improvements.	Increasing window area up to 16% of floor area provided most thermally uncomfortable improvement.	Increasing window area up to 16% of floor area provided most thermally uncomfortable improvement.	Rotating the building made the house more thermally uncomfortable.

6.2.1 Case Study House 1 in Hot and Humid Climate

Table 12 shows the inter-relationship between climate and effective design for thermal performance. While the House 1 base design and the individual variants could provide reasonable performance in Hobart, Melbourne and some other climates, they were generally not effective in providing adequate performance in hotter climates like Brisbane. This was due to the greater percentage of external walls relative to house floor area.

Suitable performance could be achieved in these climates but this required careful tuning of the built fabric to suit local conditions and Table 12 shows the effect on the base model's performance in Brisbane through applying variations *in combination.* These results also highlight the benefits of investigating multiple improvement options during the design process.

6.3 Case Study House 2

The design followed passive solar design practices but shading and the addition of thermal mass were not considered in the base design. In comparison to House 1, House 2 was larger, contained more thermal mass and a lower glazing ration. Eighteen design variations were tested for House 2. The comparative impact on thermal performance has been modelled and the results recorded in Table 13.

The thermal mass of the concrete slab-on-ground floor could bring thermal benefits in some situations and be thermal detriment in others. The other significant factor that improved the thermal performance of this house was the glazing ratio, which was 10.1% of the floor area. This resulted in more insulated external wall to reduce heat flow into or out of the house. The house did have some living spaces on the north that would allow the sun to warm the bare concrete floor, which could add thermal benefit in cold and some hot climates.

Key simulation results

The simulations demonstrated some distinctive and climate specific results. These included:

- ***Downlights*** – there was a significant benefit, in all climate types, if the recessed downlights were removed.
- ***Wall shading*** – for the hotter climates, the increase from no eaves to 450 mm, 600 mm and 1800 mm all showed an increased thermal performance as the walls and windows were shaded.
- ***Wall Insulation*** – increasing insulation had a more noticeable impact due to the low glazing ratio.
- ***Mass timber walls*** – a significant thermal improvement occurred when the existing internal stud partition walls were replaced with mass-timber walling.
- ***Double glazing*** – shifting from single to double glazing had a significant impact.
- ***Balance modifications*** – increasing floor, wall, or ceiling insulation needed to be balanced with a corresponding improvement to glazing and other insulation systems.

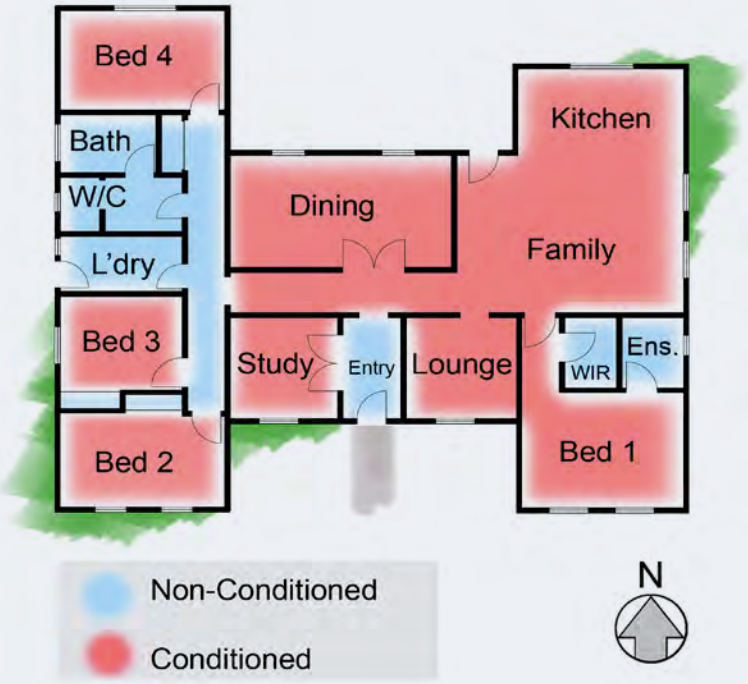


Figure 74: Plan of case study House 2.
A four bedroom house with some living areas oriented to the north.

Table 13: House 2 simulation results.

Platform Floored Case Study House	**Hobart 7000**				**Melbourne 3053**				**Adelaide 5000**				**Alice Springs 870**				**Brisbane 4000**				**Broome 6725**			
	MJ/m^2.annum				MJ/m^2.annum				MJ/m^2.annum				MJ/m^2.annum				MJ/m^2.annum				MJ/m^2.annum			
	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total	Star Rating	Heating	Cooling	Total
Base Design	5.4	195.4	1.8	197.2	5.8	114.2	19.1	133.3	6.3	57.7	41.3	99.0	5.8	23.4	107.6	131.0	5.7	9.7	40.8	50.5	5.4	0.0	330.3	330.3
Base Design +90 East	5.3	203.2	3.2	206.4	5.6	119.4	22.1	141.5	5.9	60.1	47.8	107.9	5.4	22.4	123.3	145.7	5.3	9.0	47.7	56.7	4.8	0.0	365.5	365.5
Base Design +90 West	5.4	200.4	2.9	203.3	5.6	118.0	23.3	141.3	5.0	60.2	50.2	110.4	5.1	24.0	130.9	154.9	4.4	9.6	60.9	70.5	4.8	0.0	360.6	360.6
Base Design +450 Eaves	5.1	217.1	1.1	218.2	5.6	128.5	14.5	143.0	6.2	66.7	33.3	100.0	6.2	27.7	89.5	117.2	6.5	11.4	30.5	41.9	5.9	0.0	304.8	304.8
Base Design +600 Eaves	4.9	223.9	0.9	224.8	5.5	132.9	13.4	146.3	6.2	69.7	31.4	101.1	6.2	29.3	86.2	115.5	6.5	12.1	29.7	41.8	6.0	0.0	298.7	298.7
Base Design +1800 Eaves	4.4	263.6	0.9	264.5	4.9	159.9	10.1	170.0	5.7	91.3	25.0	116.3	6.3	42.9	71.7	114.6	6.3	19.3	24.5	43.8	6.4	0.0	274.4	274.4
Base Design +50 Polystyrene under Slab	5.4	195.1	1.8	196.9	5.9	113.8	18.7	132.5	6.3	57.7	40.6	98.3	5.8	23.5	104.6	128.1	5.9	9.7	40.0	49.7	5.4	0.0	326.7	326.7
Base Design no recessed down lights	5.9	177.1	1.8	178.9	6.2	102.2	18.3	120.5	6.6	50.0	40.1	90.1	5.9	19.6	104.2	123.8	6.4	7.8	35.7	43.5	5.9	0.0	302.1	302.1
Base Design +change bedroom window for cross ventilation	5.4	196.4	2.2	198.6	5.8	115.0	21.3	136.3	6.1	58.1	45.5	103.6	5.5	23.6	116.6	140.2	5.4	9.7	43.3	53.0	5.2	0.0	341.2	341.2
Base Design + door to air lock	5.4	195.4	1.8	197.2	5.8	114.2	19.0	133.2	6.3	57.7	41.3	99.0	5.8	23.4	107.6	131.0	5.7	9.7	40.8	50.5	5.4	0.0	330.3	330.3
Base Design + door to hall way	5.4	195.4	1.8	197.2	5.8	114.2	19.0	133.2	6.3	57.7	41.3	99.0	5.8	23.4	107.6	131.0	5.7	9.7	40.8	50.5	5.4	0.0	330.3	330.3
Base Design + Remove wall between dining and family	5.4	195.1	1.7	196.8	5.9	114.0	19.1	133.1	6.2	57.7	41.6	99.3	5.7	23.4	109.3	132.7	5.7	9.8	40.8	50.6	5.4	0.0	331.3	331.3
Base Design + Study and Bedroom 4 interchanged	5.5	191.6	3.3	194.9	5.8	112.5	21.9	134.4	6.1	56.6	46.6	103.2	5.6	22.5	115.6	138.1	5.4	9.4	44.2	53.6	5.2	0.0	342.9	342.9
Base Design + R 2.5 wall insulation	5.9	174.4	1.6	176.0	6.3	100.3	17.1	117.4	6.7	49.9	36.4	86.3	6.2	19.3	96.9	116.2	6.1	7.8	38.2	46.0	5.7	0.0	316.6	316.6
Base Design + thermal mass internal walls to north facing windows (140 block grout filled)	5.4	201.5	1.1	202.6	5.9	118.1	13.9	132.0	6.6	55.7	32.7	88.4	6.8	17.6	80.6	98.2	6.7	5.7	34.8	40.5	5.7	0.0	317.8	317.8
Base Design + thermal internal wall to all rooms (140 block grout filled)	5.3	208.3	0.6	208.9	5.8	122.7	10.7	133.4	6.7	57.3	27.8	85.1	7.2	16.3	68.5	84.8	6.9	5.1	33.4	38.5	5.5	0.0	324.1	324.1
Base Design + R8 ceiling insulation	5.7	185.6	1.5	187.1	6.1	107.7	15.3	123.0	6.7	52.7	33.5	86.2	6.4	19.8	87.7	107.5	6.3	7.7	35.9	43.6	5.7	0.0	316.1	316.1
Base Design + double glazing to living rooms and dining	5.6	188.9	1.5	190.4	6.0	109.6	17.2	126.8	6.4	54.0	39.3	93.3	6.0	22.2	100.3	122.5	6.1	9.0	37.8	46.8	5.6	0.0	321.1	321.1
Base Design + double glazing to all rooms	5.9	177.7	1.4	179.1	6.2	102.6	16.1	118.7	6.7	50.9	35.7	86.6	6.3	19.8	94.0	113.8	6.3	8.0	36.1	44.1	5.8	0.0	312.9	312.9

The most significant improvements, House 2

Cool Temperate Climates (Hobart)	Temperate Climates (Melbourne)	Hot and Dry Climates (Alice Springs)	Hot and Humid Climates (Broome)
1. The most significant improvement resulted from the increase in external wall insulation. 2. Two items provided an equal second-best improvement, namely; the removal of recessed and ventilated downlights and the use of double glazing instead of single glazing. 3. The third most significant improvement was provided by increasing ceiling insulation to R8.0.	1. The most significant improvement resulted from increasing external wall insulation. 2. The adoption of double glazing instead of single glazing. 3. The removal of ventilated and recessed downlights.	1. The most significant improvement resulted from the inclusion of thermal mass in internal partition walls. 2. The increase in ceiling insulation to R8.0 provided the second-greatest thermal benefit. 3. Three actions equally provided the third most significant thermal benefit: the addition of 600 mm eaves around the entire perimeter of the house; increasing the R value of wall insulation to R2.5; and the use of double glazing rather than single glazing.	1. The addition of significantly sized eaves (+600 mm) or a 1800 mm veranda around the entire perimeter of the house shaded the walls from direct solar radiation and provided the greatest benefit. 2. The removal of vented and recessed downlights provided the second-greatest thermal benefit. 3. Four actions equally provided the third most significant thermal benefit: increasing wall insulation; increasing ceiling insulation; the adoption of double glazing instead of single glazing; and the careful placement of internalised thermal mass.
Having a veranda around the house provided the most thermally uncomfortable improvement.	Adding a veranda to this house design in Melbourne provided the most thermally uncomfortable improvement.	Rotating the building made the house more thermally uncomfortable.	Rotating the building made the house more thermally uncomfortable.

7

Thermal Comfort and Technical Principles

This section defines and describes concepts that are critical to achieving improved thermal performance with timber-framed construction in various climate zones.

7.1 Thermal Comfort

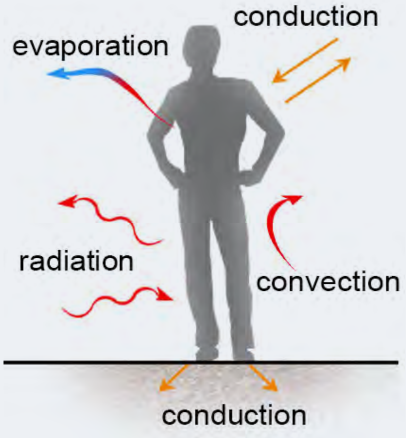


Figure 75: Personal energy balance.
Shows how heat is gained and lost from the body.

Thermal comfort is when a person feels thermally content psychologically within a particular space or environment. The way humans perceive thermal comfort is a mix of physical, physiological, psychological and other immediate influences. Subconsciously, our body attempts to regulate its temperature. Consciously, humans relate to three key variables: direct temperature, moisture and airflow, and their impact on the comfort or discomfort that our body feels. The body feels comfortable within a narrow range of these variables.

7.1.1 Mean Radiant Temperature

The mean radiant temperature is a key factor in thermal comfort as it may provide more than 60% of the thermal experience of the environment in a room. The mean radiant temperature is the average surface temperature of the floor, walls, windows, doors and ceiling, relative to position in a room (Figure 76). For example, when sitting in a room that has relatively still air, the surface temperatures of the floor, walls, windows and ceiling provide the major controlling influence on the sense of thermal comfort.

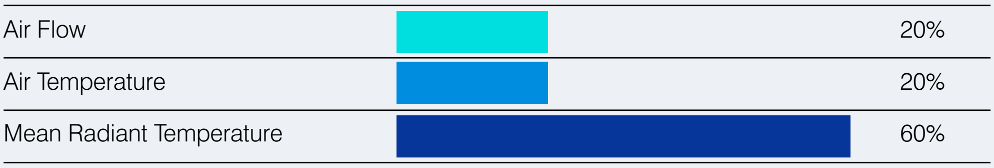


Figure 76: Relative impact of mean radiant temperature on personal comfort.

Humans might improve their thermal comfort by adding or removing clothing, becoming more or less active, or seeking shelter. Good residential design will aim for thermal conditions within a given room for specific likely activities at specific periods in a day.

It is essential to consider the room's function as function this influences the types of physical activity likely in the space, the times it is likely to be occupied and the expected internal energy loads. Thermally comfortable conditions required for sleeping are different to those required for periods of physical activity in the kitchen and they are required at different times.

7.2 Thermal Conductivity, Conductance and Resistance

Thermal conductivity (k) - is the quantity of heat that travels through a material resulting from a temperature difference between opposite faces.

- Thermal conductivity (k) is measured in Watts per metre per degree Kelvin (W/m.K)

Thermal conductance (C) - is the speed at which heat travels through a material caused by a temperature difference between the opposite surfaces.

- Thermal conductance (C) is measured in units of Watts per square metres per degree Kelvin (W/(m2.K))
- thermal conductance is thermal conductivity per thickness
- (The symbol K is for Kelvin. A temperature change of 1° Kelvin is equivalent to a temperature change of 1° Celsius).
- A high C value indicates a good conductor and a low C value indicates a good insulator

Thermal resistance (R) - A material's thermal resistance is its capacity to reduce or impede heat flow, which is the opposite of thermal conductance.

- R values are measured in units of (m2.k)/W
- high R value indicates a good insulator, and a low R value indicates a good conductor
- thermal resistance is the inverse of conductance (R-value = 1 / C).

Material	**Thickness mm**	**Thermal Conductivity (K) W/(m K)**	**Thermal Conductance (C) W/(m^2·K)**	**Thermal Resistance (R-value) (m^2.k)/W**
Glass Wool Insulation	90	0.038	0.42	2.381
Softwood	90	0.100	1.11	0.901
Hardwood	90	0.160	1.78	0.562
Paper Faced Plasterboard	10	0.160	16.00	0.063
Clay Brick Extruded	110	0.614	5.58	0.179
Glass	4	1.000	250.00	0.004
Steel	90	45.3	503.33	0.002
Aluminium	90	221.0	2455.55	0.000

Table 14: Thermal properties of common building materials.
There is considerable difference in the thermal conductivity and thermal conductance values of common building materials.

Beware when reviewing product R-values: some building materials include R-values that might not be for the given product, but for the whole of the building system once this item is installed. For building assemblies, the thermal resistance value of each material is added together to obtain a total R-value for the built system. When measuring the thermal resistance of a built assembly such as that for a timber-framed brick veneer wall shown in Table 15, the value of the more stable air film immediately adjacent to each face of the wall is also included for its insulative effect.

Thermal transmittance (U) – has the same formula as thermal conductance (W/(m^2.K) although whereas thermal conductance provides a value for each material, thermal transmittance is the overall co-efficient of heat transfer and must include the values for surface film conductance in the calculation.

Thermal Resistance of an External Wall Assembly		
System	**Thickness mm**	**Thermal Resistance (R-value) (m^2.k)/W**
Inner surface film coefficient	n/a	0.12
Internal plasterboard lining	10	0.06
R2.0 insulation in frame	n/a	2.00
Reflective foil with 40 air space	35	0.67
Clay brick veneer	110	0.18
Outer surface film coefficient	n/a	0.06
Total		3.09
Calculating the amount of heat coming through a wall		
Example of heat transfer of wall on a 33ºC day if 25ºC internally		
If the temperature inside the wall is 25°C (T_{inside}) and the exterior temperature is 33°C ($T_{outside}$), the heat flow inwards can be calculated as shown below:		
Heat Flow *inwards*	= U-Value x (T outside –T inside) = 1/3.09 x (33-25) = 0.32 x 8 = 2.56 Watts/m^2	

Table 15: Heat flow example.

7.3 Thermal Emittance and Reflectance

While dark materials tend to heat up in the sun, light coloured and reflective materials stay cooler. Thermal emittance is the heat emitted by a material's surface, which is measured relative to a black surface at the same temperature, to give an emittance value between 0 and 1. A dark surface may have an emittance of 0.9, while a reflective roof foil product may have an emittance of 0.05.

A material with a high emittance ratio will absorb excess energy and release stored energy to its surroundings as the surroundings cool, whereas a material with a very low emittance ratio will absorb and release very little energy. This is an important factor when considering the use of thermal capacitance, discussed below.

While reflective foils might be highly conductive of heat, their low emittance allows them to reflect heat. Several building materials are now marketed as reflective insulation. Most need to be installed with still airspace between the reflecting material and adjacent materials.

7.4 Thermal Capacitance

The temperature swings between warm days and cooler nights can be evened out with the addition of thermal mass to the building interior to store heat. The ability of materials to absorb and store heat from a warmer surrounding environment and release it when the surrounding environment cools is known as its thermal capacitance or thermal mass.

Thermal mass can also help in hot climates by storing night-time 'coolth' and easing daytime internal temperatures. In turn, this can reduce the reliance on energy-intensive heating and cooling systems. If properly applied, this process can be of benefit in some warm and cool climates. If applied poorly, it can make a cool house harder to heat, and store unwanted heat in a warm house.

Figure 78 and Figure 78 illustrate this concept. They show the temperatures measured inside an unconditioned room in buildings that are similar in arrangement but are of three different constructions:

- a very lightweight building – with the lowest thermal capacitance
- a lightweight building
- a medium-weight building – with the highest thermal capacitance.

During warm periods, the temperatures inside the building with the highest thermal capacitance were cooler than the very lightweight building, and warmer during cooler periods.

In cold climates, thermal mass can be used to store the days warmth and release it in the cooler evening. Conversely, in hot climates, well-shaded thermal mass can absorb unwanted heat in the day and this mass can cool again overnight through the use of night-time cross ventilation. For this to be effective, night-time temperatures must be significantly lower than the daytime temperatures – otherwise the use of thermal mass can retain heat keeping interiors excessively warm.

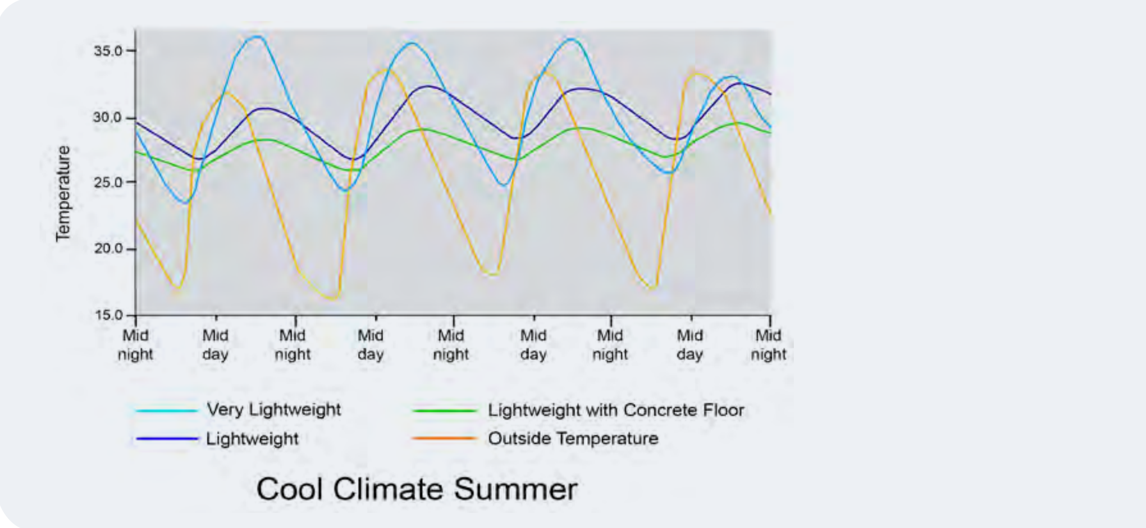


Figure 77: Thermal mass during a warm period (Launceston 2007).

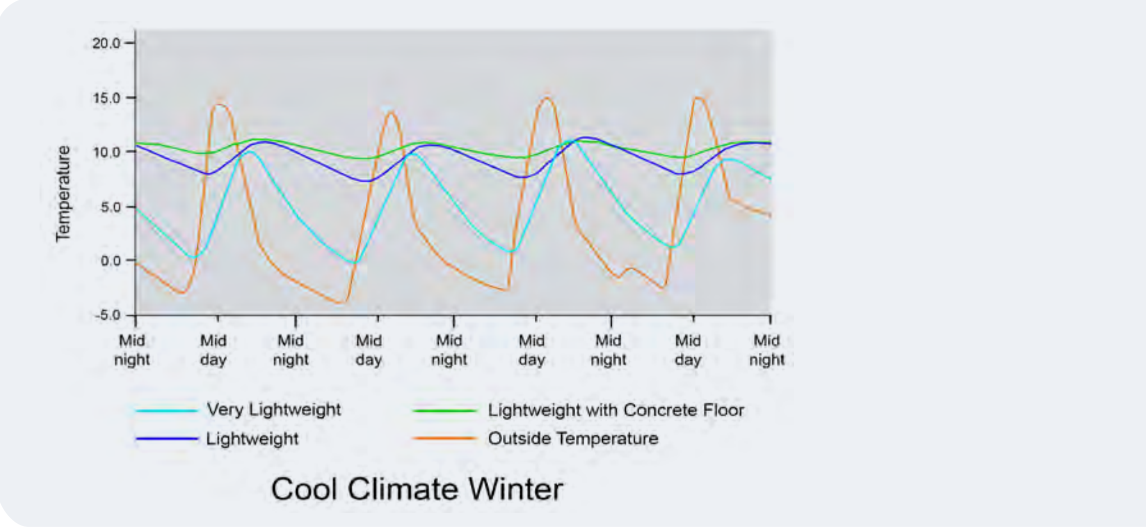


Figure 78: Thermal mass during a cool period (Launceston 2007).
Note: the most even temperatures come from the most thermal mass, keeping the internal temperatures closer to the comfort zone.

All materials within the home provide some form of thermal capacitance. Table 16 lists the values for some of these materials. Note that softwood has better properties than plasterboard and hardwood has very similar properties to clay brick. To date, timber-framed buildings have not been designed to effectively harness the ability of timber to store heat. Recent research shows the value of incorporating mass timber construction within a timber-framed house for effective thermal storage.

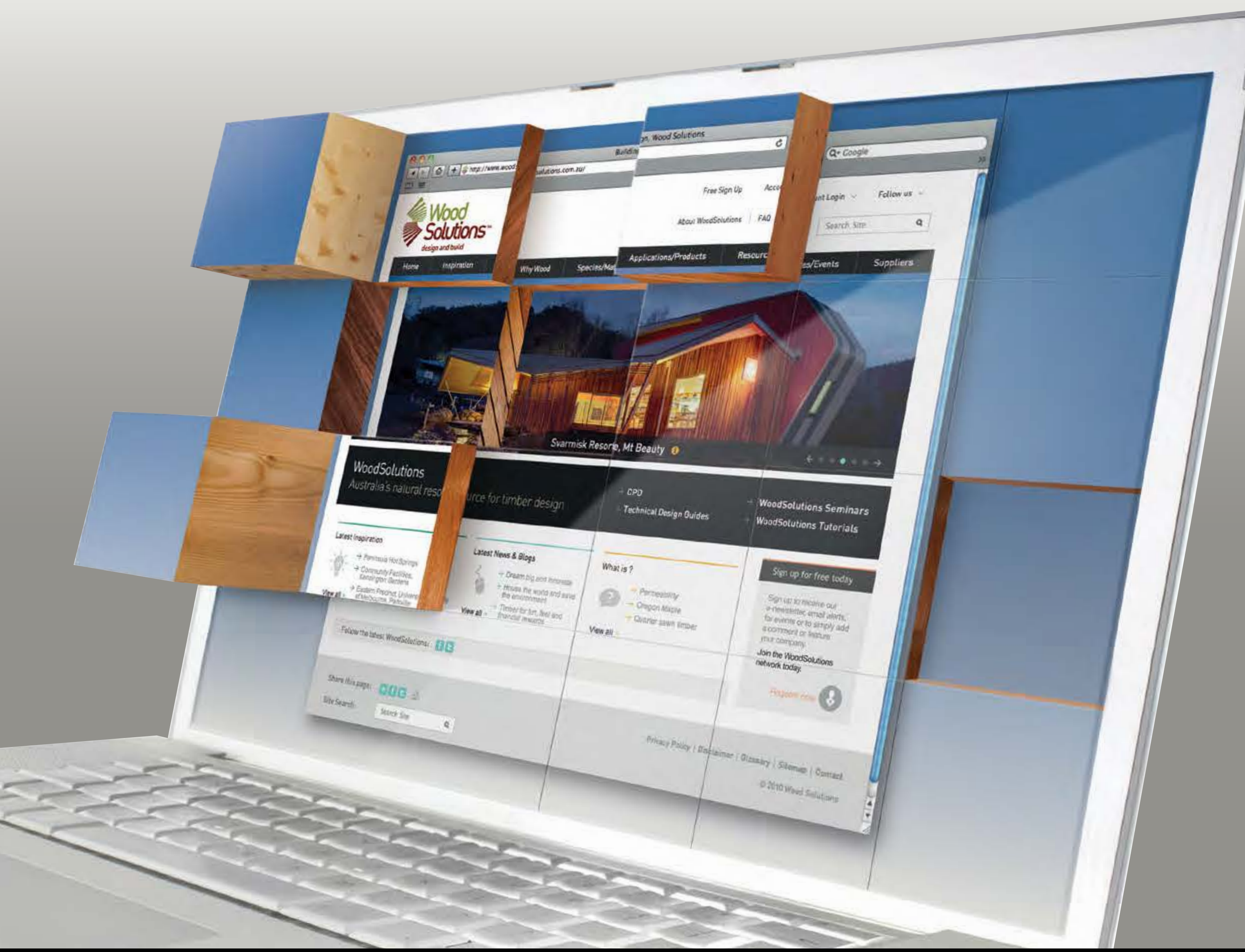
Material	**Density Kg/m³**	**Specific Heat J/(kg.K)**	**Thermal Capacitance kJ/m³.K (1m³)**
Air	0	1	0
Glass wool insulation	12	840	10
Paper faced plasterboard (6.8kg/m²)	680	1090	741
Softwood (pine)	500	1630	815
Hardwood (Euc. Obliqua)	780	1630	1271
Clay brick extruded	1700	800	1360
Concrete	2300	840	1932
Aluminium	2700	877	2367
Steel (AISE-SAE 1020)	7860	490	3851

Table 16: Thermal capacitance values for common building materials.

8

Acronyms

AS	Australian Standard
ACH	Air changes per hour
COP	Coefficient of Performance
DTS	Deemed to Satisfy the requirements of the NCC
HERS	House Energy Rating Software
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code. This includes the Building Code of Australia or BCA
R-value	Thermal resistance value
SHGC	Solar Heat Gain Co-efficient
WERS	Window Energy Rating Scheme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Contents

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Introduction

Timber's sustainability credentials are attracting world-wide interest and advancements in timber engineering have made it an increasingly cost-competitive proposition for commercial projects.

Encouraging the construction industry to adopt innovative approaches needs information and evidence. Attention to technical design, construction costs and site processes is critical to show the value proposition of timber construction to industry participants and optimise its use.

This Guide provides an introduction and overview of a research project that developed designs for four building types with timber solutions, as well as alternative designs with conventional steel portal or concrete construction.

The project aimed to provide a source of timber costing information to building professionals by comparing the cost of timber commercial buildings to the cost of those constructed using traditional materials.

The timber solutions were designed to optimise functional performance, constructability and cost effectiveness and provide guidance for compliance under the National Construction Code (NCC).

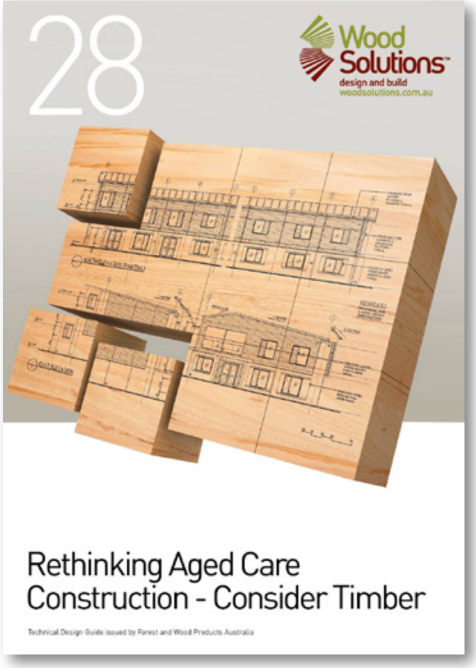
The project investigated four building types:

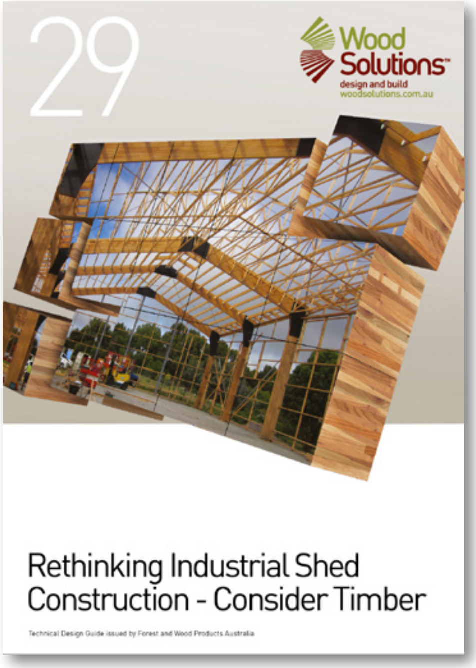
- A medium rise (7-storey) office building
- A medium rise (8-storey) apartment building
- A low rise (2-storey) aged care facility
- A single-storey industrial shed.

Each solution was designed and then independently costed for a timber option as well as a more conventional concrete-framed or steel-framed solution. The cost plans were based on a reference location in suburban Sydney. The site was assumed to have no significant cost implications concerning site access, ground conditions or neighbouring properties.

In 2018, a timber-framed design was added to the apartment building comparison to complement the cross-laminated timber design. Furthermore, the CLT design was also amended to comply with the current NCC requirements as well as to change the CLT supply from Europe to Australia. The apartment building with its three options and along with the office building where repriced to current market prices.

For details and cost comparisons for each the four building types, please refer to the Design Guide dedicated to each type:





Each of these Design Guides details a cost comparison and a commentary for the specific building type. The commentary discusses the makeup of each building, any issues encountered and how they were dealt with, as well as the outcomes and areas of possible improvement.

In all cases, the costs of the timber structural solutions were found to be significantly lower or lower than the competing non-timber solutions. Some of the main components were found to be significantly cheaper in timber for each building type investigated.

The gross savings were even greater; however, fire protection of some of these structural elements, the extra engineering cost (fire engineering) and the cost of termite protection reduced the overall cost savings. For the office building and apartment building, the major savings were generally found in the preliminary costs, an area not fully recognised when comparing costs (see Section 4).

Section 3 of this introductory Design Guide gives a summary of the cost plan results. Refer to the individual Design Guides for each building type for full descriptions of each timber solution and corresponding non-timber designs.

2

Project Development

The research project was carried out in four steps:

1. Develop a model design for the four building types.
2. Design each building using timber and also a non-timber material.
3. Develop an independent cost plan for each building type.
4. Develop a commentary on each building type to inform design professionals of the reasoning behind decisions and what was considered in the cost plan.

2.1 Model Building Designs

The first step of the project was to develop the designs for each of the model buildings being considered. It was decided to advance new designs instead of using those of existing buildings, as privacy and intellectual property issues prevented the publication of information on specific buildings. To develop the model designs, a number of industry experts and stakeholders were involved.

The project was led by the Timber Development Association (TDA) with the University of Technology Sydney (UTS) and the Royal Institute of Cost Surveyors' Building Cost Information Service (BCIS). UTS co-developed the research method and mediated the strategic direction of timber solutions pertaining to detailed design, construction, cost and site productivity issues. BCIS provided the quantity surveying, cost estimating and cost planning input for both the timber solutions and the corresponding non-timber traditional solutions. The cost plan for the apartment and office building was updated in 2018, and this was carried out by MBM.

The design teams varied for each building type. Team members collaborated in providing feedback for their particular building and driving the development process, which included meetings, interviews, concept development sessions, design charrettes, cost planning studies and detailed design studies to develop the model building under consideration and find a cost-effective timber solution for it.

Each building was designed to the extent that the key differences in costs for each one could be ascertained. For the office and apartment buildings, the design had to incorporate much more than just structural consideration; it also included heating, ventilation and air conditioning (HVAC), façade, acoustics, and so on. These aspects drove the structural design decisions and are discussed in detail in the Design Guides for the office and apartment buildings. As is the case for complex buildings, specific designs for each building varied for each building type.

Various companies within the timber industry provided input to all the building designs. Timber companies were able to explore options that could not be done under real project conditions. The companies involved were engineered timber manufacturers, suppliers and associated connections including: Tilling Timber, Meyer Timber, Nelson Pine, Carter Holt Harvey Wood Products, MiTek, Hyne and XLAM. These companies provided input on timber supply costs, the viability of designs, design properties, manufacturing processes and the availability of appropriate timber componentry.

2.1.1 Office Building Design

The designs for the office buildings were developed by design teams involving staff from the following organisations:

- Fitzpatrick and Partners – An architectural firm specialising in office design with significant experience in all the major cities in Australia. They provided feedback on client needs and helped design the model office building and the related timber solution.
- Arup Ltd – A global engineering firm with expertise spanning structural, acoustic, fire and services engineering. They provided design and engineering input into the timber solution and the corresponding concrete solution as well as assisting in HVAC and acoustic decisions.
- RBE Contracting – A construction project management company with expertise in large-scale timber construction. They provided input into the timber solution and the competing concrete solution, especially in terms of design management and site process-driven variables.

The revised cost model carried out in 2018 did not change any of the original design.

2.1.2 Apartment Building Design

The design for the apartment buildings was carried out twice. The first time as a CLT only solution, and the second time as a lightweight timber-frame and Australian CLT solution. The initial design was developed by design teams involving staff from the following organisations:

- Studio 505 – An architectural firm with a strong understanding of the design and the effects of material and system selection. They prepared and led the design of the model apartment building with case specific input into the related timber solution.
- Taylor Thompson Whitting (TTW) Consulting Engineers – An engineering firm with specialised services in structural, civil and facade engineering. They provided the structural design for the concrete solution.
- AECOM – A global multi-disciplinary engineering firm with expertise in structural, acoustic, fire and service engineering. They provided specialist advice on the design of the timber solution. TDA designed the cross-laminated timber (CLT) components in collaboration with the CLT supplier SmartStrut, and AECOM provided specialist CLT assistance.

The later revision involved additional companies;

- Zimmermann Design Studio: An Architectural firm that led the design of the timber-framed apartment building and provided input into the related timber solution. The original concept design of the building is based on a design undertaken by studio505 the firm from which Zimmermann Design Studio emerged from.
- Timber Imagineering and Tim Gibney and Associates: Heavy timber Fabrication Company and structural timber engineering services. They provided the specialised design of lateral resisting frames as well as analysis of the CLT core.

2.1.3 Aged Care Facility Design

The aged care building was much smaller and, since the chosen structural system is well established in timber and alternative materials within the marketplace, it was not necessary to establish a multi-discipline design team. The architectural model design was developed by Plan Source, a building design company experienced in residential and small commercial buildings. Structural design for both design options was provided by TDA with assistance from Tilling Timber and Meyer Timber. The design was then supplemented with input from timber and steel frame and truss suppliers.

2.1.4 Industrial Shed Design

An existing design developed for the Structural Timber Innovation Company was used for the industrial shed, so there was no need for a design team. The exercise was to reprice the existing design and an alternative timber design was considered to further explore attributes of a timber portal frame. This design explored another bay spacing arrangement and an alternative connector system.

2.2 Cost Plan Development

The Royal Institute of Cost Surveyors (RICS) provided quantity surveying, cost estimating and cost planning input for both the timber solution and the corresponding alternative solutions for the initial study. In most circumstances, RICS used the pre-existing knowledge within its own information system to develop the comparison costs. However, as the timber designs for the office and apartment building were unique, a price for each one was obtained from the marketplace that included all costs up to delivery to the reference building site. RICS sourced these prices directly from the market, independent to the research team.

SmartStruct provided the CLT price for the apartment building and the cores in the office building, while Meyer Timber provided the price for the office building's beams, columns and floor and roof cassettes.

For the aged care building, the costing information was sourced from the BCIS database, with independent prices sourced from the market place as a parallel exercise. The market place prices confirmed the accuracy of the BCIS cost information.

One key element in developing a cost plan was the consideration of the construction program time. Time savings affect preliminary costs, and this was a key difference in the costing of the office building and apartment building. An independent contractor experienced in both timber and concrete construction was used to program the office building. The apartment building was estimated by BCIS, as they have information on CLT design from their parent company in the UK, where CLT design has been used for more than 11 years.

The revised cost plan carried out in 2018 for the office building, and lightweight timber-framed and CLT apartment utilised a different company, MBM. MBM is a national independent construction consultancy specialising in quantity surveying. They provided quantity surveying, cost estimating and cost planning input for the 2018 version of the timber-framed solution and the corresponding concrete solution. They have, in recent times, developed real experience in timber construction and costings. XLAM provided the cost for the CLT.

3

Cost Plan Results

The cost comparison for each building type was only undertaken for the parts of the building that were considered to have significant different costs, both positive and negative, under the two competing design scenarios. Therefore, items such as mechanical, electrical, plumbing, floor coverings, car parking levels and fit out were excluded. In order to create stable costing, it was assumed that the building would be constructed in suburban Sydney, with no significant cost implications concerning site access, ground conditions or neighbouring properties.

In all cases, it was found that the timber solution was more cost effective than the alternative material considered (see Table 1.) The price differences shown in the tables are for elements of construction considered and do not represent the overall costs of the buildings.

Each of the main components was found to be significantly cheaper in timber for each building. The gross savings were found to be even greater; however, the fire protection to some of the structural elements, the extra engineering cost (fire engineering) and the cost of termite protection reduced the cost savings. For the office and apartment building the major cost savings were generally found in the preliminary costs – an area not fully recognised when comparing costs (see Section 4).

Building type	Cost of structural solution		Cost savings of timber compared to conventional
	Timber	Conventional	
7-storey office building	$7,237,259	$8,379,104	-$1,141,485
8-storey lightweight timber frame apartment building	$4,073,727	$4,698,581	-$624,854
8-storey CLT apartment building	$4,406,714	$4,698,581	-$291,867
2-storey aged care facility	$697,020	$809,620	-$112,600
Single-storey industrial shed	$216,342	$238,861	-$22,519

Table 1: Summary of all cost comparisons.

3.1 Office Building Cost Comparisons

For details of the 7-storey office building cost comparisons, see the *Design Guide #26 Rethinking Office Construction – Consider Timber*.

The timber building provides a saving of $1,141,845, being a 13.6% saving compared to the reinforced concrete solution (see Table 2).

Element	Timber	Concrete	Variance
Columns	$450,218	$307,224	+$142,994
Staircase	$319,700	$305,865	-$13,835
Uppper floors	$4,491,903,	$4,736,195	-$244,292
Roof	$593,105	$792,480	-$199,375
Shafts External Walls	$345,825	$522,000	-$176,175
Shaft Internal Walls	$521,268	$717,600	-$196,332
Ceiling Finishes	$997,740	$997,740	$0
Preliminary Adjustments	-$482,500	-	-$1,141,845
Total	**$7,237,259**	**$8,379,104**	**-$1,141,845**

Table 2: Office Building – Cost comparison of major items for each building solution.

In analysing the differences between the two plans, the timber building provides a saving of $1,141,845 is 13.6% cheaper than the concrete solution. Specific savings under the timber solution are as follows:

- Floor: $244,292 (4.7% less)
- Lift, Stair and Air shafts: $356,342 (23% less)
- Roof: $199,375 (25.1% less)
- Preliminary costs: $482,500 less.

Additional costs under the timber solution (relative to the concrete solution) include:

- Stairs: $13,835 (3% more)
- Columns: $142,994 (31.8% more)
- Connections: $59,769 more
- Termite & Fire Engineering: $35,000 more.

Additional savings could be possible by deleting the suspended ceiling and exposing the timber beams and floor. This would result in a further potential savings of $997,740, but this would incur additional costs for neater fixing of the mechanical air supply and lights, estimated to cost $266,064. The overall saving for the timber solution, in this case, would be $1,873,521 (22.3% less than the concrete solution), a very substantial cost saving.

3.2 Apartment Building Cost Comparisons

For details of the 8-storey apartment building cost comparisons, see the *Design Guide #27 Rethinking Apartment Construction – Consider Timber*.

Two timber solution were considered, and both provided saving. The lightweight timber-framed solution provides a saving of $624,854, being 13% lower than the reinforced concrete solution (see Table 3), while the Cross Laminated Timber solution provided a saving of $291,867 or 6% lower (see Table 3).

Element	**Timber Framed**	**Cross Laminated Timber**	**Concrete**
Columns	34,935.00	34,935.00	365,644.00
Upper Floors	1,567,887.00	2,539,961.00	1,810,398.00
Staircase	81,200.00	81,200.00	66,150.00
Roof	256,260.00	233,100.00	356,617.00
External Walls (excludes rain screen)	335,511.00	518,082.00	416,165.00
Internal Walls	1,417,544.00	1,286,436.00	1,224,522.00
Wall Finishes	Included	Included	Included
Ceiling Finishes	667,390.00	Included	459,085.00
Preliminaries	-287,000.00	-287,000.00	-
Total	**4,073,727.00**	**4,406,714.00**	**4,698,581.00**

Table 3: Apartment building – Cost comparison of major items for each building solution.

Specific savings under the timber solution (relative to concrete) were:

- •Concrete transfer slab at Level 1 ($173,091). As both the timber solution is lighter in weight (20% of the mass of concrete) than the concrete solution, a thinner and cheaper concrete transfer slab was possible.
- •The loadbearing structure, including walls, floors, columns, roof and their coverings was cheaper for the lightweight timber framed solution ($352,527) and marginal difference for the CLT solution ($9,917). Savings were possible due to the reduction of material required for the roof and core walls and also the removal of columns throughout the building by the use of loadbearing walls.
- •Preliminary costs for the project. The timber solution included an estimated saving in preliminaries of $287,000, based on a construction program saving six weeks compared to the concrete solution.

Each week was estimated to save $52,000 based on labour cost savings for site management, site sheds and plant such as crane, hoist and scaffolding hire when compared to the concrete option. An allowance of $25,000 was deducted from this saving to cover the extra cost of termite protection to the timber elements.

Additional costs under the timber solution relative to concrete were:

- Increased fire protection to the lightweight timber-framed and CLT elements. The extra cost for the timber solution related to the additional linings required for fire protection of timber load-bearing walls and floors for both timber solutions.
- Termite protection of the timber elements. The timber solution sits on top of a concrete basement (car park) and concrete retail level. As an additional precaution, the timber structure has termite protection by way of a stainless steel mesh to all hidden entry points from the ground to the concrete structure. This protection was estimated at an additional cost to the timber solution of $25,000.

3.3 Aged Care Facility Cost Comparisons

For details of the aged care facility cost comparisons, see the Design Guide #28 *Rethinking Aged Care Construction – Consider Timber.*

The timber-framed solution cost plan for the 2-storey aged care facility shows a saving of $112,600, being a 16% reduction when compared to the steel-framed solution (see Table 4). These costings include wall and floor coverings.

Item	Timber	Steel	Variance
Columns	$2,646	$3,330	-$684
Upper Floors	$63,138	$226,357	-$163,219
Roof	$259,611	$300,635	-$41,024
Walls	$371,625	$279,298	+$92,327
Total	**$697,020**	**$809,620**	**-$112,600**

Table 4: Aged care facility – Cost comparison of major items for each building solution.

Main savings for the timber solution:

- Upper floor framing $163,219 or 72% lower than the steel solution
- Roof framing $41,024 or 15% lower than the steel solution

Additional costs were found to be in the wall framing $92,327, a 33% additional cost.

An exercise was carried out to independently verify the cost plan findings via real quotations from the market place. Quotes were obtained from leading timber and steel frame suppliers as a package delivered to site. The quotes are for framing materials only; note, the cost plan included wall and ceiling coverings.

Steel	$231,000
Timber	$193,133
Difference	$37,867 (20% saving).

As with the cost-planning exercise, these figures indicate that the timber solution is cheaper, but at a lesser amount of $37,867 (20%). The savings were identified mainly in the upper floor framing, which parallels the main findings from the cost planning exercise.

3.4 Industrial Shed Cost Comparisons

An existing design was used for the industrial shed, and an alternative timber design was considered to further explore attributes of a timber portal frame. This design explored another bay spacing arrangement (see Table 5 for a summary of the cost comparisons).

For details of the industrial shed cost comparisons, see the Design Guide #29 *Rethinking Industrial Shed Construction – Consider Timber.*

Item	Timber portal solution 1 6.67 m Bay Spacing	Timber portal solution 2 10 m Bay Spacing	Steel portal solution 8.0 m Bay Spacing
Purlin	$39,483	$74,595	$46,190
Girts and columns	$20,761	$28,247	$60,496
Portal Frame	$147,310	$91,500	$98,635
Footings	$19,480	$22,000	$33,540
Total	**$227,034**	**$216,342**	**$238,861**

Table 5: Industrial shed – Cost comparison of major items for each building solution.

The timber solution with the 10.0 m portal spacing is the cheapest option, followed by the timber solution with the 6.67 m portal spacing, being 9.4% and 5.0% cheaper than the steel option, respectively.

4

Conclusion

This project developed cost plans for the structure of four building types: a 7-storey office building, an 8-storey apartment building (lightweight timber-framed and CLT version), a 2-storey aged care facility and a single-storey industrial shed. Each solution was designed and then independently costed for a timber option as well as a more conventional concrete-framed or steel-framed solution for a reference location in suburban Sydney. The site was assumed to have no significant cost implications concerning site access, ground conditions or neighbouring properties.

The investigation considered only the elements of the building for which there were significant differences and ignored the cost of elements that were the same.

This project has shown that timber building designs can be as cost-effective as traditional non-timber building designs. The overall costs of the timber solutions for these four building type scenarios were found in all cases to be less or significantly less than the competing non-timber solutions.

The cost of each of the main components was found to be cheaper in timber for each building. The gross savings were found to be even greater; however, the fire protection to some of these structural elements, and the cost of termite protection reduced the overall cost savings for some building types.

4.1 Cost Savings from Preliminaries

For the office building and apartment buildings, the major savings were generally found in the preliminary costs, an area not fully recognised when comparing costs.

A significant proportion of the savings in a timber solution were found from using pre-fabricated methods of construction for the office and apartment buildings. Pre-fabrication reduced onsite construction time due to compression of the construction program and reduced the need for expensive on-site labour. A compressed construction program saves site infrastructure costs such as scaffolding, site accommodation, hoists, craneage and construction site administration costs.

These cost savings can potentially be significant but are hard to quantify under a cost plan scenario, as they are included under a cost centre called preliminaries. Cost planners tend to use set percentage rates for preliminaries, which means these costs are often calculated as the same for each material considered. Until more timber buildings are actually built and real data is incorporated into cost planners' databases, these fixed preliminaries will hide some real advantages for timber solutions.

The two cost planners utilised for this project took a conservative view of what preliminaries savings could be used, as there is a lack of evidence to justify doing otherwise. Acceptance of the shorter program time for timber buildings is presently hard to accept, as there is little documented evidence for construction programs of real buildings available.

The cost plans developed for this project's buildings only included hire cost savings for major items such as site accommodation and plant (crane and hoists) and the reduced site administration labour cost. Further cost savings were identified but were excluded because, as stated above, there is little publically available evidence in the marketplace of actual time or material savings. The commentary that accompanies the cost plan for each building type discusses these other possible savings, and they are particularly significant in the apartment building and office building designs.

Refer to the specific Design Guides for the details of potential cost savings relating to:

- removal of scaffolding
- reduced first fix time, being the time to carry out rough-in for mechanical, electrical and plumbing within timber structures
- reduce footing/foundation costs
- reduced crane size or type.

A greater understanding of the productivity gains and their effect on preliminaries around timber product installation is required for a true cost comparison to be possible. This information will become more readily available as the use of timber solutions for commercial buildings becomes more widespread in Australia.

4.2 Other Findings

Many lessons learnt from this project are already assisting in the design of actual commercial timber buildings by the project partners. Of the four building types investigated, the designs of the timber solution buildings for the aged care and industrial buildings were well understood, easy to detail and had cost information readily available. This was not the case for the office and apartment buildings where the timber options were relatively unknown. The office building was particularly difficult to design, as the solutions available from the timber industry were numerous but there was little experience in what system worked best or suited the building constraints.

Some findings in relation to cost reduction were:

1. Maximise the use of stock timber products and sizes.

Using timber items and sizes that are readily available in the supply chain provides cheaper building solutions. Where items are especially manufactured or fabricated, costs quickly inflate. Non-standard sizes also may generate significant wastage, which also adds to the cost.

2. Increase fire resistance through timber's char capacity.

Designing for the required fire resistance was found to be cheaper when the char capacity of timber itself was used and dependence of plasterboard was reduced.

There are two general approaches in providing fire resistance; the first, which is considered the traditional approach, is to install plasterboard fire protection. The second approach is to use the char capacity of timber and oversize elements so that there is capacity in the timber element to provide fire resistance and structural resistance under fire load conditions.

The cost to install plasterboard makes systems designed around this relatively expensive. By increasing the size of key timber elements, there are substantial labour cost savings as there is less plasterboard to be installed.

3. Reduce crane movements.

It is important to consider the number of elements that need to be moved by crane as this directly affects the construction program and, consequently, costs. Having large elements or combining elements together on the ground and lifting in place saves time and costs.

However, this needs to be balanced with waste generation, best seen in CLT wall use. If a wall has a large opening in it – such as for a door or windows – this potentially creates a lot of offcuts, which become waste if they can't be used elsewhere. Dividing the panel into a number of separate components to reduce the generation of offcuts will increase the number of crane lifts required for the same amount of installed wall. Consequently, there is a balance between waste generation and construction program time increase, with costs dependent on a number of variables.

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Rethinking Office Construction - Consider Timber

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Cover image: Render of proposed timber commercial building for Sussex Street
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Introduction

Timber's sustainability credentials are attracting world-wide interest and advances in timber engineering have made timber an increasingly cost-competitive proposition.

Encouraging the construction industry to adopt innovative approaches needs information and evidence. Attention to technical design, construction costs and site processes is critical to show the value proposition of timber construction to customers and to optimise its use.

This Guide aims to help those involved in the decision chain (such as cost managers, estimators, design professionals, building developers and project managers) gain a better understanding of the value that timber construction systems offer mid-rise office building projects.

The Guide is based on a research project that developed a model mid-rise office building and a corresponding timber solution, and compared it with conventional concrete construction. The timber solution was designed to optimise functional performance, constructability and cost effectiveness and provide guidance for compliance under the National Construction Code (NCC) for Class 5 office buildings. This Guide provides an explanatory understanding of decision making issues when developing timber solutions.

This Guide was updated in mid-2017 to bring the timber design inline with the 2016 changes to the Building Code of Australia for Fire-protected timber solutions. Pricing has also been revised to reflect current market conditions.

2

What Drives Decisions When Choosing an Office Construction System?

A key objective of the research project was to provide an understanding of the decision drivers along the full length of the customer/supply chain that influence the selection of office construction systems. Key areas of investigation included:

- Gathering information about customer needs and how construction affects things like the leasability of the floor space, how the structural configuration can affect the area that can be let, and the capacity to easily adapt the space for retrofit and upgrade.
- Benchmarking against existing office construction systems, especially conventional post-tensioned concrete slab construction. This was found to be the main method used for mid-rise office building construction and was consequently used as the basis for comparison to timber. A concrete solution for the model building is provided in Appendix A.
- Integrating understanding of technical design issues, including structure, HVAC and façade systems.
- Understanding the nature of the overall delivery supply chain and related work flows, especially construction scheduling, productivity and prefabrication issues.
- Optimising the regulatory framework where it affects the viability of timber solutions.

3

Project Development

The research project was developed by a series of expert/stakeholder meetings, interviews, concept development sessions, design charrettes, cost planning studies and detailed design studies aimed at developing the model office building and a cost-effective timber solution for it.

A team of experts worked to provide input to the development process. Core collaborators included:

- **The Timber Development Association (TDA)**: A market development association for the timber industry and the project leader for this work, on behalf of the timber industry.
- **The University of Technology Sydney**: A technology-driven university with an integrated understanding of the building industry and with specific expertise in timber construction. The university co-developed the research method and mediated the strategic direction of the timber solutions in terms of detailed design, construction, cost and site productivity issues.
- **Fitzpatrick and Partners**: An architectural firm specialising in office design with significant experience in all the major cities in Australia. They provided feedback on client needs, helped design the model office building and the related timber solution.
- **Arup Ltd**: A global multi-disciplinary engineering firm with expertise spanning structural, acoustic, fire and services engineering. Arup provided design and engineering input into the timber solution and the corresponding concrete solution, as well as assisting in HVAC and acoustic decisions.
- **RBE Contracting**: A construction project management company with expertise in many forms of building construction and specific expertise in large-scale timber construction. They provided input into the timber solution and competing concrete solution, especially in terms of design management and site process–driven variables.
- **BCIS**: A global subsidiary of the Royal Institute of Chartered Surveyors who specialise in gathering building cost data used for reporting on cost trends for a variety building forms. BCIS provided quantity surveying, cost estimating and cost planning input for both the timber solution and the corresponding concrete solution.
- **MBM**: A national, indepentant construction consultancy specialising in quantity surveying. They provided quantity surveying, cost estimating and cost planning imput for both the timber and corresponding concrete solutions. MBM has recently developed experience in timber construction and costing.
- **Engineered timber manufacturers and suppliers (including Tilling Timber, Meyer Timber, Nelson Pine, Carter Holt Harvey Wood Products, MiTek)**: Their input included information on timber supply costs, practical viability, design properties, manufacturing processes and the availability of appropriate timber componentry (including supply of long span beam and panel products).

4

The Model Office Building - the Basis for Comparison and Solution Development

The model office building was created to provide a basis for defining and presenting a timber–based solution, as well as a corresponding concrete solution. Such an approach helps to model spatial, loading, fire and noise resistance conditions. Emphasis was placed on characterising a building that could apply to many suburban/urban office situations across Australia, approximating real world conditions.

A series of conceptual timber designs was developed by the research team revolving around different column and floor plate assemblies. In total, 30 initial designs were considered. Each was debated, tested for logic and then rationalised for functional performance, cost impact, construction flow, overall time efficiency, structural performance, services integration and value impact on the building owner. This informed the learning process for the research team in terms of understanding sensitive issues and key inter-relationships. From this, a refined set of options was distilled including a preferred option (as presented in the main body of this report) and three alternative options (described in a summarised format in Appendix D). Of note, this final set of options was primarily included for feedback to a broader cross-section of building owners, developers, designers and contractors.

Figures 1, 2 and 3 provide an overarching understanding of the model office building. The basic spatial characteristics and some of the detailed features of the model are provided in Table 1:

Item	What was used in the model	Relevance and Reasons
Height	• A 7-storey above-ground building, with two basement (car parking) levels. • A 26 m overall building height but with an NCC effective height of 22.2 m (referring to the upper most habitable floor but excluding the top storey, where used for items such water tanks, lifts, etc).	• This height is typical of many suburban and CBD office building situations. • The chosen height aims to maximise the floor-to-site ratio while staying below the 25 m effective building height used by the NCC as a limit for fire-protected timber soluions.
Area	• A floor plate area of 1,944 m^2 • Length 72 m x Width 27 m.	• Feedback from architects indicates that many suburban office buildings fit in a footprint range of 1,500 to 2,000 m^2. • Office buildings are often 24 to 32 m wide to allow natural light in the centre of the building and for car parking layout requirements.
Key set out criteria	• A column grid layout of 9.0 x 9.0 m has been applied repetitively across all floor levels. This negates the need for a transfer slab.	• Architectural practice emphasises large uninterrupted floor spaces, basement parking set out, flexibility of internal office layouts and freedom of worker movement. • Column spacing often uses an 8.4 x 8.4 m grid (based around parking layouts) or a larger 9.0 m x 9.0 m grid. The latter is used to show the spanning capabilities of timber.
Building ownership and fire compartment-alisation	• The building is assumed to be owned by a single entity (as is common in office building ownership).	• This avoids the need for certain fire resistant construction where large spaces are defined by multiple sole occupancy units (refer NCC for details).
Setbacks	• External walls are assumed to be at least 3.0 m away from the property boundaries and/or other buildings.	• The location of the building relative to other buildings impacts on façade fire resistance requirements.

Table 1: Spatial characteristics and features of the model office building.

4.1 Core Differences between the Timber and Concrete Solutions

Many aspects of the model design provide neutrality in terms of cost effectiveness between the timber and comparative concrete solutions.

The main difference is that the seven storeys above the ground are constructed using timber under one scenario and concrete under the other. This difference affected how each structure responded to building parameters such as fire, acoustics, ductwork and building services. These items are dealt with under dedicated headings below.

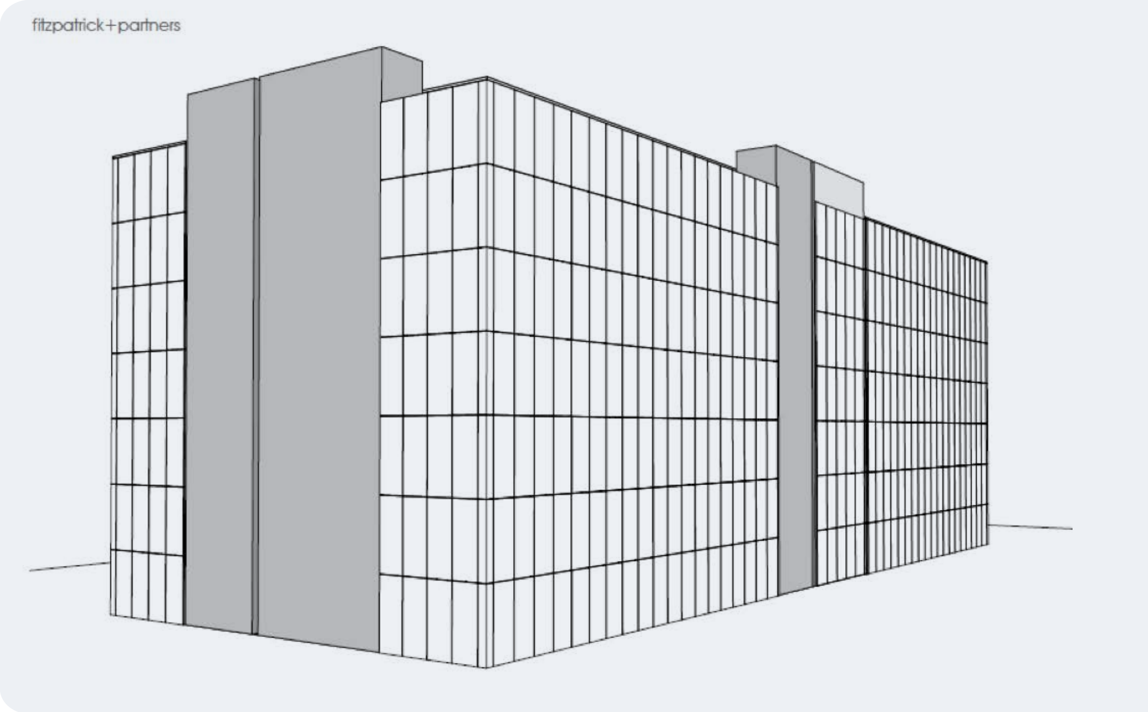

Figure 1: Model office building elevation view.

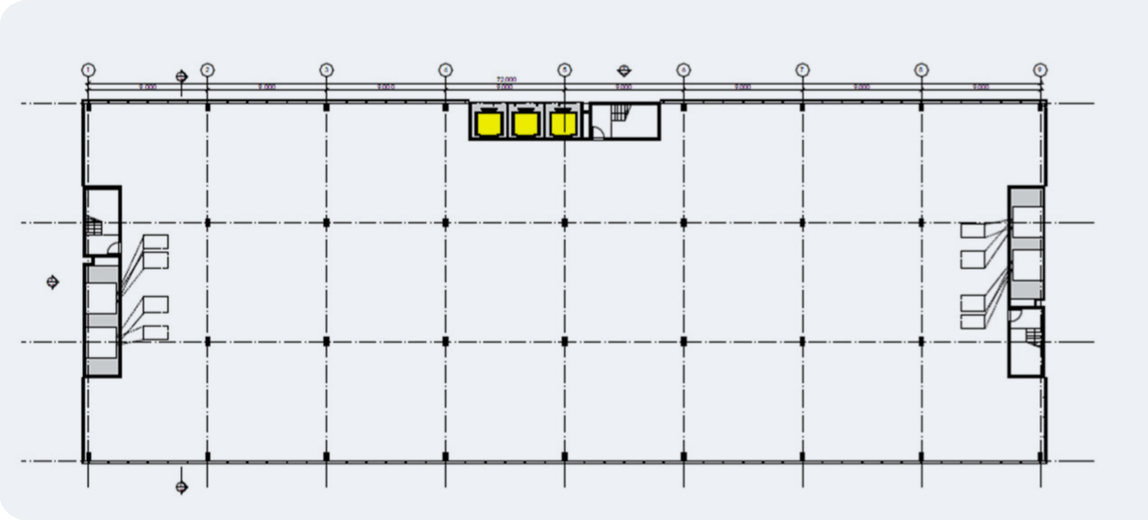

Figure 2: Model office building typical floor plate plan.

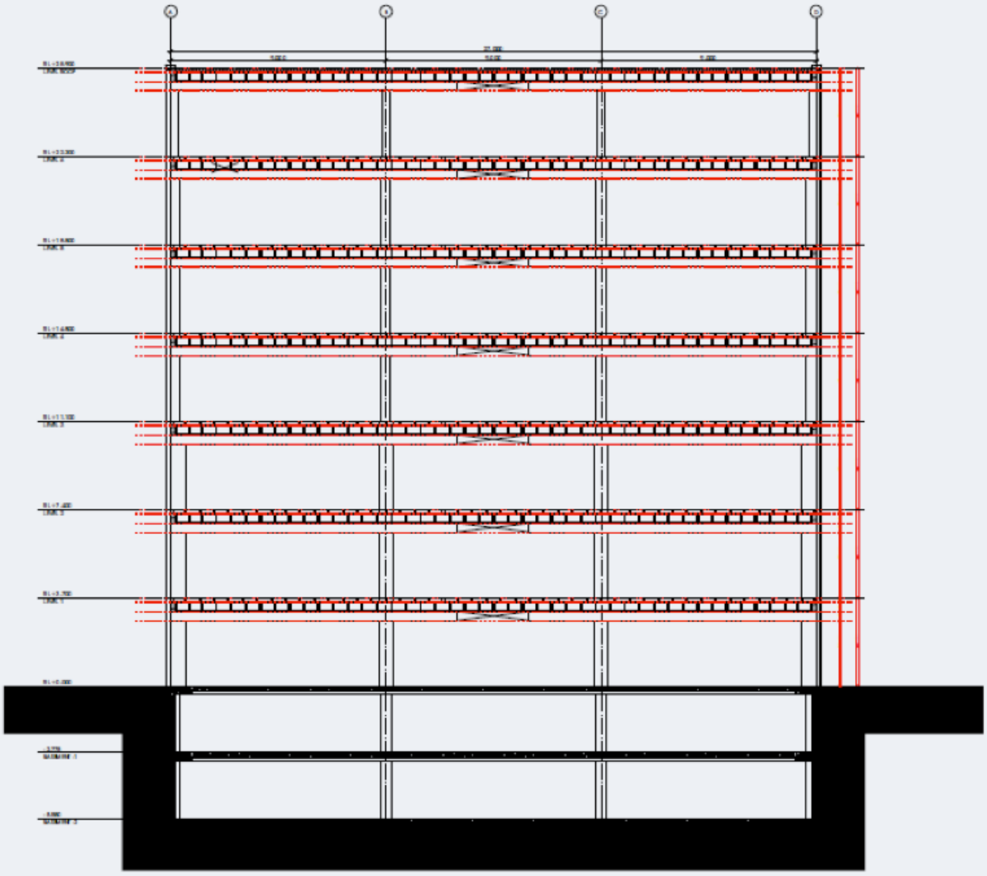

Figure 3: Section through model building.

4.2 Specific Parameters Below Ground

Parameters applied to the model:

- For the timber solution, timber starts at the ground floor level with concrete masonry construction applied to the two basement levels below.
- Weathered shale soil conditions were used in the structural analysis and cost planning exercises.

Reasons:

- While in technical terms, timber can be constructed below ground level, concrete and concrete masonry construction are less likely to attract concerns about moisture penetration and termite activity. The timber solution has a number of redundant strategies to prevent termite ingress, including the use of preservative-treated termite resistant timber for the ground floor columns, slab edge exposure around the building and a stainless steel mesh barrier at all hidden entry points between the concrete subfloor and timber structure.
- Weathered shale is a moderate foundation condition common in many parts of Australia and is relatively neutral for both timber and concrete solutions.

Additional points of interest:

- The lightweight nature of timber is particularly advantageous in poor foundation conditions. Though not dealt with specifically in this study, its lightweight nature contributes to reduced piling and footing requirements.

4.3 Building Parameters Above Ground

Parameters applied to the model:

- A 3.7 m floor-to-floor height has been applied to all such levels including a 2.7 m habitable height and a 1,000 mm height for floor structure, mechanical/air conditioning ducts, the ceiling grid and the office tenant zone. Typical allowances incorporated into the 1.0 m height include:
  - Ceiling grid – 50 mm
  - Mechanical and air conditioning – 350 mm
  - Floor structure depth – 400 mm
  - Office tenant zone – 200 mm
- Standard loading from AS1170:
  - Permanent – 2.5 kPa
  - Applied – 3.0 kPa
  - Wind – N2

Reasons:

- The floor-to-floor height meets normal industry expectations and demonstrates that a timber solution can meet this requirement.
- Permanent loading includes the concrete screed inside the floor cassette, partitions, services and the ceiling.

4.4 Building Acoustics

Parameters applied to the model:

- Floors are designed to achieve a rating of at least Rw - 45 and a minimum $L_{n,w}$ (C_I) - 62 for impact sound (this assumes that carpets are added to the floor by tenants or landlords).
- Walls to the lift core are designed to achieve a rating of Rw 45.

Reasons:

- There is no requirement in the NCC for acoustic performance in office buildings but it is generally accepted that some level of performance will be required to meet end-user expectations. Feedback suggests floor design is normally dependent on impact noise and should achieve a rating better than $L_{n,w}$ (C_I) - 62 in order to meet industry expectations. For airborne noise, a range of Rw 45 to 50 has been applied to meet industry expectations.
- The timber solution provides simple provision for an upgrade in acoustic performance as required for sensitive areas, such as meeting rooms. This is achievable via the use of an access floor or acoustic designed ceilings.

4.5 Fire Resistance

Parameters applied to the model:

- The NCC defines the model building as a Class 5 (office building); involving a 7-storey rise and Type A construction. Collectively, these factors define measurable fire resistance requirements dealt with later in this section.
- A sprinkler system is incorporated at each floor level and at the roof level for both the timber and concrete solutions. Feedback from designers suggests that this has become a commonly expected requirement irrespective of minimum NCC requirements, because it can be used to avoid constraints in the façade design (concerning fire resistance at openings).
- Load-bearing internal walls are limited to lift and stair shafts and are designed for fire resistant construction by using the fire-protected timber solution within the NCC.

Reasons:

- For ease of implementation and standardisation, the parameters above allow the model building to largely use Deemed-to-Satisfy (DtS) provisions for fire resistance in the NCC.

Additional points of interest:

- While concrete construction can avoid sprinkler systems in buildings less than 25 m in effective height, it is still commonplace for such buildings to incorporate such systems for the reasons stated above.

4.5.1 Fire Resistance of External Walls including Vertical Separation of Openings in External Walls

Parameters applied to the model:

- A non-combustible and non-load bearing glass façade is used to prevent the spread of fire relating to the outer face of the building, thus providing a cost neutral façade for both timber and concrete solutions.

Reasons:

- NCC Specification C1.1, Table 3 for Type A Construction has no Fire Resistance Level (FRL) requirements for non-load bearing external walls that are 3 m or more from boundary or another building.
- Use of a non-combustible glass facade in combination with an internal sprinkler system effectively removes the need for fire protection on the outside of the building and the vertical separation of openings (as required under the NCC Deemed-to-Satisfy requirements), thus simplifying façade design constraints.

4.5.2 Fire Resistance of Internal Walls

Parameters applied to the model:

- Internal load bearing walls have been designed under the assumption that they only occur for the lift, stair and ventilation shafts in the model design.
  - For the timber solution: These walls have been designed to comply with the fire-protected timber solution within the NCC.
  - For the concrete solution, a Deemed-to-Satisfy solution already exists and applies an FRL of 120/120/120.
- Other fire resistant internal walls (including other load-bearing walls) do not exist in the model design and subsequently NCC-defined FRLs are not required (refer NCC Specification C1.1, Table 3 for Type A Construction).

Reasons:

- For fire-resisting lift, stair and ventilation shafts walls (and load bearing internal walls), the NCC requires an FRL of 120/120/120, as defined under Specification C1.1, Table 3 Type A Construction. These walls were designed to comply with the fire-protected timber provision in the NCC, specification C1.1, 3.1 (d) and (e) and NCC provision C1.13 Fire-Protected timber: concession.
- NCC provision C2.6 removes the need for a spandrel or horizontal projection where a complying sprinkler system is installed.

4.5.3 Fire Resistance of Internal Beams

Parameters applied to the model:

- Using the Deemed-to-Satisfy provisions of the NCC, the model requires beams to have an FRL of 90/90/90. This applies to both timber and concrete solutions.
- The timber solution can utilise 'charring' of the timber itself to meet Deemed-to-Satisfy provisions as calculated by Australian Standard AS1720 Part 4 (refer to Appendix E for details).

Reasons:

- NCC Specification C1.1, Table 3 Type A Construction – FRL of Building elements – requires beams to have an FRL of 120/120/120 but, by making use of Specification C1.1 Clause 3.3, there is the ability to apply a concession for 3.0 kPa loading situations, allowing floors and floor beams to be reduced to a FRL 90/90/90.
- NCC Specification A2.3 references Australian Standard AS 1720 Part 4 as a method to calculate FRL for structural beams and columns.

4.5.4 Fire Resistance of Columns

Parameters applied to the model:

- The ground floor to sixth floor of the model uses fire-rated columns with an FRL of 90/90/90. The seventh floor (the top floor) of the model requires a lesser FRL of 60/60/60.
- The timber solution can utilise 'charring' of the timber itself to meet Deemed to Satisfy Provisions under AS 1720 Part 4 (refer to Appendix E for details).

Reasons:

- NCC Specification C1.1, Table 3 Type A Construction – FRL of building elements – requires FRL 120/120/120 (but the concession used for floors and beams, Specification C1.1 Clause 3.3, is not applicable to columns). An Alternative Solution was required to reduce the FRL to 90/90/90.
- Reducing the FRL of columns to 90/90/90 instead of NCC DtS of 120/120/120 saves around $100,000. This saving is due to column size corresponding with more readily available laminated veneer lumber (LVL) sizes.
- The top-most storey of the buildings allows the ability to apply a concession concerning internal columns and walls whereby fire resistance can be reduced to FRL 60/60/60 for this level under Specification C1.1 Clause 3.7.

4.5.5 Fire Resistance of Floors

Parameters applied to the model:

- Using the Deemed-to-Satisfy provisions of the NCC, the model requires fire rated floors to have an FRL of 90/90/90. This applies to both timber and concrete solutions.
- The timber solution can utilise 'charring' of the timber itself to meet Deemed to Satisfy Provisions under AS1720 Part 4 (refer to Appendix E for details).

Reasons:

- Specification C1.1 Table 3 Type A Construction – FRL of Building elements – requires the floor to have an FRL of 120/120/120 but, by making use of Specification C1.1 Clause 3.3, there is the ability to apply a concession for 3.0 kPa loading situations, allowing floors to be reduced to a FRL 90/90/90.

4.5.6 Fire Resistance of the Roof

Parameters applied to the model:

- Using the Deemed-to-Satisfy provisions of the NCC, the model requires fire resistance for columns supporting the roof to have FRL 60/60/60. The roof framing itself (including related beams) requires no fire rating. Element sizes for the roof structure (including related beams and columns) can be reduced as there are no specific fire resistance requirements for the top-most storey of the building.
- This applies to both timber and concrete solutions, which have similar flat roof approaches above respective structural systems. Of note, this includes a waterproof membrane with a non-combustible covering (gravel) to protect the membrane.

Reasons:

- The roof need not comply with the NCC Specification C1.1, Table 3 for Type A Construction (i.e. FRL 120/60/30) as a complying sprinkler system is installed throughout the building, removing any fire resistance requirement for the roof, refer Specification C1.1 Clause 3.5.
- Floor cassettes and beam are similar to what has been used at each floor level, using existing trades already on site.

5

The Timber Solution

In response to the model building (including fire, acoustic, building services and structural loading requirements), this section presents a timber solution that aims to optimise cost, time and constructability requirements. It uses a number of themes:

- Prefabricated cassette floors to six levels of above-ground floors and roof.
- Cross-laminated timber walls for the building core in all seven above-ground floors.
- A propped cantilever beam system for primary beams, enabling strategic positioning of the main air conditioning ducting, within the primary beam alignment.

Details are provided below. In contrast, the concrete solution uses a more commonly used post tensioned, band beam design, which is detailed in Appendix A for comparative purposes.

5.1 Primary Beams

What was used in the timber solution:

- Paired LVL beams are used as primary beams, sized at 800 x 180 mm (each) using LVL13[1] grade (Figures 4, 5 and 6).
- The paired beams form a propped cantilever, whereby they span the outer bays on opposing sides of the building and then cantilever into the central bay. The paired beams are fixed to opposing sides of the column heads (Figure 6).
- Smaller infill beams, sized at 400 x 300 (LVL13) span the remaining part of the central bay and are simply supported by the main beam ends (Figure 5).
- Timber blocks are placed as spacers to reduce fire exposure between the paired beam, at the top and bottom (Figure 7).
- All timber blocks and ledgers secured to beams are screw fixed (Figure 7).
- Beams are fixed to columns with M16 bolts and timber washers (Figure 7).
- Fire protection to beam supports at columns is provided by notching the beam and column so that there is at least 100 mm of timber thickness protection, leaving around 40 mm of timber at the column support after charring from a potential fire event (Figure 8).

Reasons:

- LVL is commonly available and well suited to long-span construction situations. It is commonly manufactured in billets of 12 m x 1.2 m and thicknesses ranging from 28 mm to 105 mm. These sections can be paired (as above), laminated up to 300 mm thick or fabricated into box beam sections.
- The propped cantilever design makes it possible to make use of the full manufactured LVL billet length for use in the beams (e.g. 12 m long) without creating waste, consequently reducing costs. This also suits the maximum transportable size of the billets.
- The paired beam configuration is used to allow the beams to pass through the column joint (Figure 5), thus enabling the cantilever action to occur. A one piece beam arrangement could also be used but would likely create greater structural issues regarding load transfer to the column heads (as discussed below).
- As the width of the building is 27 m and the LVL billets are 12 m in length, the cantilever design maximises the structural efficiency of the primary beams allowing the mid bay to use reduced depth beams (400 mm deep).
- The reduced depth beams in the central bay create a ceiling void used for the main run of HVAC ducting which services the full length of the building (as discussed in Section 5.4).
- The paired beam arrangement also reduces the span of the floor system, providing further cost savings.

[1] LVL 13 is a general grade description of LVL that has a MOE of 13.2 Mpa

- The structural properties of LVL include a Modulus of Elasticity (MOE) that ranges from 9.5 to 18 MPa. The structural design used in the beams was conservatively chosen for MOE 13.2 MPa, although it would be possible to provide a more refined result if using LVL with a higher MOE in the primary beams.
- Higher compressive strength LVL (47 MPa) is used on the Ground to Level 1 columns.
- Timber blocks are placed between the top and bottom of the paired primary beam assembly (Figure 7) to reduce exposure of the inner faces of the beams to fire. This strategy ultimately reduces the amount of timber required in the paired beams because it reduces the need for a fire-resisting 'charring layer' on the inner faces on the primary beams as the blocks prevent these faces from being exposed (see Appendix E for details about charring).
- The primary beam configuration may remain visually exposed, but has been designed so the standard office grid ceiling could be used without affecting floor-to-floor heights.

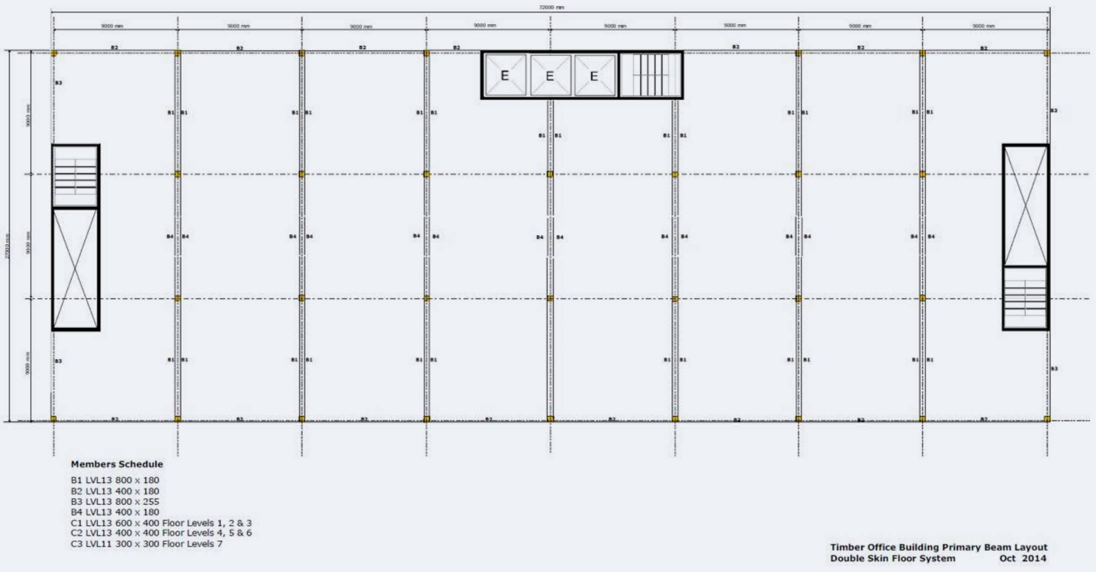

Figure 4: Primary beam layout plan.

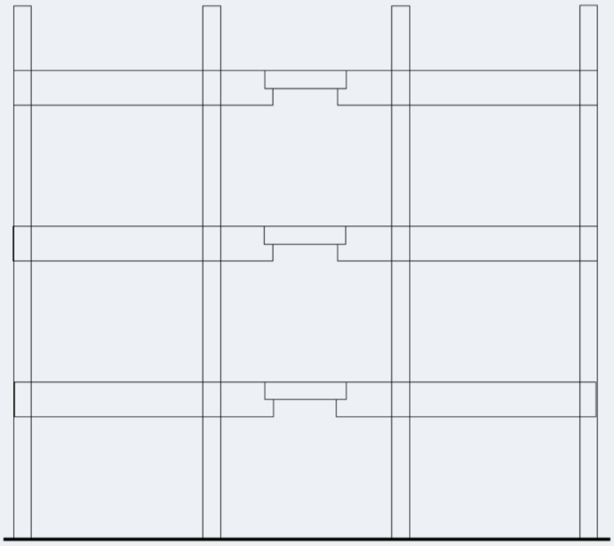

Figure 5: Propped cantilever primary beam.

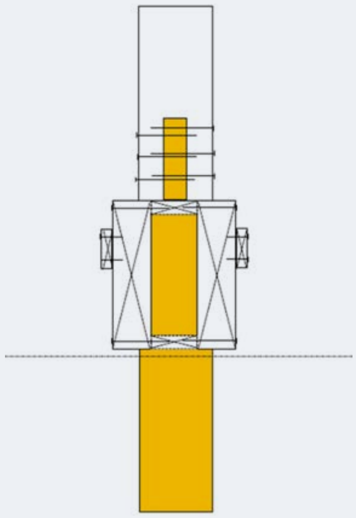

Figure 6: Primary beam support off column head and showing closed off paired beam.

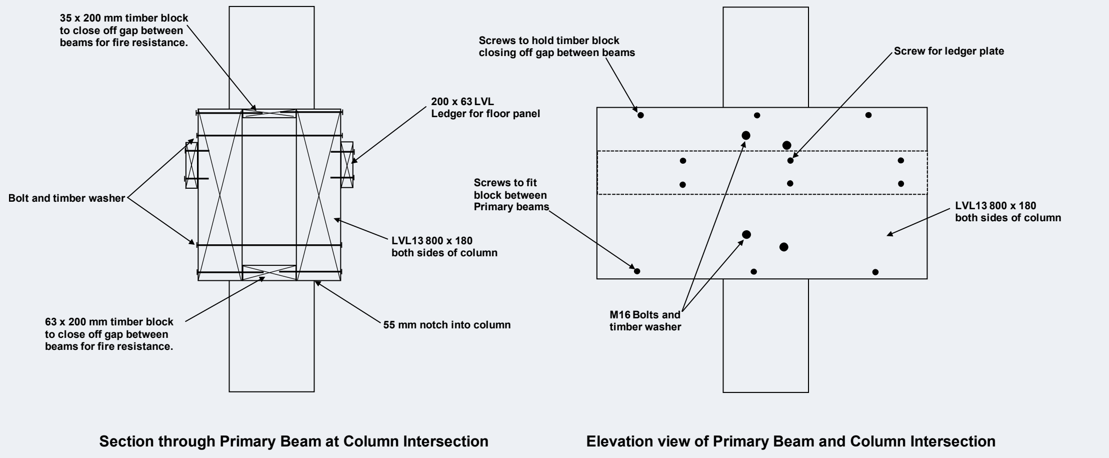

Figure 7: Screw and bolt fixing of beam to columns, Levels 2 to roof.

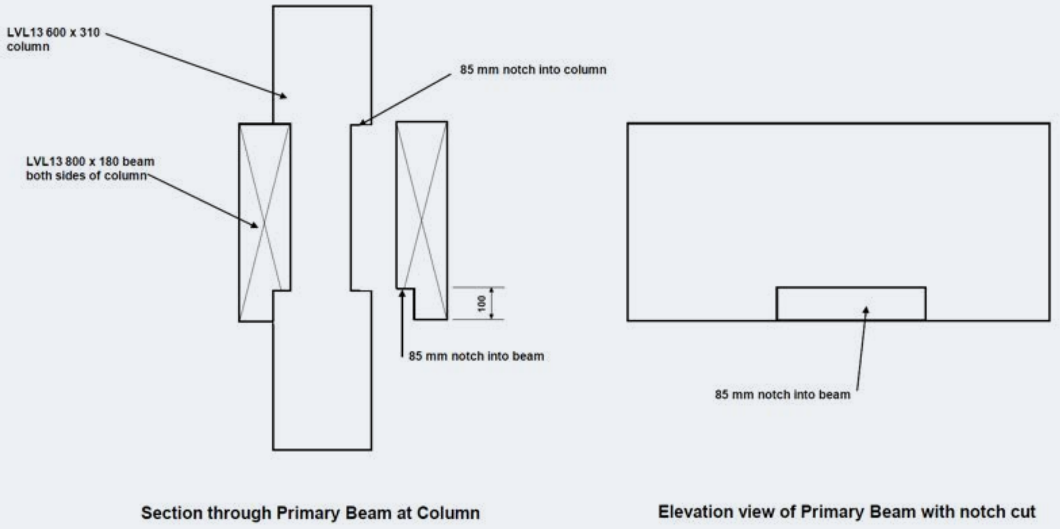

Figure 8: Notched column and beam to provide fire protection to beam support.

5.1.1 Alternative Primary Beam Options

A number of alternative options that could be used instead of the chosen primary beams are offered (below), where different design, construction and market environments exist.

The LVL box beam alternative:

- 800 x 400 mm LVL box beams instead of the paired beam configuration.
- Infill beams, consisting of 400 x 185 LVL13 beams.

Why consider this alternative:

- This alternative design is considered viable, where cost effective, to fabricate box beams and to manage the structural detailing of this beam configuration. This will vary from market to market and according to the availability of industrialised fabrication processes.
- The box beam is similar to the solution chosen for the model, except that the box beam relies on the structural capacity of the timber block while the solution used in the model design has timber blocks to reduce the char surface area and has no structural role.

The Glue Laminated Timber beam alternative (Glulam):

- A number of grades of Glulam can be used to replace the LVL paired beams, depending on the species of timber used in the base lamina. Typical options include:
  - GL10: White Cypress
  - GL17: Slash Pine or Radiata Pine
  - GL18: Tasmanian Oak or Victorian Ash

Why consider this alternative:

- Glulam has the advantage of being manufacturable in lengths greater than 12 m, 1.2 m deep and 300 mm wide.
- The selection of appropriate engineered wood products is principally dependent on the application and material specification, and as such there may be cost differences in respect to these products.

5.2 Flooring System and Perimeter Beams

What was used in the timber solution:

- Prefabricated cassette flooring elements and a perimeter beam system are used to work in a combined way in addressing structural and fabrication requirements.
- The floor cassettes use a double skin LVL assembly, which spans between the paired primary beams and measures 2,440 (W) x 8,500 (L) x 388 mm (D), see Figure 9 for details. The cassette assemblies include:
  - A bottom skin consisting of 2 x 1,220 mm (W) x 63 mm (D) LVL11 billets. The two billets are positioned side by side to make up the full 2,440 mm (W) cassette width.
  - A top skin consisting of 2 x 1,220 mm (W) x 25 mm cross-banded LVL sheets (again two panels are positioned side by side).
  - Web members separating the skins, consisting of 300 (D) x 35 mm (W) solid timber pieces at 600 mm maximum spacings and including a double laminar along the centre line of the 2,440 mm width (Figure 9).
  - Horizontal stiffeners between web members consisting of 300 (D) x 35 mm (W) solid timber packers (Figure 9).
  - 50 mm of polyfibre reinforced concrete is placed between the web members inside the cassette. Screws are placed to side of web members and in the LVL bottom skin for securing concrete in place in the event of a fire.
  - 75 mm glass wool insulation of at least 14 kg/m^3 is placed within cassette void to aid with reducing noise transfer.
  - Cassettes and primary beams contain interlocking haunches to assist seating during installation.
- The perimeter beams (secondary beams that occur in the same plane as the floor cassettes) use a 400 x 180 LVL13 and are designed to be selectively prefabricated into the edge of floor cassette assemblies, where required (as shown in Figure 10). The perimeter beams provide support for the façade system and tie the building together.

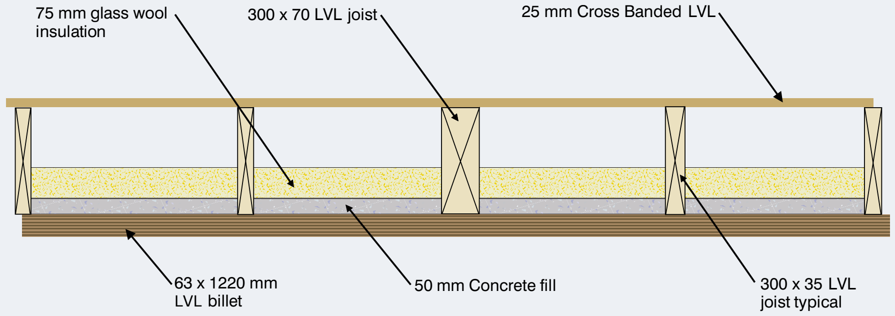

Figure 9: Cross-section of LVL floor cassette with concrete and insulation fill.

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[2] Acoustic performance was assessed by PKA Acoustic Consulting

Reasons:

- The chosen cassette and perimeter beam system was found to provide the best mix of cost effectiveness, structural efficiency and speed onsite. It was chosen from an initial set of 30 floor systems (refer to Appendix D for details). Specific features include:
  - At 388 mm deep, the floor cassette system presented the shallowest floor plate depth which saved on floor-to-floor height and provided the necessary space for HVAC services. It is only marginally deeper than the 350 mm depth used for the concrete solution.
  - The floor cassette assemblies effectively span between primary beams instead of being supported by separate secondary beams. This saved erection time and provided structural efficiency.
  - The use of solid LVL as a structural skin on the underside of the assembly removed the need for additional fire resisting ceiling layers, such as plasterboard.
  - The 50 mm concrete and insulation inside the cassettes provide acoustic performance of approximately Rw 47 to 48[2] comparable to concrete solution.
  - Though structurally independent, the perimeter beams were incorporated into the floor cassette assemblies, thus simplifying and compressing onsite erection time.
  - The cassettes fully utilise the manufactured size of the LVL billets therefore removing wastage. The cassette size also minimises the number of craneage lift cycles for installation.

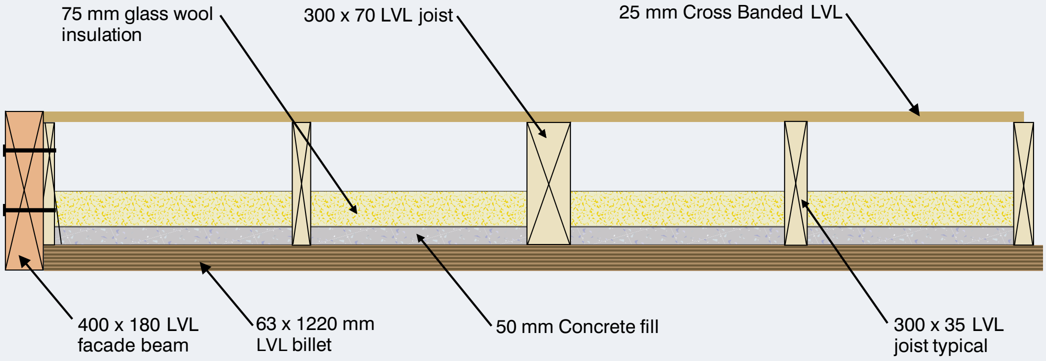

Figure 10: Cross-section of LVL floor cassette with perimeter beam attached.

5.3 Columns (including Column and Beam Junctions)

What was used in the timber solution:

- A number of different single storey column sections were used

– The cross-sectional sizes under this scenario include:

  - Ground to Level 1 – 600 x 310 LVL13 with higher compressive strength (47 MPa)
  - Level 2 and 3 – 600 x 310 LVL13
  - Level 4 and 5 – 3 off 400 x 310 LVL13
  - Level 6 – 300 x 310 LVL11

– The column heads can be nestled in between the paired primary beams, thus allowing a simplified assembly process.

– The rebate in the columns, to accept side mounting of the primary beams, is designed to allow the maximum wood fibre in the vertical direction for compressive loads and to facilitate the previously discussed propped cantilever of the primary beams.

– Erecting columns on a floor-by-floor basis allows the columns to be combined with the primary beams on the deck and lifted as one unit (refer Figure 11).

Reasons:

- Combining the column and beams into one unit removes multiple lifts required in dealing with individual columns and beam elements, speeding up the overall erection process.
- Storey high columns suit the use of a twin beam arrangement.
- Storey high columns require less work in terms of temporary support and smaller-scale materials handling equipment.

Figure 11: Column and primary beam in one lifting unit.

5.3.1 Alternative Column Options

A selective number of alternative column options are offered (below), where different design, construction and market environments exist.

What could be used as an alternative timber solution:

- Solid LVL columns spanning three floors (in each crane lift) (Figure 12) whereby the cross-sectional size of the columns decrease at each change point (see Figure 11 for details). Sizes included:
  - Ground, Level 1 and 2 – 600 x 310 LVL13
  - Level 3, 4 and 5 – 400 x 310 LVL13
  - Level 6 – 300 x 310 LVL11

Why consider this alternative:

- Three storey columns may reduce:
  - the number of crane lifts required onsite if lifted one piece at a time;
  - the number of column splices
  - material loss caused by the overlap required to produce the column splice and screws.
- This approach would require the need for more temporary support (props) during the construction process.
- The choice between single-storey and three-storey columns affects site fabrication preferences. It is worth checking with erectors and fabricators before committing to a design to ensure the most cost-effective option.

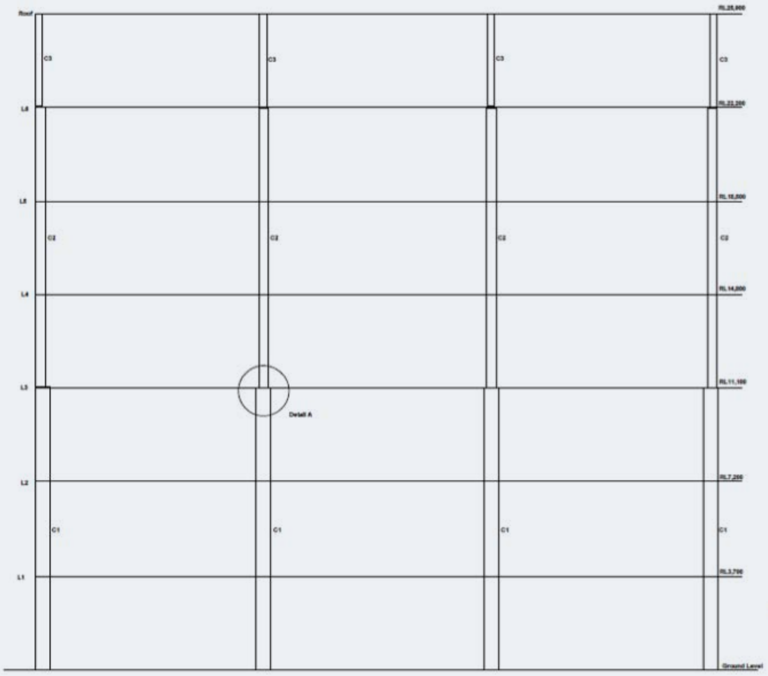

Figure 12: Elevation view of columns.

5.4 The Building Core - Providing Lateral Resistance in the Building

What was used in the timber solution:

- Cross-laminated timber (CLT) was chosen for constructing the core of the building (including lifts, stairs and MEP shafts). This subsequently provides lateral restraint for the building and includes the following features (Figure 13):
  - 185 mm thick CLT panels are used for the core walls running longitudinally over three storey sections (including structural continuity from one three-storey section to the next).
  - The floor cassettes, discussed previously, provide a diaphragm action that serves to transfer loads from the outer face of the building to the CLT core construction.
  - 16 mm fire-resistant plasterboard is used each side of the CLT walls.

Reasons:

- Use of the building core to manage lateral resistance is common to both timber and concrete building solutions. CLT provides a cost-effective material for constructing structurally efficient walls in this context.
- The use of CLT maintains the continuity of using timber as the dominant material and avoids the use of dissimilar materials, i.e. concrete. This circumvents introducing different material characteristics such as creep, settlement and shrinkage, and differential movement problems. It also reduces the need for dividing the work program into separate material-specific subcontracts.

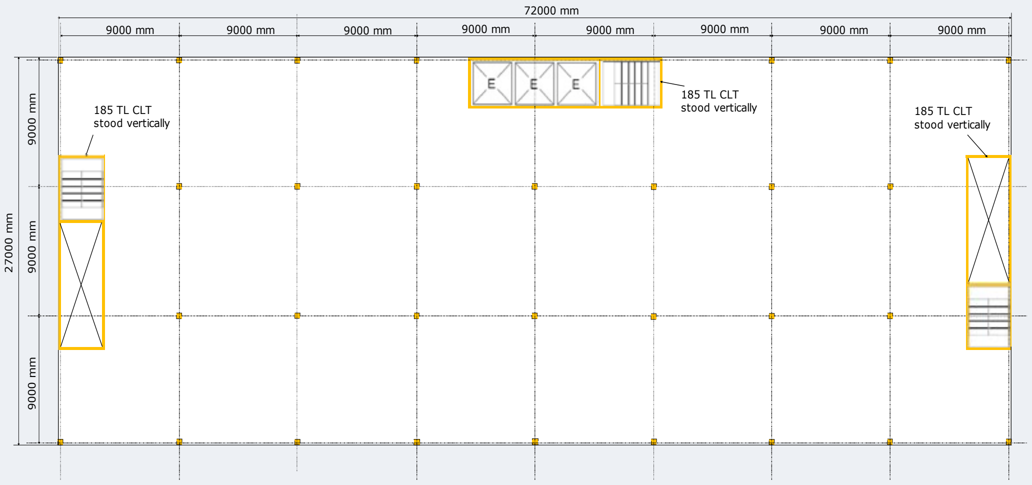

Figure 13: Plan of CLT cores.

Providing Noise Resistance

What was used in the timber solution:

- A 50 mm polyfibre reinforced concrete layer within the base of the floor cassette provides the main acoustic solution for impact sound (Figure 14).
- A 75 mm glass wool batt of at least 14 kg/m^3 placed within cassette void helps mainly with airborne sound.
- The floor cassette was estimated to have a base Rw of 47 to 48[3] without carpet or the addition of a ceiling.

Reasons:

- The concrete fill and insulation facilitates improves acoustic performance concerning airborne sound.
- The concrete and insulation are placed in the cassette during the offsite fabrication of the cassettes' construction to reduce on-site labour requirements and improve construction program time.
- Acoustic performance for sensitive areas such as meeting rooms can be easily upgraded by the addition of an access floor or acoustic ceiling.

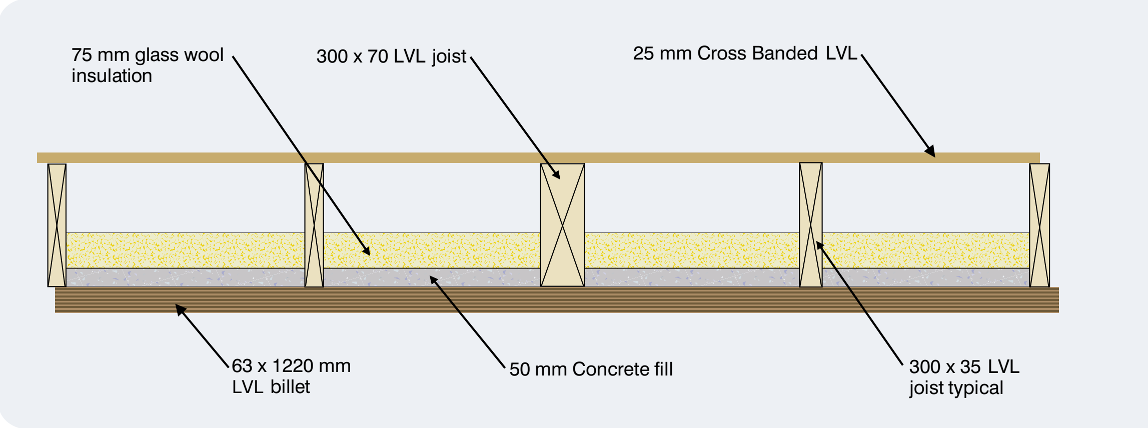

Figure 14: Floor cassette with concrete and polyester fill.

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[3] Acoustic estimates provided by PKA.

7

Interface with the Façade

What was used in the timber solution:

- A standard glazed curtain wall façade was fixed to the timber structure (Figure 15).
- A timber perimeter beam (as discussed under perimeter beams and floor system) is used to connect the façade supports to the structure.
- The façade curtain wall framing is intended to be screw fixed to the perimeter beam.

Reason:

- The intention was that the façade system should be the same for both the timber and concrete solutions, making it cost neutral in terms of comparative imput.

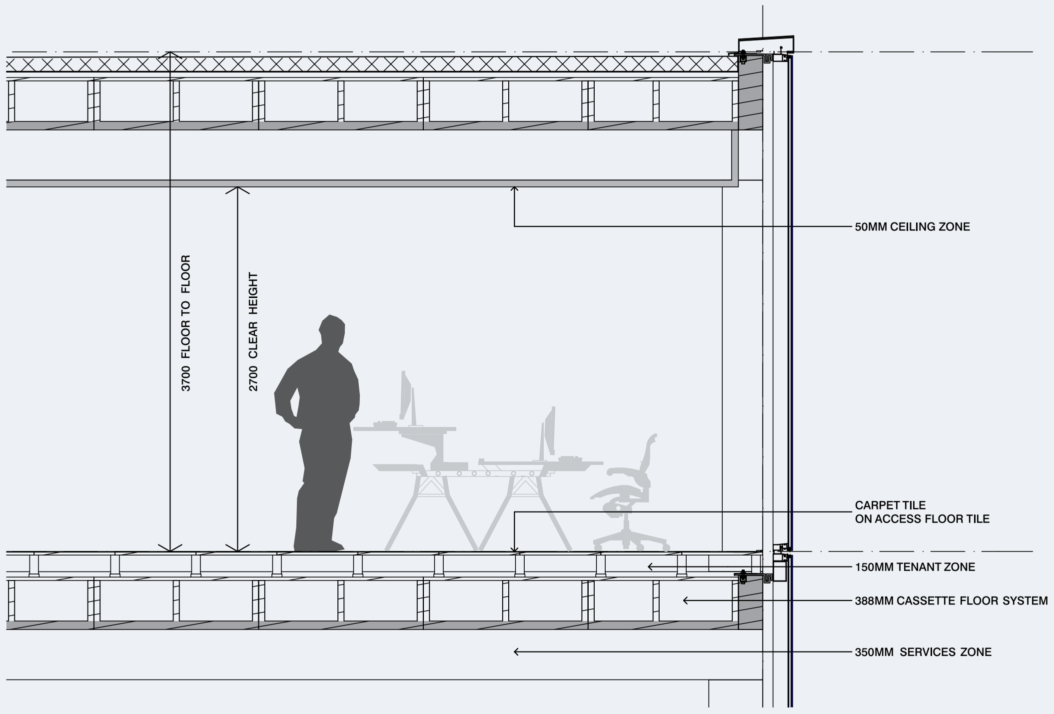


Figure 15: Illustration of standard façade screw fixed to timber perimeter beam.

8

Interface with HVAC and Other Services

What was used in the timber solution:

- Two main vertical shafts are provided at each end of the building to supply and return air to each floor level.
- On each floor level, three main ducts (2 x 600 x 250, 1 x 800 x 250) supply air along the central longitudinal axis of the floor, within a ceiling void made possible by the relatively shallow infill beams used in the primary beam arrangement (Figure 5).
- Return air is collected at two main vertical shafts.
- From the main ducts, perpendicular branch ducts supply and return air to individual bays defined by the column grid (see Figure 16 for details).
- The ducts are fixed directly to the underside of the floor cassette system.
- Any additional but minor cabling, piping or ducting services can potentially be dealt via small penetrations (up to 50 mm diameter) without affecting the primary beams. Larger holes require engineering design including reinforcement using plywood and an associated screw layout.

Reasons:

- The HVAC design has been driven by the need to maintain the targeted floor-to-floor height of 3.7 m, as would be achieved under a typical concrete-framed solution. The 250 mm deep centralised main ducts have been designed accordingly and effectively make this aspect cost neutral when compared to the competing concrete solution. Notwithstanding this, the timber solution should achieve better installation productivity due to the reduced work in fixing ducts to the timber structure.

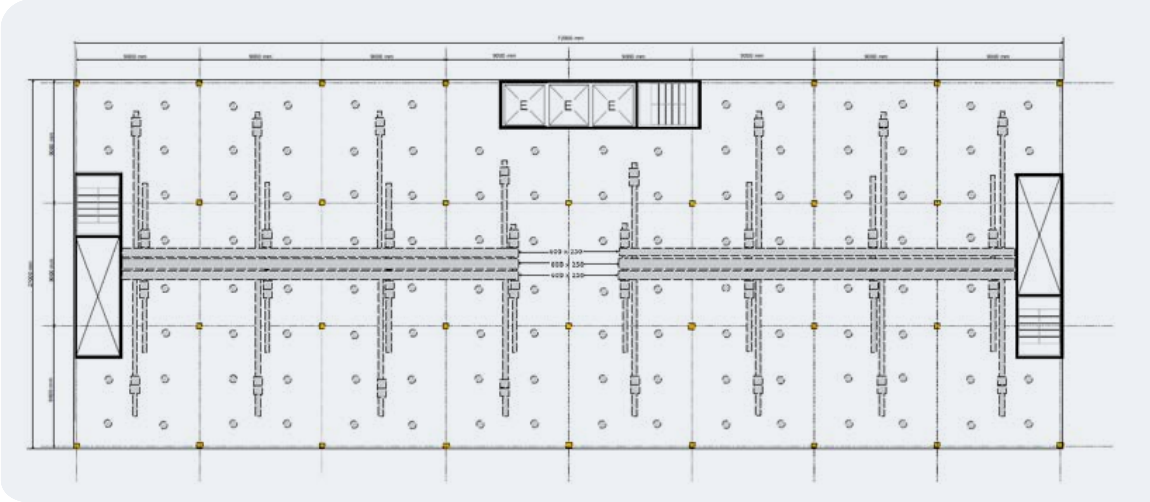


Figure 16: Plan of HVAC ducts.

8.1 Alternative HVAC Systems Options

A 'Displaced air' cavity system

- A 'Displaced air' cavity system requires a raised floor zone of between 300 to 400 mm. This system was not pursued as it required significant re-arrangement of the primary beam layout in trying to maintain the targeted floor-to-floor height. The viability of such a system may change according to project-specific requirements and with advances in the technology.

9

The Workflow and Speed Onsite of the Timber Solution

What was used in the model:

- A 78-day construction program (see Appendix C for further details) from the ground floor level to top storey (structure only) was found achievable and the program allows rough-in of MEP services to commence very early on Day 16 of the program found in Appendix C1.
- A crew of six (excluding crane driver, dogman, traffic control, etc) is assumed.
- All elements are designed so they sit on supports, i.e. beams sit on a halved column joint, or CLT core walls, and floor cassettes sit on a ledger at the side of the primary beam.
- Most joints use screw fixings inserted using commonly available power drill technology. Such fixings provide a countersunk head, which is expected to be aesthetically hidden in the final construction.
- Beam to column joints from Ground to Level 7 use standard through bolts and large washers.

Reasons:

- The project team reviewed more than 30 timber construction systems. Emphasis was placed on those systems capable of providing program savings compared to the targeted concrete system.
- Crane optimisation (i.e. minimising the number of crane lifts) dominated the ability to compress the chosen timber construction program and this especially revolved around the chosen cassette floor system. For instance, the floor system using 2,440 mm wide cassette panels spanning between the primary beams was found to deliver the least number of crane lifting cycles.
- Standard bolts and washers were used for the beam to column joints, which allowed the bolts to pull the joint together.

How does this compare to concrete:

- Post tension concrete structure was calculated to take 117 days.
- Rough-in of MEP services would commence at day 51.

Activity	Week	1					2					3					4					5				
	Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Survey & Set Out	2	■	■																							
Ground Floor Columns	3			■	■	■																				
1st Floor Primary Beams	2						■	■																		
Lift Shaft Panels 3 Storey High	5								■	■	■	■	■													
1st Fl Floor Panels	4													■	■	■	■									
2nd Floor Primary Beams	2																	■	■							
2nd Fl Internal Lift Wall Panels	2																			■	■					
2nd Fl Floor Panels	4																					■	■	■	■	

Table 2: Five-week construction program of timber frame and floor installation.

9.1 Other Time Savings

The timber model may have further construction program time savings as the follow-on trades would be able to access the first level 31 days earlier than with the concrete system. The work required for follow-on trades in timber structures is inherently easier, as fittings to the super structure do not require drilling into concrete. Though not calculated in this study, these savings would add further overall time savings.

Cost savings associated with the time saving are discussed in Section 10.

9.2 Time Savings in Other Timber Projects

A number of timber projects have been carried out around the world and most have indicated significant construction program time savings. Table 3 lists some of these projects and their associated construction program time savings.

Project Name	Location	Building Type	Storeys	Gross Floor Area (m^2)	Construction Type	Timber Superstructure Construction Program
Library at the Dock	Victoria Harbour, Melbourne, Australia	Institutional	3	3,500	Post and Beam CLT floor	10 weeks
LifeCycle Tower one	Dornbirn, Austria	Office	8	2,322	Post and Beam and Panel	8 days

Table 3: Real project time savings.

10

Cost Plan Results - Comparing the Timber Solution with Traditional Concrete Construction

Using the model building described in Section 4, the timber solution described in Section 5, and the corresponding concrete solution described in Appendix A, a cost estimate and cost planning comparison was undertaken to help determine the potential benefits of the timber solution relative to the concrete solution.

The cost comparison was only undertaken for the parts of the building that were considered to have different costs under the two competing options. The elements of the building that are identical in costs for each model, such as the façade, and mechanical, electrical and plumbing items, were therefore excluded from the cost plan.

To create stable costing conditions, it was assumed that the building would be constructed in suburban Sydney.

10.1 Process Taken to Obtain Comparison Design and Quotes

To ensure neutrality, the concrete design was independently developed by engineering firm Arup Ltd. The design was tested at a 2014 workshop of structural engineers where it was found to justly represent a typical concrete design. The timber design was developed through collaboration between the timber industry suppliers and the Timber Development Association and used a number of techniques discussed in Section 5 of this report.

The revised cost plan was developed by MBM who independently measured quantities off supplied drawings and obtained quotes from the market where needed. An important element to the cost plan was the saving brought about by construction program time saving. An independent erector with experience in timber and concrete construction developed a construction program for both models. These programs are found in Appendix C.

As concrete construction is widely used, MBM utilised current data within their database to develop a price for this model. As the timber design is relatively new, a price from the marketplace was found. Meyer Timber provided this price as they operate in the Sydney region, and have experience among fabricators and suppliers, allowing a full price to be developed for all costs up to the point of delivery to the building site.

10.2 Cost Plan Results

The basic differences in the cost plans for each model are shown in Table 4. Detailed results can be found in Appendix B.

Element	Timber	Concrete	Variance
Columns	$450,218	$307,224	+$142,994
Staircases	$319,700	$305,865	-$13,835
Upper floors	$4,491,903	$4,736,195	-$244,292
Roof	$593,105	$792,480	-$199,375
Shafts External Walls	$345,825	$522,000	-$176,175
Shafts Internal Walls	$521,268	$717,600	-$196,332
Ceiling Finishes	$997,740	$997,740	$0
Preliminary Adjustments	-$482,500	-	-$482,500
Total	**$7,237,259**	**$8,379,104**	**-$1,141,845**

Table 4: Cost comparison between each building considered.

In analysing the differences between the two plans, the timber building provides a saving of $1,141,845 being 13.6% cheaper than the concrete solution. Specific savings under the timber solution are as follows:

- Floor: $244,292 (4.7% less)
- Lift, Stair and Air shafts: $356,342 (23% less)
- Roof: $199,375 (25.1% less)
- Preliminary costs: $482,500 less.

Additional costs under the timber solution (relative to the concrete solution) include:

- Stairs: $13,835 (3% more)
- Columns: $142,994 (31.8% more)
- Connections: $59,769 more
- Termite & Fire Engineering: $35,000 more.

10.3 Qualifications and Hidden Costs

Some detailed qualifications are required to clarify certain costs that are not necessarily apparent at first glance. Of note:

- Suspended versus exposed ceiling: The suspended ceiling, common in the concrete construction model, could be deleted from the timber model, exposing the solid timber underfloor. Though there would be some additional cost to provide a neater HVAC and suspended lights (estimated to be $266,064) the overall saving for the timber solution would be $1,873,521 (being 22.3% less than the concrete solution).
- Preliminary cost savings: the emphasis on pre-fabricated construction creates savings in site infrastructure costs such as labour costs, scaffolding, site accommodation, hoist and crane. Prefabrication also provides the ability to compress the construction program, which further reduces preliminary costs. Relative to concrete, the 39-day saving on the main structure (nine working weeks) is estimated to save $157,500 per week compared to concrete (equating to a $517,500 saving across the entire project). As mentioned previously (Section 9), there is potential to leverage this situation to also compress the internal works by a further 34 days. If this is taken into account, further savings are achievable.

D1.2 Floor system discussion

Of the 30 floor systems reviewed, four floor systems were investigated further. These were:

10.4 Further Cost Saving not included in Calculations

Other cost savings are also possible for the timber model and they are discussed below, but for this cost exercise they have not been included. These are:

10.4.1 Scaffolding

The timber structures can be constructed with safety hand rails already attached to floor cassettes. This removes the need for traditional scaffolding to the outside of the building.

10.4.2 Screens

Timber structures can also be constructed without the need of temporary screens to the outside face of the scaffolding.

10.4.3 Time before First Fix can Occur

The time to carry out first fix of MEP services in timber structures is generally less, as there is less time needed to fix brackets and supports onto the superstructure. Timber structures use cordless screw guns, which are light, and quick and easy to use. Concrete structures require drilling into concrete, which is slow, noisy and dirty work.

Overseas experience has shown that with the introduction of massive timber structures, the internal building trades do not initially recognise the significant time savings possible, and quote the job as if it was concrete. With time, internal building trades will learn to recognise the savings that are possible with timber and pass a portion of this back.

10.4.4 Footing Consideration

The timber model is estimated to be 50% lighter in weight than the concrete model, as timber is 20% of the weight of concrete for the same spanning conditions. Though not taken into account, this would allow lighter footings for the timber model, potentially providing greater savings. The cost plan assumes the footing design is the same for both models.

10.4.5 Columns

The timber columns come with a weather protection sealer. No additional surface treatment is required. The concrete model normally requires all columns to have frames or furring channels and plasterboard sheets.

10.4.6 Crane Size and Type

The cost comparison assumes that the same tower crane is used for both building models. The crane savings included in the timber cost plan result from less hire time required. The timber model’s largest element is 4.0 tonnes, being a standard floor cassette. It is conceivable that a light electrical and remote crane could be used in lieu of a standard tower crane, offering further savings not taken into account in the cost plan.

10.5 Cost Neutral Items

Many of the items in the cost plan have not been included as they are cost neutral between each model building. These include:

- Mechanical, electrical and plumbing: both model buildings use the same layout and assumptions.
- Façade cost: both model buildings are the same height and use identical cladding that is fixed in a similar manner.
- Floor finishes: floor finishes are not included in either model building.
- Crane cost: it is assumed the same crane has been used in both model buildings.
- Scaffold: it is assumed the same scaffold has been used in both model buildings.

10.6 Additional Costs

The timber model has additional costs. These include:

10.6.1 Additional Engineering Costs

The timber model would need additional fees for fire engineers to provide Performance Solutions for a 30-minute reduction to the fire resistance level to the columns. The fire engineering fees were estimated to be $20,000, based on quotes from Sydney-based fire engineers. These have been included in the timber model's costs.

10.6.2 Termite Protection

Both models sit over a two-level concrete basement garage. The timber structure has considered termite protection by:

- Glue line preservative treatment to the LVL columns from ground to level one.
- Concrete slab edge exposure at the ground level.
- Stainless mesh steel protection to all hidden entry points to the structure.

This protection resulted in a conservative additional cost to the timber model of $35,000 and this has been included in the timber model's costs.

11

Conclusion

A model seven-storey office building was designed, engineered, planned for construction, and costed using an optimised structural timber solution and a more conventional structural concrete solution. The costing exercise focused on areas where significant cost differences would occur and excluded common aspects of the building that are predominantly cost neutral.

The timber solution was found to be $1,141,845 more cost effective, which equates to a 13.6% saving compared to the concrete solution, even when additional costs such as fire engineering and termite protection are included. The timber model was more cost effective in all structural aspects except for the columns, which were 31.8% more expensive.

The cost plan also investigated the effect of removing the suspended ceiling, as the timber model may not require it. If the suspended ceiling was removed, the timber model would be $1,973,521 more cost effective, equating to a 23.3% saving on the concrete model, even after taking additional costs of neater HVAC ducts and suspended lights into account.

The cost plan exercise showed that timber can be a cost-effective option for medium rise office building construction compared to more conventional construction methods. Further areas for cost savings are also identified, particular in terms of preliminary costs that have not been fully taken into account in this comparison.

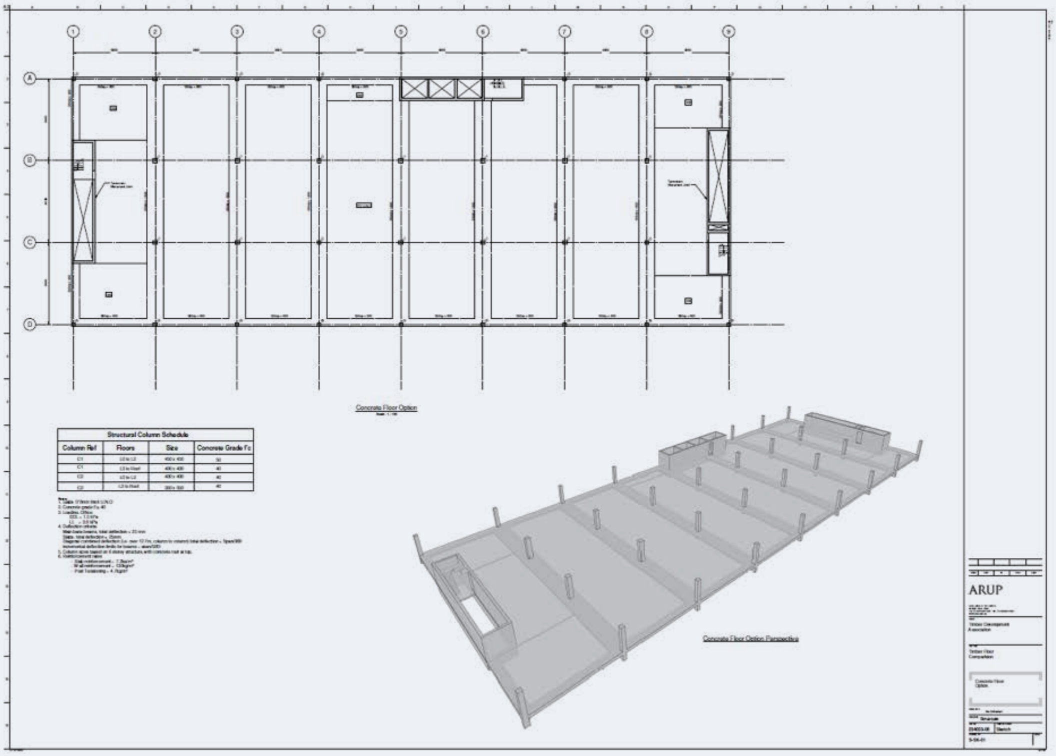
This Guide shows that timber office buildings should be considered as a viable alternative to conventional concrete construction. This is particularly borne out when there are restrictions on the site such as poor ground conditions that need a lightweight structure solution, such as extensions to the top of existing buildings or air right locations (vertical space above a property), short construction programs or sites with highly restrictive access issues.

The area where significant cost savings can be made with a timber construction system is in the area of preliminary costs. Therefore, when considering a cost plan for a timber structure, it is recommended that a detailed investigation of the preliminary costs is required. Considering only installed material costs ignores significant savings that can be made with timber construction systems.

A

Appendix A: Comparison Design: Concrete Construction

Assumptions about post-tensioned concrete slab construction (used for competitive benchmarking purposes)



Appendix B: Detailed Cost Plan

Project Name: **Office Building - Timber-Framed (LVL)**

Client Name: Timber Development Association for Forest and Wood Products Australia

Date of Estimate: 17/07/2017

Element		Qty	Unit	Unit Rate ($)	Cost ($)
1	**Timber Framed (LVL)**				
1.1	**Columns**				
1.1.1	600 x 300 Laminated Veneered Lumber (LVL13) 3 storey column, 3700 storey height, 75 notch on two sides at storey levels to receive 800 deep timber beams, 450 extension tongue at head to receive upper column; including protective treatment.	18	No.	6,786	122,148
1.1.2	600 x 300 Laminated Veneered Lumber (LVL13) 3 storey column, 3700 storey height, 75 notch on three sides at storey levels to receive 800 deep timber beams, 450 extension tongue at head to receive upper column; including protective treatment.	12	No.	6,786	81,432
1.1.3	400 x 300 Laminated Veneered Lumber (LVL13) 3 storey column, 3700 storey height, 75 notch on two sides at storey levels to receive 800 deep timber beams, holed at base to receive lower tongue column section, 450 extension tongue at head to receive upper column; including protective treatment.	18	No.	6,609	118,962
1.1.4	400 x 300 Laminated Veneered Lumber (LVL13) 3 storey column, 3700 storey height, 75 notch on three sides at storey levels to receive 800 deep timber beams, holed at base to receive lower tongue column section, 450 extension tongue at head to receive upper column; including protective treatment.	12	No.	6,609	79,308
1.1.5	400 x 300 Laminated Veneered Lumber (LVL13) single storey column, 3700 storey height, 75 notch on two sides at storey level to receive 800 deep timber beams, holed at base to receive lower tongue column section; including protective treatment.	18	No.	1,157	20,826
1.1.6	300 x 300 Laminated Veneered Lumber (LVL13) single storey column, 3700 storey height, 75 notch on three sides at storey levels to receive 800 deep timber beams, holed at base to receive lower tongue column section; including protective treatment.	12	No.	1,157	13,884
1.1.7	Add for screw-connections	1	Item	13,658	13,658
					450,218
1.2	**Staircases**				
1.2.1	Stairs 'AirStair' - supply cost - 2 x 9 levels	18	level	6,500	117,000
1.2.2	Stairs 'AirStair' - supply cost - 1 x 10 levels	10	level	6,500	65,000
1.2.3	Installation	81	m/rise	1,250	101,250
1.2.4	Extra over above for fixings and handrails	81	m/rise	450	36,450
					319,700
1.3	**Upper Floors**				
1.3.1	Composite beam 8750 long, comprising 2No 800 x 180 LVL13 members, 240 x 63 hySPAN blocking piece top and and 240x35 hySPAN blocking piece on bottom; 200 x 63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	72	No.	10,358	771,878
1.3.2	Composite beam 2810 long, comprising 2No 800 x 180 LVL13 members, 240 x 63 hySPAN blocking piece top and 240 x 35 hySPAN blocking piece on bottom, 200 x 63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	84	No.	3,308	287,598
1.3.3	Composite beam 5400 long, comprising 2No 800 x 180 LVL13 members, 240x63 hySPAN blocking piece top and 240 x 35 hySPAN blocking piece on bottom, 200x63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	12	No.	6,295	78,184
1.3.4	Beam 6500 long; 600 x 180 LVL13, 200x63 hySPAN ledger to one long edge; including protective treatment.	24	No.	3,221	80,010
1.3.5	Beam 8750 long; 400 x 180 LVL13; including protective treatment.	78	No.	3,105	250,667
1.3.6	Beam 3800 long; 400 x 180 LVL13; including protective treatment.	6	No.	1,398	8,682

Element		**Qty**	**Unit**	**Unit Rate ($)**	**Cost ($)**
1.3.7	Beam 8200 long; 400 x 180 LVL13; including protective treatment.	6	No.	2,905	18,040
1.3.8	Beam 3860 long; 400 x 300 LVL13; including protective treatment.	42	No.	1,697	73,769
1.3.9	LVL double skin floor panel 8500 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	36	No.	5,302	197,553
1.3.10	LVL double skin floor panel 8500 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	372	No.	5,621	2,164,197
1.3.11	LVL double skin floor panel 8500 x 2440, checked around core, comprising 300 x 35 LVL joists, 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	36	No.	5,621	209,438
1.3.12	LVL double skin floor panel 4650 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	48	No.	3,121	155,051
1.3.13	LVL double skin floor panel 5150 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	12	No.	3,209	39,856
1.3.14	LVL double skin floor panel 4200 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	6	No.	2,725	16,922
1.3.15	LVL double skin floor panel 8500 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	6	No.	5,302	32,925
1.3.16	LVL double skin floor panel 8000 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 63 LVL lower skin, softwood solid blocking, 50 concrete fill to void, 75 insulation, 200 x 50 ledger each short side.	6	No.	5,998	37,248
1.3.17	Add for screw-connections	1	Item	67,523.00	69,886
					4,491,903
1.4	**Roof**				
1.4.1	Composite beam 8750 long, comprising 2No 800 x 135 LVL13 members, 240x63 hySPAN blocking piece top and 240 x 35 hySPAN blocking piece on bottom, 200x63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	12	No.	8,587	105,105
1.4.2	Composite beam 2810 long, comprising 2No 800 x 135 LVL13 members, 240x63 hySPAN blocking piece top and 240x35 hySPAN blocking piece on bottom, 200 x 63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	14	No.	2,850	40,698
1.4.3	Composite beam 5400 long, comprising 2No 800 x 135 LVL13 members, 240x63 hySPAN blocking piece top and 240 x 35 hySPAN blocking piece on bottom, 200x63 hySPAN ledger pieces each side to take floor edges; including protective treatment.	2	No.	5,321	10,855
1.4.4	Beam 6500 long; 600 x 135 LVL13, 200x63 hySPAN ledger to one long edge; including protective treatment.	4	No.	2,845	11,608
1.4.5	Beam 8750 long; 400 x 180 LVL13; including protective treatment.	13	No.	3,105	41,172
1.4.6	Beam 3800 long; 400 x 180 LVL13; including protective treatment.	1	No.	1,398	1,426
1.4.7	Beam 8200 long; 400 x 180 LVL13; including protective treatment.	1	No.	2,905	2,963
1.4.8	Beam 3860 long; 400 x 300 LVL13; including protective treatment.	7	No.	1,697	12,117

Element		**Qty**	**Unit**	**Unit Rate ($)**	**Cost ($)**
1.4.9	LVL double skin floor panel 8500 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	6	No.	4,152	25,410
1.4.10	LVL double skin floor panel 8500 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	62	No.	4,410	278,888
1.4.11	LVL double skin floor panel 8500 x 2440, checked around core, comprising 300 x 35 LVL joists, 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	6	No.	4,410	26,989
1.4.12	LVL double skin floor panel 4650 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	8	No.	2,440	19,910
1.4.13	LVL double skin floor panel 5150 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	2	No.	2,536	5,173
1.4.14	LVL double skin floor panel 4200 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	1	No.	2,241	2,286
1.4.15	LVL double skin floor panel 8500 x 2300 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	1	No.	4,152	4,235
1.4.16	LVL double skin floor panel 8000 x 2440 comprising 300 x 35 LVL joists 25 Xband LVL upper skin, 25 LVL lower skin, softwood solid blocking, 150 x 50 ledger each short side; all as Dwg OBF 22A	1	No.	4,185	4,269
					593,105
1.5	**External Walls**				
1.5.1	External walls; 185TL CLT set vertically	1,305	m^2	265	345,825
1.5.2	Add for screw-connections	1	Item		Incl.
					345,825
1.6	**Internal Walls**				
1.6.1	Internal walls; 185TL CLT set vertically	1,794	m^2	280	502,320
1.6.2	Add for screw-connections		Item	18,948	18,948
					521,268
1.7	**Ceiling Finishes**				
1.7.1	Suspended ceiling with 300 mm suspension	11,086	m^2	90	997,740
					997,740
1.8	**Preliminaries Adjustment**				
1.8.1	Provision of time related preliminaries based on the duration of structure construction time.				0
1.8.2	Preliminaries based on reduced Construction duration of:	9	Weeks	-$57,500	-517,500
1.8.3	Termite Protection Allowance	1	Item	35,000	35,000
					-482,500
Total Cost					**7,237,259**

Client Name: Timber Development Association for Forest and Wood Products Australia **Date of Estimate**: 17/07/2017

Element		Qty	Unit	Unit Rate ($)	Cost ($)
1.1	**Columns**				
1.1.1	450 x 450 reinforced concrete columns; 50MPa; Formwork; Reinforcement 240kg/m^3; 42No.	141	m	505	71,205
1.1.2	400 x 400 reinforced concrete columns; 40MPa; Formwork; Reinforcement 240kg/m^3; 104No.	349	m	440	153,560
1.1.3	350 x 350 reinforced concrete columns; 40MPa; Formwork; Reinforcement 240kg/m^3; 64No.	217	m	380	82,460
					307,224
1.2	**Staircases**				
1.2.1	Concrete fire stairs inclusive of handrails and associated works	63	m/rise	3,150	198,450
1.2.2	Concrete fire stairs inclusive of handrails & associated works incl.overrun to roof	34	m/rise	3,150	107,415
					305,865
1.3	**Upper Floors**				
1.3.1	Reinforced in situ concrete suspended slab, 200 thick; 40MPa Concrete; Formwork; Reinforcement 7.2kg/m^2; Post Tensioning 4.7kg/m^2	1,150	m^2	275	316,248
1.3.2	Reinforced in situ concrete suspended slab, 170 thick; 40MPa Concrete; Formwork; Reinforcement 7.2kg/m^2; Post Tensioning 4.7kg/m^2	9,936	m^2	270	2,682,768
1.3.3	Reinforced in situ concrete attached beam, 1,800 wide x 350 deep; 40MPa Concrete; Formwork; Reinforcement 180kg/m^3	1,098	m	885	971,730
1.3.4	Reinforced in situ concrete edge beam, 900 wide x 350 deep; 40MPa Concrete; Formwork; Reinforcement 180kg/m^3	1,458	m	525	765,450
					4,736,195
1.4	**Roof**				
1.4.1	Reinforced in situ concrete suspended slab, 200 thick; 40MPa Concrete; Formwork; Reinforcement 7.2kg/m2; Post Tensioning 4.7kg/m^2	178	m^2	278	49,484
1.4.2	Reinforced in situ concrete suspended slab, 170 thick; 40MPa Concrete; Formwork; Reinforcement 7.2kg/m2; Post Tensioning 4.7kg/m^2	1,767	m^2	270	477,090
1.4.3	Reinforced in situ concrete attached beam, 1,800 wide x 350 deep; 40MPa Concrete; Formwork; Reinforcement 180kg/m^3	183	m	885	161,955
1.4.4	Reinforced in situ concrete edge beam, 900 wide x 350 deep; 40MPa Concrete; Formwork; Reinforcement 180kg/m^3	198	m	525	103,950
					792,480
1.5	**External Walls**				
1.5.1	Reinforced in situ concrete external walls, 200 thick; 40MPa Concrete; Formwork; Reinforcement 130kg/m^3; Post Tensioning 4.7kg/m^2	1,305	m^2	400	522,000
					522,000
1.6	**Internal Walls**				
1.6.1	Reinforced in situ concrete internal walls, 200 thick; 40MPa Concrete; Formwork; Reinforcement 130kg/m^3; Post Tensioning 4.7kg/m^2	1,794	m^2	400	717,600
					717,600

Project Name: **Office Building - Concrete (Conventional Construction)**

Client Name: Timber Development Association for Forest and Wood Products Australia **Date of Estimate**: 17/07/2017

Element		**Qty**	**Unit**	**Unit Rate ($)**	**Cost ($)**
1.7	**Ceiling FInishes**				
1.7.1	Suspended ceiling with 300mm suspension	11,086	m^2	90	997,740
					997,740
1.8	**Preliminaries Adjustment**				
1.8.1	Provision of time related preliminaries based on the duration of structure construction time.				
1.8.2	Preliminaries based on reduced Construction duration of:	0	Weeks		0
					0
Total Cost					**8,379,104**

Notes

1. The cost estimates are priced at September 2014 prices and based on construction in the Sydney Region.

2. RC concrete frame is traditionally a slower construction than both steel frame and timber frame that have prefabricated components produced off-site. The longer construction period of RC Frame will therefore have higher time-related preliminaries costs incurred by both the sub-contractors and Head Contractor. The comparison makes provision for the time-related preliminaries associated with the RC frame construction portion of the Building Construction.

3. The cost comparison of RC, Steel and Timber Frames uses the RC Frame program duration as the base; and subsequently there is no adjustment to the preliminaries above.

4. RC frame concrete rates are inclusive of the concrete pumping costs. When compared to steel or timber frame all lifting costs would incur craneage cost.

5. The RC Frame construction detailed above includes traditional timber soffit formwork. An option to reduce program duration by the substitution of Bondek soffit formwork in lieu of timber formwork. The impact is to increase formwork soffit rates by $10 to $15/m2. It is often found that the savings to time-related preliminaries outweighs the construction rate cost premium.

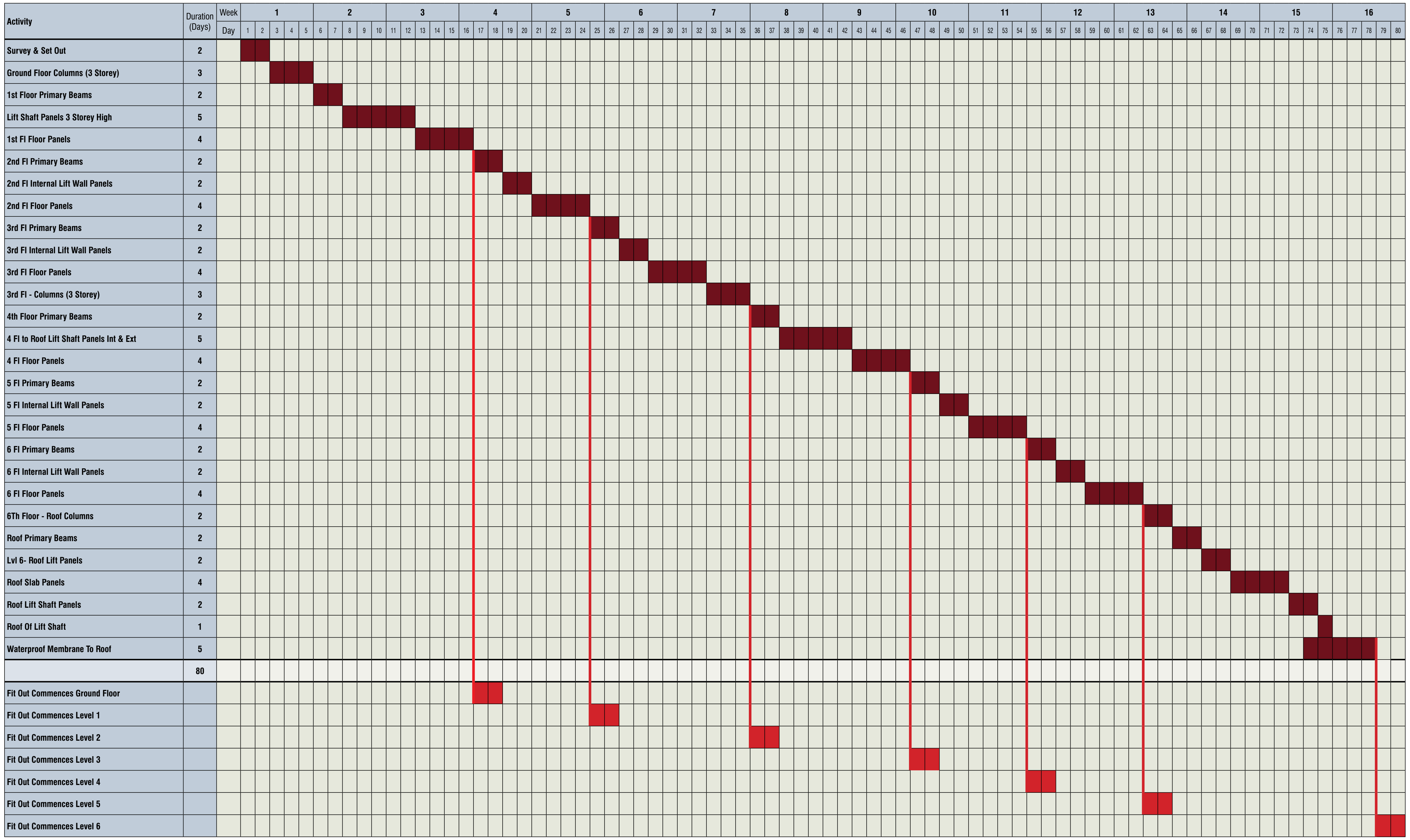
6. Traditional timber formwork is site labour intensive and the costs for formwork can vary up to 30% depending on the current market's supply and demand of formwork labour in the region.

C

Appendix C: Construction Programs

C1 Timber Model Program

Example: 7 Story Building
Construction: Timber Beam, Columns and Floor Cassettes
Program Length: 78 Days

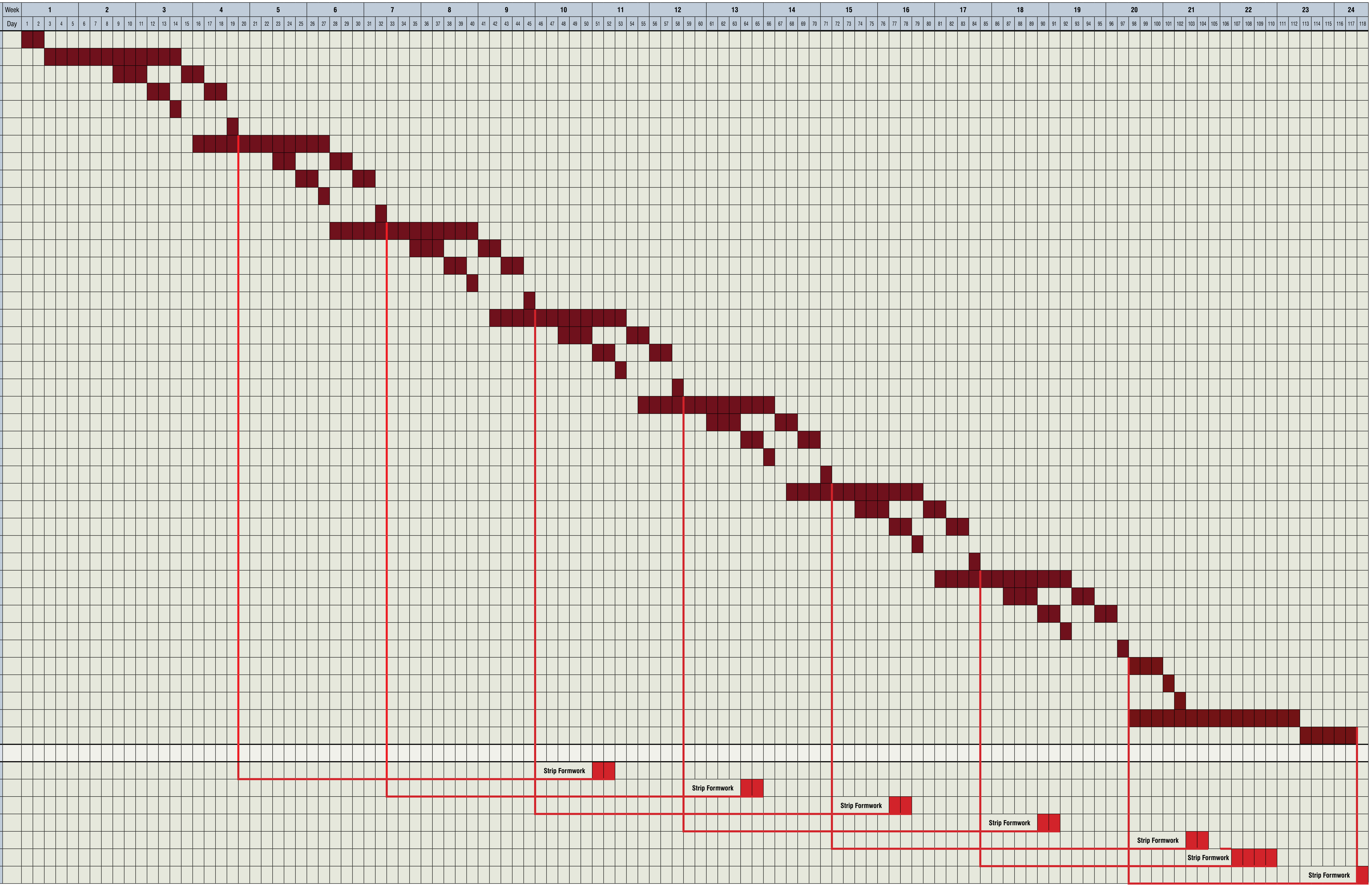


Activity	Duration (Days)
Survey & Set Out	2
Ground Floor Columns (3 Storey)	3
1st Floor Primary Beams	2
Lift Shaft Panels 3 Storey High	5
1st Fl Floor Panels	4
2nd Fl Primary Beams	2
2nd Fl Internal Lift Wall Panels	2
2nd Fl Floor Panels	4
3rd Fl Primary Beams	2
3rd Fl Internal Lift Wall Panels	2
3rd Fl Floor Panels	4
3rd Fl - Columns (3 Storey)	3
4th Floor Primary Beams	2
4 Fl to Roof Lift Shaft Panels Int & Ext	5
4 Fl Floor Panels	4
5 Fl Primary Beams	2
5 Fl Internal Lift Wall Panels	2
5 Fl Floor Panels	4
6 Fl Primary Beams	2
6 Fl Internal Lift Wall Panels	2
6 Fl Floor Panels	4
6Th Floor - Roof Columns	2
Roof Primary Beams	2
Lvl 6- Roof Lift Panels	2
Roof Slab Panels	4
Roof Lift Shaft Panels	2
Roof Of Lift Shaft	1
Waterproof Membrane To Roof	5
	80
Fit Out Commences Ground Floor	
Fit Out Commences Level 1	
Fit Out Commences Level 2	
Fit Out Commences Level 3	
Fit Out Commences Level 4	
Fit Out Commences Level 5	
Fit Out Commences Level 6	

C2 Concrete Model Program

Example: 6 Story Building
Option 6: Reinforced Concrete Frame and Slab in Post Tension
Program Length: 117 Days

Activity	Duration (Days)
Survey & Set Out	2
Level 1 Formwork to Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables and Services	4
L1 Concrete Pour 1st Half	1
L1 Concrete Pour 2nd Half	1
Level 2 Formwork to Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	4
Post Tension Cables And Services	4
L2 Concrete Pour 1st Half	1
L2 Concrete Pour 2nd Half	1
Level 3 Formwork To Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables And Services	4
L3 Concrete Pour 1st Half	1
L3 Concrete Pour 2nd Half	1
Level 4 Formwork To Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables and Services	4
L4 Concrete Pour 1st Half	1
L4 Concrete Pour 2nd Half	1
Level 5 Formwork To Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables And Services	4
L5 Concrete Pour 1st Half	1
L5 Concrete Pour 2nd Half	1
Level6 Formwork To Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables And Services	4
L6 Concrete Pour 1st Half	1
L6 Concrete Pour 2nd Half	1
Roof Formwork To Slab, Beams, Columns, Lift Shaft & Const Joints (30 Men)	12
Reinforcement	5
Post Tension Cables And Services	4
Roof Concrete Pour 1st Half	1
Roof Concrete Pour 2nd Half	1
Roof Lift Shaft Formwork to Lift Shaft and Slab	3
Reinforcement	1
Concrete Pour	1
Cure Concrete to Roof Slab	15
Waterproof Membrane to Roof	5
	117
Fit Out Commences Ground Floor	
Fit Out Commences Level 1	
Fit Out Commences Level 2	
Fit Out Commences Level 3	
Fit Out Commences Level 4	
Fit Out Commences Level 5	
Fit Out Commences Level 6	



D

Appendix D: Other Timber Floor Solutions

While the previous discussion has focused on a single specific timber solution, the full breadth of the study investigated multiple options (30 separate floor systems were investigated). Some of the competitive alternatives are presented in this Appendix. The main drivers of this selection process focused on the floor construction system and the spatial requirements of MEP services, which dominated costing issues.

D1 Floor Design between Primary Beams

D1.1 Floor Design Key Considerations

1. Structural depth to allow HVAC and other services
2. Fire protection
3. Acoustic design
4. Floor vibrations/dynamics

D1.1.1 Structural Depth to Allow HVAC and Other Services

A key aspect of the floor selection was the ability to fit the mechanical air supply, floor structure, office tenant zone, lighting and ceiling construction within a 1,000 mm floor height. This was crucial in order to compete with traditional concrete construction.

D1.1.2 Fire Protection

There were two approaches used to provide fire resistance in timber construction, including:

- install a fire-resisting plasterboard ceiling, or
- utilise the char capacity of solid timber elements.

The decision to use either approach is dependent on the char capacity and size of the timber element. Solid thick elements like CLT and LVL can be designed first for structural requirements under fire load conditions, and then the cross-sectional size of the timber components can be upsized to provide a charring layer to meet targeted fire resistance levels. This method was chosen for the cassette system using 63 mm thick LVL panel to achieve this requirement on the underside of the cassettes.

This approach is less effective for thinner frame flooring options, as the timber frame components would be more easily consumed by the fire. In this case, a fire rated ceiling can be achieved by using layered plasterboard sheeting. Alternatively, a mix of the two solutions can also be provided where appropriate to do so.

What drove the use of ‘massive timber’ as a preferred fire resistance barrier in the chosen option was the fact that the timber itself could be used for a number of other purposes such as deflection and vibration control, decorative surfaces (removing the need of additional cost from ceiling or linings), sound reduction, diaphragm action and reduced construction program time (removes the installation of a number of layers or coverings) and site labour. All of these add to cost savings relative to the concrete model.

D1.1.3 Acoustic Design

The acoustic design dominated the floor system selection including time and cost. The use of the concrete fill and insulation within the cassette – installed off-site – helped resolve this issue by providing noise resistant construction without adding additional construction effort onsite or introducing an extra wet trade to a relatively dry trade site.

D1.1.4 Floor Vibrations

Another key criterion was the response factor (measure of intermittent footfall vibration). For a typical commercial building, a target design value of a response factor (RF) <8 for intermittent footfall vibration was aimed for. The inclusion of concrete fill within the cassette void helped to control this vibration issue.

D1.2 Floor system discussion

Of the 30 floor systems reviewed, four floor systems were investigated further. These were:

1. Timber concrete composite
2. Mass timber panels supported by secondary beams
3. I-beam cassette floor
4. Double skin massive timber cassettes

The four floor systems investigated are discussed below in terms of their advantages and disadvantages.

D1.2.1 Timber Concrete Composite

The timber concrete composite floor consisted of two 400 x 63 mm LVL11 joists at 800 mm centres, and a 100 mm concrete topping slab (Figures D1 and D2). Shear keying is provided by notches into joists and coach bolts. Fire resistance provided by concrete thickness and the char capacity of the timber joists.

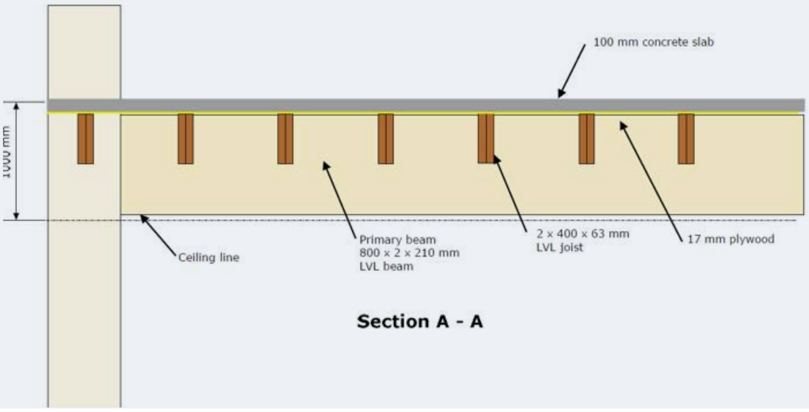


Figure D1: Timber concrete composite floor.

Figure D2: Timber concrete composite floor – Merits Office Building Christchurch. (Photo: TDA)

Advantages:

- Depth of floor system is 500 mm
- Panel width is around 2.7 m
- Overall floor cavity depth <1000 mm required
- Improved acoustics
- Top surface is concrete being similar to traditional office floors
- Joist are spaced widely allowing HVAC access

Disadvantages:

- Re-introduction of wet trades on to the building site
- May require back propping
- LVL joists can’t be notched for services

D1.2.2 Massive Timber Panels supported by Secondary Beams

This system utilised the fire resistance capacity of massive timber panels of either CLT or LVL (refer to Figure D3). Two secondary beam spacing options were considered, the first at 4.5 m centres and the second at 3.0 m centres. The 3.0 m centres allow a thinner floor panel and consequently a more cost-effective solution.

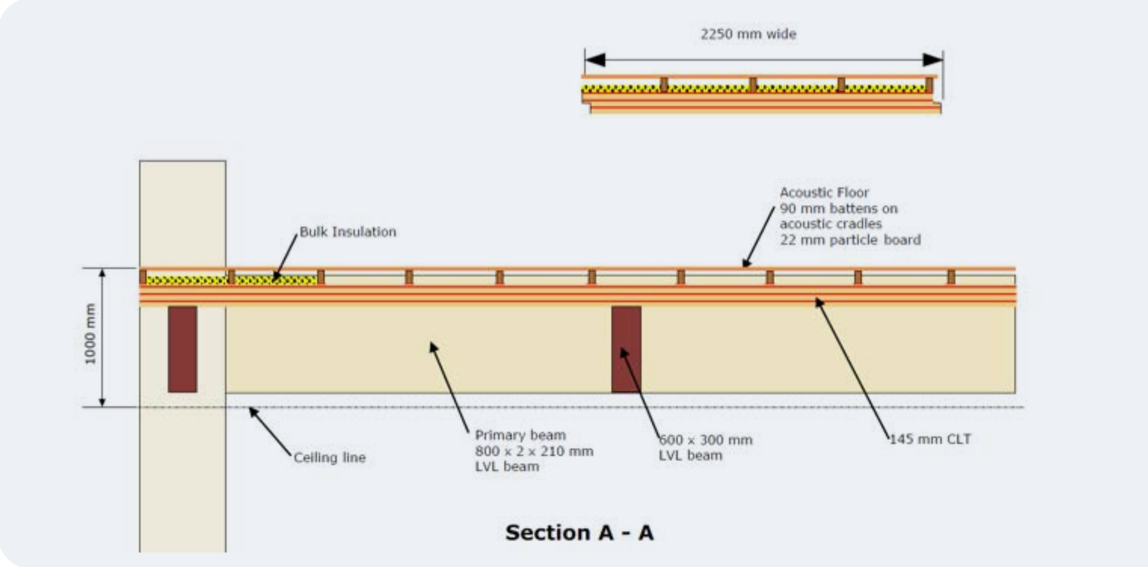


Figure D3: Massive timber panels supported on primary and secondary beams.

Advantages:

- Simple beam layout and floor panel concept
- No fire rated ceiling required
- Overall floor cavity depth <1000 mm
- Improved acoustics
- Conventional HVAC can be used

Disadvantages:

- Depth of floor system is 800 mm but has space for HVAC
- Secondary beams interfere with secondary HVAC ducts but could be notched to overcome this issue
- Tennant zone can occur in access floor

D1.2.3 I-beam Cassette Floor

This 2.7 m wide floor cassette consists of joists made from 400 mm deep I-beams at 600 centres, 21 mm plywood top and bottom (refer Figure D4).

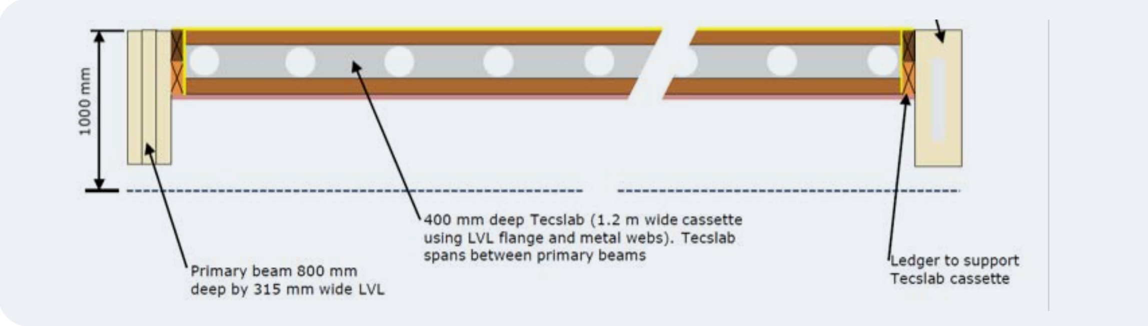


Figure D4: Tecbeam floor cassette.

Advantages:

- Enables competitive cassette depth
- Cassette 2.7 m wide require less crane lifts
- Could be built by Frame and Truss operation
- Overall floor cavity depth <1000 mm

Disadvantages:

- Requires fire-resisting ceiling

D2 Floor System Adopted in Model

This system uses a double skin LVL cassette. It offered potential reduction in construction program, price and the fact that there are fabricators with the capacity to make these panels in major city centres (Figure D5).

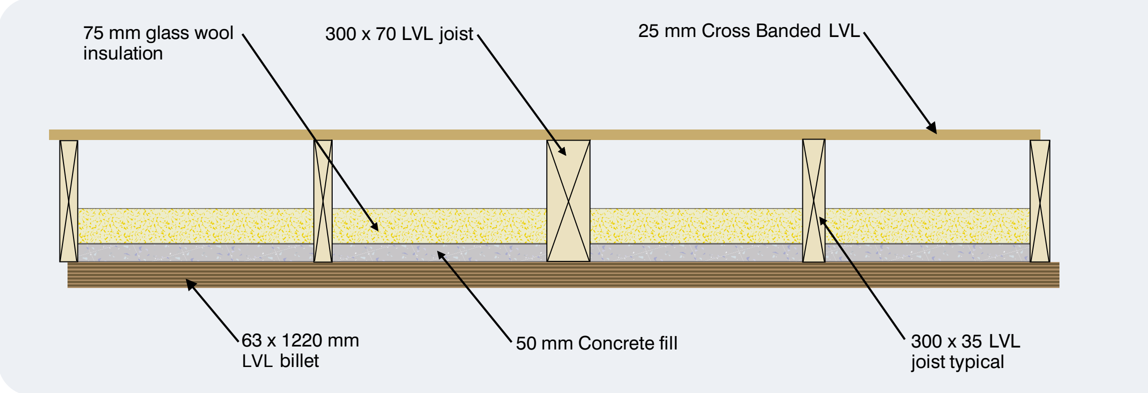


Figure D5: Section through LVL double skin cassette with concrete and insulation.

D2.1 Construction Program

Construction programs were investigated for all the floor systems short listed. The time taken is compared against a post tension slab and the results are provided in Table D1.

Floor System	Programmed Days	Days saved
LVL Double Skin Cassettes (used)	78	39
I-Beam Cassette	78	39
Timber Concrete Composite	119	-2
Secondary Beam CLT plate	105	12
Secondary Beam LVL plate	126	-7
Post Tensioned Concrete	117	0

Table D1: Construction time for various floor systems.

The construction program difference between secondary beam supported LVL and CLT floor planes is due to more crane lifts required for LVL as they are narrower panels.

E

Appendix E: Boosting the Fire Rating of Timber Elements using Timber Charring or Plasterboard

The previous discussion defined fire resistance requirements for wall, floor and roof elements; the following section more specifically determines how to address this as part of a timber-based solution.

Put simply, fire resistance in timber element (such as beams and columns) is typically achieved in two separate ways:

- Encapsulating the elements in fire protective coverings (such as plasterboard) (Figure E1).
- Designing a sacrificial charring layer in the timber element, which serves to protect the structural part of the elements. This is because the charring layer serves to insulate against fire penetration into the inner timber.

E1 Encapsulating Structural Timber Elements in Fire Protective Coverings

What was considered:

- Floor: FRL 90/90/90 - 2 x 16 mm fire-resisting plasterboard ceiling under floor
- Beam: FRL 90/90/90 - 2 x 16 mm fire-resisting plasterboard round all exposed sides of the beam
- Columns: FRL 120/120/120[3] - 3 x 16 mm fire-resisting plasterboard round all exposed sides of the column

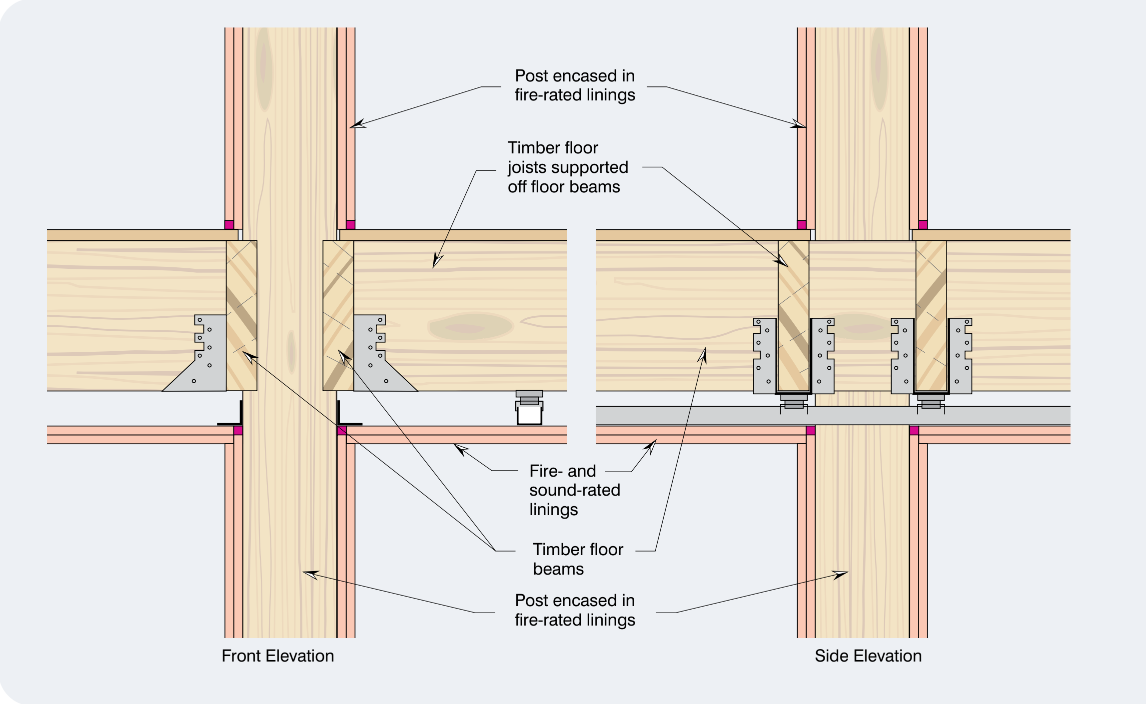


Figure E1: Plasterboard protecting timber elements.

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[3] *CSR Gyprock Red Book, System CSR 496*

E2 Designing a Sacrificial Charring Layer into Structural Timber Elements (except CLT)

What was used:

- Floor: FRL 90/90/90 - 67 mm thickness of timber
- Beam: FRL 90/90/90 - 67 mm thickness of timber
- Columns: FRL 120/120/120 - 87 mm thickness of timber

Reason:

- A protective layer of timber can be used and can be calculated from Standard *AS 1720.4 Timber Structures – Fire-Resistance of Structural Timber Members*

Notional Charring Rate

$C = 0.4 + (280/D)^2$

Where

C = notional charring rate in mm/min
D = timber density at a moisture content of 12% in kg/m^3

Density and species of timber

The density of plywood and LVL is approximately equivalent to the density of the timber species used to manufacture the product. The density of pine plywood is in the range 500-650 kg/m^3.

Use 600 kg/m^3.

$$\begin{aligned} C &= 0.4 + (280/600)^2 \\ &= 0.61 \text{ mm/min} \end{aligned}$$

Effective Depth of Charring

$de = C.t + 7.5$

Where

de = calculated effective depth of charring in mm (refer to Figure B2)

C = notional charring rate in mm/min, calculated above

T = period of time, in minutes 90 mins

$$\begin{aligned} de &= C.t + 7.5 \\ &= 0.61 \times 90 + 7.5 \text{ mm} \\ &= 62.8 \text{ mm} > 63 \text{ mm} \end{aligned}$$

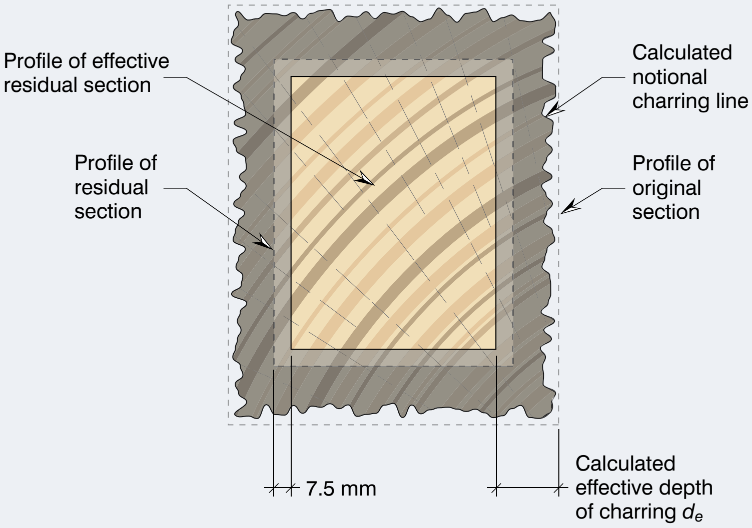


Figure E2: Char to timber element.

E3 Beam Discussion

The fire rating required for a beam is an FRL of 90/90/90. This is to be provided by char layer on the beam. Using the paired beam arrangement in the timber model would mean that the charring would occur on three sides of each beam (Figure E3). A more efficient solution would be to use a 63 mm timber block fitted in the gap top and bottom between the paired beams sealing and protecting the two internal faces of the beams from the fire (Figure E4).

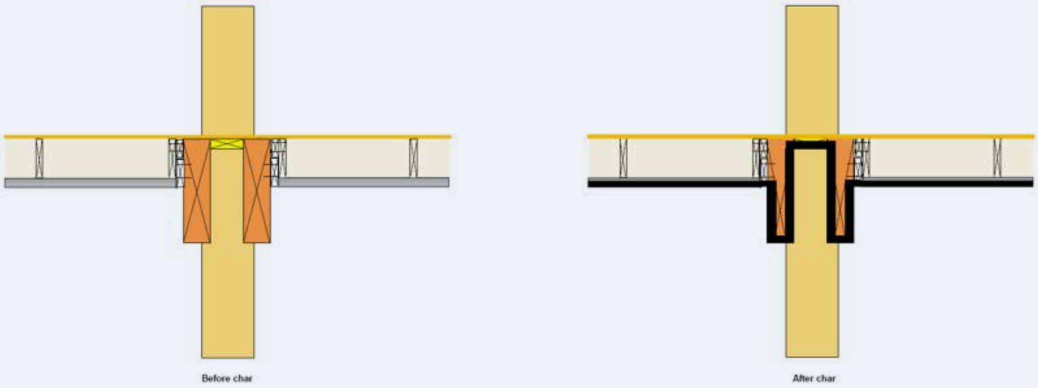


Figure E3: Char difference between blocked and unblocked paired beams.

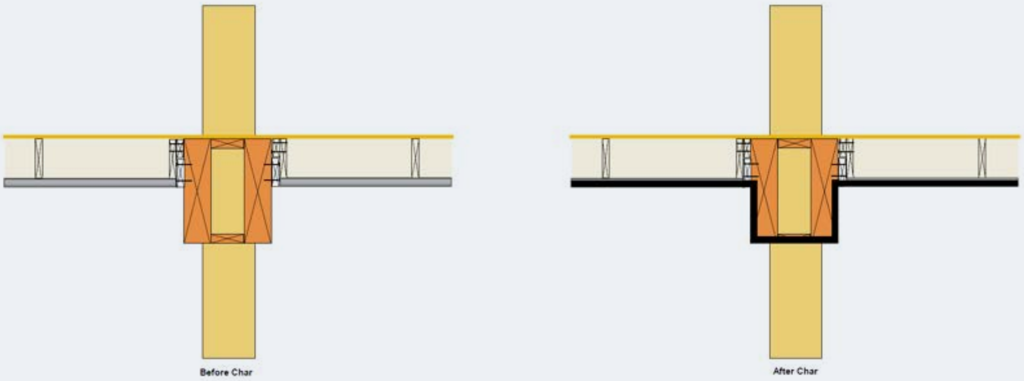


Figure E4: Char difference between blocked and unblocked paired.

E4 Char Capacity of CLT

CLT is not recognised in AS1720.4 as the product char rate is dependent on production methods. Consequently, manufacturers' information is required to be used.

F

Appendix F: Boosting the Acoustic Performance of Timber Elements

F1 Acoustic Design

There are three methods generally employed

1. Suspended ceiling
2. Concrete screed
3. Access floor

F1.1 Suspended Ceiling

Which acoustic solution is used depends on the floor system. A lightweight timber cassette system could utilise the fire-resisting plasterboard ceiling and suspend it using noise-isolating supports to provide the acoustic separation (Figure F1). Massive timber floors that use char capacity for fire protection generally don’t use suspended ceilings as the addition of another layer of construction interferes with the visual appearance. A suspended ceiling is sometimes seen in areas where there are higher noise issues, such as corridors. This zone may also include services.

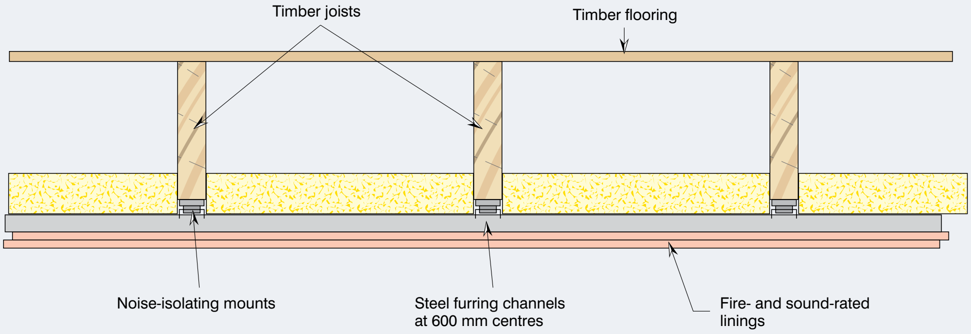


Figure F1: Suspended ceiling.

F1.2 Concrete Screed

Using a concrete screed is a common method to improve acoustic performance. Normally, a resilient mat is included between the screed and the structural floor. The depth of the screed depends on the acoustic performance required. Generally, 40 mm is the minimum (Figure F2). Issues such as cracking and curling of the screed may result in other depths. If a concrete screed is to be used for acoustic reasons, it should also be used (if needed) to help provide some composite structural action. For this reason, a Timber Concrete Composite has been considered in the cost plan.

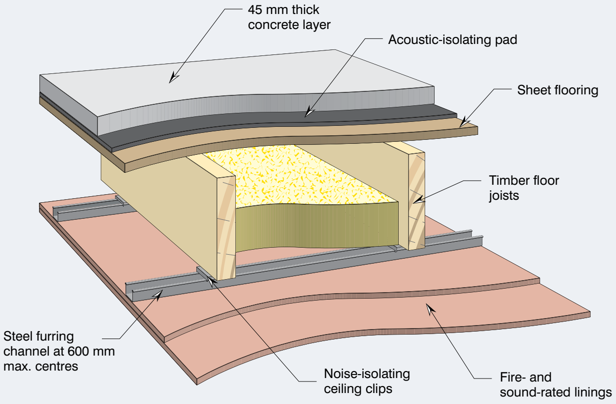


Figure F2: Concrete screed on rubber mat.

F1.3 Access Floor

Where a screed or suspended ceiling is not possible, an access floor is an option. Access floors give opportunity for services and further improvements to acoustic performance when required (Figure F3).

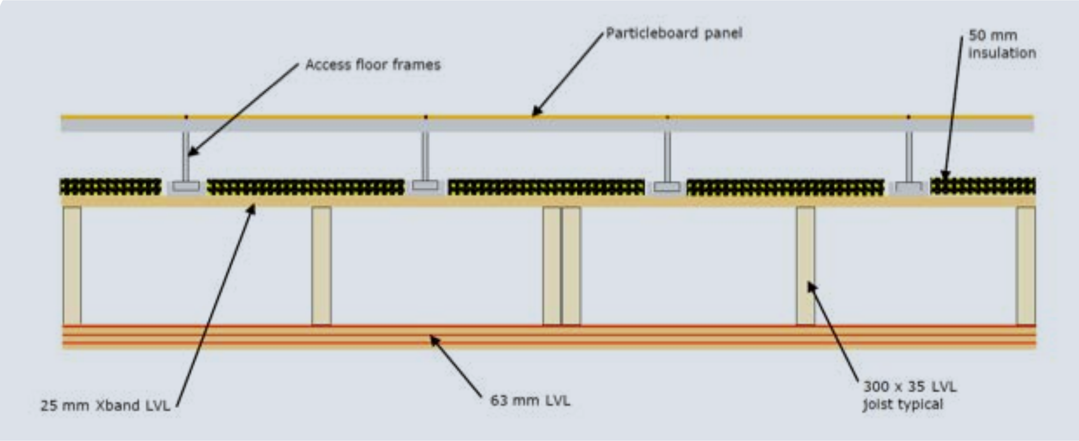
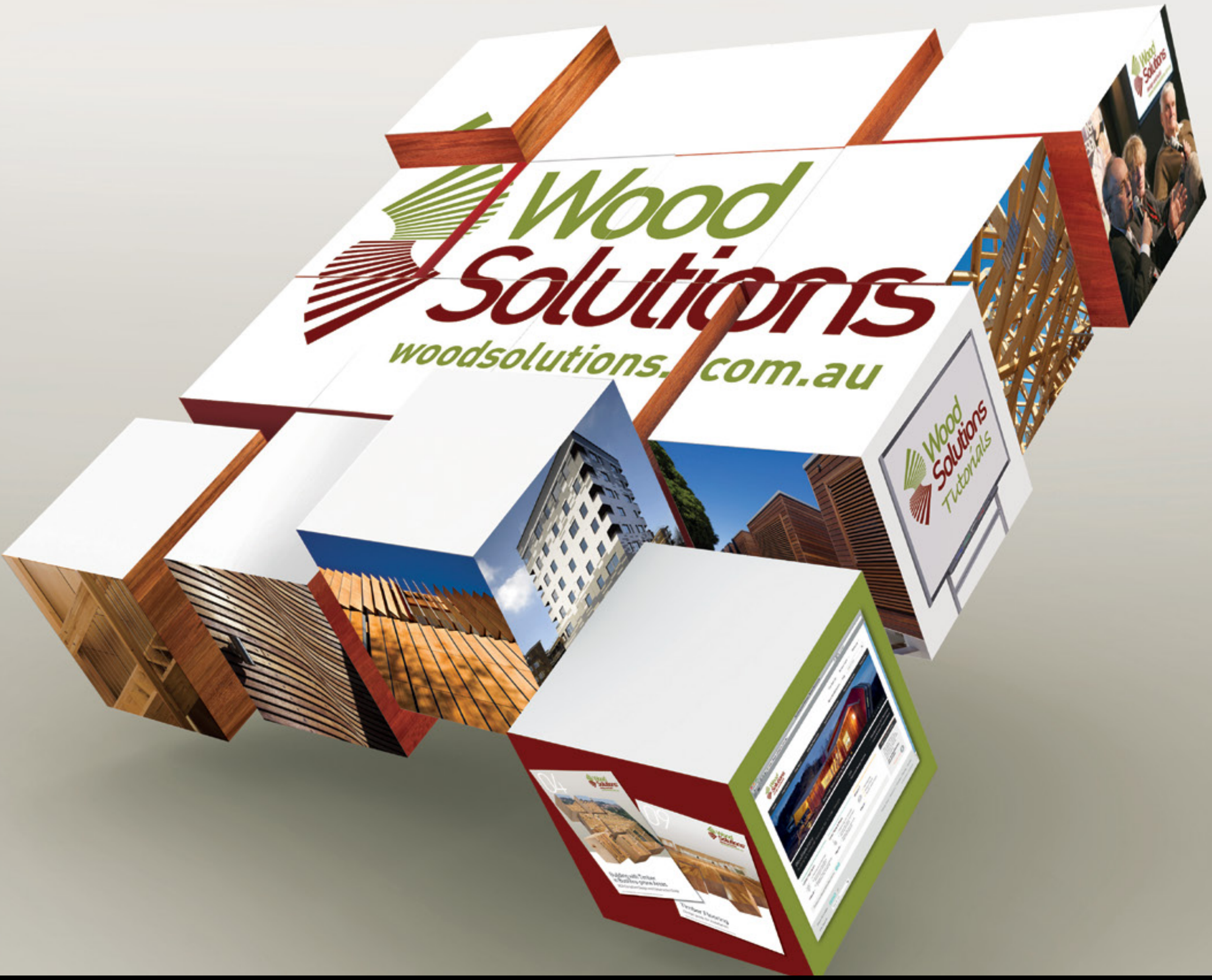


Figure F3: Access floor in combination with timber model floor cassette.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Rethinking Apartment Building Construction - Consider Timber

Technical Design Guide issued by Forest and Wood Products Australia

01 Timber-framed Construction for Townhouse Buildings Class 1a
Design and construction guide for BCA compliant sound and fire-rated construction

04 Building with Timber in Bushfire-prone Areas
BCA Compliant Design and Construction Guide

09 Timber Flooring
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Contents

1

Introduction

Timber's sustainability credentials are attracting world-wide interest and advances in timber engineering have made timber an increasingly cost-competitive proposition.

Encouraging the construction industry to adopt innovative approaches needs information and evidence. Attention to technical design, construction costs and site processes is critical to show the value proposition of timber construction to customers and optimise its use.

This Guide[1] aims to help those involved in the decision chain (such as cost managers, estimators, design professionals, building developers and project managers) gain a better understanding of the value that timber construction systems offer apartment building projects.

The Guide is revision and addition to a previous guide that developed a model apartment building and corresponding timber solutions in Cross Laminated Timber and compared it with conventional concrete construction. The guide has now been updated to include a lightweight timber framed design as well as pricing to mid-2017 rates.

The revision also included feedback from users of the guide and accordingly took the opportunity to address omissions in the first edition; being the absence of concrete toppings to the floor of the timber solution and the lack of stairs to all solutions. As the original timber solution was designed prior to the development of the timber based Deemed-to-Satisfy (DTS) solution within the National Construction Code (NCC), the timber solutions were updated or designed so that all designs fully complies with the DTS solution within the NCC.

Other changes included modification to the façade so that the same rain screen solution was used for all building types, noting that there are differences to the external wall's structural and fire solution throughout each design and finally the CLT solution was redesigned so that it is now based on an Australian manaufacturered and sized product.

The intent of the base building's design was intended to be neutral to all three solution so that not one solution was favoured. This meant that the functional performance, constructability and cost effectiveness and compliance under the National Construction Code (NCC) remained evenly treated. Ultimately the guide provides a basis to provide explanation to the decision making that was required to develop the timber solutions.

---

[1] WoodSolutions Guide No 27 Rethinking Apartment Building Construction - Consider Timber

2

What Drives Decisions When Choosing Apartment Construction Systems?

A key objective of the research project was to understand the decision drivers along the customer/supply chain for the selection of apartment construction systems. Key areas of investigation included:

- Gathering information about customer needs and how construction affects things like the spatial requirements and liveability issues, especially when designing for high-end apartment living.
- Benchmarking against existing apartment construction systems, especially conventional post-tensioned concrete slab construction. This was found to be the main method used for apartment construction and was consequently used as the basis for comparison to timber.
- Understanding the nature of the overall delivery supply chain and related work flows, especially construction scheduling, productivity and prefabrication issues.
- Optimising the regulatory framework where it affects the viability of timber solutions, including fire and acoustic issues.
- Elements that have a significant difference in cost between the construction solutions. Cost neutral items or insignificant cost differences have been ignored. This resulted in the cost comparison focusing mainly on the superstructure costs.

3

Project Development

The research project was developed by a series of expert/stakeholder meetings, interviews, concept development sessions, design charrettes, cost planning studies, construction programming studies and design detailing studies aimed at developing the model apartment building and a cost-effective timber solution for it.

A team of experts worked together to provide input to the development process. Core collaborators included:

- **The Timber Development Association**: A market development association for the timber industry and the project leader for this work, on behalf of the timber industry.
- **The University of Technology Sydney:** A technology-driven university with an integrated understanding of the building industry and specific expertise in timber construction. The university co-developed the research method and mediated the strategic direction of the timber solutions in terms of detailed design, cost and site productivity issues.
- **studio505**: An architectural firm with a strong understanding of design and the effects of material and system selection. They prepared and led the design of the model apartment building with case specific input into the related timber solution.
- **Zimmermann Design Studio**: An Architectural firm that led the design of the timber framed apartment building and provided input into the related timber solution. The original concept design of the building is based on a design undertaken by studio505 the firm from which Zimmermann Design Studio emerged from.
- **MiTek**: A supply and support company for the timber framed Frame and Truss fabrication sector. They provided specialised services in structural design of timber frames, bracing and tie-down.
- **Taylor Thompson Whitting Consulting Engineers**: An engineering firm with specialised services in structural, civil and facade engineering that provided the structural concrete design for the concrete solution.
- **BCIS**: A global subsidiary of the Royal Institute of Chartered Surveyors who specialise in gathering building cost data used for reporting on cost trends for a variety building forms. BCIS provided quantity surveying, cost estimating and cost planning input for the 2014 version of the timber solution and the corresponding concrete solution.
- **MBM**: A national independent construction consultancy specialising in quantity surveying. They provided quantity surveying, cost estimating and cost planning input for the 2017 version of the timber framed solution and the corresponding concrete solution. They have in recent times developed real experience in timber construction and costings.
- **Timber Imagineering and Tim Gibney and Associates**: Heavy timber Fabrication Company and structural timber engineering services. They provided specialised design of lateral resisting frames as well as analysis of the CLT core.

Two timber solutions were chosen as the main element used in the timber solutions, being Cross Laminated Timber (CLT)[2] (Figure 1) and Lightweight Timber Framing (LTF) (Figure 2). Cross Laminated Timber was used in the lift and stair core in both design. Based on this, a preferred timber design solution was derived and tested on a cross-section of building owners, developers, designers and contractors to provide critical feedback. This design was then compared against a typical post-tension concrete design using band beams and columns (as detailed in Appendix A).

---

[2] For more information on Cross Laminated Timber refer to WoodSolutions Guide No 16;
Massive Timber Construction Systems - Cross-laminated Timber (CLT)

Figure 1: Cross-Laminated Timber construction.

Architect: Waugh Thistleton, Engineer: Techniker, Contractor: Telford Homes, CLT Supply and Installation: KLH UK, Photography: KLH UK

Figure 2: Timber Framed Apartment Building “The Green” by Frasers Property

4

The Model Apartment Building – the Basis for Comparison and Solution Development

The model apartment building was created to provide a basis for defining and presenting a timber-based solution, as well as a corresponding concrete solution. It provides a prototypical situation for modelling spatial, loading, fire and noise resistance conditions, enabling a neutral base for creating both the timber and competing concrete solutions.

The model building aimed to meet high-end consumer needs, including large and open room layouts. An emphasis was placed on characterising a building that could apply to many suburban/urban apartment situations across Australia.

The model apartment building is shown Figure 3. The building is divided into three distinct parts: car parking in the basement, retail space on the ground floor and seven stories of apartments. This mix of spaces mimics real world situations and creates a mix of different building classifications under the National Construction Code.

Figures 4 to 8 provide an overarching understanding of the model building, including the multiple faceted style façade, which creates an interesting yet complex aesthetic for the building. The basic spatial characteristics of the model are provided in Table 1.

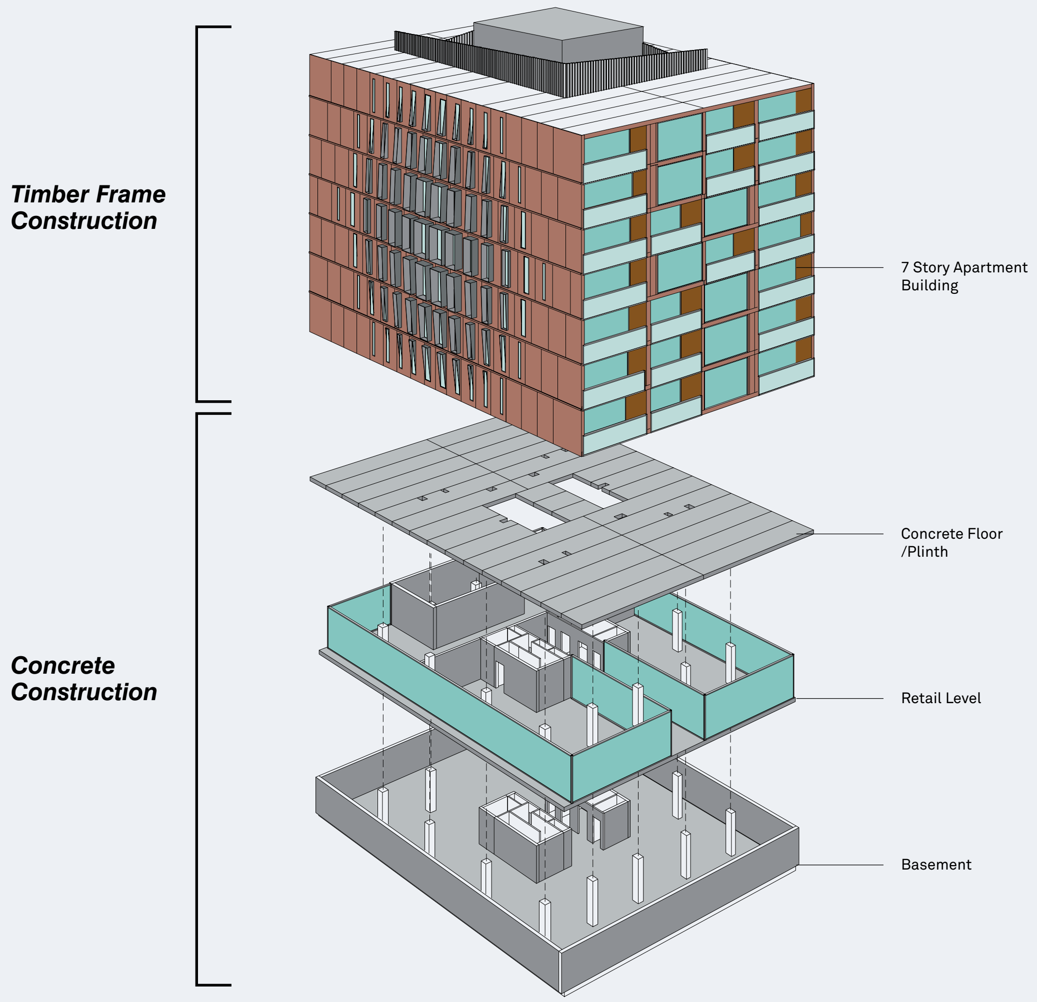


Figure 3: The building broken into three distinct zones.
Design and image: Zimmermann Design Studio and studio505:

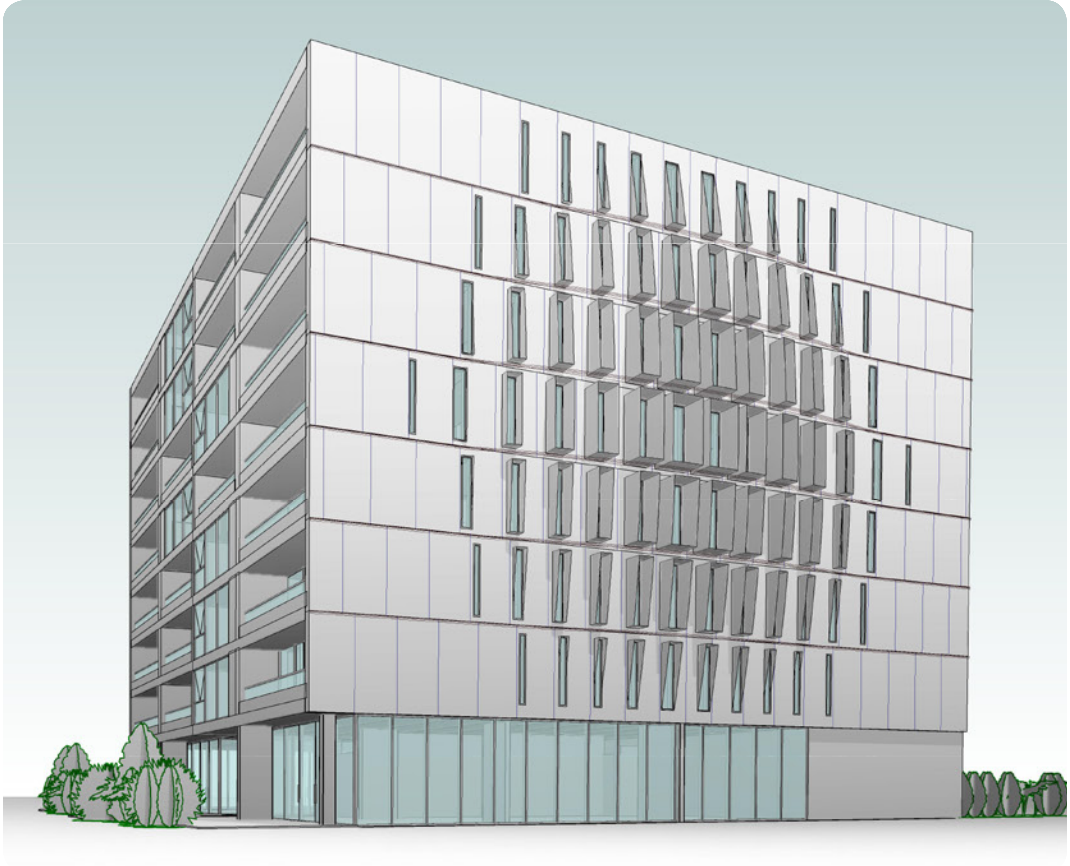


Figure 4: 3D exterior views. *Design and images: Zimmermann Design Studio and studio505:*

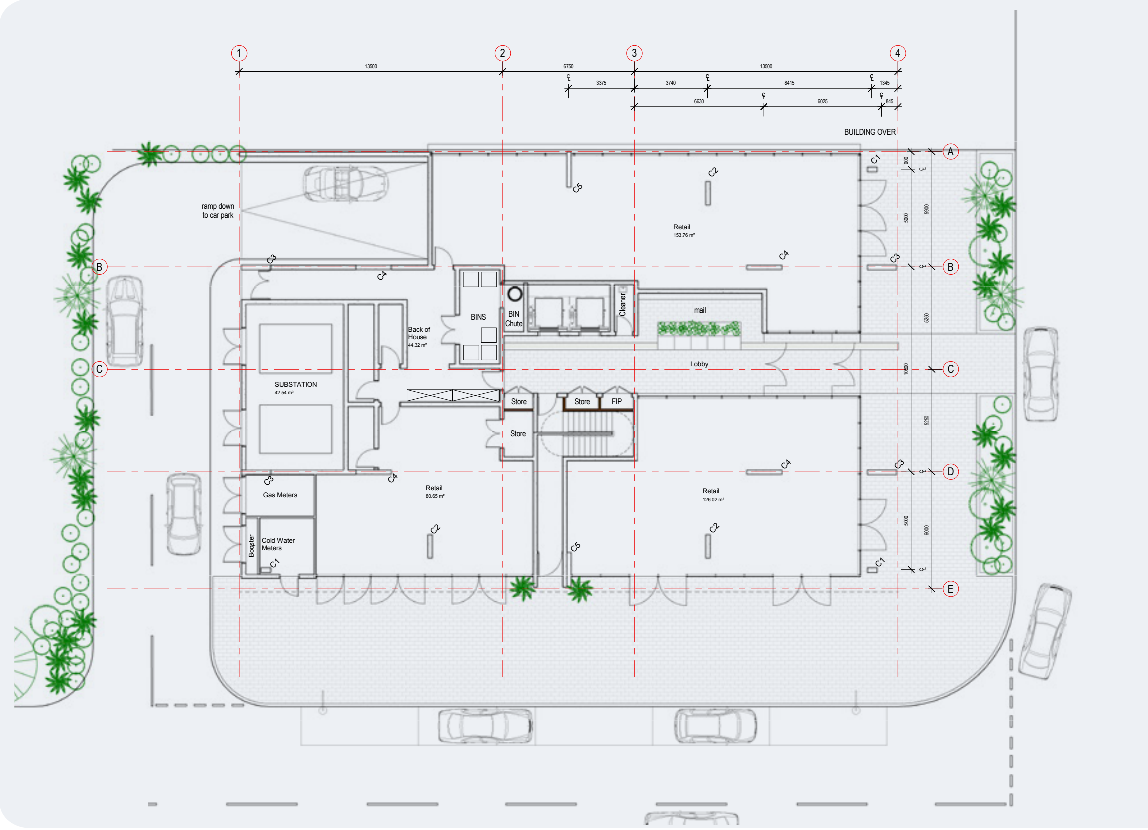


Figure 5: Plan view of retail level (ground floor).
Design and images: Zimmermann Design Studio and studio505:

Figure 5: Typical floor plan for apartment levels.
Design and images: Zimmermann Design Studio and studio505:

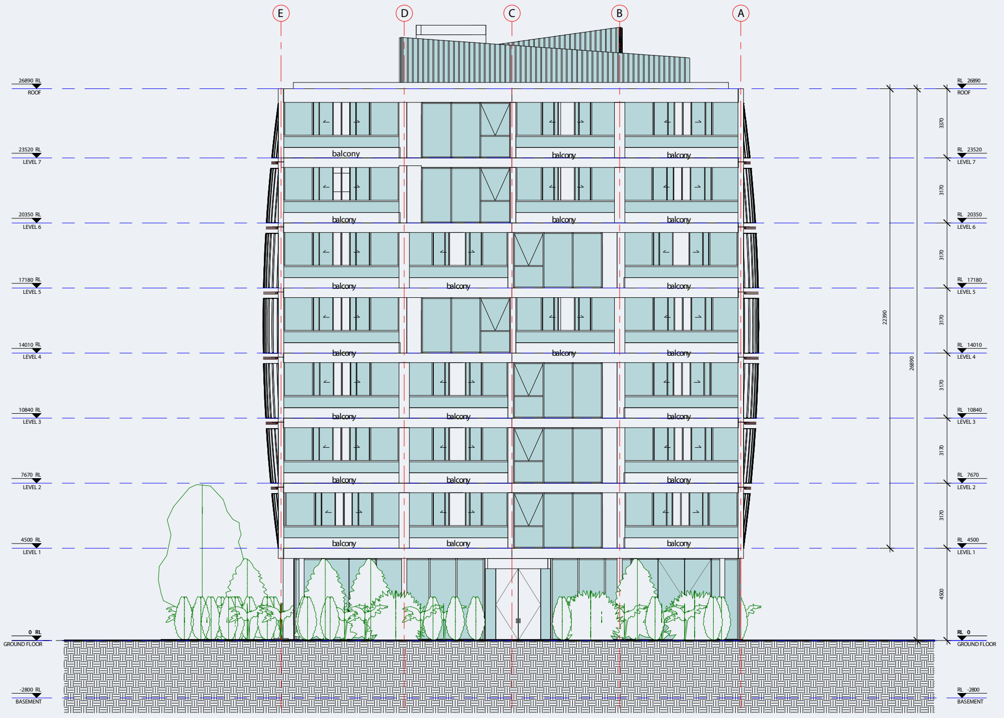


Figure 7: Section view - short section.
Design and images: Zimmermann Design Studio and studio505:

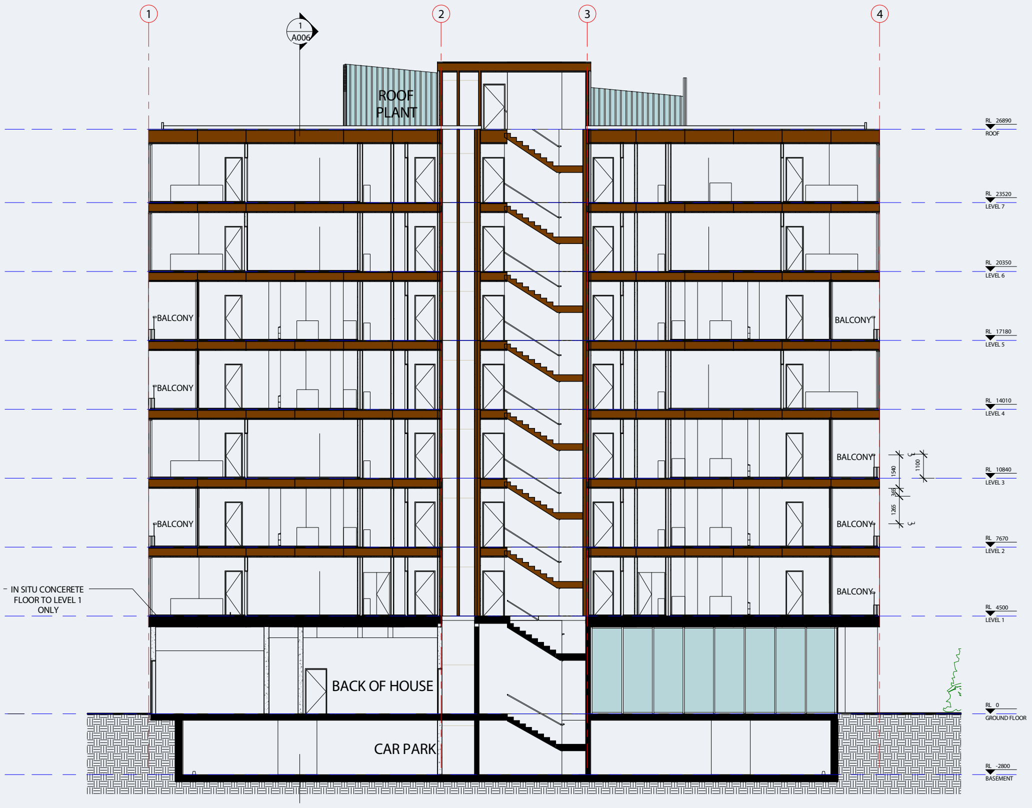


Figure 8: Section view - long section.
Design and images: Zimmermann Design Studio and studio505:

Table 1: Key spatial characteristics of the model apartment building.

Item	What was used in the model	Relevance and Reasons
Height	• An 8-storey design height above ground level, including 7 apartment levels and 1 retail level. • Timber Framed - A 26.9 m overall building height, with an NCC effective height of 23.7 m. - A 3.2 m floor to floor height for the apartment levels and 4.0 m for the retail level. • CLT and Concrete - A 26.2 m overall building height with an NCC effective height of 23.1 m. - A 3.1 m floor to floor height for the apartment levels and 4.0 m for the retail level.	• The apartment levels provide a 2.7 m habitable height plus room for the structure and services. Lower ceiling heights may also be possible in accordance with the NCC. • The retail level provides for a maximum depth of 650 mm (concrete) 500 mm (CLT and timber framed) thick transfer slab above, i.e. as used to transition loads from the timber to concrete parts of the building.
Area	• A floor plate area of 770 m^2. The apartment levels include 42 apartments (94–96 m2 each). • The retail level assumes three shops varying in area from 77–150 m^2. It also includes a foyer area, an entrance to basement car parking, utility meter rooms, an electrical substation and a waste area.	• Feedback and analysis indicates that many suburban mid-rise apartment buildings fit the scenario provided.
Key set out criteria	• Length 34.0 m x Width 22.5m (edge to edge of floor plates). • An 8.2 x 8.2 m column grid used on the retail level (Level 1) and the basement level below.	• The width of the building accommodates the size and set-out of the large, high-end apartments. • The grid layout accommodates car parking in the basement.
Building ownership and fire compartment-alisation	• The building is considered to be strata titled including the retail area on the ground floor.	• Strata title creates the need for each title to be defined as a separate Sole Occupancy Unit under the NCC which creates fire and noise performance requirements.
Setbacks	• External wall distances are (at minimum) less than 1.5 m from the property boundary.	• The location of the building relative to other buildings or properties affects façade fire resistance requirements.

Note: Effective height refers to the distance from the floor level above the ground to floor level of the upper most habitable space but excluding the top most storey where used for items such water tanks, lifts, etc).

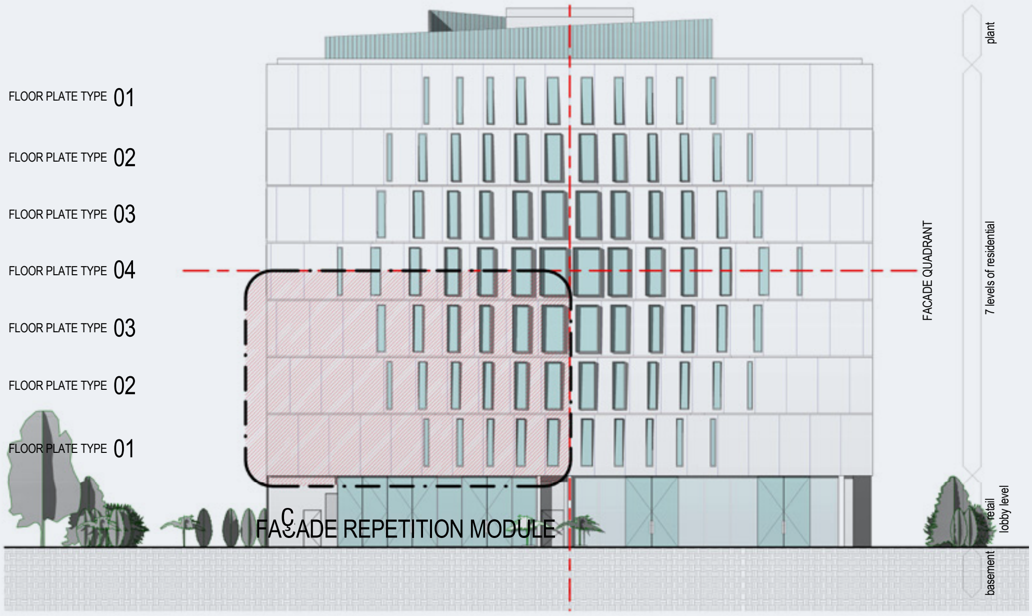
4.1 North and South Façade

The building's north and south façades is multifaceted with varying sized windows occurring on each level, (Figure 9). The façade is divided into four zones and they are repeated four times (Figure 10).

The intricate façade design is a consequence of the design team wanting the building to have more interesting architecture, while adding a degree of difficulty to the project's design. The façade's irregular window size means that opening do not line up on top of each other (Figure 11). This façade design drove the need to fully protect the buildings with sprinklers, as it removed the need for spandrel projection or panels.

The solution for this façade was provided by clipping on non-loadbearing pre-fabricated rain screen.

Figure 9: North and south façade.
Design and images: Zimmermann Design Studio and studio505:



10: Façade repetition. *Design and images: Zimmermann Design Studio and studio505:*

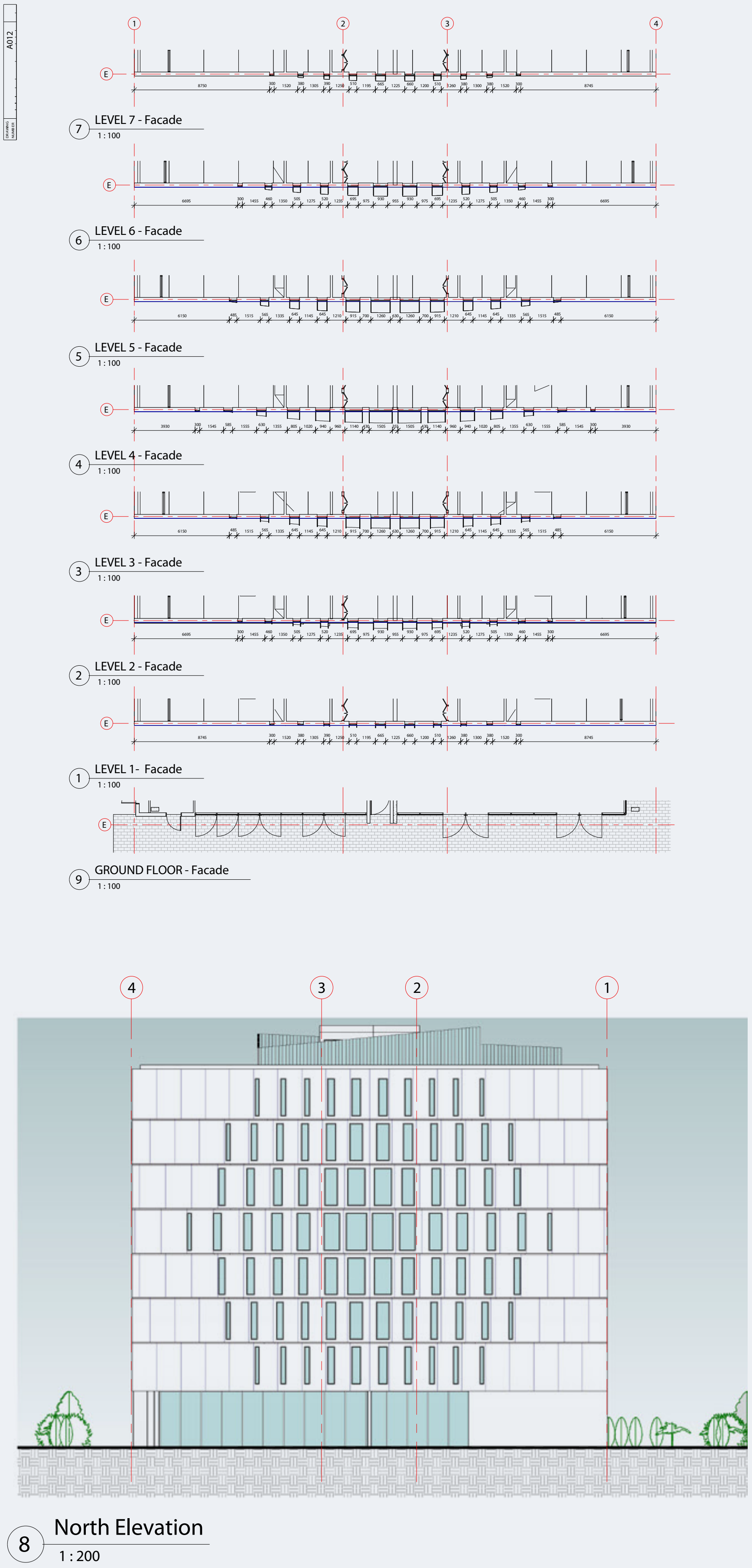


Figure 11: Difference in external wall location on various floor levels
Design and images: Zimmermann Design Studio and studio505:

4.2 Core Differences between the Timber and Concrete Solutions

The main difference between the timber solutions and competing concrete solution concerns the wall and floor structure throughout the apartment levels of the building (i.e. the seven levels above the ground floor retail level).

Parameters pertaining to fire, acoustic and building services requirements (which affect both the timber and concrete solutions) are provided under dedicated headings below.

Other aspects are essentially the same and provide relative neutrality when comparing the two competing solutions. Consequently, discussion of the solution below Level 1 (retail level and basement car parking) has been excluded from this Guide.

4.3 Structural Themes

Parameters applied to the model:

- •Deemed-to-Satisfy applied, imposed and wind loadings were taken from AS 1170 series of Standards.
- Load paths are managed in the apartment levels via cellular timber construction which converts to a concrete slab and column (grid) structure for the retail and basement levels below. The transition between the two is managed by a 500 mm deep concrete transfer slab for the timber solution. The concrete solution uses a concrete column and flat plate solution with infill non-loadbearing walls to separate SOU's. The columns in the apartment zone do not line up with column layout in the retail and basement zone requiring a concrete slab transfer solution.
- Weathered shale soil conditions have been applied in the structural design.

Reasons:

- While in technical terms, timber can be constructed below ground level, concrete construction is less likely to attract concerns about moisture penetration and termite activity. To allay such concerns, the timber solution uses a stainless steel mesh barrier at all hidden entry points between the concrete levels and the timber levels above.
- Concrete construction is used for the retail and basement levels because:
  - These levels pertain to Class 7b (car parking) and Class 6 (retail) under the NCC, and subsequently have higher fire resistance requirements than the main Class 2 apartment levels of the building. It was found more cost effective to use concrete construction on these lower levels.
  - The transfer slab was found to be the most cost-effective means of transferring loads, especially at the change between the apartment and retail zone.
- Weathered shale is a moderate foundation condition common in many parts of Australia and is relatively neutral for both timber and concrete solutions.

Additional points of interest:

- The lightweight nature of timber is particularly advantageous in poor foundation conditions. Though not dealt with specifically in this study, its lightweight nature contributes to reduced piling or smaller footing sizes.

4.4 Building Acoustics

Parameters applied to the model were designed to achieve above NCC's Deemed-to-Satisfy requirements including:

Floors:

- Rw + Ctr (airborne) between 50 and 55
- Ln,w (impact) between 40 (carpet) and 55 (hard surfaces).

Walls:

- Walls between neighbouring units: Rw + Ctr (airborne) of 50 to 55 and is discontinuous construction i.e. separate wall leaves.
- Walls to plant room, lift shafts, stair shafts and corridors: between Rw 50 - 55. These walls must also be discontinuous construction.
- Service shafts; Rw + Ctr (airborne) of 40.
- Doors to apartments: Rw 30.

Reasons:

- Since the apartments aim to meet high-end consumer standards, the nominated acoustic requirements have been selected to surpass minimum NCC's Deemed-to-Satisfy requirements..

4.5 Fire Resistance

Parameters applied to the model:

- The NCC defines the model building as being mixed use including Class 7a – car parking; Class 6 – retail; and Class 2 – residential. It involves a rise of 8 storeys which subsequently requires Type A fire resistant construction. For the apartment levels, this determines the Fire Resistance Levels required of individual building elements further dealt with below. Here, Deemed-to-Satisfy (DtS) provisions were applied to all of the concrete solution as well as the timber solution and the Fire Resistance Levels (FRLs) are identical for the concrete and timber solutions. The timber solution utilised the recent NCC Code change[3] that allowed fire-protected timber construction to an effective height of 25 m.
- A sprinkler system was applied to the building at each floor level as well as the under-roof area for both the timber and concrete solutions to reduce spread of fire requirements that would otherwise limit design options for the external face of the building (as discussed in Section 4.1).

Reasons:

- A Deemed-to-Satisfy solution was applied to each solution to remove the need to develop a Performance Solution. It is recognised that a Performance Solution to elements of the building design for both solution may provide extra saving. This has been ignored in this comparison.
- The use of a sprinkler system removed the need for fire protection of openings in the exterior façade, therefore avoiding usage of spandrel panels and similar facade treatments. (NCC provision C2.6 removes the need for spandrel panels or horizontal projections where complying sprinklers are installed.) While this choice benefited the timber solution and was less necessary for the concrete solution, feedback from architects suggests that this potential economy associated with concrete (and similar) spandrel panels is rarely used because of the unwanted design limitations it places on the appearance of the building.

4.5.1 External Walls

Parameters applied to the model:

- The NCC (Table 3 Specification C1.1. Clause 3) Deemed-to-Satisfy Fire Resistance Level (FRL) has been applied to external wall elements for the concrete and timber solution. As the external walls are considered to be less than 1.5 m away from adjoining property
  - Loadbearing walls 90/90/90, and
  - Non-loadbearing walls - /90/90.
- The north and south façade's rain screen was pre-fabricated from non-combustible materials and span between each floor of the building. There is no difference in the rain screens construction technique between the timber and concrete solution.

---

[3] The 2016 NCC added a new DTS solution for timber buildings up to an effective height of 25 m.

4.5.1.1 Vertical separation of openings in external walls

Parameters applied to the model:

- There are no spandrel or horizontal projections relied on in the solution.

Reasons:

- The use of spandrel or horizontal projections interfered with the facade appearance (Section 4.1) and are not necessary when complying sprinklers are installed (NCC Provision C2.6).

4.5.2 Internal Walls

Parameters applied to the model:

- The NCC (Table 3 Specification C1.1. Clause 3) Deemed-to-Satisfy Fire Resistance Level (FRL) has been applied to fire-resisting lift and stair shaft walls; walls bounding public corridors and lobbies; walls between or bounding apartments; and walls relating to service shafts. The FRLs used are:
  - fire-resisting lift and stair shafts – loadbearing walls: 90/90/90 and non-loadbearing walls: -/90/90
  - walls bounding public corridors and lobbies – loadbearing: 90/90/90 and non-loadbearing: -/60/60
  - between or bounding apartments – loadbearing walls: 90/90/90 and non-loadbearing walls: -/60/60
  - service shafts – loadbearing walls: 90/90/90 and non-loadbearing walls: -/90/90

4.5.3 Floor Structure

Parameters applied to the model:

- The NCC (Table 3 Specification C1.1. Clause 3) Deemed-to-Satisfy Fire Resistance Level (FRL) has been applied to floor structure. The FRL used is 90/90/90.

4.5.4 Roof Structure:

Parameters applied to the model:

- A non-combustible roof covering is used.
- There is no fire resistance requirement for roof elements.
- Fire-rated walls extend to the underside of the non-combustible roof coverings.

Reasons:

- NCC (Spec C1.1 Clause 3.5) provides a concession for roofs in Class 2 buildings, requiring no fire resistance as long as a complying sprinkler systems and a non-combustible roof covering is used.

5

The Timber Solution

In response to the model building (including fire, acoustic, building services and structural loading requirements), this section presents a timber solution that aims to optimise cost, time and constructability requirements. It focuses on the seven levels constituting the Class 2 apartment section of the building (levels 1 to 8) and uses a number of themes:

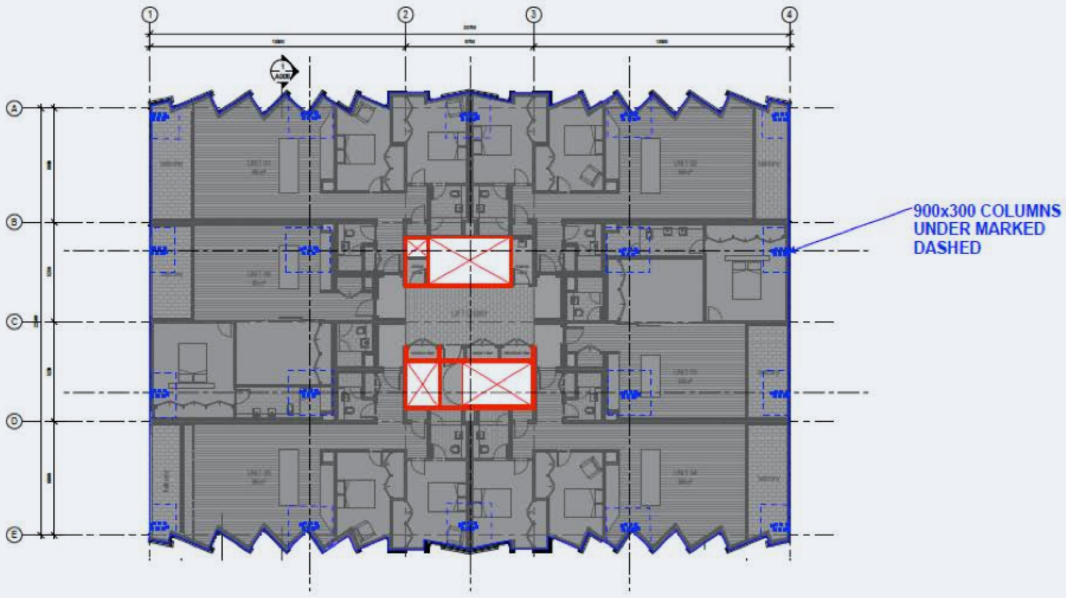
- Two timber design solutions, one using Cross Laminated Timber and the other using lightweight timber framing for loadbearing walls, fire-rated walls, partition walls for non-loadbearing and/or non-fire resistant internal walls, floor and roof elements.
- Use of Cross-Laminated Timber for lift shaft and stair shaft as well as the stairs in both solutions.
- Level 1 floor and below is in concrete (Figure 12 provides details of concrete transfer slab).

Construction solutions are provided below in Section 5.1 for lightweight timber frame and Section 5.2 for Cross Laminated Timber.

In contrast, the concrete solution uses a more commonly used post tensioned flat plate design, which is detailed in Appendix A for comparative purposes.

Many other aspects of the overall construction are common to both the timber and concrete solutions and have subsequently been excluded from the ongoing discussion. This includes the:

- Basement construction
- Retail level construction
- Façade rain screen (structural component of external walls are included in the comparison



LEVEL 1

Notes:
1. Slab to be 500mm thick U.N.O
2. Drop Panels to be 1800 x 1800 x 650mm deep U.N.O
3. Slab:
   - PT rate = 6.0 kg/m^2
   - Reinforcement rate = 45 kg/m^3
4. All concrete f_c = 40 Mpa
5. Column sizes denoted on plan with a reinforcement rate of 240 kg/m^3
6. Core walls to be 200mm (W) with a reinforcement rate of 140 kg/m^3

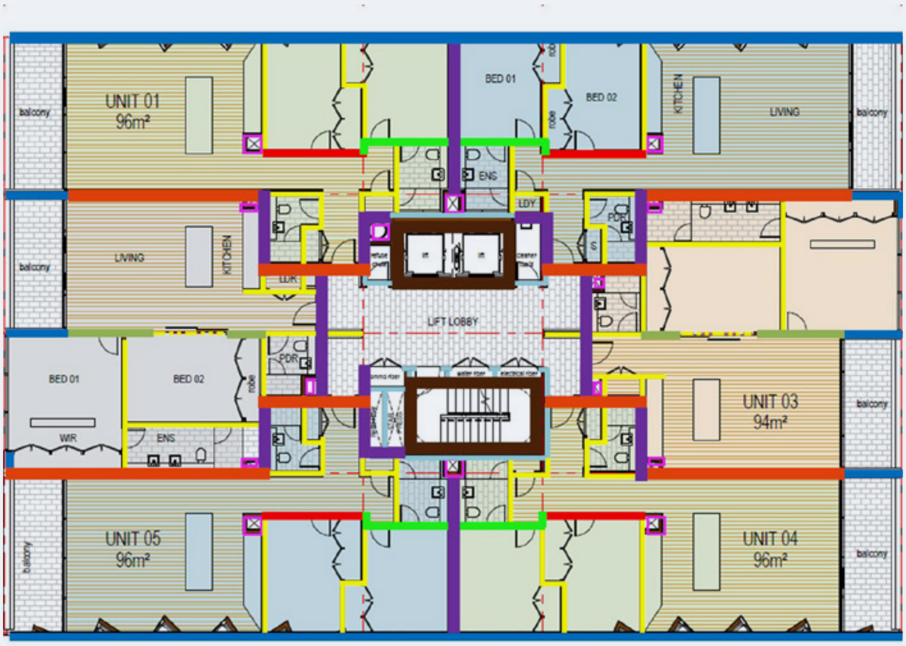
Figure 12: Details of the concrete transfer slab at Level 1 for the timber solution

5.1 Lightweight Timber Frame Solution

5.1.1 External and Internal Walls

What was used in the lightweight timber solution:

- Lightweight timber framing has been used for all external and internal walls (excluding stair and lift shafts) that are loadbearing and/or require fire resistance levels (see Figure 13 for details). Specific element sizes vary according to application and the location in the building i.e. lower levels because of higher loads use either larger or higher strength studs. Refer to Table 2 for the location of each wall type and Tables 3, 4 and 5 for the corresponding sizing of the studs.



Wall Location	Wall Number & Colour Code	Description
External	1	Single stud load-bearing fire-rated wall
Apartment bounding Walls	2	Double stud load-bearing fire and acoustic rated wall
	3	Double stud non load-bearing fire and acoustic rated wall
Internal Apartment Walls	4	Single stud load-bearing fire-rated wall – FLW 5.3 m
	5	Single stud load-bearing fire-rated wall – FLW 4.4 m
	6	Single stud load-bearing fire-rated wall – FLW 3.4 m
	7	Single stud non load-bearing fire-rated wall
	8	Single stud non load-bearing wall
Shafts	9	Lift and stair shaft
	10	Service shaft

Figure 13: Typical Floor Plan showing timber framed wall types

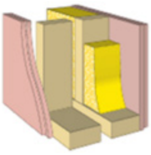
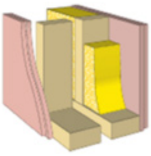
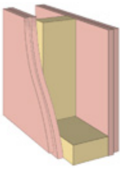
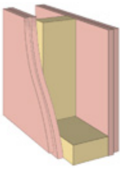
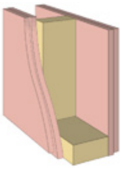
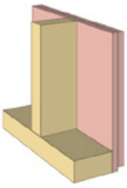
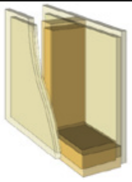
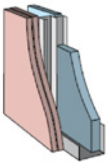
Zimmermann Design Studio, studio505 and TDA:

NOTE: FLW means "Floor Load Width" a common term used to indicate the width of the floor bearing onto a wall.

---

[3] Further information on Timber char capacity can be found in WoodSolutions Guide No 3: Timber-framed Construction for Commercial Buildings Class 5, 6, 9a & 9b - Design & construction guide for BCA compliant fire-rated construction

Table 2: Wall Systems Description

	Diagram of Wall System	Structural System	Linings & Insulation	Acoustic Rating Rw + Ctr	Fire Rating
1		Refer to Table 3 for stud and plate sizes	Inside: 2 x 13 mm fire grade plasterboard Outside: 2 x 13 mm fire grade plasterboard + Aluminium composite panel on battens. 75 mm mineral wool in between battens	N/A	90/90/90
2		Refer to Table 4 for stud and plate sizes	2 x 13 mm fire grade plasterboard both sides of wall with 75 mm glasswool in the cavity	52#	90/90/90
3		Studs and Plates: MGP10 70 x 45 @ 600 crs	2 x 13 mm fire grade plasterboard both sides of wall with 75 mm glasswool in the cavity	N/A	90/90/90
4		Refer to Table 5 and FLW 5.3 m for stud and plate sizes	2 x 13 mm fire grade plasterboard both sides of wall	N/A	90/90/90
5		Refer to Table 5 and FLW 4.4 m for stud and plate sizes	2 x 13 mm fire grade plasterboard both sides of wall	N/A	90/90/90
6		Refer to Table 5 and FLW 3.4 m for stud and plate sizes	2 x 13 mm fire grade plasterboard both sides of wall	N/A	90/90/90
7		Studs and Plates: MGP10 70 x 45 @ 600 crs	2 x 13 mm fire grade plasterboard both sides of wall with 75 mm glasswool in the cavity	N/A	90/90/90
8		Studs and Plates: MGP10 70 x 35 @ 600 crs	10 mm standard grade plasterboard or 6 mm fibre cement (if in wet area)	N/A	N/A
9		125 mm 5 layer CLT	1 x 16 mm fire grade plasterboard each side of CLT	52* (Note: in combination with Wall 7)	90/90/90
10		102 mm metal frame	25 mm plasterboard shaft liner 2 x 13 mm fire grade plasterboard	40#	90/90/90

Acoustic estimates from CSR Red Book
*Acoustic estimate from FWPA CLT Acoustic Research Program

Table 3: External Wall Stud and Plate Sizes

	External Walls
	Level 7
Plates	MGP10 90 x 35
Studs	MGP10 90 x 35 @ 600 crs
	Level 6
Plates	MGP10 90 x 35
Studs	LVL 90 x 35 @ 600 crs
	Level 5
Plates	MGP10 90 x 35
Studs	LVL 90 x 35 @ 600 crs
	Level 4
Plates	LVL 130 x 35
Studs	LVL 130 x 35 @ 600 crs
	Level 3
Plates	LVL 130 x 35
Studs	LVL 130 x 35 @ 600 crs
	Level 2
Plates	LVL 130 x 35
Studs	LVL 130 x 35 @ 600 crs
	Level 1
Plates	LVL 130 x 35
Studs	LVL 130 x 35 @ 600 crs

Table 4: Apartment bounding wall stud and plate sizes

	Double Stud Walls Load Bearing
	Level 7
Plates	MGP10 90 x 35
Studs	MGP10 90 x 35 @ 600 crs
	Level 6
Plates	MGP10 90 x 35
Studs	LVL 90 x 35 @ 600 crs
	Level 5
Plates	MGP10 90 x 35
Studs	LVL 90 x 45 @ 600 crs
	Level 4
Plates	MGP10 90 x 35
Studs	LVL 2 x 90 x 35 @ 600 crs
	Level 3
Plates	MGP10 90 x 35
Studs	LVL 2 x 90 x 35 @ 600 crs
	Level 2
Plates	MGP10 90 x 35
Studs	LVL 2 x 90 x 45 @ 600 crs
	Level 1
Plates	MGP10 90 x 35
Studs	LVL 3 x 90 x 45 @ 600 crs

Table 5: Internal apartment single stud and plate sizes

	Single Stud FLW = 5.3 m	Single Stud FLW = 4.4 m	Single Stud FLW = 3.4 m
	Level 7		
Plates	MGP10 90 x 35	MGP10 90 x 35	MGP10 70 x 35
Studs	MGP10 90 x 45 @ 450 crs	MGP10 90 x 45 @ 600 crs	MGP10 70 x 45 @ 450 crs
	Level 6		
Plates	MGP10 120 x 45	MGP10 120 x 35	MGP10 90 x 35
Studs	MGP10 120 x 45 @ 450 crs	MGP10 120 x 45 @ 600	MGP12 90 x 45 @ 450 crs
	Level 5		
Plates	MGP10 140 x 35	LVL 130 x 35	MGP10 120 x 35
Studs	MGP12 140 x 35 @ 450 crs	LVL 130 x 35 @ 600 crs	MGP12 120 x 35 @ 450 crs
	Level 4		
Plates	LVL 130 x 35	LVL 130 x 35	MGP10 120 x 35
Studs	LVL 130 x 35 @ 450 crs	LVL 130 x 35 @ 600 crs	MGP12 120 x 45 @ 450 crs
	Level 3		
Plates	Ribbon Nogging[1]	Ribbon Nogging[1]	LVL 130 x 35
Studs	LVL 130 x 35 @ 450 crs	LVL 130 x 35 @ 600 crs	LVL 130 X 35 @ 450 crs
	Level 2		
Plates	Ribbon Nogging[1]	Ribbon Nogging[1]	LVL 130 x 35
Studs	LVL 130 x 35 @ 450 crs	LVL 130 x 35 @ 600 crs	LVL 130 X 35 @ 450 crs
	Level 1		
Plates	Ribbon Nogging[1]	Ribbon Nogging[1]	LVL 130 x 35
Studs	LVL 130 x 35 @ 450 crs	LVL 130 x 35 @ 600 crs	LVL 130 X 35 @ 450 crs

NOTES: [1]Ribbon Nogging are plates on edge housed into studs. Refer below for more explanation.

Reasons:

Avoidance of Compression Perpendicular to Grain Issues

Timber's compressive strength perpendicular to grain is much less than it is parallel to grain and if left without consideration could cause axial shortening issues within the building leading to misalignment of plumbing, flashing and cladding. Two techniques have been used within this design to minimise these effects and they are discussed below.

Balloon Framing

Traditional framing techniques used in house construction, termed platform construction, have a portion of timber framing perpendicular to grain to the load path, i.e. floor framing, beams and wall plates, refer Figure 14.

To minimise perpendicular to grain crushing an old construction system termed "balloon framing" is used. Balloon framing is where the studs are more than one storey high and the floor system is hung off the side of the stud. This design uses a modern version of this termed "semi-balloon framing". This is where the studs are floor to floor in height and have the floor framing supported off the side of the studs, refer Figure 15.

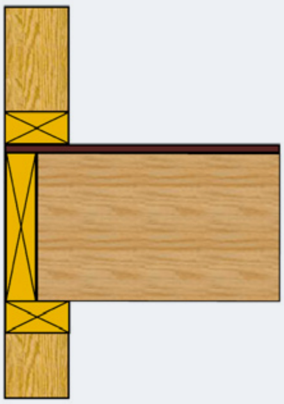


Figure 14: Platform Framing System

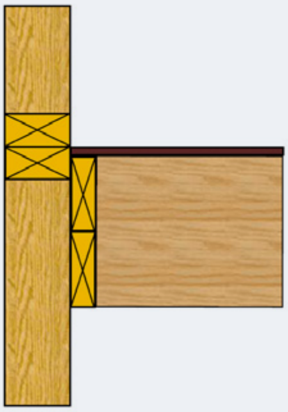


Figure 15: Semi Balloon Framing

Ribbon Nogging

Although Semi-Balloon framing remove most of the horizontal timber out of the design, timber wall plates are still contained within the wall frame and load path. The lower storeys of this design where dominated by the bearing strength of the wall plates, so much so the stud sizes were being determined by this issue.

To avoid using studs sizes greater than need the studs were aligned on top of each other and the wall plates where placed on edge and rebated into the studs, refer Figure 16. This configuration allowed the stud ends to bear directly onto each other.

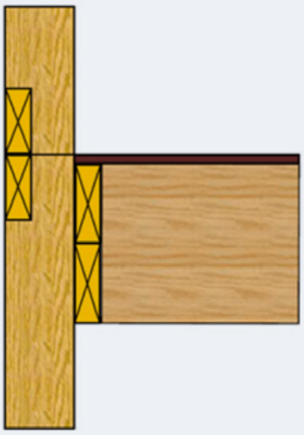


Figure 16: Ribbon nogging replacing wall plates

5.1.2 Stair and lift shaft

The system use 125 mm thick 5 ply Cross laminated timber.

Fire protection to the CLT varies depending on whether a stud wall abuts it or that it is in the inside of the shaft. Stud wall's fire protection is as for other walls utilising two layers of 13 mm fire grade plasterboard. Where there is no frame wall abutting the shaft, 16 mm fire grade plasterboard is direct fixed to the CLT.

Reasons:

- Where required for acoustic reasons, CLT wall panels have additional stud construction to improve sound performance (Table 2).

5.1.3 Floor and Roof Structure

What was used in the timber solution:

Lightweight timber framed floor cassettes where used, refer Figure 17. They have an overall depth of 382 mm including floor sheets. Timber framing consists of parallel chord trusses at 450 centres. Top and bottom chords are made from 90 x 45 MGP 12 and webs from pressed metal, refer Figure 17. Cassettes vary in length and width depending on the layout. Generally the floor cassettes length is the span between supporting walls and 2.7 m wide, being a common floor sheet size and width of truck used to deliver the cassettes.

Figure 17: Section through timber floor cassette.

The cassettes sit onto a timber ledger. One half of the ledger is screwed to the side of the wall studs and the other to the end of the cassette, refer Figure 18. This joining method makes the installation easier and quicker as well as providing an element that can be used as a cavity barrier.

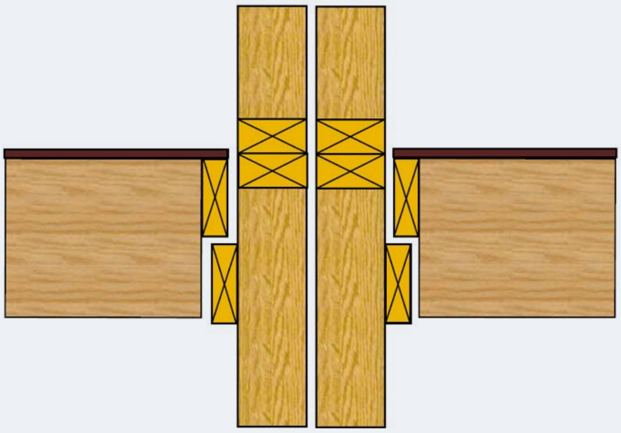


Figure 18: Illustration of ledger support for timber floor cassette.

Reasons:

- The timber framed floor cassettes are used to speed up installation of the floor framing.
- Floor trusses as used to allow plumbing services to transverse through the floor.
- Due to the walls running from floor to floor, the floor cassettes must span between wall frames.
- Timber ledgers on wall studs and cassettes also act as cavity barrier, a NCC requirement.

Fire Resistance

- Fire resisting to the underside of the floor is provided by two layers of 16 mm fire resisting plasterboard fixed to a resilient mounted furring channel. This configuration provides an FRL 90/90/90 and meets the NCC's requirement for Clause A 1.1 for Fire-Protected Timber.
- Fire resistance is not required for the roof as the walls abut the underside of the non-combustible roof coverings.

Acoustic

Sound attenuation is provided by a number of elements in the floor system, refer Figure 19. These include;

- 40 mm thick cement based screed
- 10 mm rubber mat between cement based screed and structural flooring
- Furring channels hung on resilient mounts attached to the underside of the floor cassettes framing
- 75 mm glasswool insulation at 14 kg/m^3

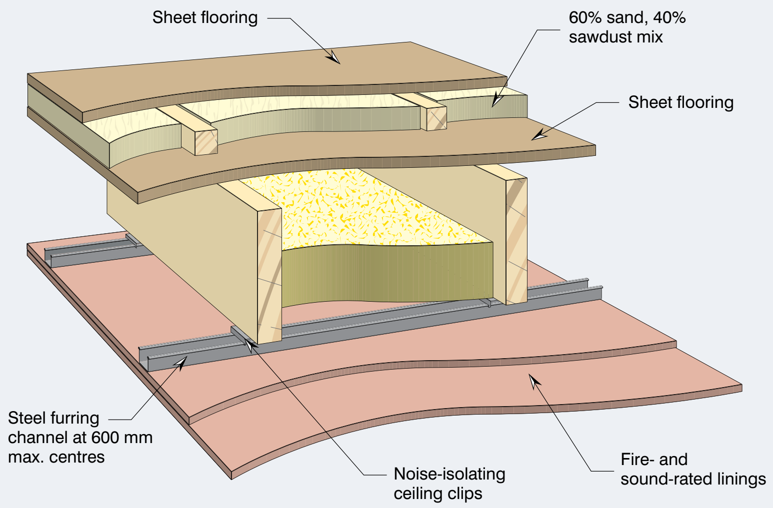


Figure 19: Section through acoustic floor framing

The acoustic performance

- Rw + Ctr: 51
- Ln: 40 to 55 (depends on floor coverings used)

Beams are required in two internal openings:

- Two 240 x 90 LVL13 beams under the floor in opening in wall in Units 3 and 6.

5.1.4 Lateral Resistance

Lateral resistance and over turning of the building is dealt in a number of solutions. Firstly the CLT used for the lift and stair shaft is assumed to provide one third of the lateral resistance. Additional lateral resistance is provided by the use of varying number of shear walls on each level of the building. The lowest storeys requires more shear walls than the top storey.

Three shear walls are used;

- Galvanised metal cross bracing, AS1684.2 Table 8.18 (d)
- Double skin plywood walls with tie-down rods, AS1684.2 Table 8.18 (i)
- Laminated Veneer Lumber (LVL) moment frames

A typical shear wall layout is found in Figure 20.

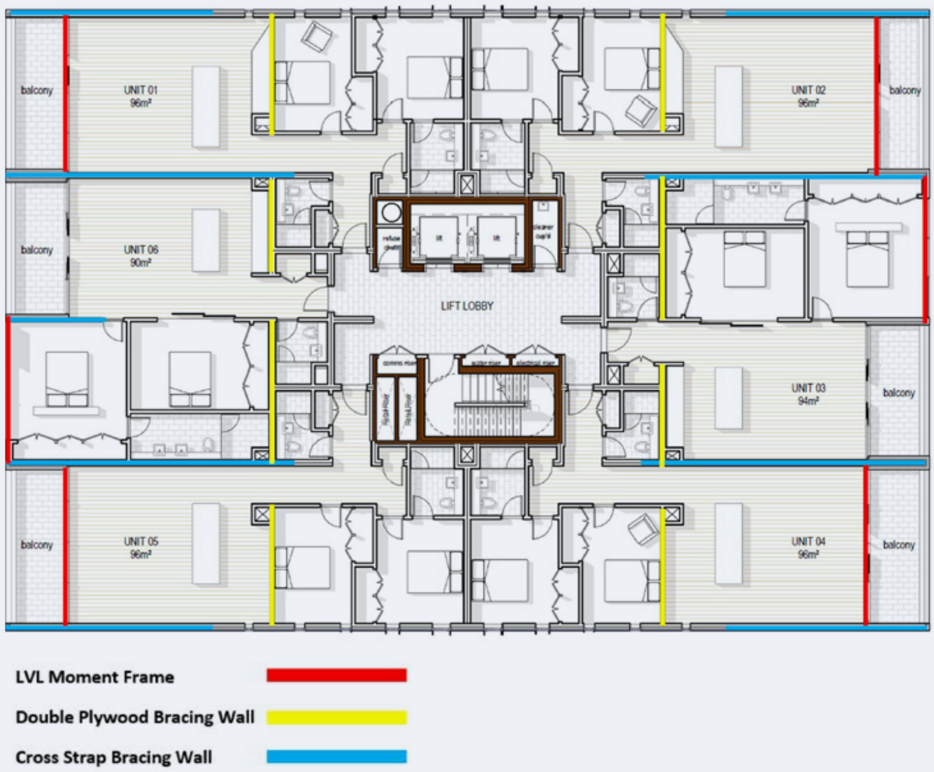


Figure 20: Level 1 Shear Wall Layout
Design and images: Zimmermann Design Studio, studio505 and TDA:

Reason:

- The CLT core of the building has large lateral resistance capacity.
- Metal cross bracing are used as they don't increase the wall thickness.
- Double skin plywood wall with tie-down rods are very efficient shear walls. They do increase the wall thickness but this effect can be reduced by utilising internal apartment walls. Internal apartment walls with cupboards attached hide the additional wall thickness.
- LVL moment frames are used on the east and west façade as they frame around the openings without interfering with the window or door opening.

5.2 Cross Laminated Timber Solution

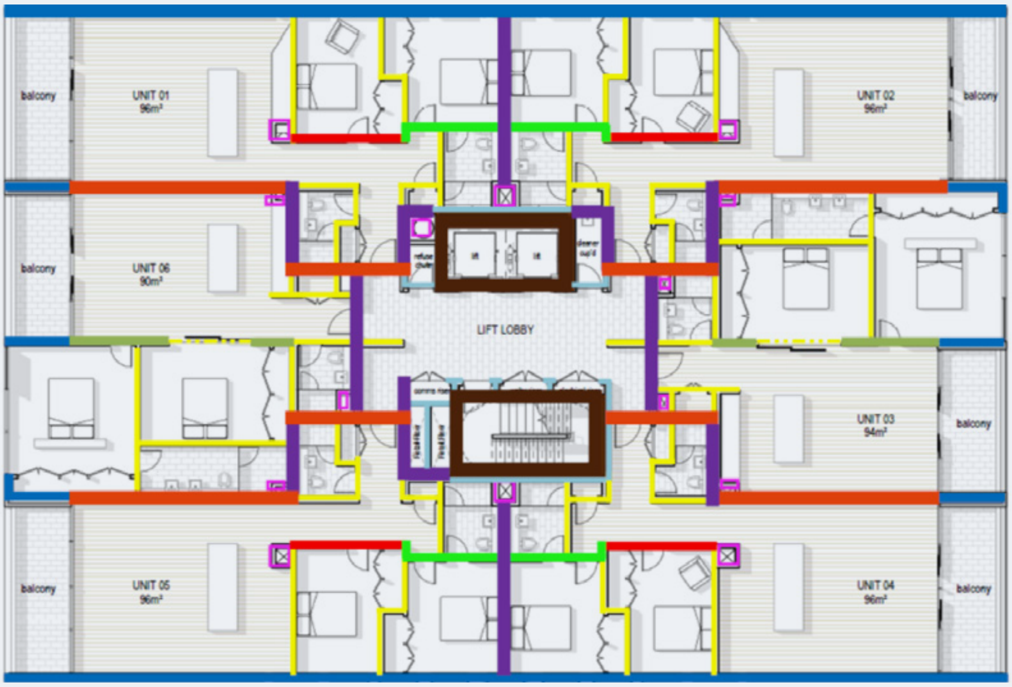
5.2.1 External and Internal Walls

What was used in the timber solution:

Cross laminated timber has been used for all external and internal walls (including stair and lift shafts) that are loadbearing and/or require fire resistance levels (refer to Figure 21 for details).

Partition walls within apartments that are not fire resisting are lightweight timber stud walls. CLT element sizes vary according to application, refer to Table 6 which includes:

- Fire protection to the CLT was used in all cases.
- Where required for acoustic reasons, CLT wall panels have additional stud construction to improve sound performance, refer Table 6.
- The stair and lift shaft are twin wall CLT systems, separated by a 20 mm cavity.
- Service shafts are constructed from metal stud with 13 mm plasterboard and 25 mm shaft wall system.
- Non-loadbearing and/or non-fire resisting partition walls within apartments are constructed from 70 x 35 mm timber framed studs at 600 mm centres walls with plasterboard or fibre cement linings.



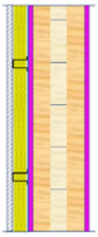
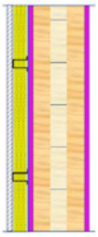
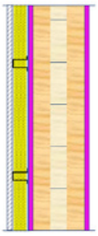
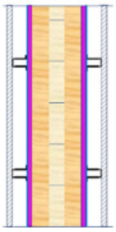
Wall Location	Colour Code	Description
External – North & South	1	Fire protected CLT with rain screen supporting FLW 3.0 m
External – East & West	2	Fire protected CLT with rain screen supporting FLW 5.3 m
External Wall Balcony	3	Fire protected CLT with rain screen supporting FLW 5.6 m
External Wall Balcony both side	4	Fire protected CLT with rain screen both sides supporting FLW 5.6 m
Apartment bounding Walls - Load bearing	5	Fire protected CLT with stud wall to one side supporting FLW 5.6
Apartment bounding wall – non-load-bearing	6	Fire protected CLT with stud wall to one side
Internal Apartment Walls - Load bearing	7	Fire protected CLT supporting FLW 5.25 m
Internal Apartment Walls	8	Fire protected CLT supporting FLW 4.4 m
Internal Apartment Walls	9	Fire protected CLT supporting FLW 3.9 m
Internal Apartment Walls/ Lift and Stair shaft	10	Fire protected CLT supporting FLW 1.5 m
Interior Lift and Stair shaft	11	Fire protected CLT with plasterboard on outside
Partition walls	12	Timber framed walls
Service shaft	13	Steel studs and shaft liner

NOTE: FLW means "Floor Load Width" a common term used to indicate the width of the floor bearing onto a wall.

Figure 21: Typical Floor Plan showing timber framed wall types

Design and images: Zimmermann Design Studio, studio505 and TDA:

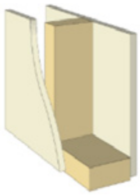
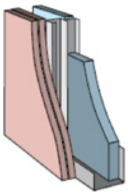
Table 2: Wall Systems Description

Colour Code	Wall Location	Illustration	Level	Description	Coverings	Acoustic Rating Rw + Ctr	Fire Rating
1	External – North & South FLW 3.0 m		8	XLAM CL3 85	Interior: 16 mm Fire grade PBD. Exterior: 16 mm fire grade plasterboard, vapour permeable membrane, battens and fibre cement panels	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 105			
			3	XLAM CL3 105			
			2	XLAM CL3 115			
2	External – East & West FLW 5.3 m		8	XLAM CL3 85	Interior: 16 mm Fire grade PBD. Exterior: 16 mm fire grade plasterboard, vapour permeable membrane, battens and fibre cement panels	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 125			
			3	XLAM CL3 135			
			2	XLAM CL3 135			
3	External East & West FLW 5.6 m		8	XLAM CL3 85	Interior: 16 mm Fire grade PBD Exterior: 16 mm fire grade plasterboard, vapour permeable membrane, battens and fibre cement panels	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 125			
			3	XLAM CL3 145			
			2	XLAM CL3 150			
4	External wall between balconies		8	XLAM CL3 85	Exterior both sides: 16 mm fire grade plasterboard, vapour permeable membrane, battens and fibre cement panels	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 125			
			3	XLAM CL3 145			
			2	XLAM CL3 150			
5	Apartment bounding Walls -Load bearing FLW 5.6		8	XLAM CL3 85	Exterior both sides: 16 mm fire grade plasterboard, vapour permeable membrane, battens and fibre cement panels	50*	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 125			
			3	XLAM CL3 145			
			2	XLAM CL3 150			
6	Apartment bounding wall – non-load-bearing		8	XLAM CL3 85	16 mm Fire grade plasterboard direct fixed both sides of CLT. 20 mm gap, 70 mm timber frame with 13 mm standard grade plasterboard on stud wall face with 75 glasswool insulation between frames	50*	90/90/90
			7	XLAM CL3 85			
			6	XLAM CL3 85			
			5	XLAM CL3 85			
			4	XLAM CL3 85			
			3	XLAM CL3 85			
			2	XLAM CL3 85			

Acoustic estimates from CSR Red Book

*Acoustic estimate from FWPA CLT Acoustic Research Program

Table 2: Wall Systems Description (Continued)

Colour Code	Wall Location	Illustration	Level	Description	Coverings	Acoustic Rating Rw + Ctr	Fire Rating
7	Internal Apartment Walls - Load bearing FLW 5.3 m		8	XLAM CL3 85	16 mm fire grade plasterboard direct fixed both sides of CLT.	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 125			
			4	XLAM CL3 135			
			3	XLAM CL5 150			
			2	XLAM CL5 150			
8	Internal loadbearing apartment walls FLW 4.4 m		8	XLAM CL3 85	16 mm fire grade plasterboard direct fixed both sides of CLT.	N/A	90/90/90
			7	XLAM CL3 105			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 115			
			3	XLAM CL3 125			
			2	XLAM CL3 135			
9	Internal loadbearing apartment walls FLW 3.9 m		8	XLAM CL3 85	16 mm Fire grade PBD direct fixed both sides of CLT.	N/A	90/90/90
			7	XLAM CL3 85			
			6	XLAM CL3 105			
			5	XLAM CL3 105			
			4	XLAM CL3 115			
			3	XLAM CL3 125			
			2	XLAM CL3 125			
10	Internal loadbearing apartment walls/lift and stair shaft FLW 1.5 m		8	XLAM CL3 85	16 mm Fire grade PBD direct fixed one sides of CLT.	52* When combined with wall 11. Resilient strip placed between CLT to maintain 20 mm gap and discontinuous construction	90/90/90
			7	XLAM CL3 85			
			6	XLAM CL3 85			
			5	XLAM CL3 85			
			4	XLAM CL3 105			
			3	XLAM CL3 105			
			2	XLAM CL3 105			
11	Interior Lift and Stair shaft		All Levels	XLAM CL3 105	16 mm Fire grade PBD direct fixed one sides of CLT when twinned with wall abutting apartment and other service shafts, otherwise 16 mm fire grade pbd both sides	52* When combined with wall 10. Resilient strip placed between CLT to maintain 20 mm gap and discontinuous construction	90/90/90
12	Partition walls		All Levels	Studs and Plates: MGP10 70 x 35 @ 600 crs	10 mm standard grade plasterboard or 6 mm fibre cement (if in wet area)	N/A	N/A
13	Service shaft		All Levels	Steel stud and	25 mm plasterboard shaft liner	N/A	N/A

* Acoustic estimate from FWPA's CLT Acoustic Research Program
# Acoustic estimates from CSR Red Book

5.2.2 Floor Structure

What was used in the timber solution:

- 225 mm thick 5-ply longitudinal-faced CLT panel spanning over three supports with a maximum span of 6 m (Figure 23 and Table 7).
- Beams under CLT panels reinforce areas over openings:
  - Two 240 x 90 LVL13 beams under the floor in opening in wall in Units 3 and 6.

Reasons:

- The CLT panel thickness provides the best spanning capacity and vibration control relative to the other timber options available.
- The layout and CLT panel arrangement minimises waste material and transportation costs.

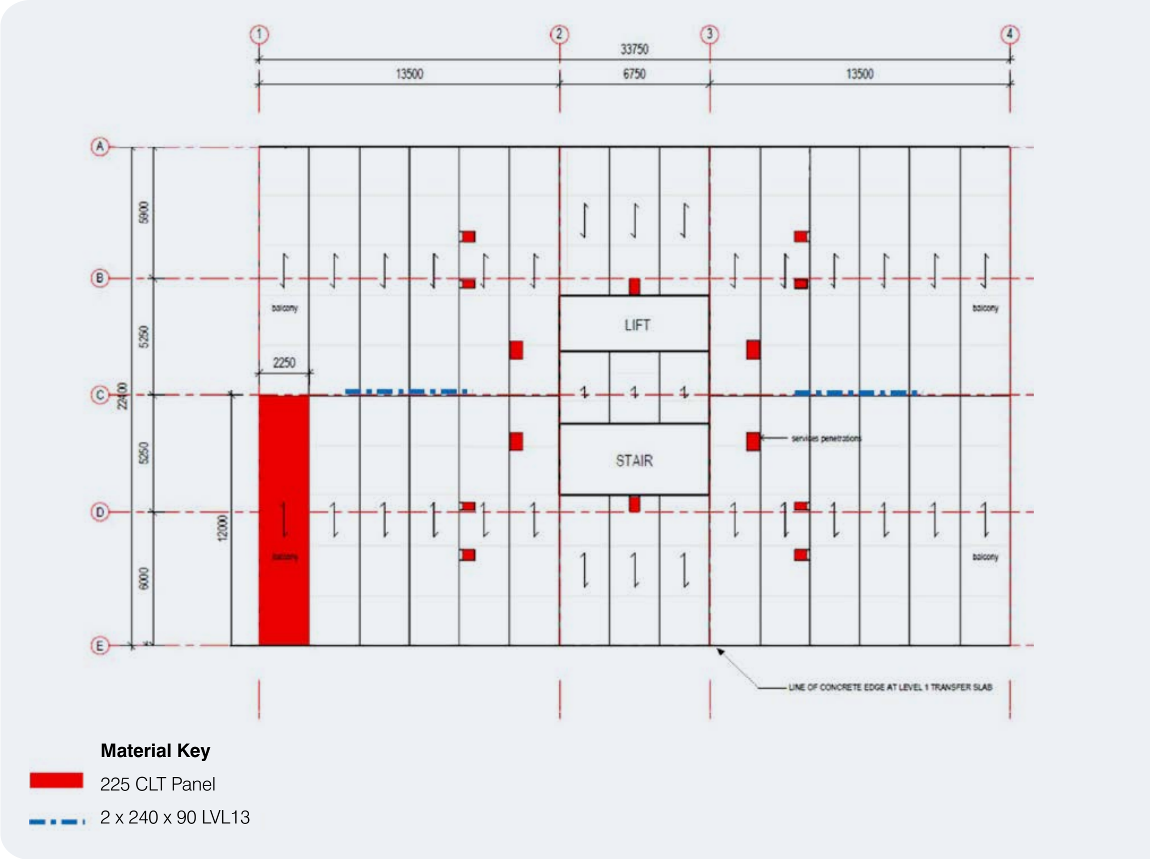


Figure 23: Floor and Roof System Plan Design and image: Studio 505

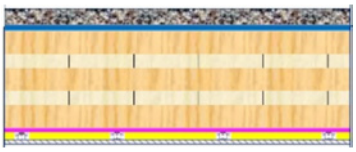
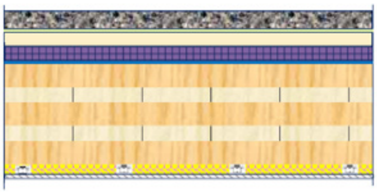
Type	Diagram of Floor System	Description	Acoustic		Fire rating
			Rw + Ctr	Ln,w (Ci)	
Floor		Layer 1 – 40 mm cement screed Layer 2 – 10 mm recycled rubber mat Layer 3 – XLAM CL5 225 Layer 4 – 16 mm fire grade plasterboard Layer 5 – 50 mm insulation (14 kg/m^3) Layer 6 – Adjustable clips Layer 7 – Furring Channel Layer 8 – 13 mm Standard grade plasterboard	51	55	90/90/90
Roof		Layer 1 - Gravel Layer 2 – 40 mm styrofoam Layer 3 – Geotext separation fabric Layer 4 - Drainage cell Layer 5 – Water proof membrane Layer 6 – XLAM CL5 150 Layer 7 – 50 mm insulation(14 kg/m^3) Layer 8 – Adjustable clips Layer 9 – Furring Channel Layer 10 – 10 mm Standard grade plasterboard	N/A	N/A	N/A

Figure 23: Floor and Roof System Plan Design and image: Studio 505

Note: Acoustic results based on Auckland Uni CLT Acoustic test (based on 140 mm thick CLT)

5.2.3 Floor Structure

What was used in the timber solution:

- 150 mm thick 5-ply longitudinal-faced CLT panel spanning over three supports with a maximum span of 6 m (Figure 23 and Table 7).
- Beams under CLT panels reinforce areas over openings:

  - Two 240 x 90 LVL13 beams under the floor in opening in wall in Units 3 and 6.

Reasons:

- Thinner CLT can be used for the roof in comparison to the floor as the roof has no fire rating and no screed applied.
- Falls for drainage can be formed by sloping the top of level 7 walls, removing the need to apply a screed.

5.2.4 Lateral Resistance

- Lateral resistance and over turning of the building is dealt in the use of CLT. CLT is used for all bounding walls to SOUs, lift and stair shaft and provide the lateral resistance requirements of the building.

Reasons:

- CLT in combination with brackets and screws is an excellent median to transfer lateral loads.

6

The Workflow and Speed Onsite of the Timber Solution

What was assumed in terms of planning construction of the model:

- A crew of six site workers were used for the installation of the timber solution (excluding crane driver, dogman, traffic control, site management staff etc.).
- All connection of timber framing and CLT elements used nails, brackets and/or screw fixings.
- The construction program associated with the installation of the core structural elements above the Level 1 transfer slab until completion of the façade only, was considered.
- The installation time for the façade's rain screen, MEP, interior coverings, and so on, was assumed to be similar for both solutions.
- The Cost Plan used a 6 week construction saving for both the timber frame and CLT erection.

Reasons:

- Each solution is identical until the Level 1 transfer slab commences and the model has assumed that they take the same length of time until this point.
- Above the concrete transfer level, the time taken to install the superstructure to roof level for the concrete solution was estimated to take 6 weeks longer than both timber solutions.
- Construction time beyond the installation of the superstructure was assumed to be identical.
- Refer to Section 7.7 for other potential cost savings

7

Cost Plan Results - Comparing the Timber and Concrete Solutions

Using the model apartment building described in Section 4, the timber solutions described in Section 5 and the corresponding concrete solution described in Appendix A, a cost estimate and cost planning comparison was undertaken to help determine the potential benefits of the timber solutions. The cost comparison was only undertaken for the parts of the building that were considered to have different costs. The elements of the building that are identical in costs for each model, such as the façade, and mechanical, electrical and plumbing items, were excluded from the cost plan.

To create stable costing conditions, it was assumed that the building would be constructed in suburban Sydney.

7.1 Process Taken to Obtain Comparison Design and Quotes

From the parameters of the model apartment building discussed in Section 5, three designs were developed: one in the conventional material (concrete in this case) and this was compared to a lightweight timber framing and CLT.

The cost plan was developed by the MBM (see Appendix B for full cost plan results) an independent firm that is developing a data base of successful timber buildings. MBM independently measured quantities off supplied drawings and obtained quotes from the market where needed or utilised current data within their database to develop a price for this model.

An all-inclusive price for the optimisation of design, shop detailing, fabrication, freight and supply considerations (off-site storage, etc), fixtures and fittings and just-in-time delivery to site was made and used in the study.

7.2 Cost Plan Results

The basic differences in the cost plans for each model are shown in Table 6. MBM's detailed results can be found in Appendix B.

Element	Timber Framed	Cross Laminated Timber	Concrete
Columns	34,935.00	34,935.00	365,644.00
Upper Floors	1,567,887.00	2,539,961.00	1,810,398.00
Staircase	81,200.00	81,200.00	66,150.00
Roof	256,260.00	233,100.00	356,617.00
External Walls (excludes rain screen)	335,511.00	518,082.00	416,165.00
Internal Walls	1,417,544.00	1,286,436.00	1,224,522.00
Wall Finishes	Included	Included	Included
Ceiling Finishes	667,390.00	Included	459,085.00
Preliminaries	-287,000.00	-287,000.00	-
Total	**4,073,727.00**	**4,406,714.00**	**4,698,581.00**

Table 6: Cost Plan Results.

In analysing the differences between the plans, it can be seen that the timber building provides a saving of

- Timber Framed: $624,854.00 or 13% cheaper than the concrete solution and $332,987 or 7.5% cheaper than Cross Laminated Timber solution
- Cross Laminated Timber: $291,867.00 or 6% cheaper than the concrete solution

Significant savings under the timber solution are found in:

- the concrete transfer slab at Level 1
- the loadbearing structure including some walls, floors, columns and roof
- the preliminary costs for the project (including crane, site sheds, supervision, scaffolding, and traffic control costs)

Additional costs under the timber solution (relative to the concrete solution) are in:

- the fire protection of the timber elements
- the termite protection of the timber elements

Each is discussed in more detail below.

7.3 Savings in the Concrete Transfer Slab

As the timber solution is lighter in weight (20% of the mass of concrete) than the concrete solution, a thinner and cheaper concrete transfer slab is possible.

- Timber $364,350.00
- Concrete $537,441.00
- Difference -$173,091 (32% cheaper)

7.4 Preliminary Cost Savings

The timber solution includes an estimated saving in preliminaries of approximately $280,000, based on a construction program saving six weeks over the concrete solution. MBM calculate that the traditional 12 month construction program and found it could be reduced to 10 ½ months. Based on a total project prelims cost of $2.5m the approximate cost per week is $52,000.00 per week. This equates to a potential saving of $287,000 when additional costs such as termite protection is removed.

7.5 Additional Costs

There were a number of additional cost considered for the timber framed solution and they were

- Extra costs for the additional linings required for fire protection of timber load bearing walls and floors.
- The timber and CLT solutions sit atop a concrete basement (car park) and concrete retail level. As an additional precaution, the timber and CLT structure has termite protection by way of stainless mesh steel protection to all hidden entry points from the ground to the concrete structure. This protection was estimated to add $25,000 to the timber and CLT solution.

7.6 Other Potential Cost Saving for the Timber Solution

The following items include areas where cost saving potential exists in the timber solution, but for this cost exercise they have not been included.

- **Smarter Scaffold Erection Potential**: The timber structure only requires the use of scaffolding for the installation of the façade panels. The installation of cladding to the timber frame panels, before erecting, could remove the need for scaffold and be replaced with hand rails already attached to floor cassettes. Joints in the cladding could be completed by the use of mobile elevated platform.
- **Earlier start time on internal works**: Additional time savings are possible due to the earlier start time for internal work, as achieved by the earlier completion for the main structure (as discussed previously). Activities such as services rough-ins and internal wet area construction could all begin earlier compared to the concrete solution.
- **Easier substrate for linings and finishes:** The time to carry out fit-out activities is generally less than for concrete structures. For instance, cordless screw guns and nailing can be used, which is light, quick and easy to use. Concrete structures require drilling into concrete, which is slow, noisy and dirty, and requires anchor or friction-style fixings.
- **Footing Costs**: The timber solution is calculated to be 50% lighter than the concrete solution which potentially provides lighter and cheaper footings.
- **Crane size and type:** Crane savings discussed previously focus on the reduced hire period required for the timber solution, but there is also potential to use a lighter, remotely controlled crane (i.e. operated from the floor deck under construction). For instance, the timber solution's maximum panel weight is only 2,500 kg.
- **Truck Deliveries**: Deliveries for the timber solution are significantly reduced, saving supervision, handling at the road level and traffic management. Just-in-time delivery of timber can avoid panel storage on site.

8

Conclusion

A model eight-storey, high-end 42-apartment building was designed and costed using two timber solutions and a conventional concrete-framed solution for a theoretical location in suburban Sydney. The site was assumed to have no significant cost implications concerning site access, ground conditions or neighbouring properties.

The timber solutions investigated were cross laminated timber and lightweight timber frame. This review was previous carried out in 2014 for cross laminated timber only. Since this time the CLT apartment has been redesigned to meet all aspects of the new NCC's Deemed-to-Satisfy fire protected timber requirements. Furthermore the design was change to sizes and spans that suit Australian produced CLT as well as including missing items from the first study being cement screed to floors and stairs. In addition a lightweight timber framed design was also considered.

The study found the superstructure costs for the timber framed solution to be $624,854.00, more cost effective, which equates to a 13% saving compared to the concrete solution. The Cross Laminated Timber solution was also found to be $291,867 or 6% cheaper. The main structural component costs were found to be lower in the timber model, but the fire protection requirements to some of these elements and the cost of termite protection offset some of this advantage.

Savings also existed in the preliminary costs for the project, an area not fully recognised when comparing costs.

This Guide recommends that timber apartment building be considered as a viable alternative to traditional post tensioned concrete frame construction, particularly where:

- a lightweight structure provides structural benefits (including in poor foundations)
- prefabricated construction offers advantages
- the timber solution can be optimised for a given design
- the need for a short construction program is apparent
- there is a genuine intent to reduce preliminary costs

Importantly, the level of cost comparison with concrete must go beyond a basic comparison of material costs and should instead weigh up a holistic spectrum of cost-sensitive issues affecting the construction process.

Appendix A: Comparison Design: The Concrete Solution

A1 Floor and Roof

Generally, a 200 mm flat plate concrete slab reinforced using conventional steel reinforcement and post tensioning cables, refer to Figures A1 and A2 on reinforced concrete columns.

Table A1 details the acoustic performance.

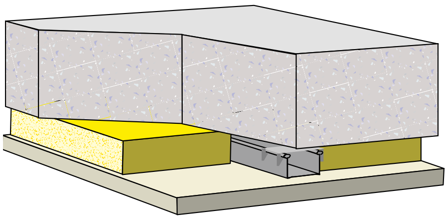
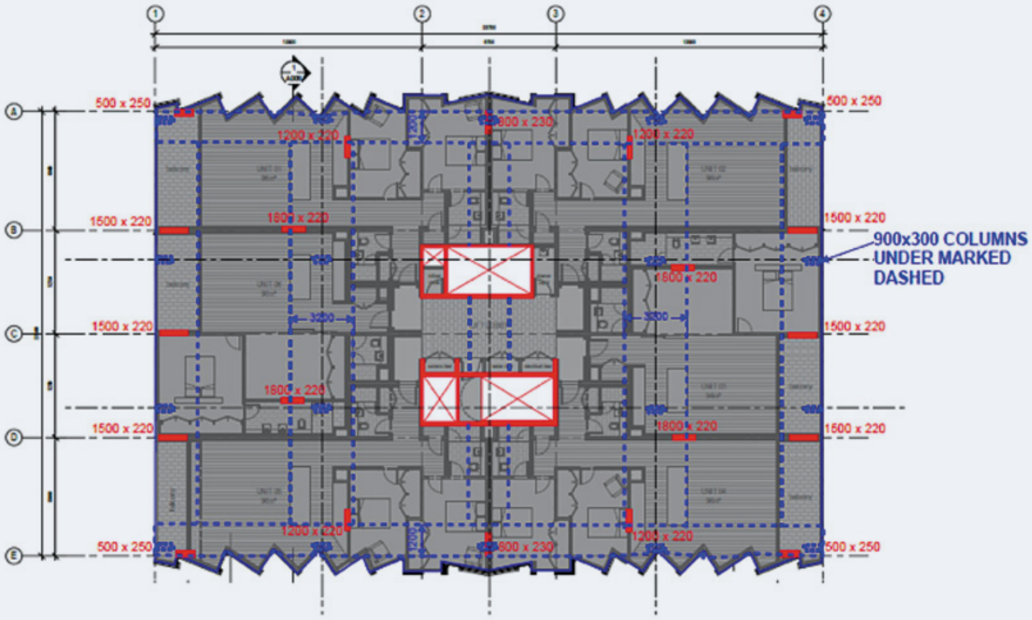
Type	Diagram of Floor System	Description	Acoustic		Fire rating
			Rw + Ctr	Ln,w (Ci)	
Floor		200 mm concrete slab, with furring channel at 600 crs, supporting 10 mm plasterboard. 50 mm polyester insulation is placed between furring channel	53[9]	35 to 40 with carpet and underlay	90/90/90

Table A1: Acoustic and fire performance of concrete floor.



LEVEL 1

Notes:
1. Slab to be 170mm thick U.N.O
2. Band beams to be 650mm deep U.N.O
3. Band beams to be 2100mm wide U.N.O
2. Slab:
   - PT rate = 4.2 kg/m²
   - Reinforcement rate = 35 kg/m³
3. Band Beam:
   - PT rate = 10.5 kg/m²
   - Reinforcement rate = 50 kg/m³
3. All concrete f_c = 40 Mpa
4. Column sizes denoted on plan with a reinforcement rate of 240 kg/m³
5. Core walls to be 200mm (W) with a reinforcement rate of 140 kg/m³

Figure A1: Level 1 concrete slab. *Design and image: TTW*

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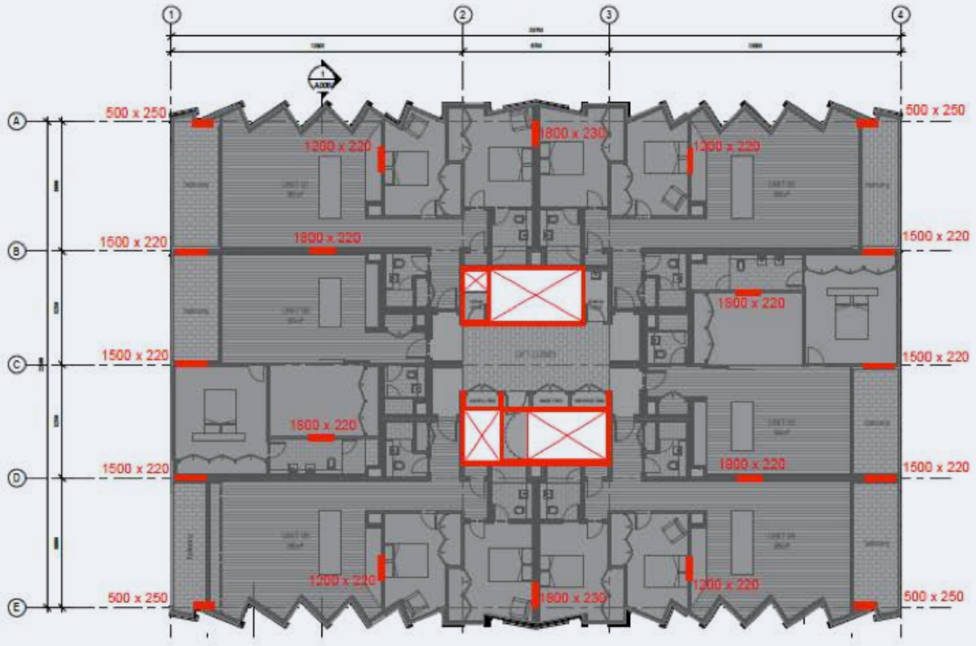
[9] Boral Plasterboard System CFA10U



LEVEL 7

Notes:
1. Slab to be 200mm thick U.N.O
2. Slab:
   - PT rate = 4.2 kg/m²
   - Reinforcement rate = 35 kg/m³
3. All concrete f_c = 40 Mpa
4. Column sizes denoted on plan with a reinforcement rate of 240 kg/m³
5. Core walls to be 200mm (W) with a reinforcement rate of 140 kg/m³

Figure A2: Level 2 to 7 and roof concrete slab. *Design and image: TTW*

A2 Wall Systems

What was used in the timber solution:

- An aerated concrete wall system with metal studs, refer to Table A2.

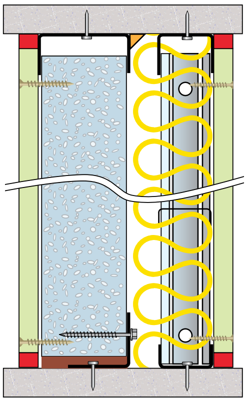
Wall Type	Diagram of Wall System	Description		Acoustic Rw + Ctr	Fire rating
		Structural	**Linings & Insulation**		
Internal		75 mm aerated lightweight concrete panel, with 64 mm steel stud with 20 mm air gap between aerated concrete and steel stud	13 mm fire-resisting plasterboard linings both side of wall (moisture-resistant used in wet areas). 75 mm glass wool in air gap	53[10]	90/90/90

Table A2: Acoustic and fire performance of concrete solution walls.

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[10] High Rise Multi-Residential Intertenancy and Service Walls Design and Installation Guide, Hebel, 2014

APPENDIX B

ESTIMATE REPORT

Costs for Timber Framed, CLT and Concrete Construction in Low Rise Residential

For Timber Development Association

MBM1545-0002 – 5 October 2017

Prepared by – Kelvin Perrie

QUANTITY SURVEYING | BUILDING CONSULTANCY |
TAX & ASSET SERVICES | PPP ADVISORY | INFRASTRUCTURE |
FACILITIES MANAGEMENT ADVISORY | EXPERT WITNESS

mbm

1. Executive Summary

MBM have been engaged by TDA to update the cost estimates previously prepared for the TDA for Timber Framed (LVL), CLT and concrete construction for a residential apartment building.

We have updated the costs based on recent market feedback as well as supplier information where relevant. The result of these updates is an increase across all 3 methodologies, although the bottom line is lower than the previously issued estimates due to the exclusion of the facade as this is deemed to be typical across all construction methodologies. The cost increases in the remaining trades are due in large to an overall increase in cost across the construction market with a greater impact on the concrete constructed option.

These cost estimates only consider the components of the building that were deemed to have different costs. The elements of the building that were considered common for each model, such as the façade, the basement and the services costs are excluded from the estimates.

Whilst we appreciate that this approach is not 100% accurate, it was acknowledged by all involved in this report (design and costing) that for the purposes of this exercise - and given the early level of design documentation available - the potential cost differences were negligible enough to the extent that they had no material effect on the results. Hence their exclusion.

To create stable costing conditions, it was assumed that the building would be constructed in suburban Sydney.

Please refer to Appendix A and Appendix B for detailed cost estimates.

1.1 Estimate Summaries

The below table summarises the ***current*** cost estimate for the timber framed option and the concrete constructed option:

Description	TIMBER FRAMED	CROSS LAMINATED TIMBER (CLT)	CONCRETE
Columns	$ 34,935.00	$ 34,935.00	$ 365,644.00
Upper Floors	$ 1,567,887.00	$ 2,539,961.00	$ 1,810,398.00
Staircases	$ 81,200.00	$ 81,200.00	$ 66,150.00
Roof	$ 256,260.00	$ 233,100.00	$ 356,617.00
External Walls	$ 335,511.00	$ 518,082.00	$ 416,165.00
Internal Walls	$ 1,417,544.00	$ 1,286,436.00	$ 1,224,522.00
Wall Finishes	Included	Included	Included
Ceiling Finishes	$ 667,390.00	Included	$ 459,085.00
Preliminaries Adjustment	-$ 287,000.00	-$ 287,000.00	$ -
Total Estimate Cost	**$ 4,073,727.00**	**$ 4,406,714.00**	**$ 4,698,581.00**

The below table summarises the ***previous*** cost estimate (by others) for the timber framed option and the concrete constructed option:

Description	TIMBER FRAMED	CROSS LAMINATED TIMBER (CLT)	CONCRETE
Columns	$ 33,150.00	$ 33,150.00	$ 337,373.00
Upper Floors	$ 1,405,872.00	$ 1,470,378.00	$ 1,517,633.00
Staircases	Excluded	Excluded	Excluded
Roof	$ 256,260.00	$ 290,138.00	$ 329,603.00
External Walls	$ 1,047,822.00	$ 1,086,240.00	$ 1,135,070.00
Internal Walls	$ 1,432,204.00	$ 690,438.00	$ 1,193,057.00
Wall Finishes	Included	$ 866,068.00	Included
Ceiling Finishes	$ 597,955.00	$ 597,955.00	$ 459,085.00
Preliminaries Adjustment	-$ 287,000.00	-$ 287,000.00	$ -
Total Cost	**$ 4,486,263.00**	**$ 4,747,367.00**	**$ 4,971,821.00**

The most notable increase to both estimates is the inclusion of the Staircases. “Airstair” is a timber product which has been included at advised rates with the preliminaries adjusted accordingly to account for the reduced programme using the “Airstair” when compared with concrete fire stair construction.

The concrete construction estimate has risen largely due to increases seen recently in the construction market, particularly regarding formwork.

1.2 Estimate Analysis

In analysing the differences between the three cost estimates, it can be seen that the Timber Framed and CLT methodologies provide a saving of $624,854 and $291,867 or 15% and 6% respectively when compared to the Concrete estimate.

Significant savings under the timber solutions (the same principles apply to both) are found in:

- the concrete transfer slab at Level 1
- the loadbearing structure including walls, floors, columns and roof
- the preliminary costs for the project (including crane, site sheds, supervision, scaffolding, and traffic control costs)

Despite the savings it is acknowledged that the timber solution does carry some negative price adjustments (relative to the concrete solution) in:

- the fire protection of the CLT elements
- the termite protection of the timber elements

2 Added Cost Benefits

2.1 Australian Sourced Timber

Australia's first cross laminated timber manufacturing plant will be built this year with many more to follow to meet the increasing demand of timber construction. These facilities will ensure builders will be able to choose and utilise CLT products that have been designed and sustainably produced in Australia from Australian Timber. Locally sourced CLT will have vast cost benefits in terms of reducing time and transport costs and furthermore, encourage the support of local manufacturers and labour forces which will subsequently benefit the Australian economy. Developing Australian sourced CLT will boost Australia's competitiveness internationally in terms innovative design and manufacturing. This will also be incredibly beneficial in recognising and improving the green performance of Australian construction, with these systems rewarding the use of locally produced materials in building designs.

2.2 Life Cycle Cost Analysis

The reduced life cycle costs of CLT are evident from studies that have been carried out overseas (i.e. for projects completed outside of Australia.) Data on Australian projects is sparse at this stage but nonetheless supporting the same message from international studies. CLT outperforms concrete systems in terms of thermal insulation, internal moisture management, acoustic insulation, air tightness and fire resistance. Due to the performance capabilities of CLT, the energy efficiency of the building increases, with the embodied energy within ensuring reduced operational costs. The durability and robust nature of CLT also ensures that there are fewer maintenance and operation requirements throughout the life cycle of the building. CLT can additionally be recycled ensuring zero waste in the production process and therefore minimal disposal costs. Exemplifying the overall reduced life cycle costs.

MBM are currently in the process of compiling local studies on life cycle cost and these will be presented in next years' report.

2.3 Marketing and Sales Information

Demand for CLT has increased year on year over the last 5 – 7 years. This increase shows no signs of slowing down. The increase is not only due to the cost and time savings which timber offers but more interestingly the demand is a result of the public (and industry) shift towards a more sustainable and environmentally conscious market that acknowledge the environmental, economic and social benefits within timber design and construction.

This growth is paramount in Australia, with the demand for affordable and innovative designs evident and witnessed via the rapid occupancy and sales of recently developed CLT projects.

CLT satisfies not only the sophisticated, innovative and practical needs of homebuyers but also the ideology of contemporary marketing and sales teams.

2.4 Conclusion

The LVL and CLT options were found to be more cost effective - not only in MBM's opinion but also by the begrudging agreement of contractors.

The current savings achieved with the use of timber are arguably at a higher point than can typically be expected given the significant increase in concrete construction across the construction industry, even so, it is MBMs opinion that as the industry accepts the timber methodology as a viable alternative to concrete and steel, this saving is likely to increase.

Put simply, the benefits of timber in terms of simplicity of design engineering, the speed of construction and the potential workmanship quality, translate to tangible cost savings as well as a host of other - more social, environmental and societal - gains.

The facts are unarguable. Timber is a viable and necessary alternative to concrete construction.

3 Appendices

3.1 Appendix A: Timber Framed (LVL) Estimate

03. Timber Framing - Cost Plan Rev 2 - 171011

mbm

Timber Framed Construction

Project Number: 0001	Reviewed By: Richard Smith	Prepared By: Kelvin Perrie
Document Title	Issued To:	Issue Date:
Residential - Timber Framed (LVL) - Estimate Update	TDA	5th October 2017

03. Timber Framing - Cost Plan Rev 2 - 171011

SUMMARY		$
Timber Framing		4,073,727
	PROJECT TOTAL (Excl GST)	4,073,727

Notes:

MBM
Client: Timber Development Association
Project Code: 0001
Printing Date: 11/10/2017
Report Name: 03. Timber Framing - Cost Plan Rev 2 - 171011

DETAILED SUMMARY

Client: Timber Development Association
Project: Timber Framed Construction

Details: 03. Timber Framing - Cost Plan Rev 2 - 171011
MBM0001
Date - 11/10/2017

Code	Description	Starting Page	% of Cost	Cost/m2	Total
1	**Timber Framing**				
1.1	Columns	Page 4	0.86		34,935
1.2	Upper Floors	Page 4	38.49		1,567,887
1.3	Staircases	Page 4	1.99		81,200
1.4	Roof	Page 4	6.29		256,260
1.5	External Walls	Page 4	8.24		335,511
1.6	Internal Walls	Page 5	34.80		1,417,544
1.7	Wall Finishes				Included
1.8	Ceiling Finishes	Page 7	16.38		667,390
1.9	Preliminaries Adjustment	Page 7	-7.05		-287,000
					4,073,727

Code	Description	Quantity	Unit	Rate	Amount
1	**Timber Framing**				
1.1	**Columns**				
1.1.1	900 x 300 RC columns incl. 40MPa concrete, formwork, reinforcement at 240kg/m3 and post-tensioning at 6kg/m2; 18no.	51	m	685.00	34,935
					34,935
1.2	**Upper Floors**				
1.2.1	RC suspended slab, 500 thick incl. 40MPa concrete, formwork, reinforcement at 45kg/m3 and post-tensioning at 6kg/m2; 18no.	772	m2	435.00	335,820
1.2.2	RC drop slab to underside of transfer slab, 1800 x 1800 x 650 thick, incl. 40MPa concrete, formwork, reinforcement at 45kg/m3	18	no.	1,585.00	28,530
1.2.3	Truss Cassettes				
1.2.4	Total floor area - 6 Levels	4,629	m2	180.00	833,220
1.2.5	40mm unreinforced topping slab incl. 10mm resilient matting to all floor areas - 6 levels	4,629	m2	80.00	370,317
					1,567,887
1.3	**Staircases**				
1.3.1	Stairs 'AirStair' - supply cost - 1 x 7 levels	7	level	6,500.00	45,500
1.3.2	Installation	21	m/rise	1,250.00	26,250
1.3.3	Extra over above for fixings and handrails	21	m/rise	450.00	9,450
					81,200
1.4	**Roof**				
1.4.1	Truss Cassettes				
1.4.2	As per lower levels	772	m2	145.00	111,940
1.4.3	50mm thick cement and sand mortar bedding laid to falls and finished tc receive waterproofing	772	m2	55.00	42,460
1.4.4	Approved roof waterproofing membrane applied to concrete roof slab above screed	772	m2	50.00	38,600
1.4.5	Drainage cell laid above the waterproofing	772	m2	25.00	19,300
1.4.6	Dow Wrapshield HP geotextile separation fabric laid above drainage cell below insulation	772	m2	5.00	3,860
1.4.7	40mm thick R2.0, Dow Styrofoam RTM-X closed cell insulation laid above drainage cell	772	m2	45.00	34,740
1.4.8	Dow Wrapshield HP geotextile separation fabric laid above insulation below concrete paving	772	m2	5.00	3,860
1.4.9	Allow for dressing around drainage outlet including forming cut out in drainage cell, Insulation system, making good and the like; 200mm dia	1	item	1,500.00	1,500
					256,260
1.5	**External Walls**				
1.5.1	Level 1				
1.5.2	With insulation, internal lining and associated items, 130mm thick stud	80	Lm	630.00	50,507
1.5.3	Level 2				
1.5.4	With insulation, internal lining and associated items, 130mm thick stud	80	Lm	630.00	50,507
1.5.5	Level 3				
1.5.6	With insulation, internal lining and associated items, 130mm thick stud	80	Lm	630.00	50,507
1.5.7	Level 4				
1.5.8	With insulation, internal lining and associated items, 130mm thick stud	80	Lm	630.00	50,507

Code	Description	Quantity	Unit	Rate	Amount
1.5	**External Walls**				
1.5.9	Level 5				
1.5.10	With insulation, internal lining and associated items, 90mm thick stud	80	Lm	555.00	44,494
1.5.11	Level 6				
1.5.12	With insulation, internal lining and associated items, 90mm thick stud	80	Lm	555.00	44,494
1.5.13	Level 7				
1.5.14	With insulation, internal lining and associated items, 90mm thick stud	80	Lm	555.00	44,494
					335,511
1.6	**Internal Walls**				
1.6.1	*Wall thicknesses reduce as the loading reduces at higher levels*		Note		
1.6.2	CLT				
1.6.3	CL5, 125mm	644	m2	265.00	170,660
1.6.4	Bracing				
1.6.5	*Bracing is generally included in wall rates*	NOTE			
1.6.6	Allowance for moment framing - generally above openings - 400mm high, LVL	183	Lm	90.00	16,470
1.6.7	Level 1				
1.6.8	Single stud, load-bearing, fire rated, LVL 130 x 35 @ 450cts	9	Lm	610.00	5,765
1.6.9	Double stud, load-bearing, fire rated, 3 x 90mm x 45mm studs @ 600 cts	49	Lm	1,010.00	49,046
1.6.10	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.11	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 450 cts	15	Lm	640.00	9,914
1.6.12	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 600 cts	15	Lm	610.00	9,242
1.6.13	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.14	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.15	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.16	Level 2				
1.6.17	Single stud, load-bearing, fire rated, LVL 130 x 35 @ 450cts	9	Lm	610.00	5,765
1.6.18	Double stud, load-bearing, fire rated, 2 x 90mm x 45mm studs @ 600 cts	49	Lm	830.00	40,305
1.6.19	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.20	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 450 cts	15	Lm	640.00	9,914
1.6.21	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 600 cts	15	Lm	610.00	9,242
1.6.22	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.23	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.24	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.25	Level 3				
1.6.26	Single stud, load-bearing, fire rated, LVL 130 x 35 @ 450cts	9	Lm	610.00	5,765
1.6.27	Double stud, load-bearing, fire rated, 2 x 90mm x 45mm studs @ 600 cts	49	Lm	830.00	40,305
1.6.28	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.29	Single stud, load-bearing, fire rated, 130mm x 35mm @ 450 cts	15	Lm	640.00	9,914
1.6.30	Single stud, load-bearing, fire rated, 130mm x 35mm @ 600 cts	15	Lm	610.00	9,242

Code	Description	Quantity	Unit	Rate	Amount
1.6	**Internal Walls**				
1.6.31	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.32	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.33	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.34	Level 4				
1.6.35	Single stud, load-bearing, fire rated, LVL 120 x 35 @ 450cts	9	Lm	570.00	5,387
1.6.36	Double stud, load-bearing, fire rated, 2 x 90mm x 45mm studs @ 600 cts	49	Lm	830.00	40,305
1.6.37	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.38	Single stud, load-bearing, fire rated, LVL 120mm x 45mm @ 450 cts	15	Lm	570.00	8,829
1.6.39	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 600 cts	15	Lm	610.00	9,242
1.6.40	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.41	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.42	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.43	Level 5				
1.6.44	Single stud, load-bearing, fire rated, LVL 120 x 35 @ 450cts	9	Lm	568.00	5,368
1.6.45	Double stud, load-bearing, fire rated, 90mm x 45mm studs @ 600 cts	49	Lm	690.00	33,506
1.6.46	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.47	Single stud, load-bearing, fire rated, LVL 120mm x 35mm @ 450 cts	15	Lm	568.00	8,798
1.6.48	Single stud, load-bearing, fire rated, LVL 130mm x 35mm @ 600 cts	15	Lm	610.00	9,242
1.6.49	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.50	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.51	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.52	Level 6				
1.6.53	Single stud, load-bearing, fire rated, LVL 90 x 45 @ 450cts	9	Lm	560.00	5,292
1.6.54	Double stud, load-bearing, fire rated, 90mm x 45mm studs @ 600 cts	49	Lm	690.00	33,506
1.6.55	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.56	Single stud, load-bearing, fire rated, 90mm x 45mm @ 450 cts	15	Lm	560.00	8,674
1.6.57	Single stud, load-bearing, fire rated, 120mm x 45mm @ 600 cts	15	Lm	595.00	9,014
1.6.58	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.59	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410
1.6.60	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
1.6.61	Level 7				
1.6.62	Single stud, load-bearing, fire rated, LVL 70 x 35 @ 450cts	9	Lm	540.00	5,103
1.6.63	Double stud, load-bearing, fire rated, 90mm x 45mm studs @ 600 cts	49	Lm	690.00	33,506
1.6.64	Single stud, non-load-bearing, fire rated wall, 70mm x 45mm @ 600 cts	25	Lm	590.00	14,768
1.6.65	Single stud, load-bearing, fire rated, 70mm x 45mm @ 450 cts	15	Lm	540.00	8,365
1.6.66	Single stud, load-bearing, fire rated, 90mm x 45mm @ 600 cts	15	Lm	560.00	8,484
1.6.67	Double stud, non-load-bearing wall, 2 x 70mm x 45mm @ 600 cts	41	Lm	770.00	31,778
1.6.68	Service shaft, fire rated, 102mm metal frame	32	Lm	600.00	19,410

Code	Description	Quantity	Unit	Rate	Amount
1.6	**Internal Walls**				
1.6.69	Single stud, non-load-bearing (assumed non-fire rated), 70mm x 35mm @ 600 cts	120	Lm	395.00	47,384
					1,417,544
1.8	**Ceiling Finishes**				
1.8.1	Standard suspended ceiling grid, 15mm drop; 10mm PB to and including top hat channels; 50mm insulation to underside of roof only	772	m2	85.00	65,620
1.8.2	2x16mm FRPB on resilient mount ceiling and furring channel incl. 75mm (14kg/m3) insulation to other levels	4,629	m2	130.00	601,770
					667,390
1.9	**Preliminaries Adjustment**				
1.9.1	Provision of time related preliminaries based on the duration of structure construction time.		NOTE		0
1.9.2	Preliminaries based on reduced construction duration of:	6	weeks	-52,000.00	-312,000
1.9.3	Termite Protection Allowance	1	item	25,000.00	25,000
					-287,000

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This report is qualified in its entirety by and should be considered in the light of the agreed terms of engagement and the following:

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In no event, regardless of whether MBM's consent has been provided, shall MBM assume any liability or responsibility to any third party to whom this report is disclosed or otherwise made available.

Without the prior written consent of MBM, this report is not to be used in conjunction with any public or private offering of securities or other similar purpose where it might be relied upon to any degree by any person other than the Addressee.

MBM has used its reasonable endeavour so that the data contained in this report reflects the most accurate and timely information available and is based on information that was current as of the date of this report.

The preparation of this report has relied on information provided by the Addressee and by third parties. MBM has not verified this information and we assume no responsibility and make no representations with respect to adequacy, accuracy or completeness of such information.

This report is based on estimates, assumptions and other information developed by MBM from our independent research, intelligence, general knowledge of the industry and consultations with the addressee, addressee employee and representatives.

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3.2 Appendix B: CLT Estimate

Cross Laminated Timber

Project Number: 0001	Reviewed By: Richard Smith	Prepared By: Kelvin Perrie
Document Title	Issued To:	Issue Date:
Residential - CLT - Estimate Update	TDA	5th October 2017

01. CLT - Cost Plan Rev 2 - 170915

SUMMARY		$
CLT		4,406,714
	PROJECT TOTAL (Excl GST)	**4,406,714**

Notes:

DETAILED SUMMARY

Client: Timber Development Association
Project: Cross Laminated Timber

Details: 01. CLT - Cost Plan Rev 2 - 170915
MBM0001
Date - 5/10/2017

Code	Description	Starting Page	% of Cost	Cost/m2	Total
1	**CLT**				
1.1	Columns	Page 4	0.79		34,935
1.2	Upper Floors	Page 4	57.64		2,539,961
1.3	Staircases	Page 4	1.84		81,200
1.4	Roof	Page 4	5.29		233,100
1.5	External Walls	Page 4	11.76		518,082
1.6	Internal Walls	Page 5	29.19		1,286,436
1.7	Wall Finishes				Included
1.8	Ceiling Finishes				Included
1.9	Preliminaries Adjustment	Page 5	-6.51		-287,000
					4,406,714

Code	Description	Quantity	Unit	Rate	Amount
1	**CLT**				
1.1	**Columns**				
1.1.1	900 x 300 RC columns incl. 40MPa concrete, formwork, reinforcement at 240kg/m3 and post-tensioning at 6kg/m2; 18no.	51	m	685.00	34,935
					34,935
1.2	**Upper Floors**				
1.2.1	RC suspended slab, 500 thick incl. 40MPa concrete, formwork, reinforcement at 45kg/m3 and post-tensioning at 6kg/m2; 18no.	772	m2	435.00	335,820
1.2.2	RC drop slab to underside of transfer slab, 1800 x 1800 x 650 thick, incl. 40MPa concrete, formwork, reinforcement at 45kg/m3	18	no.	1,585.00	28,530
1.2.3	CLT floor - 40mm cement, 10mm recylced rubber mat, 225mm thick CLT, 16mm FRPB, adjustable clips and furring channel with 50mm glasswool insulation and 13mm FRPB	4,629	m2	470.00	2,175,611
					2,539,961
1.3	**Staircases**				
1.3.1	Stairs 'AirStair' - supply cost - 1 x 7 levels	7	level	6,500.00	45,500
1.3.2	Installation	21	m/rise	1,250.00	26,250
1.3.3	Extra over above for fixings and handrails	21	m/rise	450.00	9,450
					81,200
1.4	**Roof**				
1.4.1	CLT				
1.4.2	As per lower levels	772	m2	115.00	88,780
1.4.3	CLT roof – 150 mm thick with adjustable clips and furring channel and 10mm plasterboard ceiling	772	m2	55.00	42,460
1.4.4	Approved roof waterproofing membrane applied to CLT roof slab	772	m2	50.00	38,600
1.4.5	Drainage cell laid above the waterproofing	772	m2	25.00	19,300
1.4.6	Dow Wrapshield HP geotextile separation fabric laid above drainage cell below insulation	772	m2	5.00	3,860
1.4.7	40mm thick R2.0, Dow Styrofoam RTM-X closed cell insulation laid above drainage cell	772	m2	45.00	34,740
1.4.8	Dow Wrapshield HP geotextile separation fabric laid above insulation	772	m2	5.00	3,860
1.4.9	Allow for dressing around drainage outlet including forming cut out in drainage cell, Insulation system, making good and the like; 200mm dia	1	item	1,500.00	1,500
					233,100
1.5	**External Walls**				
1.5.1	*The below rates include for the CLT supplied and fixed, internal and external fire resistant linings, waterproofing and other minor associated items*		Note		
1.5.2	External - East & West FLW 5.25 - CL5 135mm	14	m2	360.00	5,040
1.5.3	External - East & West FLW 5.25 - CL3 135mm	14	m2	321.00	4,494
1.5.4	External - East & West FLW 5.25 - CL3 125mm	14	m2	311.00	4,354
1.5.5	External - East & West FLW 5.25 - CL3 105mm	42	m2	336.00	14,112
1.5.6	External - East & West FLW 5.25 - CL3 85mm	14	m2	260.00	3,640
1.5.7	External - North & South FLW 3.0m - CL3 125mm	207	m2	311.00	64,378
1.5.8	External - North & South FLW 3.0m - CL3 105mm	1,237	m2	295.00	364,909
1.5.9	External Wall Balcony FLW 5.625m - CL5 135mm	27	m2	360.00	9,720

Code	Description	Quantity	Unit	Rate	Amount
1.5	**External Walls**				
1.5.10	External Wall Balcony FLW 5.625m - CL5 145mm	27	m2	352.00	9,504
1.5.11	External Wall Balcony FLW 5.625m - CL3 125mm	27	m2	311.00	8,397
1.5.12	External Wall Balcony FLW 5.625m - CL3 105mm	79	m2	285.00	22,515
1.5.13	External Wall Balcony FLW 5.625m - CL3 85mm	27	m2	260.00	7,020
					518,082
1.6	**Internal Walls**				
1.6.1	Wall height is 2844mm as advised		Note		
1.6.2	Internal Apartment bounding Walls - Load Bearing FLW 5.625m - CL3 150mm	105	m2	410.00	43,050
1.6.3	Internal Apartment bounding Walls - Load Bearing FLW 5.625m - CL3 145mm	105	m2	402.00	42,210
1.6.4	Internal Apartment bounding Walls - Load Bearing FLW 5.625m - CL3 125mm	105	m2	361.00	37,905
1.6.5	Internal Apartment bounding Walls - Load Bearing FLW 5.625m - CL3 105mm	313	m2	335.00	104,853
1.6.6	Internal Apartment bounding Walls - Load Bearing FLW 5.625m - CL3 85mm	105	m2	310.00	32,550
1.6.7	Internal Apartment bounding Walls - non-load bearing - CL3 85mm	660	m2	310.00	204,600
1.6.8	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 150mm	27	m2	255.00	6,885
1.6.9	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 150mm	27	m2	216.00	5,832
1.6.10	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 135mm	27	m2	206.00	5,562
1.6.11	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 125mm	27	m2	191.00	5,157
1.6.12	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 105mm	54	m2	181.00	9,774
1.6.13	Internal Apartment Walls - Load Bearing FLW 5.25m - CL3 85mm	27	m2	155.00	4,185
1.6.14	Internal Apartment Walls FLW 4.4m - CL3 135mm	45	m2	255.00	11,475
1.6.15	Internal Apartment Walls FLW 4.4m - CL3 125mm	45	m2	216.00	9,720
1.6.16	Internal Apartment Walls FLW 4.4m - CL3 115mm	45	m2	191.00	8,595
1.6.17	Internal Apartment Walls FLW 4.4m - CL3 105mm	135	m2	181.00	24,434
1.6.18	Internal Apartment Walls FLW 4.4m - CL3 85mm	45	m2	155.00	6,975
1.6.19	Internal Apartment Walls FLW 3.9m - CL3 125mm	77	m2	216.00	16,632
1.6.20	Internal Apartment Walls FLW 3.9m - CL3 125mm	77	m2	206.00	15,862
1.6.21	Internal Apartment Walls FLW 3.9m - CL3 115mm	77	m2	191.00	14,707
1.6.22	Internal Apartment Walls FLW 3.9m - CL3 105mm	154	m2	181.00	27,873
1.6.23	Internal Apartment Walls FLW 3.9m - CL3 85mm	154	m2	155.00	23,870
1.6.24	Internal Apartment Walls / Lift Shaft and Stair Shaft FLW 1.5m - CL3 105mm	242	m2	163.00	39,447
1.6.25	Internal Apartment Walls / Lift Shaft and Stair Shaft FLW 1.5m - CL3 85mm	322	m2	138.00	44,436
1.6.26	Interior Lift and Stair Shaft - CL3 105mm	698	m2	206.00	143,791
1.6.27	Internal Partition Walls	2,313	m2	125.00	289,125
1.6.28	Service Shaft	578	m2	185.00	106,930
					1,286,436
1.9	**Preliminaries Adjustment**				
1.9.1	Provision of time related preliminaries based on the duration of structure construction time.		NOTE		

Code	Description	Quantity	Unit	Rate	Amount
1.9	**Preliminaries Adjustment**				
1.9.2	Preliminaries based on reduced construction duration of:	6	weeks	-52,000.00	-312,000
1.9.3	Termite Protection Allowance	1	item	25,000.00	25,000
					-287,000

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3.3 Appendix C: Concrete Construction Estimate

02. Concrete Construction - Rev 2 - 170915

Concrete Construction

Project Number: 0001	Reviewed By: Richard Smith	Prepared By: Kelvin Perrie
Document Title	Issued To:	Issue Date:
Residential - Conventional (Concrete) - Estimate Update	TDA	5th October 2017

02. Concrete Construction - Rev 2 - 170915

SUMMARY		$
Concrete (Conventional)		4,698,582
	PROJECT TOTAL (Excl GST)	**4,698,582**

Notes:

DETAILED SUMMARY

Client: Timber Development Association
Project: Concrete Construction

Details: 02. Concrete Construction - Rev 2 - 170915
MBM0001
Date - 5/10/2017

Code	Description	Starting Page	% of Cost	Cost/m2	Total
1	**Concrete (Conventional)**				
1.1	Columns	Page 4	7.78		365,644
1.2	Upper Floors	Page 4	38.53		1,810,398
1.3	Staircases	Page 4	1.41		66,150
1.4	Roof	Page 4	7.59		356,617
1.5	External Walls	Page 4	8.86		416,165
1.6	Internal Walls	Page 5	26.06		1,224,522
1.7	Wall Finishes				Included
1.8	Ceiling Finishes	Page 5	9.77		459,085
					4,698,582

Code	Description	Quantity	Unit	Rate	Amount
1	**Concrete (Conventional)**				
1.1	**Columns**				
1.1.1	RC columns 500 x 250 incl. 40MPa concrete, formwork, reinforcement at 240kg/m3; 28no.	82	m	410.00	33,620
1.1.2	RC columns 1500 x 220 incl. 40MPa concrete, formwrok, reinforcement at 240kg/m3; 42no.	123	m	870.00	107,009
1.1.3	RC columns 1200 x 220 incl. 40MPa concrete, formwork, reinforcement at 240kg/m3; 28no.	82	m	725.00	59,450
1.1.4	RC columns 1800 x 220 incl. 40MPa concrete, formwork, reinforcement at 240kg/m3; 28no.	82	m	1,015.00	83,230
1.1.5	RC columns 1800 x 230 incl. 40MPa concrete, formwork, reinforcement at 240kg/m3; 14no.	41	m	1,035.00	42,435
1.1.6	900 x 300 RC columns incl. 40MPa concrete, formwork, reinforcement at 240kg/m3, post-tensioning at 6kg/m2; 18no.	57	m	700.00	39,900
					365,644
1.2	**Upper Floors**				
1.2.1	RC suspended transfer slab 170 thick, incl. 40MPa concrete, formwork, reinforcement at 40kg/m3, post-tensioning at 4.2kg/m2	772	m2	270.00	208,441
1.2.2	RC attached beams to transfer slab (measured above), 2100 x 650, incl. 40MPa concrete, formwork, reinforcement at 40kg/m3	280	m	1,175.00	329,000
1.2.3	RC suspended slab 200 thick, incl. 40MPa concrete, formwork, reinforcement at 35kg/m3, post-tensioning at 4.2kg/m2	4,629	m2	275.00	1,272,957
					1,810,398
1.3	**Staircases**				
1.3.1	Concrete fire stairs inclusive of handrails and associated works	21	m/rise	3,150.00	66,150
					66,150
1.4	**Roof**				
1.4.1	RC suspended transfer slab 200 thick, incl. 40MPa concrete, formwork, reinforcement at 35kg/m3, post-tensioning at 4.2kg/m2	772	m2	275.00	212,297
1.4.2	50mm thick cement and sand mortar bedding laid to falls and finished tc receive waterproofing	772	m2	55.00	42,460
1.4.3	Approved roof waterproofing membrane applied to concrete roof slab above screed	772	m2	50.00	38,600
1.4.4	Drainage cell laid above the waterproofing	772	m2	25.00	19,300
1.4.5	Dow Wrapshield HP geotextile separation fabric laid above drainage cell below insulation	772	m2	5.00	3,860
1.4.6	40mm thick R2.0, Dow Styrofoam RTM-X closed cell insulation laid above drainage cell	772	m2	45.00	34,740
1.4.7	Dow Wrapshield HP geotextile separation fabric laid above insulation below concrete paving	772	m2	5.00	3,860
1.4.8	Allow for dressing around drainage outlet including forming cut out in drainage cell, Insulation system, making good and the like; 200mm dia	1	item	1,500.00	1,500
					356,617
1.5	**External Walls**				
1.5.1	75mm Hebel external wall panel, Wall Type 1, 1290 x 3069	28	no.	635.00	17,780
1.5.2	75mm Hebel external wall panel, Wall Type 1, 2590 x 3069	42	no.	1,270.00	53,340
1.5.3	75mm Hebel external wall panel, Wall Type 1, 2230 x 3069	42	no.	1,095.00	45,990
1.5.4	75mm Hebel external wall panel, Wall Type 1, 2120 x 3069	28	no.	1,040.00	29,120
1.5.5	75mm Hebel external wall panel, Wall Type 1, 1650 x 3069	28	no.	810.00	22,680

Code	Description	Quantity	Unit	Rate	Amount
1.5	**External Walls**				
1.5.6	75mm Hebel external wall panel, Wall Type 1, 4590 x 3069	28	no.	2,255.00	63,140
1.5.7	75mm Hebel external wall panel, Wall Type 1, 2470 x 3069	28	no.	1,250.00	35,000
1.5.8	75mm Hebel external wall panel, Wall Type 1, 2350 x 3069	28	no.	1,155.00	32,340
1.5.9	75mm Hebel external wall panel, Wall Type 1, 2940 x 3069	28	no.	1,490.00	41,720
1.5.10	75mm Hebel external wall panel, Wall Type 1, 1290 x 3069	14	no.	1,445.00	20,230
1.5.11	RC walls, 200 thick, incl. 40MPa concrete, formwork and reinforcement at 140kg/m3	129	m2	425.00	54,825
1.5.12	Alucobond on and including timber framing to Hebel external wall panels (measured elsewhere), Wall Type 1 - EXCLUDED FROM ALL OPTIONS		Excluded		
					416,165
1.6	**Internal Walls**				
1.6.1	RC walls 200 thick, incl. 40MPa concrete, formwork and reinforcement at 140kg/m2	899	m2	425.00	382,075
1.6.2	Wall Type 2, incl. Hebel panel, stud frame with insulation and 13mm plasterboard to both sides	1,611	m2	214.00	344,754
1.6.3	General internal walls, incl. 64mm stud framing, with 13m plasterboard to both sides	2,799	m2	97.00	271,503
1.6.4	Internal walls to we areas, incl. 64mm stud framing, with 6mm FC sheet to one side and 13mm plasterboard to other side	305	m2	116.00	35,380
1.6.5	Wall Type 7, 102mm C-H metal stud framed wall, lined between studs with 25mm FR PB, 2/13mm FR PB to finish	607	m2	230.00	139,610
1.6.6	10mm plasterboard lining to inside face of external Hebel wall panels	2,048	m2	25.00	51,200
					1,224,522
1.8	**Ceiling Finishes**				
1.8.1	Suspended plasterboard ceiling throughout	5,401	m2	85.00	459,085
					459,085

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Contents

1

Introduction

Timber's sustainability credentials are attracting world-wide interest and advances in timber engineering have made timber an increasingly cost-competitive proposition.

Encouraging the construction industry to adopt innovative approaches needs information and evidence. Attention to technical design, construction costs and site processes is critical to show the value proposition of timber construction to customers and optimise its use.

This Guide aims to help those involved in the decision chain (such as cost managers, estimators, design professionals, building developers and project managers) gain a better understanding of the value that timber construction systems offer aged care projects.

The Guide is based on a research project that developed a model aged care building and a corresponding lightweight timber-framed solution, and compared it with a corresponding lightweight steel-framed solution. Both solutions were designed to optimise functional performance, constructability and cost-effectiveness and provide guidance for compliance under the National Construction Code (NCC). The Guide provides an explanatory understanding of decision-making issues when developing timber solutions.

2

What Drives Decisions When Choosing a Construction System for Aged Care Projects

A central objective of the project was to provide an understanding of the decision drivers along the customer/supply chain in the selection of construction systems for aged care projects.

Key areas of exploration included:

- Gathering information about customer needs and how construction systems affect decision making.
- Benchmarking against existing construction systems typically used in aged care projects, especially lightweight steel framing as used in brick veneer construction. The steel-framed solution for the model building is provided for comparative purposes in Appendix A.
- Understanding the nature of the overall delivery supply chain and related workflows, especially construction scheduling, productivity and prefabrication issues.
- Optimising the regulatory framework where it affects the viability of timber solutions.

3

Project Development

The research project was developed by a series of expert/stakeholder meetings, interviews, concept development sessions, design charrettes, cost planning studies, construction programming studies and detailed design studies aimed at developing the model building and a cost-effective timber solution for it.

A team of experts worked together to provide input to the development process. Core collaborators included:

- **The Timber Development Association:** A market development association for the timber industry and the project leader for this work.
- **The University of Technology Sydney**: A technology-driven university with an integrated understanding of the building industry and specific expertise in timber construction. The university co-developed the research method and mediated the strategic direction of the timber solutions in terms of detailed design, cost and site productivity issues.
- **BCIS**: A global subsidiary of the Royal Institute of Chartered Surveyors that specialises in gathering building cost data used for reporting on cost trends for a variety of building forms. BCIS provided quantity surveying and cost planning input for both the timber solution and the corresponding steel solution.
- **Engineered timber manufacturers, suppliers and industry associations** (including Tilling Timber, Hyne Timber, Meyer Timber, Nelson Pine Industries, Carter Holt Harvey Wood Products, MiTek): Their input helped ensure the practical viability, design properties and availability of appropriate timber componentry.
- **Plan Source:** A building designer with good knowledge of framed construction systems. A concept design was developed to represent a typical aged care project, including the development of the timber and steel-framed solutions for the model.

4

A Model Aged Care Building - the Basis for Comparison and Solution Development

The model aged care building (Figure 1) demonstrates a prototypical situation for modelling spatial, loading, fire and noise resistance conditions, providing a neutral base for creating both the timber and competing steel solutions. The full design drawings are in Appendix B. The model's basic spatial characteristics are provided in Table 1.

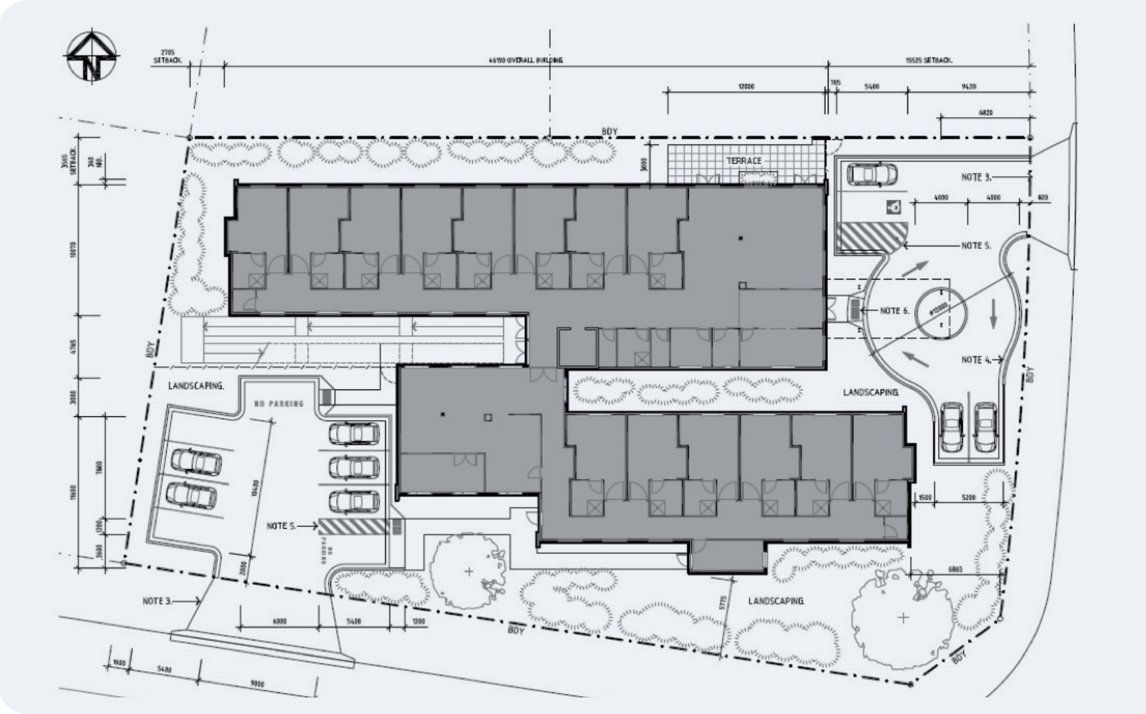


Figure 1: Site plan of two-storey aged care building.

Item	What was used in the model	Relevance and reasons
Height	• Two-storey construction • 6.85 m overall height • 6.0 m to underside of eaves	• This represents a typical height for buildings of this style
Area	• Gross Floor Area - 1,681 m^2 • Floor Space Ratio - 0.67:1	• The area and floor-to-space ratio aim to be indicative of common aged care building situations
Setbacks	• External wall distances are at least 3.0 m from property boundaries	• The location of the building relative to other buildings/properties affects façade fire-resistance requirements
NCC Building classification	• Class 9c building, i.e. aged care buildings	• The classification influences performance and compliance requirements

Table 1: Key spatial characteristics of the aged care building.

4.1 Core Differences between the Timber and Steel Solutions

The only difference between the timber solution and steel-framed solution concerns the wall and floor structure throughout the residential levels of the building (i.e. the levels above the ground floor slab). Parameters pertaining to fire, acoustic and building services requirements (that affect both the timber and steel solutions) are provided under dedicated headings below. Other aspects of the two competing solutions are essentially the same and provide relative neutrality for comparisons.

Discussions of the solutions that are identical have been excluded. Examples of this are the roof coverings, window and doors, services, finishes and fire penetrations.

4.2 Structural Themes

Parameters applied to the model:

- Deemed-to-Satisfy loading was taken from AS 1170, e.g. applied imposed wind loads.
- Wind speed: N2 (AS 4055).
- Load paths are managed in the apartment levels via load-bearing walls and beams.
- Weathered shale soil conditions have been applied in the structural design.

Reasons:

- The selected wind speed reflects typical conditions the model building would likely face in real-world conditions.
- The selected foundation is common in large parts of the greater Sydney basin and other parts of Australia where these buildings would often be found.

4.3 Building Acoustics

Parameters applied to the model:

Class 9c Residential Care Buildings have different acoustic requirements than for residential buildings that are classified as Class 2 or 3, i.e. apartments and hotels. In general, the acoustic rating is lower, and there is no ctr adjustment factor, except for the covering of services.

- Walls between bed-sitters, between bed-sitters and neighbouring bathrooms, and between bed-sitters and kitchen, laundry and plant or utility rooms are required to have an Rw of not less than 45, as per NCC Clause F5.5.
- Floors between bed-sitters must have an Rw of not less than 45.
- Ducts, soil, waste, water supply pipes or stormwater, including a duct or pipe that is located in a wall or floor cavity, must be separated from any sole-occupancy unit by construction with an Rw + Ctr (airborne) not less than –
  - Adjacent room is a habitable room (other than a kitchen) - 40
  - Adjacent room is a kitchen or non-habitable room - 25

4.4 Fire Resistance (based on NCC Requirements)

Parameters applied to the model:

- Type C construction was used, as allowed by the BCA Provision C1.5 for a building with a Rise of Storey of two if it has sprinkler (BCA Specification E1.5 only) throughout and the maximum compartment size is no larger than 3,000 m2 or 18,000 m3. Therefore, the building's Deemed-to-Satisfy (DTS) fire resistance requirements are:
    - external walls: no fire resistance requirements as they are more than 3.0 m from the boundary unless supporting the fire-rated floor where they will be required to be 60/60/60
    - external columns: not applicable
    - common or firewall: not applicable
    - internal wall: no fire resistance required unless supporting the fire-rated floor and must have fire-resistance of 60/60/60
    - floor: BCA's Provision C2.5 (b) (ii) requires all floors to be 60/60/60
    - beams and columns: no fire resistance required unless supporting the fire-rated floor and must have fire-resistance of 60/60/60
    - roof: no fire resistance required.
- Additional NSW-based requirements:
    - sprinklers are installed
    - internal walls to be covered in 13 mm standard grade plasterboard, unless required to be fire-rated
    - where insulation is used, the insulation must be non-combustible
    - internal walls must be smoke-sealed at any construction joint, space between the top of the wall and the floor, ceiling or roof.

Reasons:

- The building is assumed to be in NSW, and therefore the NCC BCA's variation for NSW applies.
- The building is two storeys in height, has a sprinkler and meets the NCC BCA's Provision Clause C1.5 that allows 9c buildings to be defined as Type C fire-resistant construction.
- Type C construction has fire resistance requirements for:
    - floor – 60/60/60
    - walls that support the floor – 60/60/60
    - beam and columns that support the floor – 60/60/60
    - walls surround the lift – 60/60/60.
- Type C construction does not have any fire resistance requirements for:
    - external walls (except loadbearing) or columns (as they are more than 3.0 m from a fire source)
    - internal non-loadbearing walls bounding corridors, between bed-sitters and stairs
    - stairs (not required to be 'fire isolated' under NCC BCA's Clause D1.3)
    - roof.

5

The Timber Solution

This section presents core design information for the timber solutions.

5.1 Internal and External Walls

Wall systems used in the timber solution (see Table 2):

- For all walls separating bed-sitter bathroom and corridor or storeroom:
  - SY1 – ground floor
  - SY1 – first floor.
- For all walls separating bed-sitter bathroom and neighbouring bed-sitter bathrooms:
  - SY2 – ground floor
  - SY2 – first floor.
- For all walls separating bed-sitter and neighbouring bed-sitter, corridors or common rooms:
  - SY3 – ground floor
  - SY3 – first floor.
- SY4 for walls surround the lift shaft and other loadbearing walls, ground and first floor.
- SY5 for walls surrounding the office, kitchen, store and public toilet, and not abutting a bed-sitter, ground and first floor.
- SY6 for smoke-proof, ground and first floor.
- External walls system:
  - external wall – ground floor – brick veneer
  - external wall – first floor – lightweight timber cladding.

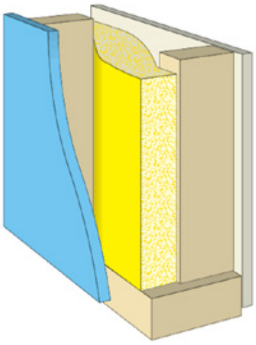
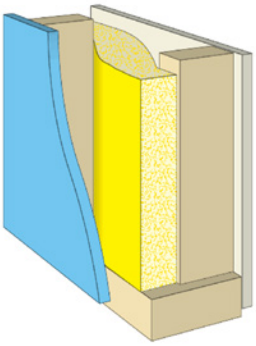
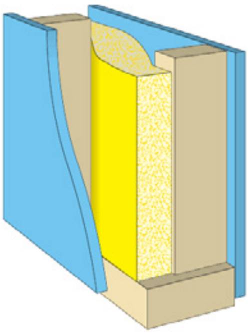
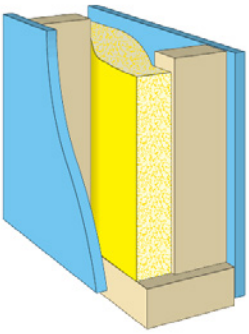
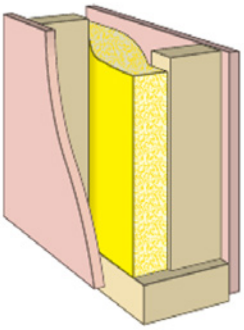
Wall Type	**Diagram of Wall System**	**Description**		**Acoustic** Rw	**Fire rating**
		Structural	**Linings & Insulation**		
SY1 – Ground Floor		Staggered stud walls consisting of 90 x 35 mm top and bottom plates and 70 x 45 mm studs at 300 mm centres.	11 x 13 mm moisture resistant grade plasterboard bathroom side and 1 x 13 mm impact-grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, and 75 mm non-combustible glass wool batts.	46 CSR 2226	Nil
SY1 – First Floor		Staggered stud walls consisting of 90 x 35 mm top and bottom plates and 70 x 35 mm studs at 300 mm centres	1 x 13 mm moisture resistant grade plasterboard bathroom side and 1 x 13 mm impact-grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, and 75 mm non-combustible glass wool batts.	46 CSR 2226	Nil
SY2 – Ground Floor		Staggered stud walls consisting of 90 x 35 mm top and bottom plates and 70 x 45 mm studs at 300 mm centres	1 x 16 mm fire-protective and moisture resistant grade plasterboard, both sides, and 75 mm non-combustible glass wool batts	47 CSR 2257	60/60/60
SY2 – First Floor		Staggered stud walls consisting of 90 x 35 mm top and bottom plates and 70 x 35 mm studs at 300 mm centres	1 x 13 mm moisture resistant grade plasterboard, both sides, and 75 mm non-combustible glass wool batts	47 CSR 2227	Nil
SY3 - Ground Floor		Staggered stud walls consisting of 90 x 35 mm, top and bottom plates and 70 x 45 mm studs at 300 mm centres	1 x 16 mm fire-protective grade plasterboard, both sides, and 75 mm non-combustible glass wool batts	46 CSR 2225	60/60/60

Table 2: Wall systems.

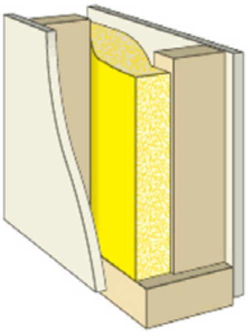
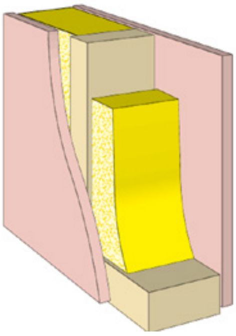
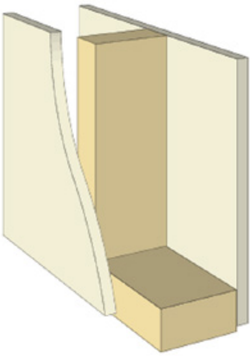
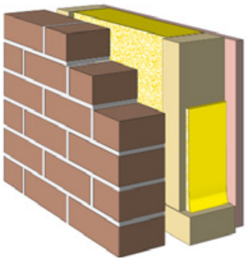
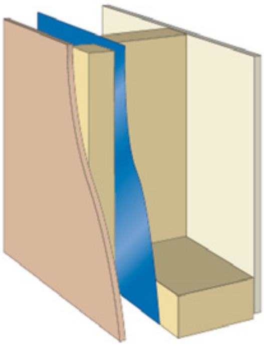
Wall Type	Diagram of Wall System	Description		Acoustic Rw	Fire rating
		Structural	Linings & Insulation		
SY3 - First Floor		Staggered stud walls consisting of 90 x 35 mm top and bottom plates and 70 x 35 mm studs at 300 mm centres	1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, both sides, and 75 mm non-combustible glass wool batts	46 CSR 2225	Nil
SY4 Walls around the lift shaft and other loadbearing ground floor walls		Single stud walls consisting of 90 x 35 mm top and bottom plates and 90 x 35 mm studs at 600 mm centres	1 x 16 mm fire-protective grade plasterboard, both sides, and 75 mm non-combustible glass wool batts	No rating required	60/60/60 CSR 2060
SY5 and Smoke-Proof Wall – Ground and First Floor Walls		Single stud walls consisting of 90 x 35 mm top and bottom plates and 90 x 35 mm studs at 300 mm centres	1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, both sides.	No rating required	No rating required
External Wall – Ground Floor		Single stud walls consisting of 90 x 35 mm top and bottom plates and 90 x 35 mm studs at 600 mm centres	Inside face: 1 x 16 mm fire-protective grade plasterboard. External face: 90 mm brick veneer, and 75 mm non-combustible glass wool batts	No rating required	60/60/60 CSR 920
External Wall – First Floor		Single stud walls consisting of 90 x 35 mm top and bottom plates and 90 x 35 mm studs at 600 mm centres	Inside face: 1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height. External face: lightweight timber cladding, and 75 mm non-combustible glass wool batts	No rating required	No rating required

Table 2: Wall systems (continued).

5.2 Floor Structure

Floor systems used in the timber solution (see Table 3):

- Floors
  - Internal floor general areas (excluding wet areas) – Type 1
  - Internal floor wet areas and external balcony floor – Type 2

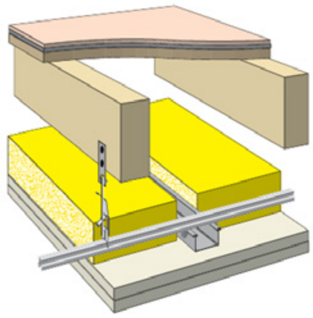
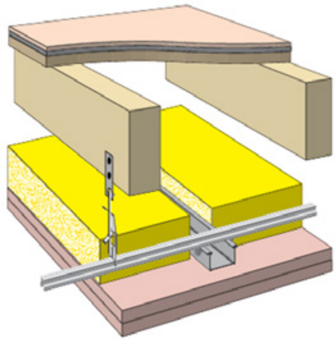
Type	Diagram of Floor System	Description	Acoustic		Fire rating
			Rw	Ln,w	
1		• 240 mm deep I-joists at 450 crs • 19 mm particleboard flooring to all interior areas • Suspension system and furring channel at 600 crs • 2 x 13 mm fire-protective plasterboard ceilings	57	NA	60/60/60 CSR 6267
2		• 240 mm deep I-joists at 450 crs • 18 mm fibre cement to all wet areas and balcony • Suspension system and furring channel at 600 crs • 2 x 13 mm fire-protective plasterboard ceilings	57	NA	60/60/60 CSR 6267

Table 3: Floors Systems used in the timber building.

5.3 Beams

Beams were used over openings in walls or rooms to break up the floor joist spans. They were incorporated into fire-rating of the ceiling and therefore required no additional fire-resistance protection.

5.4 Columns

Columns were used to support the floor beams on the ground level. These columns were placed into ground floor walls that had no fire rating and therefore required to be fire-rated to 60/60/60. Their fire resistance was provided by 45 mm effective depth of char, calculated from AS/NZS 1720.4.

[1] CSR Red Book System Number 821

5.5 Roof/Ceiling Space to Top-Most Storey

Applied to the model

- 75 mm non-combustible glass wool batts are used 1,200 mm either side of the acoustic-rated wall (Figure 2).

Reasons:

- All systems used meet NCC minimum requirements and therefore require acoustic treatment to this zone.
- Systems configuration between steel and timber are effectively the same.

Comparison to steel design:

- The system configuration is effectively the same.

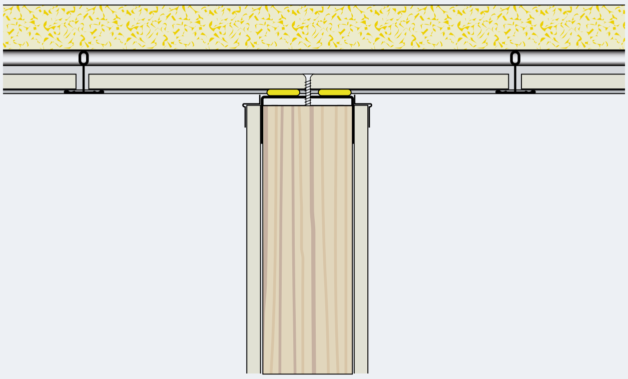


Figure 2: Sound-rated insulation above top-most ceiling.

6

Cost Plan Results – Comparing the Timber and Concrete Solutions

Cost comparison of the two competing solutions involved developing a cost plan for both the timber frame and steel frame solutions. A Bill of Quantities was developed, and the Australian Institute of Quantity Surveyors Building Cost Index was used to determine the rates to be applied.

The Building Cost Index contained rates for most items. Where no cost information was available. a price from the market was used.

6.1 Cost Plan Conclusions

Table 4 compares major items considered in the cost plan. Detailed cost information is contained in Appendix C.

Element	Timber	Steel	Variance
Columns	$1,430	$4,050	-$2,620
Upper Floor	$53,898	$85,400	-$31,502
Roof	$87,351	$87,515	-$164
Ceiling	$158,663	$158,663	0
External Walls	$271,878	$266,680	$5,198
Interior Walls	$332,454	$325,390	$7,064
	$905,674	**$927,698**	**$22,024**

Table 4: Cost comparison between each building considered.

The timber solution shows costs that are $22,024 (2.4%) lower than the steel frame solution.

Reduced costs for the timber solution were mainly in the upper floor framing, i.e. $31,502 or 37% lower than steel solution. Additional timber costs were in the wall framing, i.e. $12,291, or a 0.4% increase.

7

Conclusion

The timber solution was found to be cheaper – $22,024 (2.4%) – than the steel framing solution in the cost planning exercise.

All aspects of the model, aged care building, were the same, except for the competing framing systems used. Of note, the timber solution used stud walls, roof trusses and I-joists; the steel solution used studs, trusses and C-section joists. These elements became the basis of the cost plan, and other equivalent items that were the same cost were not considered.

The deep floor joists for the upper floor construction was the main differentiating feature between the two options, where the timber option was much less expensive than steel joists. Of less impact, timber wall frames were slightly more expensive than steel wall framing.

The Australian Institute of Quantity Surveyors, Building Cost Index was used to determine the rates for both the timber and steel frame solution. Where costs were not available, they were estimated by obtaining a market price and adding labour, delivery and other installation costs. The missing Building Cost Index data occurred for the same elements, and accordingly, the steel and timber systems were treated in the same way.

Further saving may be possible from the timber solutions as the Building Cost Index did not estimate timber systems well. Comparisons of cost from the market and the Building Cost Index varied considerably, even when labour, delivery and other install costs were considered.

Using timber for aged care building construction should be considered a viable alternative to steel frame construction, and it is recommended that market prices should be used instead of a cost index.

A

Appendix A: Comparison Design: The Steel-Framed Solution

A1 Internal and External Walls

Wall systems used in the timber solution (see Table A1):

- For all walls separating bed-sitter bathroom and corridor or storeroom:
  - SY1 – Ground and first floor
- For all walls separating bed-sitter bathroom and neighbouring bed-sitter bathrooms:
  - SY2 – Ground floor
  - SY2 – First floor
- For all walls separating bed-sitter and neighbouring bed-sitter, corridors or common rooms:
  - SY3 – Ground
  - SY3 – First floor
- SY4 for walls surround the lift shaft and other loadbearing walls – ground and first floor
- SY5 for walls surrounding the office, kitchen, store and public toilet, and not abutting a bed-sitter – ground and first floor
- SY6 for Smoke-proof – ground and first floor
- External walls system:
  - External wall – lower for fire-rated brick veneer
  - External wall – upper for lightweight timber cladding

---

[1] CSR system 110

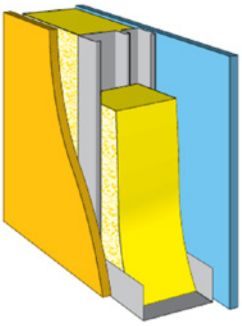
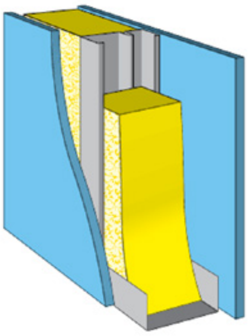
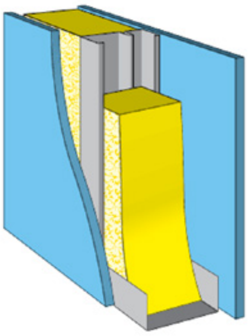
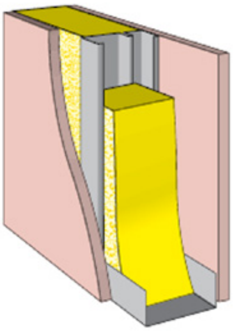
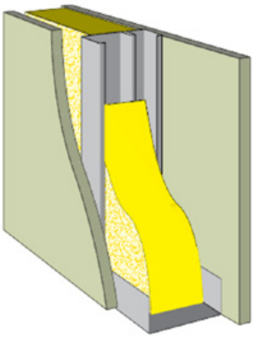
<table>
<tr><th rowspan="2">Wall Type</th><th rowspan="2">Diagram of Wall System</th><th colspan="2">Description</th><th rowspan="2">Acoustic Rw</th><th rowspan="2">Fire rating</th></tr>
<tr><th>Structural</th><th>Linings & Insulation</th></tr>
<tr><td>SY1 – Ground and Floor</td><td></td><td>CSR's 92 mm Quiet Stud at 600 mm centres and track</td><td>1 x 13 mm moisture resistant grade plasterboard bathroom side and 1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height. 75 mm non-combustible glass wool batts.</td><td>51
CSR 1108</td><td>Nil</td></tr>
<tr><td>SY2 – Ground Floor</td><td></td><td>CSR's 92 mm Quiet Stud at 600 mm centres and track</td><td>1 x 16 mm fire-protective and moisture resistant grade plasterboard, both sides, and 75 mm non-combustible glass wool batts.</td><td>50
CSR 1127</td><td>60/60/60</td></tr>
<tr><td>SY2 – First Floor</td><td></td><td>CSR's 92 mm Quiet Stud at 600 mm centres and track</td><td>1 x 13 mm moisture resistant grade plasterboard, both sides, and 75 mm non-combustible glass wool batts.</td><td>49
CSR 1105</td><td>Nil</td></tr>
<tr><td>SY3 – Ground Floor</td><td></td><td>CSR's 92 mm Quiet Stud at 600 mm centres and track</td><td>1 x 16 mm fire-protective and moisture resistant grade plasterboard, both sides, and 75 mm non-combustible glass wool batts.</td><td>50
CSR
1133</td><td>60/60/60</td></tr>
<tr><td>SY3 – First Floor</td><td></td><td>CSR's 92 mm Quiet Stud at 600 mm centres and track</td><td>1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, both sides, and 75 mm non-combustible glass wool batts.</td><td>49
CSR 1105</td><td>Nil</td></tr>
</table>

Table A1: Walls systems used in the timber building.

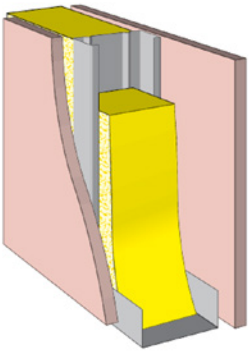
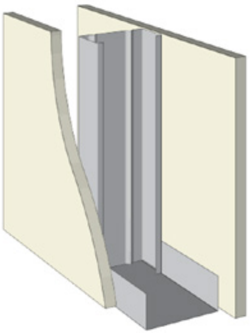
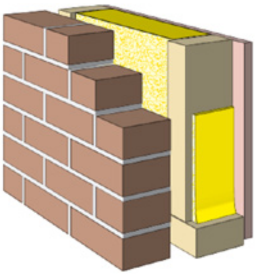
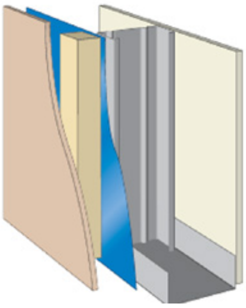
Wall Type	**Diagram of Wall System**	**Description**		**Acoustic** Rw	**Fire rating**
		Structural	**Linings & Insulation**		
SY4 Walls around the lift shaft and other loadbearing ground floor walls		92 mm metal stud walls 600 mm centres and track	1 x 16 mm fire-protective grade plasterboard, both sides, and 75 mm non-combustible glass wool batts	No rating required	60/60/60 CSR 2070
SY5 and Smoke-Proof Wall – Ground and First Floor Walls		92 mm metal stud walls 600 mm centres and track	1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height, both sides.	No rating required	No rating required
External Wall – Ground Floor		92 mm metal stud walls 600 mm centres and track	Inside face: 1 x 16 mm fire-protective grade plasterboard. External face: 90 mm brick veneer external face, and 75 mm non-combustible glass wool batts.	No rating required	60/60/60 CSR 5891
External Wall – First Floor		92 mm metal stud walls 600 mm centres and track	Inside face: 1 x 13 mm impact grade plasterboard for the first 1,200 mm from floor level with 13 mm standard grade plasterboard above this height. External face: lightweight timber cladding, and 75 mm non-combustible glass wool batts.	No rating required	No rating required

Table A1: Walls systems used in the timber building (continued).

A2 Floor Structure

Floor systems used in the timber solution (see Table A2):

- Floors
  - Internal floor general areas (excluding wet areas) – Type 1
  - Internal floor wet areas and external balcony floor – Type 2

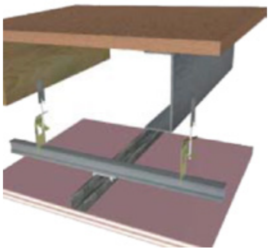
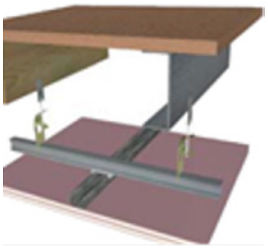
Type	Diagram of Floor System	Description	Acoustic		Fire rating
			Rw	Ln,w	
1		283 x 64 mm deep C-section at 450 crs 19 mm particleboard flooring to all interior areas Suspension system and furring channel at 600 crs 2 x 13 mm fire-protective plasterboard ceilings	57	NA	60/60/60 CSR 6267
2		283 x 64 mm deep C-section at 450 crs 18 mm fibre cement to all wet areas and balcony Suspension system and furring channel at 600 crs 2 x 13 mm fire-protective plasterboard ceilings	57	NA	60/60/60 CSR 6267

Table A2: Floor systems.

A3 Beams

Beams were used over openings in walls or rooms to break up the floor joist spans. They were incorporated into fire-rating of the ceiling and therefore required no additional fire-resistance protection.

A4 Columns

Columns were used to support the floor beams on the ground level. These columns are required to be fire-rated to 60/60/60 and their fire resistance was provided by 2 x 13 mm fire-protective grade plasterboard.

A5 Roof/Ceiling Space to Top-Most Storey

What was applied to the model:

- Floors
  - 75 mm non-combustible glass wool batts are used 1,200 mm either side of the acoustic rated wall, refer Figure A1.

Reasons:

- All system used meets NCC minimum requirements
- Systems configuration between steel and timber are effectively the same.

How does this compare with the timber design?

- The system configuration is effectively the same for both materials considered in the cost comparison.
- All other cost has been assumed to be the same although there maybe variations, they were too insignificant to consider.

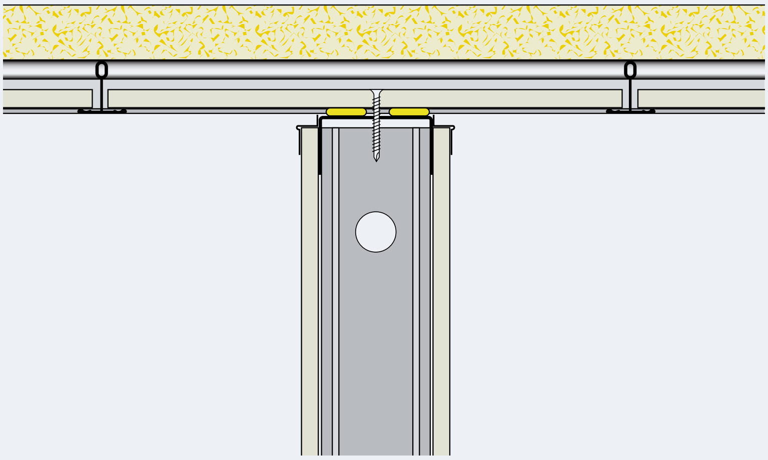


Figure A1: Sound-rated insulation above top-most ceiling.

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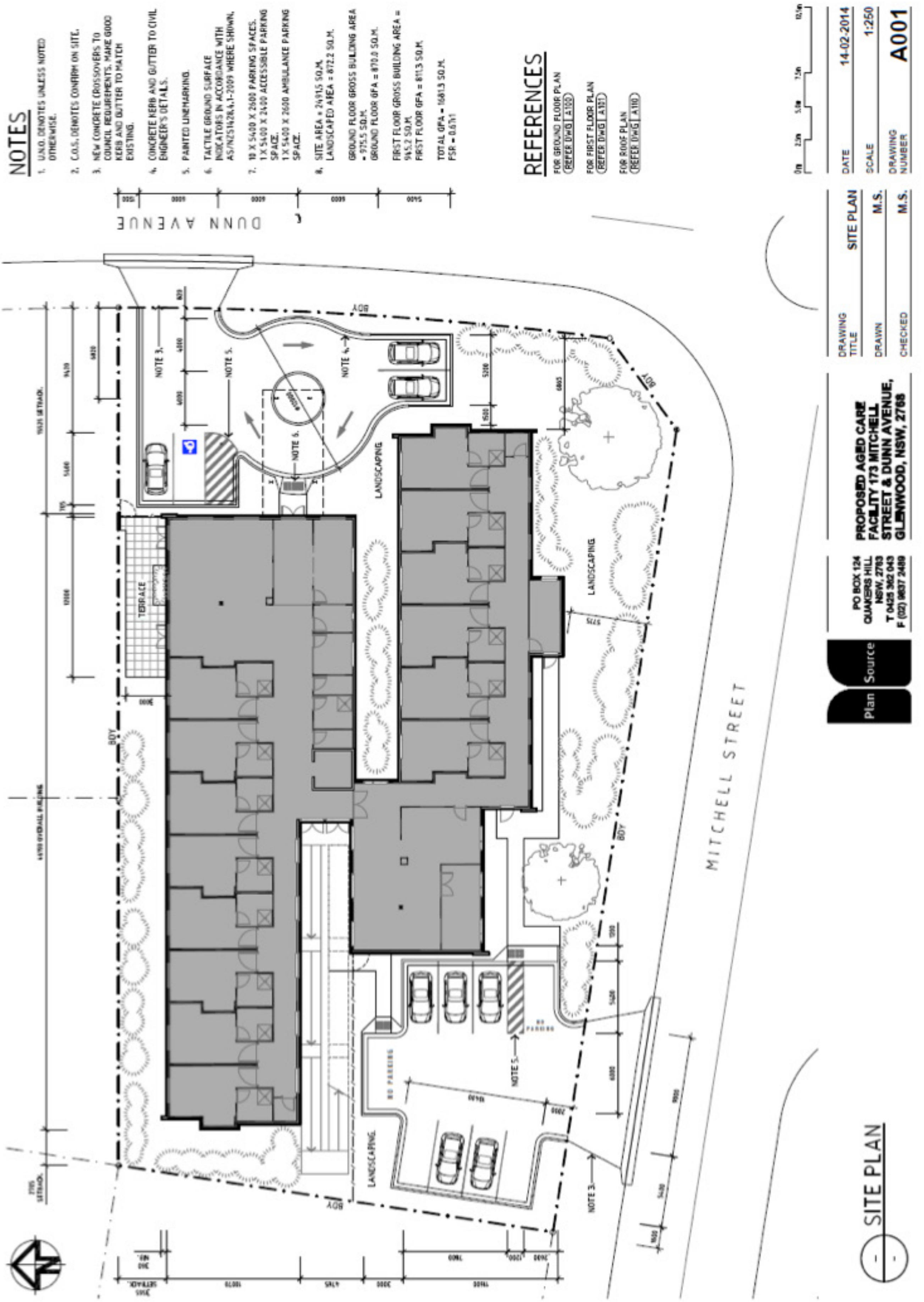
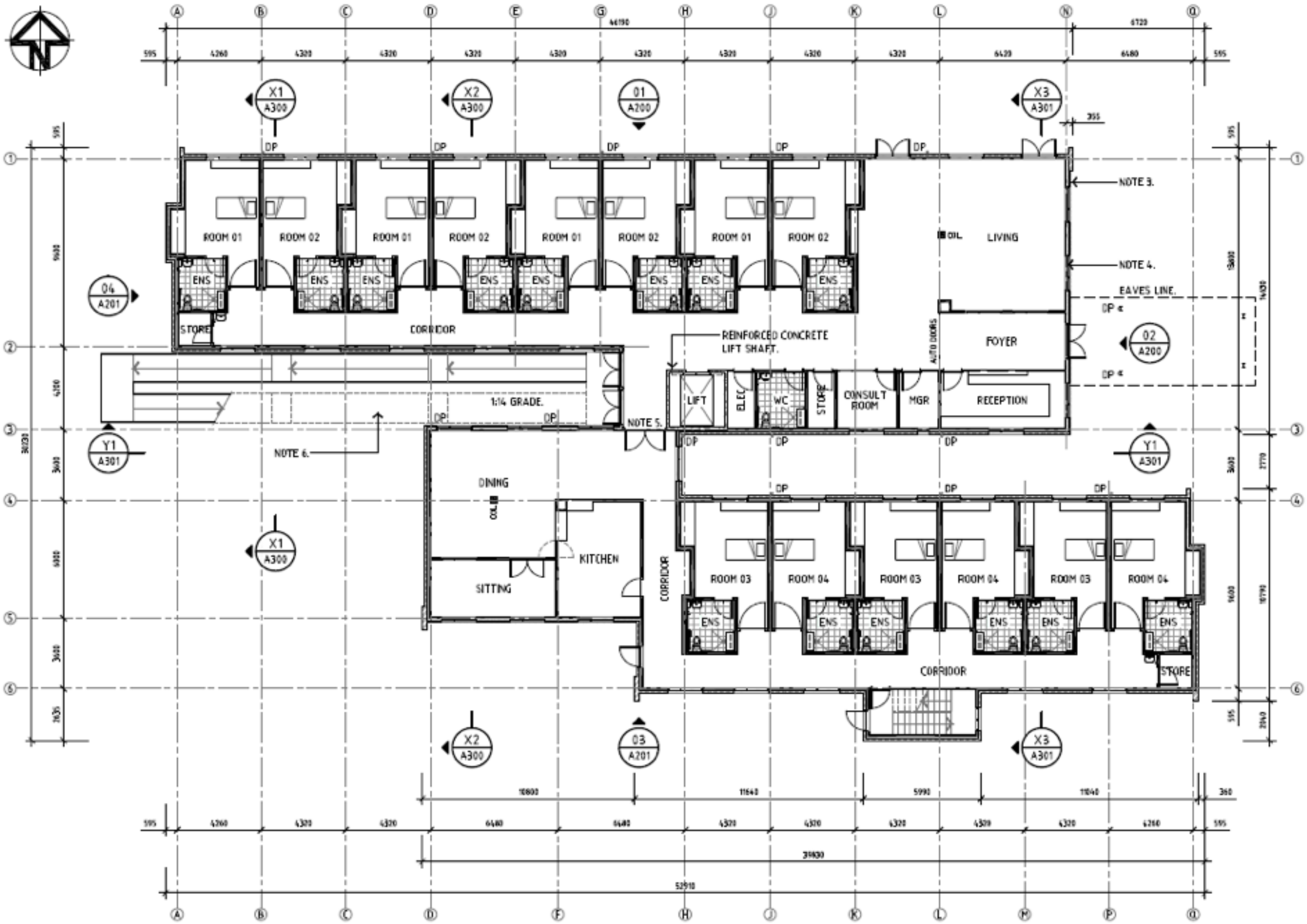
[3] CSR system 110

Appendix B: Complete Architectural Drawings





OVERALL GROUND FLOOR PLAN

NOTES

1. U.N.O. DENOTES UNLESS NOTED OTHERWISE.
2. C.O.S. DENOTES CONFIRM ON SITE.
3. BRICK VENEER WALL CONSTRUCTION TO GROUND FLOOR PERIMETER WALLS.
4. RYLOCK AA SERIES DOUBLE GLAZED WINDOWS & DOORS TYPICAL. BREEZEWAY LOUVRE WINDOW GALLERY INSERTS WHERE SHOWN.
5. SMOKE-PROOF WALLS AND SELF-CLOSING OR AUTOMATIC CLOSING -/60/30 FIRE DOORS IN THIS LOCATION TO BCA REQUIREMENTS.
6. REINFORCED CONCRETE ACCESS RAMP TO STRUCTURAL ENGINEERS DETAIL.

LEGEND

DP - DOWNPIPE.

REFERENCES

FOR EXTERNAL FINISHES SCHEDULE
REFER DWG | A200

FOR EXTERNAL DOOR & WINDOW SCHEDULE
REFER DWG | A300

DESIGN CRITERIA

A. BUILDING CLASSIFICATION: 9C AGED CARE BUILDING.

B. THE BUILDING SHALL BE CONSTRUCTED TO MEET THE REQUIREMENTS FOR TYPE C CONSTRUCTION IN ACCORDANCE WITH BCA CLAUSE E1.5 (B).

C. THE BUILDING SHALL BE PROTECTED THROUGHOUT WITH A SPRINKLER SYSTEM COMPLYING WITH BCA SPECIFICATION E1.5.

0m 2m 4m 6m 10m

Plan Source

PO BOX 124
QUAKERS HILL
NSW, 2763
T 0425 362 043
F (02) 9637 2489

PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768

DRAWING TITLE: OVERALL GROUND FLOOR PLAN
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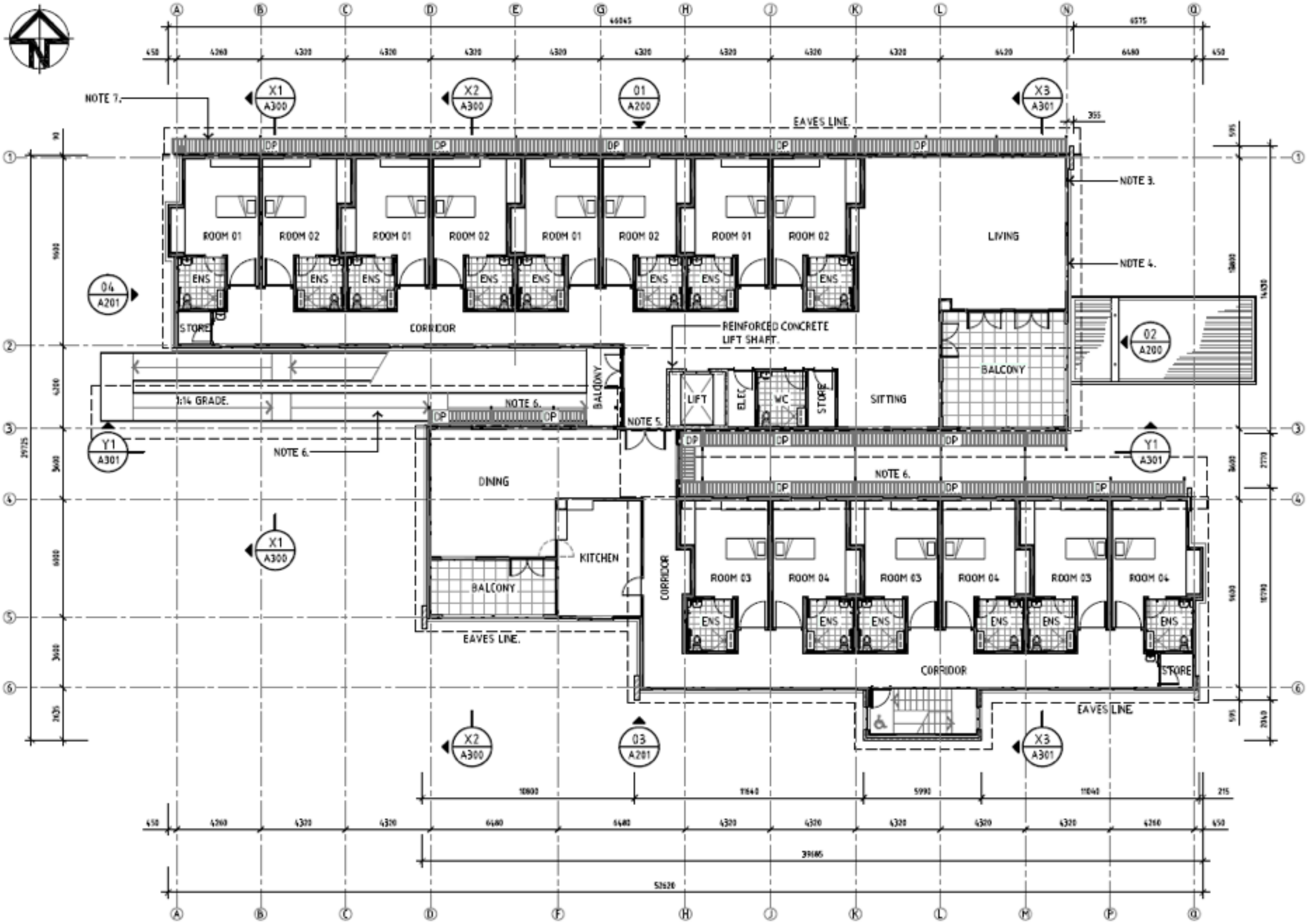
CHECKED: M.S.
DATE: 14-02-2014
SCALE: 1:200
DRAWING NUMBER: **A100**



NOTES

1. U.N.O. DENOTES UNLESS NOTED OTHERWISE.
2. C.O.S. DENOTES CONFIRM ON SITE.
3. CLAD FRAME WALL CONSTRUCTION TO FIRST FLOOR PERIMETER WALLS.
4. RYLOCK AA SERIES DOUBLE GLAZED WINDOWS & DOORS TYPICAL. BREEZEWAY LOUVRE WINDOW GALLERY INSERTS WHERE SHOWN.
5. SMOKE-PROOF WALLS AND SELF-CLOSING OR AUTOMATIC CLOSING -/60/30 FIRE DOORS IN THIS LOCATION TO BCA REQUIREMENTS.
6. REINFORCED CONCRETE ACCESS RAMP TO STRUCTURAL ENGINEERS DETAIL.
7. STRUCTURAL STEEL SUNSHADES & MAINTENANCE PLATFORMS.

LEGEND

DP - DOWNPIPE

REFERENCES

FOR EXTERNAL FINISHES SCHEDULE
REFER DWG A200

FOR EXTERNAL DOOR & WINDOW SCHEDULE
REFER DWG A300

FOR BUILDING DESIGN CRITERIA
REFER DWG A100

OVERALL FIRST FLOOR PLAN

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PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768

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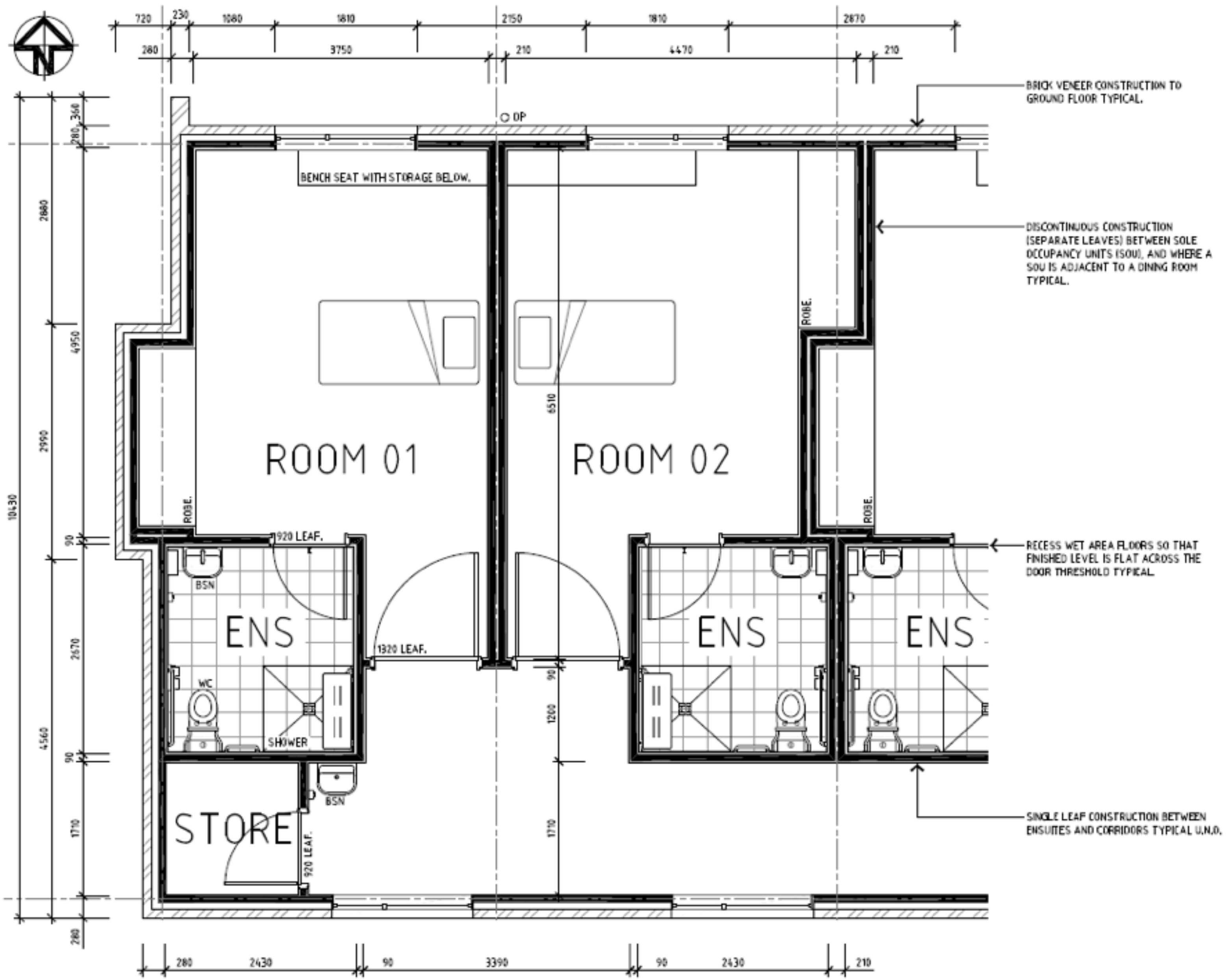
CHECKED: M.S.
DATE: 14-02-2014
SCALE: 1:200
DRAWING NUMBER: A101



NOTES

1. U.N.O. DENOTES UNLESS NOTED OTHERWISE.
2. C.O.S. DENOTES CONFIRM ON SITE.
3. SETOUT DIMENSIONS ARE MEASURED TO THE UNLINED FACE OF WALL FRAMING OR BRICKWORK.
4. GENERALLY ALL OPENINGS ARE SIZED TO SUIT STANDARD BRICKWORK MODULAR SIZES.

LEGEND

BSN - BASIN.
DP - DOWNPIPE.
WC - WATER CLOSET.

0m 0.5m 1.0m 1.5m 2.5m

TYPICAL GROUND FLOOR RESIDENT ROOM PLAN

Plan Source

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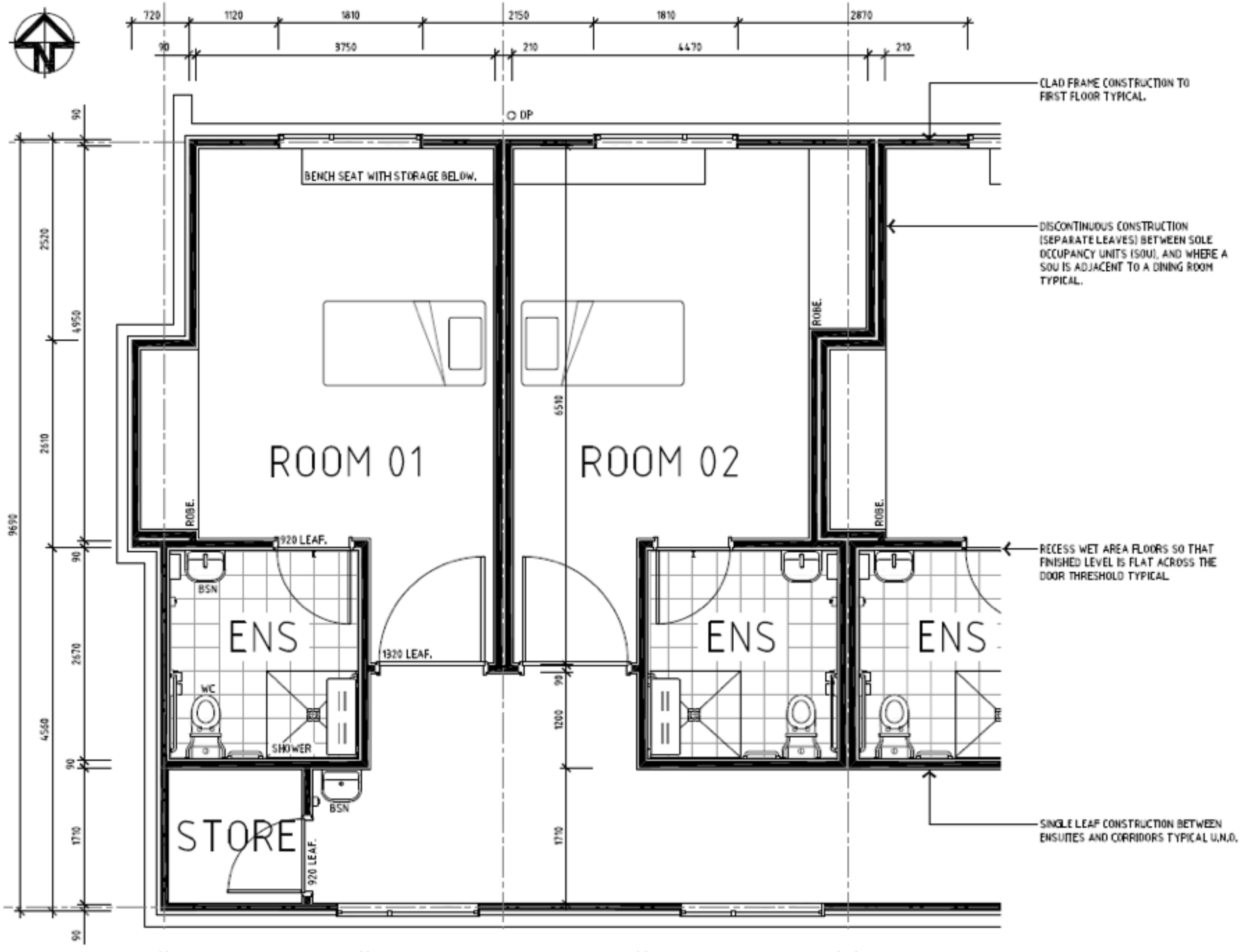
CHECKED	M.S.
DATE	14-02-2014
SCALE	1:50
DRAWING NUMBER	A102



CLAD FRAME CONSTRUCTION TO FIRST FLOOR TYPICAL.

DISCONTINUOUS CONSTRUCTION (SEPARATE LEAVES) BETWEEN SOLE OCCUPANCY UNITS (SOU), AND WHERE A SOU IS ADJACENT TO A DINING ROOM TYPICAL.

RECESS WET AREA FLOORS SO THAT FINISHED LEVEL IS FLAT ACROSS THE DOOR THRESHOLD TYPICAL.

SINGLE LEAF CONSTRUCTION BETWEEN ENSUITES AND CORRIDORS TYPICAL U.N.O.

NOTES

1. U.N.O. DENOTES UNLESS NOTED OTHERWISE.
2. C.O.S. DENOTES CONFIRM ON SITE.
3. SETOUT DIMENSIONS ARE MEASURED TO THE UNLINED FACE OF WALL FRAMING.

LEGEND

BSN - BASIN.
DP - DOWNPIPE.
WC - WATER CLOSET.

0m 0.5m 1.0m 1.5m 2.5m

TYPICAL FIRST FLOOR RESIDENT ROOM PLAN

Plan Source

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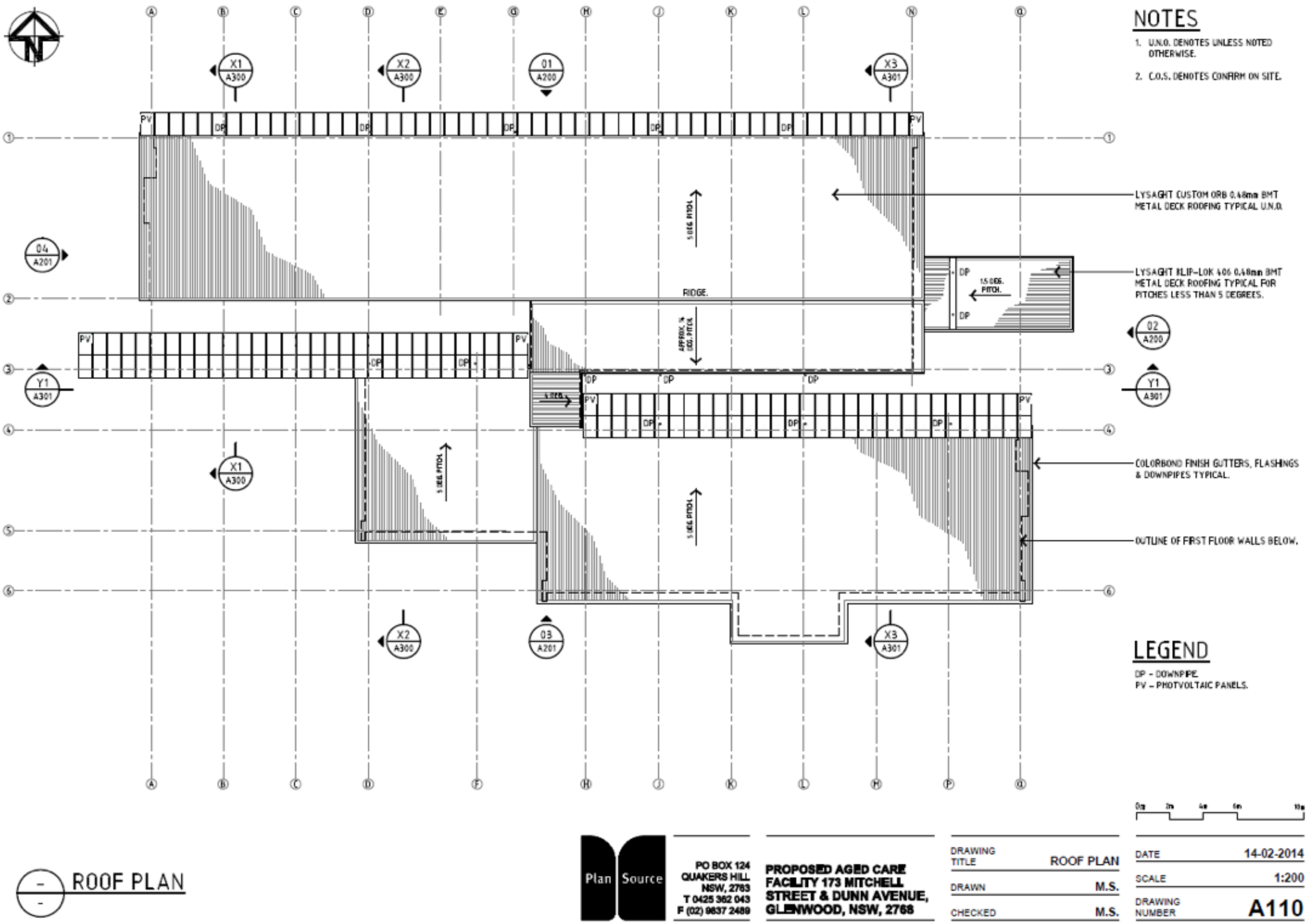
DRAWING NUMBER	A103



NOTES

1. U.N.O. DENOTES UNLESS NOTED OTHERWISE.
2. C.O.S. DENOTES CONFIRM ON SITE.

LEGEND

DP – DOWNPIPE.
PV – PHOTVOLTAIC PANELS.

Plan Source

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PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768

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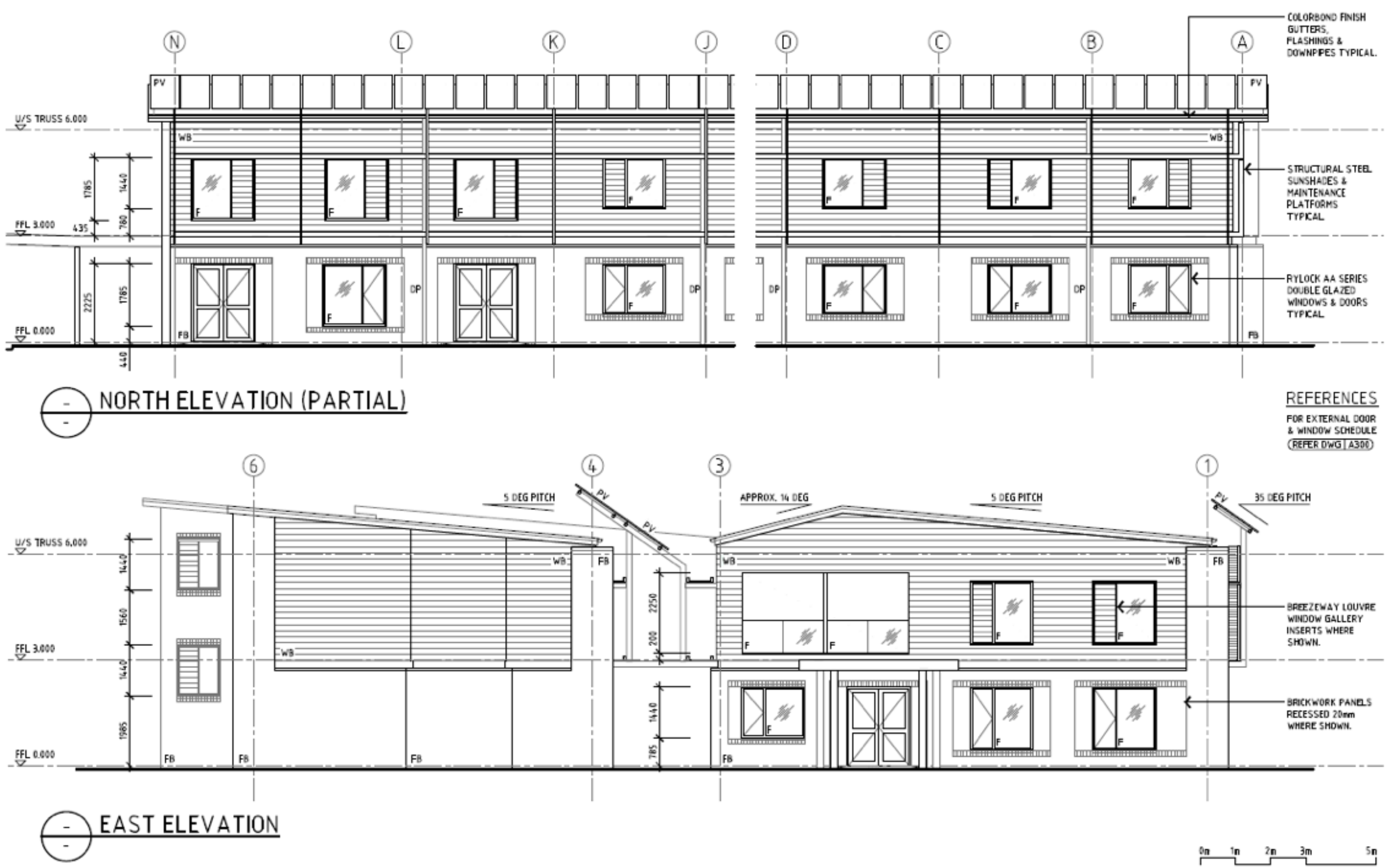
CHECKED	M.S.	DRAWING NUMBER	A110



LEGEND

DP – DOWNPIPE.
F – FIXED GLAZING.
FB – FACE BRICKWORK.
PV – PHOTVOLTAIC PANELS.
WB – WEATHERBOARD CLADDING.

EXTERNAL FINISHES SCHEDULE

TAG	DESCRIPTION
FB	BOWRAL BRICKS MURRAY GREY & ST PAULS CREAM RECESSED PANELS
WB	WEATHERTEX PRIMELOK SHADOWOOD SMOOTH

Plan Source

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PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768

DRAWING TITLE	ELEVATIONS	DATE	14-02-2014
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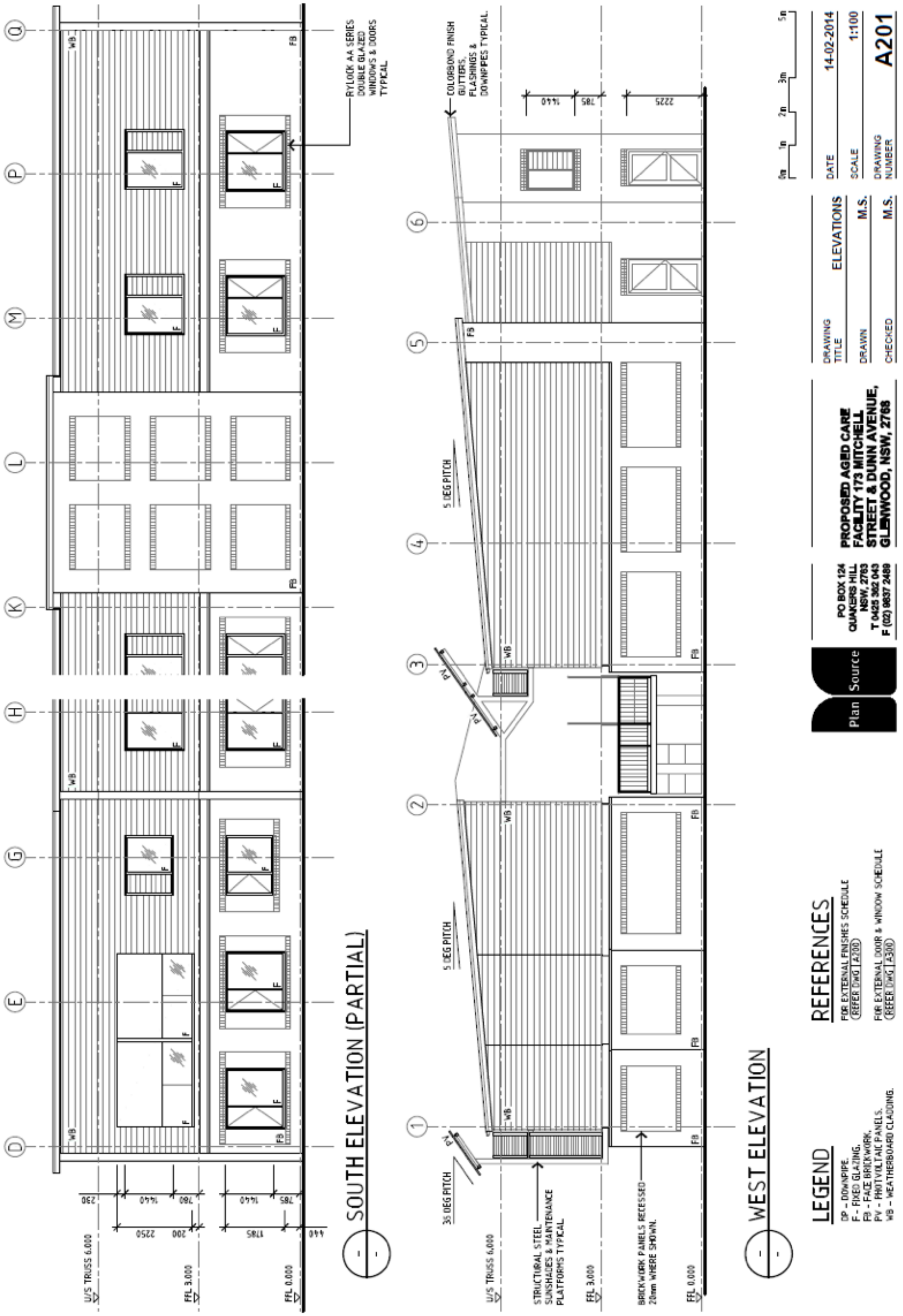
CHECKED	M.S.	DRAWING NUMBER	A200


SOUTH ELEVATION (PARTIAL)
WEST ELEVATION
D
E
G
H
K
L
M
P
Q
1
2
3
4
5
6
WB
FB
F
PV
RYLOCK AA SERIES DOUBLE GLAZED WINDOWS & DOORS TYPICAL
COLORBOND FINISH GUTTERS, FLASHINGS & DOWNPIPES TYPICAL.
5 DEG PITCH
35 DEG PITCH
U/S TRUSS 6.000
FFL 3.000
FFL 0.000
STRUCTURAL STEEL SUNSHADES & MAINTENANCE PLATFORMS TYPICAL
BRICKWORK PANELS RECESSED 20mm WHERE SHOWN.
230
1440
780
2250
200
1785
785
440
2225
LEGEND
DP - DOWNPIPE.
F - FIXED GLAZING.
FB - FACE BRICKWORK.
PV - PHOTOVOLTAIC PANELS.
WB - WEATHERBOARD CLADDING.
REFERENCES
FOR EXTERNAL FINISHES SCHEDULE REFER DWG A200
FOR EXTERNAL DOOR & WINDOW SCHEDULE REFER DWG A300
Plan Source
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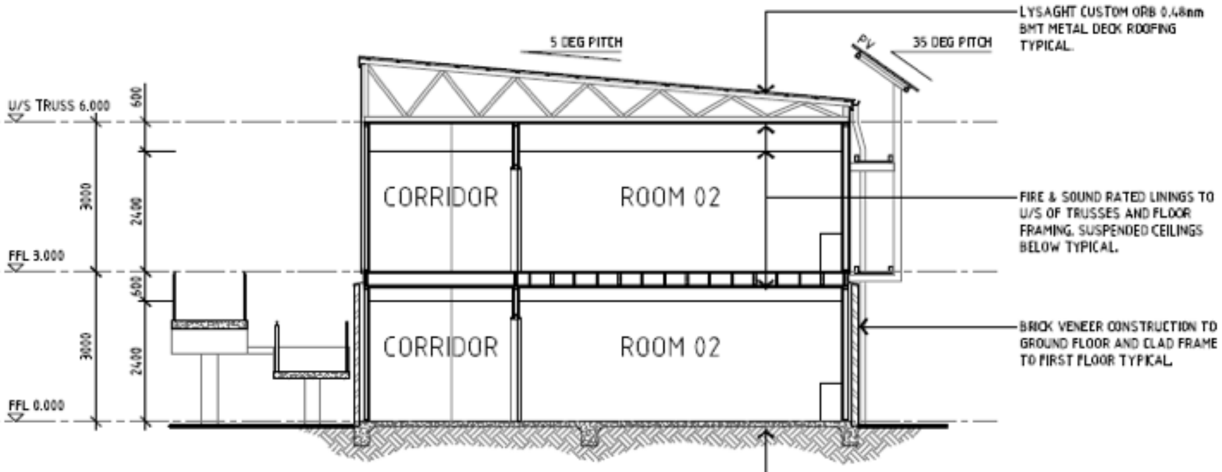
PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768
DRAWING TITLE
ELEVATIONS
DRAWN
M.S.
CHECKED
M.S.
DATE
14-02-2014
SCALE
1:100
DRAWING NUMBER
A201
0m
1m
2m
3m
5m



X1
-
SECTION

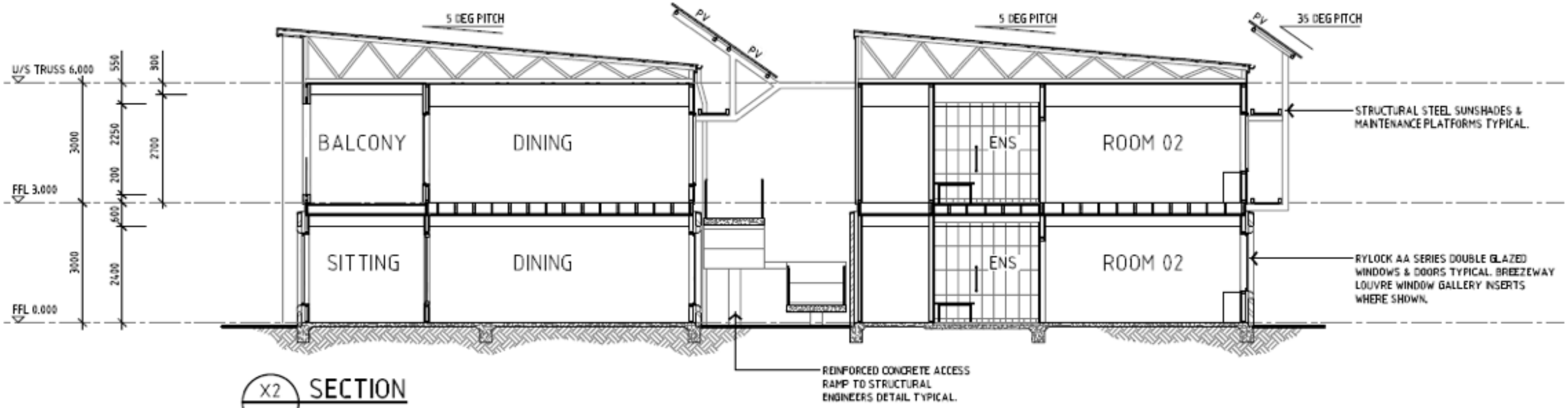
EXTERNAL DOOR & WINDOW SCHEDULE			
DESCRIPTION	QTY.	FRAME OPENING HEIGHT	FRAME OPENING WIDTH
FRENCH DOORS: LIVING, FOYER, CORRIDOR TO ACCESS RAMP, FIRST FLOOR BALCONIES	10	2240	1810
DOORS: SOUTHERN WING CORRIDOR & STAIRWELL	2	2240	1090
WINDOWS: RESIDENT ROOMS, RECEPTION, CORRIDOR OPPOSITE DINING ROOM, KITCHEN	34	1465	1810
WINDOWS: CORRIDOR, LIVING, DINING, CONSULT ROOM, SITTING ROOM, BALCONIES	41	1810	1810
MANAGER	1	1810	610
SOUTHERN WING STAIRWELL	3	1810	1210

LEGEND

DP - DOWNPIPE.
F – FIXED GLAZING.
FB – FACE BRICKWORK.
PV – PHOTVOLTAIC PANELS.
WB - WEATHERBOARD CLADDING.

REFERENCES

FOR EXTERNAL FINISHES SCHEDULE
(REFER DWG | A200)



X2
-
SECTION

0m 1m 2m 3m 5m

Plan Source

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PROPOSED AGED CARE FACILITY 173 MITCHELL STREET & DUNN AVENUE, GLENWOOD, NSW, 2768

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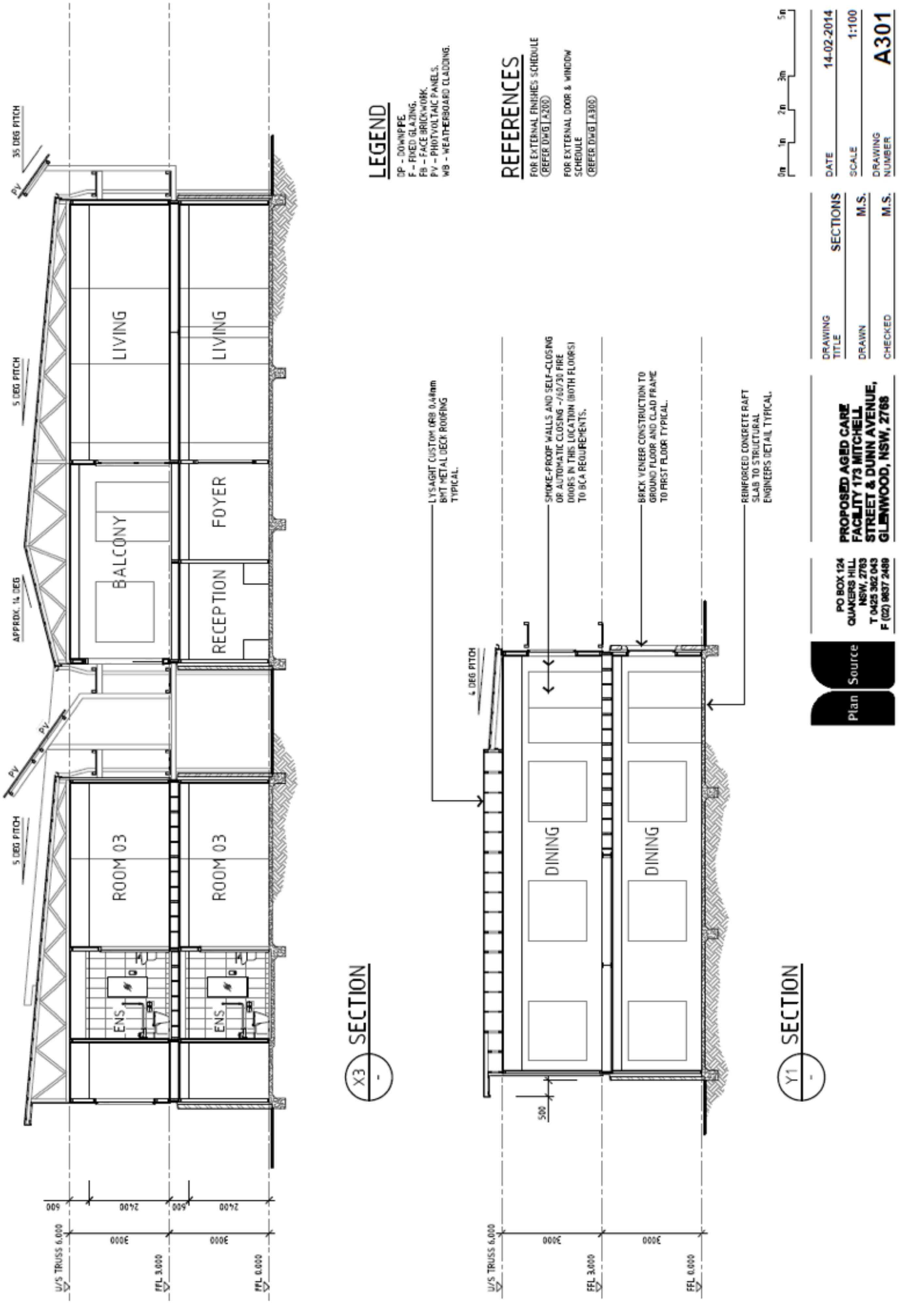
35 DEG PITCH
PV
5 DEG PITCH
APPROX. 14 DEG
PV
PV
5 DEG PITCH
LIVING
LIVING
BALCONY
FOYER
RECEPTION
ROOM 03
ROOM 03
ENS
ENS
X3
-
SECTION
U/S TRUSS 6.000
FFL 3.000
FFL 0.000
600
2400
600
2400
3000
3000
LEGEND
DP - DOWNPIPE.
F - FIXED GLAZING.
FB - FACE BRICKWORK.
PV - PHOTOVOLTAIC PANELS.
WB - WEATHERBOARD CLADDING.
REFERENCES
FOR EXTERNAL FINISHES SCHEDULE
REFER DWG A200
FOR EXTERNAL DOOR & WINDOW SCHEDULE
REFER DWG A300
4 DEG PITCH
LYSAGHT CUSTOM ORB 0.48mm BMT METAL DECK ROOFING TYPICAL.
SMOKE-PROOF WALLS AND SELF-CLOSING OR AUTOMATIC CLOSING -/60/30 FIRE DOORS IN THIS LOCATION (BOTH FLOORS) TO BCA REQUIREMENTS.
BRICK VENEER CONSTRUCTION TO GROUND FLOOR AND CLAD FRAME TO FIRST FLOOR TYPICAL.
REINFORCED CONCRETE RAFT SLAB TO STRUCTURAL ENGINEERS DETAIL TYPICAL.
DINING
DINING
500
Y1
-
SECTION
U/S TRUSS 6.000
FFL 3.000
FFL 0.000
3000
3000
0m
1m
2m
3m
5m
Plan Source
PO BOX 124
QUAKERS HILL
NSW, 2763
T 0425 362 043
F (02) 9837 2489
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Appendix C: Detailed Cost Information

Project Name: **Aged Care Building** **- Timber Framed**

Client Name: Timber Development Association for Forest and Wood Products Australia

Element		**\$/m^2 GFA**	**Quantity**	**Unit**	**Unit Rate ($)**	**Cost ($)**
			1,501	**m^2**	**$603.38**	**$905,674**
Columns		**$1.76**				**$2,646**
1	115 x 115 LVL15 column, 3000 long	$0.95	14	No.	$102	$1,430
Upper Floors		**$35.91**				**$53,898**
1	Beam B1; 3/300 x 58 LVL 15, Ref B1, 2000 long	$0.10	1	No.	$174	$150
2	Beam B2; 2/240 x 42 LVL 15, Ref B2, 3000 long	$0.33	4	No.	$123	$492
3	Beam B3; 2/240 x 58 LVL 15, Ref B3, 3000 long	$0.62	6	No.	$156	$938
4	Beam B4; 170 x 58 LVL 15, Ref B4, 2000 long	$0.17	5	No.	$52	$262
5	Beam B5; 2/240 x 42 LVL 15, Ref B5, 3600 long	$0.20	2	No.	$148	$295
6	Beam B6; 240 x 75 LVL 15, Ref B6, 3600 long	$0.27	3	No.	$133	$398
7	Beam B7; 2/240 x 75 LVL 15, Ref B7, 4500 long	$0.38	2	No.	$287	$575
8	I-Joists 360 x 90	$7.97	352	m	$34	$11,968
9	I-Joists 200 x 44	$25.86	1,941	m	$20	$38,820
Roof		**$58.20**				**$87,351**
1	Prefabricated timber truss, 13700 long, unequal pitch 5° and 14°	$11.53	39	No.	$444	$17,308
2	Prefabricated timber truss, 9600 long, pitch 5°, 600 mm overhang at end	$12.98	45	No.	$433	$19,485
3	Prefabricated timber truss, 12100 long, pitch 5°	$5.19	18	No.	$433	$7,794
4	Prefabricated timber truss, 9600 long, pitch 5°	$11.24	39	No.	$433	$16,876
5	Prefabricated timber truss, 3000 long, pitch 4°	$1.34	7	No.	$287	$2,008
6	Timber bracing to trusses	$15.91	597	m	$40	$23,880
Ceilings		**$105.70**				**$158,663**
1	Under Roof, suspension system, 1 x 13 mm flush fixed standard plasterboard and 75 fibreglass insulation	$45.30	735	m^2	$92	$67,988
2	Upper Floor: suspension system, 2 x 13 mm fire-protective flush fixed plasterboard, and 75 fibreglass insulation	$60.40	775	m^2	$117	$90,675
External Wall		**$181.13**				**$271,878**
1	Lower Floor: 90 x 35 studs at 600 crs, Interior lined with 16 mm fire-protective grade plasterboard, and 75 mm insulation. Exterior cladding 110 mm common clay bricks	$115.33	18	No.	$433	$7,794
2	Upper Floor: 90 x 35 studs at 600 crs, Interior lined with 13 mm impact board and Standard grade plasterboard, and 75 mm insulation. Exterior timber cladding	$65.80	226	m	$437	$98,762

Project Name: Office Building - Timber Framed

Client Name: Timber Development Association for Forest and Wood Products Australia

Element		$/m^2 GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
Internal Walls		**$221.49**				**$332,454**
1	Lower floor – SY1: Staggered studs 90 x 35 plates & 70 x 45 studs at 300 crs and 75 mm glass insulation. Lined with 13 mm impact board and Standard grade plasterboard, both sides of the wall.	$17.94	3,831	m	$30	$114,930
2	Upper floor – SY1: Staggered studs 90 x 35 plates & 70 x 35 studs at 300 crs and 75 mm glass insulation. Lined with 13 mm impact board and Standard grade plasterboard, both sides of the wall.		47	m	$573	$26,931
3	Lower floor – SY2: Staggered studs 90 x 35 plates & 70 x 45 studs at 300 crs and 75 mm glass insulation. Lined with 1 x 16 mm fire-protective and moisture resistant grade plasterboard, both sides of the wall.	$17.63	47	m	$563	$26,461
4	Upper floor – SY2: Staggered studs 90 x 35 plates & 70 x 35 studs at 300 crs and 75 mm glass insulation. Lined with 1 x 13 mm moisture resistant grade plasterboard, both sides of the wall.	$7.20	17	m	$636	$10,812
5	Lower floor – SY3: Staggered studs 90 x 35 plates & 70 x 45 studs at 300 crs and 75 mm glass insulation. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$6.16	17	m	$544	$9,248
6	Upper floor – SY3: Staggered studs 90 x 35 plates & 70 x 35 studs at 300 crs and 75 mm glass insulation. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$42.52	111	m	$575	$63,825
7	Lower floor – SY4: 90 x 35 plates and studs at 600 crs. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$41.93	111	m	$567	$62,937
8	Upper floor – SY4: 90 x 35 plates and studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$7.72	23	m	$504	$11,592
9	Lower floor – SY5: 90 x 35 plates and studs at 600 crs. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$2.01	6	m	$504	$3,024
10	Upper floor – SY5: 90 x 35 plates and studs at 600 crs. Lined with 1 x 13 mm impact board and Standard grade plasterboard, both sides of the wall.	$38.51	114	m	$507	$57,798
11	Lower floor – smoke wall: 90 x 35 plates and studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$38.51	114	m	$507	$57,798
12	Upper floor – smoke wall: 90 x 35 plates and studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$0.68	2	m	$507	$1,014
Preliminaries Adjustment		**$0.00**				**$0**
1	Provision of time related preliminaries based on the duration of structure construction time.					
2	Preliminaries based on reduced Construction duration of:	$0.00	0	Weeks		$0
Total Cost						**$905,674**

Notes

1. The cost estimates are priced at April 2020 prices and based on construction in the Sydney region.
2. Timber frame construction will have a marginally faster construction program than steel, but this has been ignored in this comparison.
3. The timber frame rates are based on feedback from the Sydney market.

Project Name: **Aged Care Building - Steel Framed**

Client Name: Timber Development Association for Forest and Wood Products Australia

Element		$\$/\text{m}^2$ GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
			1,501	**m^2**	**$618.05**	**$927,698**
Columns		**$2.70**				**$4,050**
1	89 x 89 x 3.5 SHS column, 3000 long; 9.06 kg/m	$1.71	10	No.	$257	$2,570
2	2 x 16 mm fire-protective plasterboard	$0.99	10	No.	$148	$1,480
Upper Floors		**$56.90**				**$85,400**
1	Beam B1; 180UB16.1, Ref B1, 2000 long	$0.17	1	No.	$255	$255
2	Beam B2; RHS 125 x 75 x 3.0; Ref B2, 3000 long; 24 kg/m	$1.63	4	No.	$612	$2,448
3	Beam B3; RHS 125 x 75 x 3.0, Ref B3, 3000 long; 24 kg/m	$2.45	6	No.	$612	$3,672
4	Beam B4; RHS 125 x 75 x 3.0; Ref B4, 2000 long, 24 kg/m	$1.36	5	No.	$408	$2040
5	Beam B5; 150UB14, Ref B5, 3600 long	$0.53	2	No.	$398	$796
6	Beam B6; RHS 125 x 75 x 3.0, Ref B6, 3600 long; 24 kg/m	$1.47	3	No.	$734	$2,202
7	Beam B7; 180UB16.1, Ref B7, 4500 long	$0.76	2	No.	$572	$1,144
8	Joist; Stramit J28324; 283 x 64 @ 450 crs; to Upper Floors, 8.04 kg/m	$8.44	352	m	$36	$12,672
9	Joist; Stramit J28319; 283 x 64 @ 450 crs; to Upper Floors, 6.37 kg/m	$40.09	1,941	m	$31	$60,171
Roof		**$58.20**				**$87,351**
1	Prefabricated timber truss, 13,700 long, unequal pitch 5° and 14°	$11.78	27	No.	$655	$17,685
2	Prefabricated timber truss, 9,600 long, pitch 5°, 600 mm overhang at end	$13.22	31	No.	$640	$19,840
3	Prefabricated timber truss, 12,100 long, pitch 5°	$5.54	13	No.	$640	$8,320
4	Prefabricated timber truss, 9,600 long, pitch 5°	$11.09	26	No.	$640	$16,640
5	Prefabricated timber truss, 3,000 long, pitch 4°	$1.43	5	No.	$430	$2,150
6	Timber bracing to trusses	$15.24	597	m	$40	$22,880
Ceilings		**$105.70**				**$158,663**
1	Under Roof, suspension system, 1 x 13 mm flush fixed standard plasterboard and 75 fibreglass insulation	$45.30	735	m^2	$92	$67,988
2	Upper Floor: suspension system, 2 x 13 mm fire-protective flush fixed plasterboard, and 75 fibreglass insulation	$60.40	775	m^2	$117	$90,675
External Wall		**$177.67**				**$266,680**
1	Lower Floor: 92 mm studs at 600 crs, Interior lined with 16 mm fire-protective grade plasterboard, and 75 mm insulation. Exterior cladding 110 mm common clay bricks	$113.68	226	m	$755	$170,630
2	Upper Floor: 92 mm studs at 600 crs, Interior lined with 13 mm impact board and Standard grade plasterboard, and 75 mm insulation. Exterior timber cladding	$63.99	226	m	$425	$96,050

Project Name: **Aged Care Building - Steel Framed**

Client Name: Timber Development Association for Forest and Wood Products Australia

Element		$/m² GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
Internal Walls		**$216.78**				**$325,390**
1	Lower floor – SY1: 92 mm Quiet Studs at 600 crs and 75 mm glass insulation.	$17.44	47	m	$557	$26,179
2	Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$17.44	47	m	$557	$26,179
3	Upper floor – SY1: 92 mm Quiet Studs at 600 crs and 75 mm glass insulation.	$7.02	17	m	$620	$10,540
4	Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$6.09	17	m	$538	$9,146
5	Lower floor – SY2: 92 mm Quiet Studs at 600 crs and 75 mm glass insulation. Lined with 1 x 16 mm fire-protective and moisture resistant grade plasterboard, both sides of the wall.	$41.26	111	m	$558	$61,938
6	Upper floor – SY3: 92 mm Quiet Studs at 600 crs and 75 mm glass insulation. Lined with 13 mm impact board and standard grade plasterboard, both sides of the wall.	$41.49	111	m	$561	$62,271
7	Lower floor – SY4: 92 mm studs at 600 crs. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$7.55	23	m	$493	$11,339
8	Upper floor – SY4: 92 mm studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of wall.	$1.97	6	m	$493	$2,958
9	Lower floor – SY5: 92 mm studs at 600 crs. Lined with 1 x 16 mm fire-protective grade plasterboard, both sides of the wall.	$37.59	114	m	$495	$56,430
10	Upper floor – SY5: 92 mm studs at 600 crs. Lined with 1x 13 mm impact board and standard grade plasterboard, both sides of the wall.	$37.59	114	m	$495	$56,430
11	Lower floor – smoke wall: 92 mm studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of wall.	$0.66	2	m	$495	$990
12	Upper floor – smoke wall: 92 mm studs at 600 crs. Lined with 13 mm impact board and standard grade plasterboard, both sides of wall.	$0.66	2	m	$495	$990
Preliminaries Adjustment		**$0.00**				**$0**
1	Provision of time related preliminaries based on the duration of structure construction time.					
2	Preliminaries based on reduced Construction duration of:	$0.00	0	Weeks		$0
Total Cost						**$927,698**

Notes

1. The cost estimates are priced at April 2020 prices and based on construction in the Sydney Region.
2. The steelwork is assumed to be pre-fabricated and bolted together on site with minimum welding required.
3. The steel roof trusses included above are relatively high cost compared to standard timber trusses.


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Technical Design Guide issued by Forest and Wood Products Australia

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Contents

1

Introduction

Timber's sustainability credentials are attracting world-wide interest, and advancements in timber engineering have made timber an increasingly cost-competitive proposition.

Encouraging the construction industry to adopt innovative approaches needs information and evidence. Attention to technical design, construction costs and site processes is critical to show the value proposition of timber construction to customers and optimise its use.

This Guide aims to help those involved in the decision chain (such as cost managers, estimators, design professionals, building developers and project managers) gain a better understanding of the value that timber construction systems offer industrial shed projects.

The Guide is based on a research project that developed a model single-storey shed building with a timber solution and compared it with conventional steel portal construction. The timber solution was designed to optimise functional performance, constructability and cost-effectiveness and provides guidance for compliance under the National Construction Code (NCC). This Guide provides an explanation of decision-making issues when developing timber solutions.

The Guide was revised to update the cost plans for all design options as there has been a significant shift in costs since the original cost plan was developed in 2014. The revision also included corrections made to the Bill of Quantities.

2

What Drives Decisions When Choosing Industrial Shed Construction Systems

A key objective of the project was to provide an understanding of the decision drivers along the customer/supply chain for the selection of industrial construction systems. Key areas of exploration included:

- Benchmarking against existing industrial shed construction systems, especially steel portal frame constructions. A steel solution for the model building is provided in Section 5.3 for comparative purposes.
- Understanding the nature of the overall delivery supply chain and related work flows – especially construction scheduling, productivity and prefabrication issues.
- Optimising the regulatory framework where it affects the viability of timber solutions.

3

Project Development

The research project was developed by a series of expert/stakeholder meetings, interviews, concept development sessions, design charrettes, cost planning studies, construction programming studies and detailed design studies aimed at developing the model shed building and a cost-effective timber solution for it.

A team of experts worked together to provide input to the development process.
Core collaborators included:

- **The Timber Development Association (TDA)**: A market development association for the timber industry and the project leader for this work, on behalf of the timber industry.
- **The University of Technology Sydney (UTS)**: A technology-driven university with an integrated understanding of the building industry and specific expertise in timber construction. The university co-developed the research method and mediated the strategic direction of the timber solutions in terms of detailed design, cost and site productivity issues.
- **Arup Ltd**: A global multi-disciplinary engineering firm with expertise spanning structural, acoustic, fire and services engineering. Arup Ltd provided design and engineering input into the timber solution and the corresponding steel solution.
- **Taylor Thompson Whitting Consulting Engineers**: An engineering firm with specialised services in structural, civil and facade engineering who provided the structural design for the re-engineered steel solution.
- **BCIS**: A global subsidiary of the Royal Institute of Chartered Surveyors who specialise in gathering building cost data used for reporting on cost trends for a variety building forms. BCIS provided quantity surveying, cost estimating and cost planning input for both the timber solution and the corresponding concrete solution.
- **Engineered timber manufacturers, suppliers and industry associations** (including Tilling Timber, Hyne Timber, Meyer Timber, Nelson Pine Industries, Carter Holt Harvey Wood Products, MiTek): Their input helped ensure the practical viability, design properties and availability of appropriate timber componentry.

Using the above team, two timber portal concept designs were developed (revolving around different portal, girt and purlin assemblies). Both were debated, tested against construction logistics and rationalised for cost, construction flow, structural performance and services integration. These design concepts were then tested more broadly on a cross section of building owners, developers, designers and contractors for critical feedback.

The designs considered included:

- Version 1: Timber Portals based on 6.7 m bay spacing (as detailed in Timber Solution 1)
- Version 2: Timber Portals based on 10.0 m bay spacing (as detailed in Timber Solution 2)

These were compared against a typical steel portal design utilising an 8.0 m spacing bay spacing (as detailed in Steel Solution).

Different bay spaces were used to test the robustness of the timber solution, relative to the steel option. In each case, the spacing was selected by the design engineer based on common scenarios faced in practice.

4

The Model Industrial Shed – the Basis for Comparison and Solution Development

The model shed is shown Figure 1. The model demonstrates a prototypical situation for modelling spatial, loading and fire resistance conditions, providing a neutral base for creating both the timber and competing steel solutions. The basic spatial characteristics of the model are provided in Table 1.

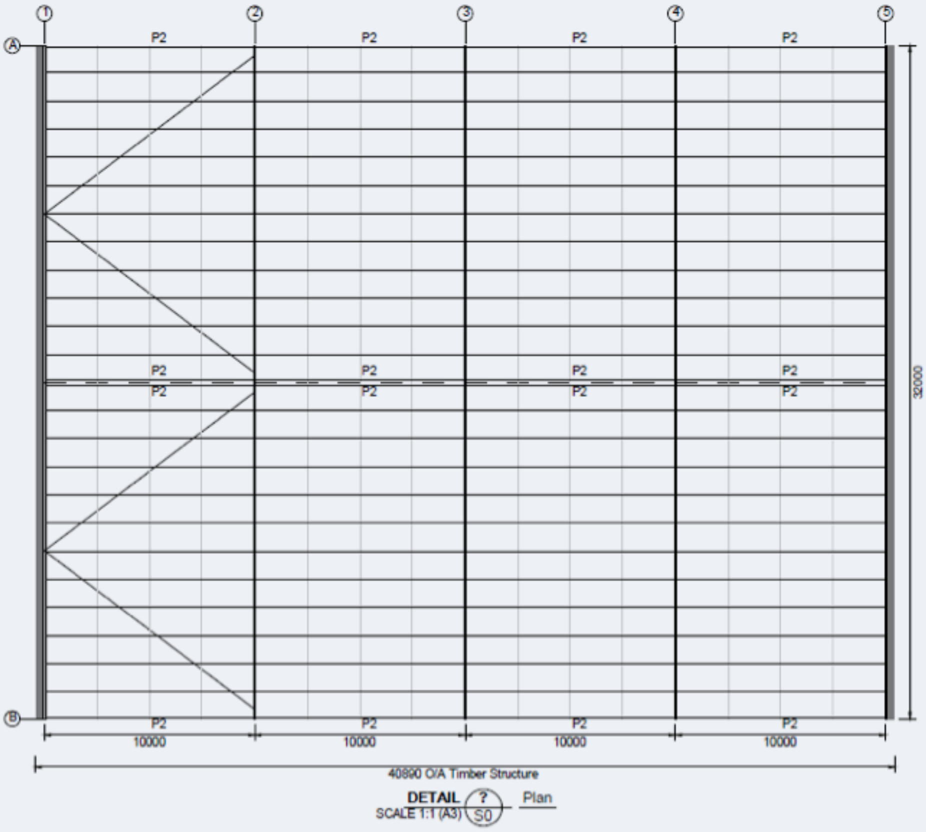

Figure 1: Plan of the industrial building (10 m timber bay shown).

Item	What was used in the model	Relevance and Reasons
Height	• Single storey construction • 8.0 m overall height • 5.0 m to underside of eaves	• This represents a typical height for buildings of this style
Area	• 32.0 m span x 40.0 m length • 1,200 m^2 footprint/GFA	• The area and length-to-width ratio are a common size for industrial sheds
Setbacks	• External wall distances are at least 3.0 m from property boundaries	• The location of the building relative to other buildings/properties affects façade fire resistance requirements
NCC Building classification	• Class 7b building i.e. a wholesale distribution shed	• The classification influences performance and compliance requirements

Table 1: Key spatial characteristics of the model shed building.

In considering information about the model shed, it is important to realise that the only differences between the timber solution(s) and competing steel solution concern the footing, portal, purlins and girts construction. Other aspects are the same. Even so, discussion that clarifies NCC performance requirements and design settings (as relevant to the competing solutions) can be found under the dedicated sub-headings below.

4.1 Key Structural Parameters

Parameters applied to the model:

- Wind speed: Region A and Terrain Category 2 exposure.
  - Wind direction, Shielding multiplier and Topographic multiplier all set as 1.
- Foundation: Moderately reactive clay soil conditions applied to footing design.

Reasons:

- The selected wind speed deals with typical conditions the model building would likely face in real world conditions.
- The selected foundation is common in large parts of the greater Sydney basin and other parts of Australia where these buildings would often be found. If poorer foundations were encountered, then this would likely favour the timber solution(s), i.e. using larger bay spacings and lighter construction.

4.2 Fire Resistance (based on NCC requirements)

Parameters applied to the model:

- The Type of construction used was Type C, therefore:
  - external walls: no fire resistance requirements as they are more than 3.0 m from the boundary
  - external columns: not applicable
  - common or fire wall: not applicable
  - internal wall: not applicable (no internal walls are present in the design)
  - roof: no fire resistance requirement under the stated Building classification.

Reasons:

- The chosen parameters require no fire rating, which therefore removes the complexity that fire resistant construction can have on each material.
- Timber fire resistance is easier to achieve than steel construction fire resistance, due to timber's charring[1] capacity. Consideration of a fire rating would have skewed the result towards a timber outcome.

4.3 Sound Resistance (based on NCC requirements)

Parameters applied to the model:

- Not applicable. No sound resistance is required for 7B building classifications.

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[1] Further information on Timber char capacity can be found in WoodSolution Guide No 3 - Timber-framed Construction for Commercial Buildings Class 5, 6, 9a & 9b - Design & construction guide for BCA compliant fire-rated construction

5

The Timber and Steel Solutions

The following section presents core design information for the two timber solutions and the competing steel solution (see Figure 2 for a section through 10.0 m bay timber solution).

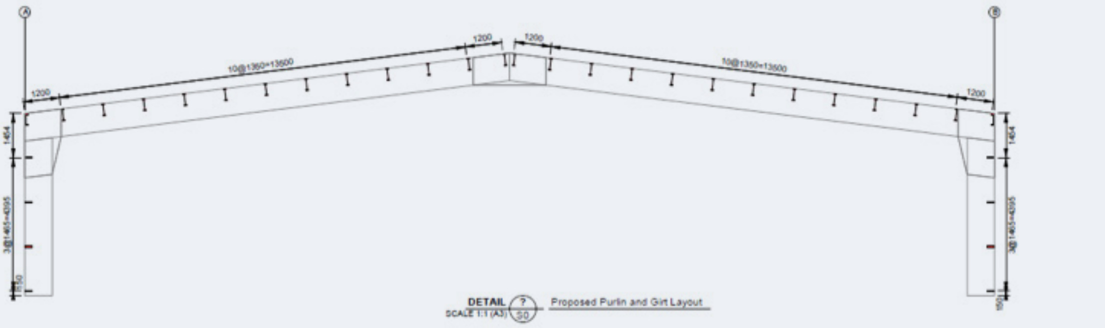

Figure 2: Section of Timber Portal Frame (10.0 m portal spacing shown).

5.1 Timber Solution 1 (6.7 m portal spacing) details

Refer to Appendix A for the structural drawing of Timber Solution 1. All timber elements are termite treated to H2S, and all fabricated components have one coat of finish weather protection.

- Columns:
  - Main – 1,220 x 135 mm block bonded LVL13
  - End Bay – 800 x 135 mm block bonded LVL13
- Rafter:
  - Main – 1,220 x 135 mm block bonded LVL13
  - End bay – 800 x 135 mm block bonded LVL13
- Eave Rafter: 400 x 135 mm block bonded LVL13
- Purlins: 300 x 45 mm LVL13
- Girts: End Bay – 300 x 45 mm LVL13
- Mullions: 400 x 63 mm LVL13
- Bracing: 24 mm diameter galvanised rod
- Flybrace: 90 x 45 LVL11

5.2 Timber Solution 2 (10.0 m portal spacing) details

Refer to Appendix B for the structural drawing of Timber Solution 2. All timber elements are termite treated to H2S, and all fabricated components have one coat of finish weather protection.

- Columns:
  - Main – 1,050 x 105 LVL16
- Rafter:
  - Main – 1,050 x 105 mm LVL16
  - End bay mullions – 400 and 300 x 63 mm LVL13
- Eave Rafter: 400 x 63 mm LVL13
- Purlins: 400 x 90 mm I-beam
- Girts:
  - Side Wall – 200 x 45 LVL13 @ 1465 cs
  - End Wall – 240 x 45 LVL13 @ 1550 cs
- Girt support columns:
  - Side Wall – 200 x 45 mm LVL13
  - End Wall – 240 x 45 mm LVL13
- Mullions: 400 x 63 mm LVL13
- Bracing: 24 mm diameter galvanised rod
- Lateral restraint blocking: 90 x 45 mm LVL13
- Flybrace: 90 x 45 mm LVL13

5.3 Steel Solution (8.0 m portal spacing) details

Refer to Appendix C for the structural drawing of the steel solution. All steel zinc is silicate treated.

- Columns:
  - Main – 530UB82
  - End Bay – 460 UB67
- Rafter:
  - Main – 530UB82
  - End Bay – 460UB67
- Purlin: 200Z24
- Girts: 200Z24 & one row of bridging
- Girt support columns: 250UB31
- Flybrace: 50 x 50 x 5 steel angle, 3 per rafter
- Bracing: 165 x 5 CHS

6

Cost Plan Results - Comparing the Timber and Concrete Solutions

Using the model industrial building described in Section 4, and the two timber solutions and the corresponding steel solution described in Section 5, a cost estimate and cost planning comparison helped determine the potential benefits of the timber solution.

The cost comparison was only undertaken for the parts of the building that were considered to have different costs under the competing scenarios. Some items were excluded, such as concrete slab, roof and wall sheeting, mechanical, electrical and plumbing. Effectively, the building superstructures were compared. Furthermore, construction costs that were also equal in all models were removed, such as crane costs, contractor's margin and all preliminaries. In order to create stable costing conditions, it was assumed that the building would be constructed in suburban Sydney.

The Cost Plan was initially developed by the Building Cost Information Service (BCIS), which independently measured off from supplied drawings, the quantities of materials used. This recent version continues to be based on this, with some amendments to take-off from errors that had been found. The updated steel and concrete price was obtained from the Australian Institute of Quantity Surveyors, Building Cost Index for March 2020. The timber prices were obtained as quotes from the market where needed. As the timber solution is a relatively new construction system, a price from the marketplace was necessary. The timber quote for both Timber Solutions was attained from Meyer Timber. Refer to Appendix D for full Cost Plan results.

A basic comparison of each model cost plan is shown in Table 1. Detailed results can be found in Appendix D.

Element	Timber Portal Solution 1 6.67 m Bay Spacing	Timber Portal Solution 2 10 m Bay Spacing	Steel Portal Solution 8.0 m Bay Spacing
Substructure	$22,160	$17,810	$36,490
Columns	$53,873	$23,815	$52,693
Roof	$192,083	$181,352	$186,640
External Walls	$44,612	$37,203	$43,638
Total	**$312,728**	**$260,180**	**$319,461**

Table 1: Comparison of material cost used in all three solutions.

Table 1 compares vital cost items that differentiate competing timber and steel solutions. The timber solution with the 10.0 m bay spacing is by far the cheapest of the three options (18.5% cheaper than steel), followed by the timber solution with the 6.67 m bay spacing (2.1% cheaper than steel).

There are a number of reasons the 10 m bay spacing is cheaper. The primary reason is that the building's components were designed using timber sizes that are available directly from the mill, without any need to fabricate, other than minor straight line cuts. This meant that there is no need to block bond elements together, unlike the 6.7 m bay spacing timber solution, saving considerable costs. Both the 6.7 m bay timber solution and the steel frame solution require fabrication that often increases the base cost of the element by many factors.

The other reason is that the wider bay spacing of the 10 m bay space timber solution had less timber in it than the 6.7 m bay space timber solution. The 10 m bay spaces timber solution had two fewer portal frames. Further reduction in the wood volume was by using I-beam purlins, instead of solid LVL. Even though girt and purlin costs are higher for the larger portal spacing, it is still the portal frame costs that dominate the overall cost profile for shed construction, and so where all other variables are equal, the larger bay spacing offers the lowest cost option.

It was also found that girt costs for the two timber solutions contributed only a minor proportion to overall costs difference and also remained relatively stable, irrespective of portal bay spacing. The inclusion of intermediate support columns means that the load on girts is less sensitive to changes in bay spacing. As such, timber I-beam girts offer a cost-effective and relatively cost-stable proposition, even as portal bay spacing change.

Further, purlins can be cost-effectively increased in span by simply increasing the depth of the plywood web of the 'I' beams used (i.e. by an extra 100 mm). Timber I-beam purlins may, therefore, provide a similarly cost-effective component in the steel solution (as a replacement for steel purlins).

7

Factors Affecting the Cost Competitiveness of Timber

The following section discusses other methods or techniques that may provide further savings to the timber solution. These methods or procedures have not been included in the costing exercise, described in Section 6.

7.1 Erection Onsite

For productivity and process improvement, an increasingly popular technique for the erection of timber portal buildings is to fabricate certain assemblies off the slab and then crane them into position. For instance, the rafter and purlin assemblies are typically fabricated off the deck for every second portal bay. These bay assemblies are then craned into place (see Figure 3), by sitting the rafters into the premade pockets of the pre-positioned columns. Once these assemblies are in place, the purlins for the neighbouring bays are placed in a more conventional manner. Overall, this approach improves cost and – to some extent – safety, as the amount of work undertaken at height is substantially reduced.

Figure 3: Timber portal roof structure constructed on the ground. *Image: Timberbuilt*

7.2 Timber Connectors

Most timber connectors are designed to mimic steel connection systems so that the approach to fabrication is similar for the two competing systems. Details on specific joints are provided below.

7.2.1 Portal Frame Knee Connector

The connection between the portal frame column and the rafter is designed to transfer bending moments at this point and provides a complex connection for both timber and steel. In the two timber options, different approaches were taken to the key joints in the portal frames that aim to simplify fabrication on-site, using prepared components, including:

- **Timber Solution 1 (6.7 m portal spacing)** – This solution used a recently established moment connected, called QuickConnect[2], developed by the Structural Timber Innovation Company and Auckland University. The Quick-Connect moment connection is a moment resisting joint for timber portal frame buildings. It is based on a system of pre-tensioned rods which are placed at the upper and lower extremities of the portal frame members. Bending moment is transferred across the joint by means of a moment couple carried by steel rods. The rods are housed in U-shaped timber sleeves attached to the sides of the portal frame members, by inclined screws, refer to Figure 4.

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[2] Further information can be found Quick Connect moment joints from the WoodSolutions Design Guide No. 33-EXPAN Quick Connect Moment Connection.

Figure 4: Quick connect moment connector in Netball Central*[3] *(Image: Geoff Ambler; Ethan Rohloff).

- Timber Solution 2 (10.0 m portal spacing) – LVL Gusset is a more traditional moment connector used for timber portal frames. The gussets are nailed onto the rafter and column with many nails. Often the nailing pattern contains many rings around the edge of gussets (see Figure 3).

7.2.2 Purlin and Girt Connection

In both timber solutions 1 and 2, the I-beam or LVL purlins and girts are connected to the main rafter through a block fixed to the side of the portal's rafter or column (fixed prior to purlin or girt's placement). For the I-beam purlin, the block is screw fixed to the web of the I-beam such that it fits between the two flanges of the I-beam and sits directly under the top flange of the I-beam. This provides a convenient means of locating the purlin, which is also able to rest on the block. The I-beam purlin is then screwed or nailed fixed through the web, into the block (see Figure 5).

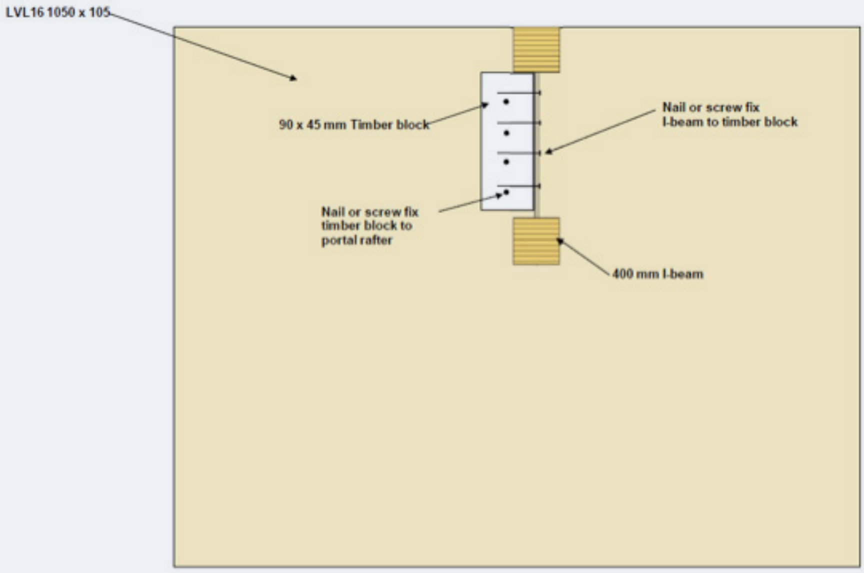

Figure 5: I-beam purling connection via timber block to rafter.

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[3] Further information on Netball Central can be found in WoodSolutions web site - Case Studies

7.3 Timber Portal Frame Member Sizes

One aspect that differentiates the two timber solutions from the steel solution is the need for deeper column and rafter elements. The deeper columns and rafter impact of timber options can be reduced by mounting the purlins and girts to the side of the column or rafter. This results for Timber Solution 1 – 390 mm and Timber 2 Solution only 220 mm overall height increase. For instance:

- Steel solution: 610 UB with 200Z24 over purlins (830 mm overall depth)
- Timber Solution 1: 1,220 mm rafter and columns (1,220 mm overall depth)
- Timber Solution 2: 1,050 mm rafter (1,050 mm overall depth).

Further, the timber purlins and girts are designed as simply supported beams. This is primarily driven by the I-beams or LVL used for this purpose are not long enough to span continuously over multiple portal bay spacing, i.e. I-beam or LVL is commercially available to a maximum length is 13.2 m, while a double span purlin or girt would require up to 20.0 m length. Even so, the side mounting of the purlins and girts (mentioned above) does serve to assist in providing lateral stability to the portal rafters.

8

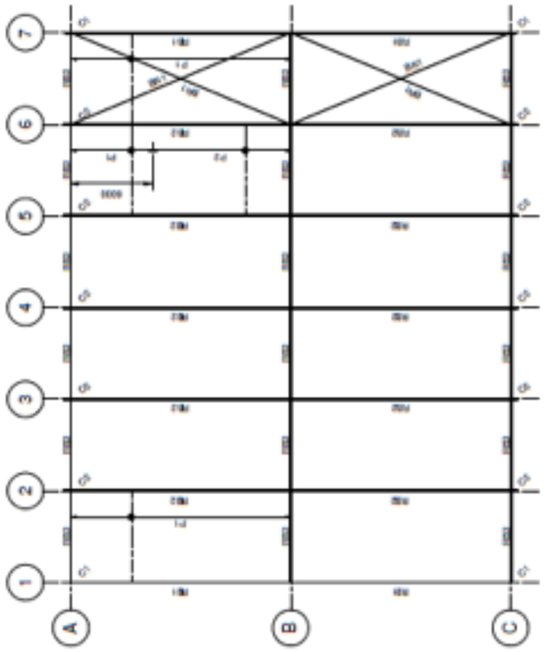
Conclusion

A model single-storey industrial shed was designed and priced using a timber solution, with two portal bay spacing considered, and a more conventional steel-framed solution for a theoretical location in suburban Sydney. The site was assumed to have no significant cost implications concerning site access, ground conditions or neighbouring properties. Furthermore, only the costs that were different were considered; this substantially meant only the superstructure was measured.

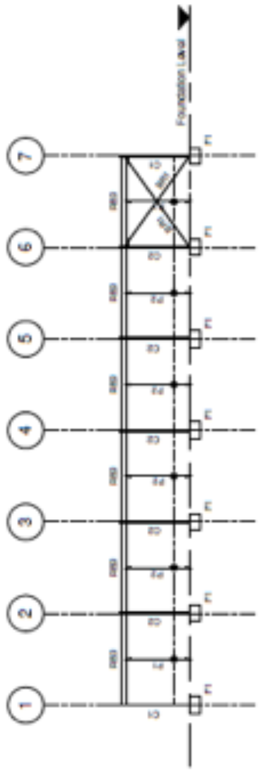
Timber Solution 2 (10.0 m bay spacing) was found to cost $59,281 or 18.5% less than the steel solution, while there was little difference between Timber Solution 1 and the steel solution. The significant cost difference between Timber Solution 2 and the steel solution and Timber Solution 1 was due to using timber elements that don't need a secondary fabrication process. Using timber sizes that are available from mills and only require minor cutting to length, resulted in these savings. Also, Timber Solution 2 had considerably less timber in it as the number of portal frames were less and the solution used I-beams instead of solid timber.

It is recommended that industrial timber sheds be considered as a viable alternative to traditional steel frames. Importantly, the level of cost comparison with steel must go beyond a basic comparison of material costs, and must instead weigh up the full range of cost-sensitive issues affecting the construction process.

Appendix A: Timber Solution 1 – 6.7 m bay spacing



Roof Plan
Scale : 1 : 200



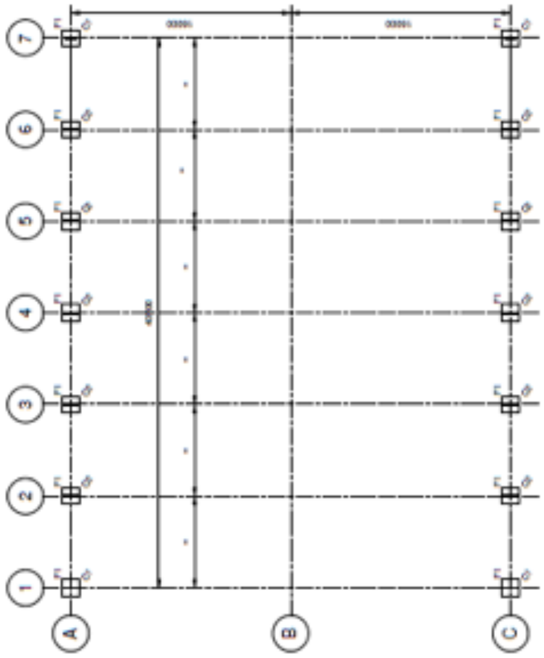
South Elevation
Scale : 1 : 200

Member Schedule		
Type Mark	Northern Wind Region	Southern Wind Region
BH1	25 Dia. Rod (hung from purlins)	25 Dia. Rod (hung from purlins)
C1	1100x110	800x110
C2	1300x110	1100x110
F1	1600x1600x1000dp	1200x1200x800dp
RB1	1100x110	800x110
RB2	1200x110	1100x110
RB3	600x110	400x110

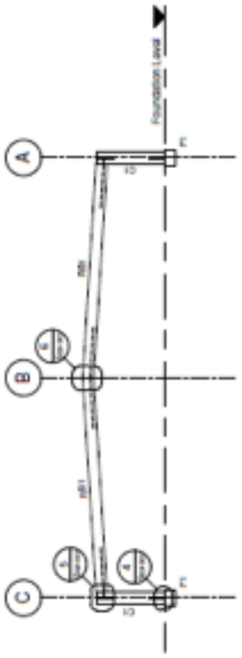
Note:

For Type Mark P1:
- For Northern Region – 400x110 at 1100 crs.
- For Southern Region – 250x110 at 1500 crs.

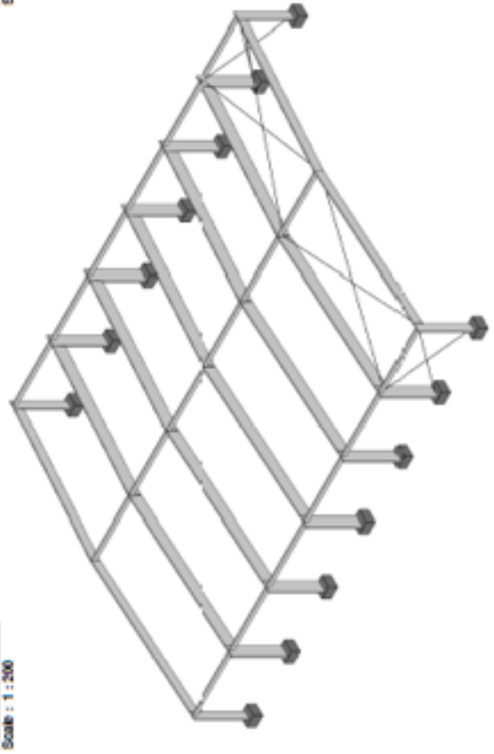
For Type Mark P2:
- For Northern Region – 300x110 at 1100 crs.
- For Southern Region – 150x110 at 1500 crs.



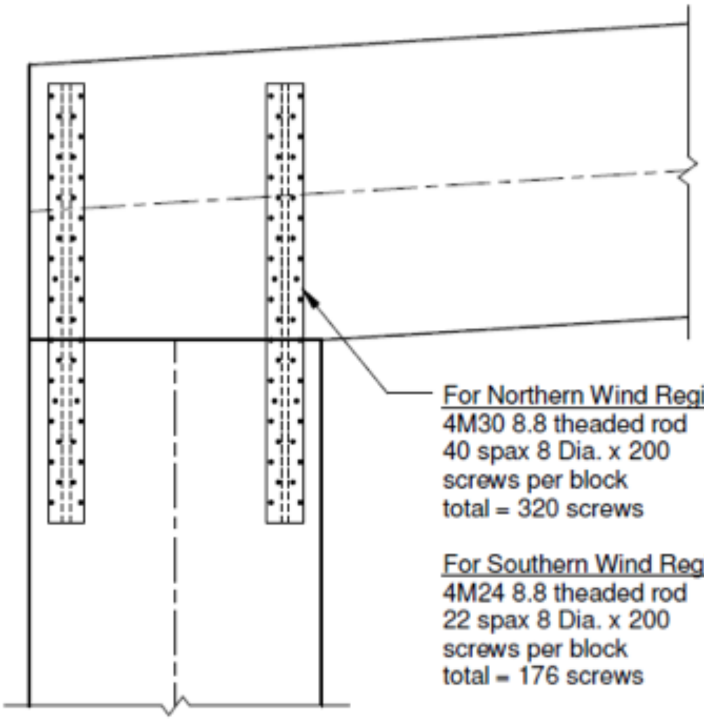
Foundation Plan
Scale : 1 : 200



East Elevation
Scale : 1 : 200



3D View

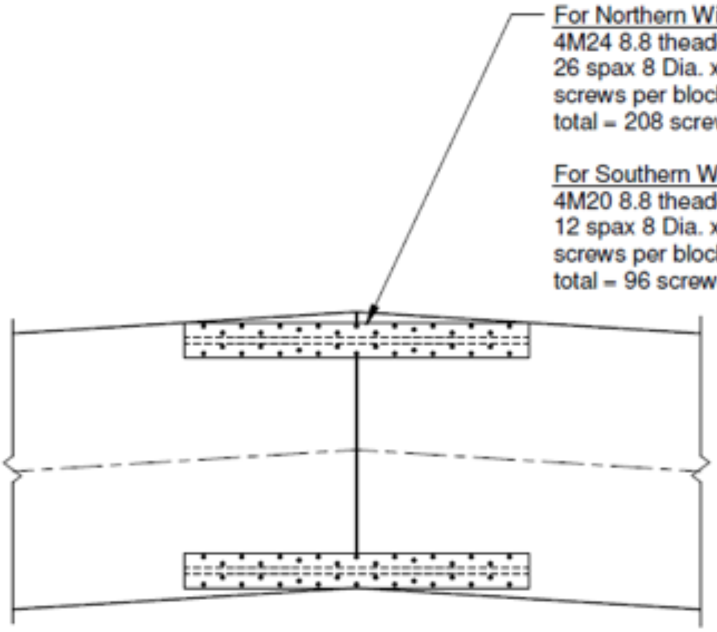


For Northern Wind Region:
4M30 8.8 theaded rod
40 spax 8 Dia. x 200
screws per block
total = 320 screws

For Southern Wind Region:
4M24 8.8 theaded rod
22 spax 8 Dia. x 200
screws per block
total = 176 screws

Detail 5

Scale : 1 : 20



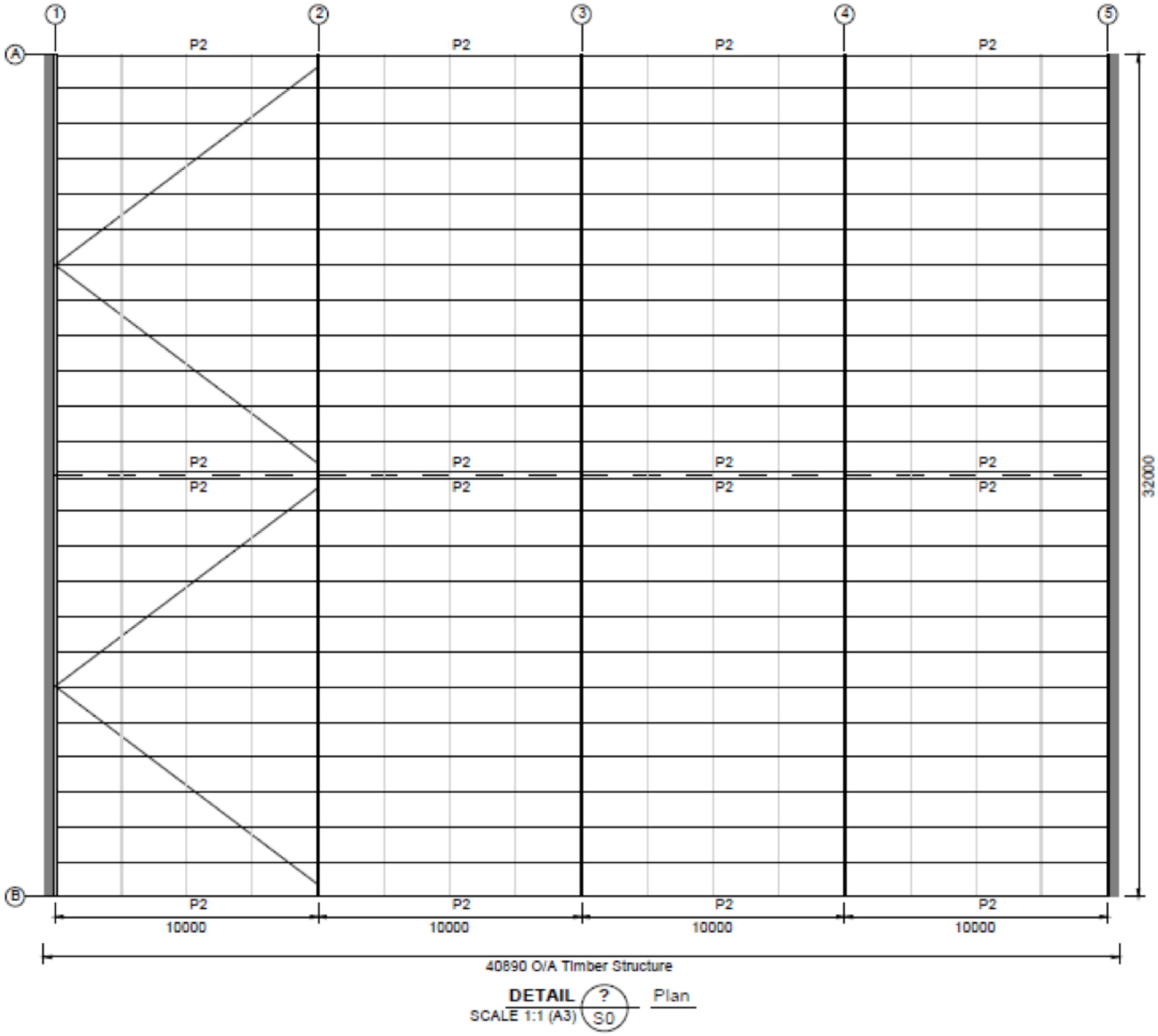
For Northern Wind Region:
4M24 8.8 theaded rod
26 spax 8 Dia. x 200
screws per block
total = 208 screws

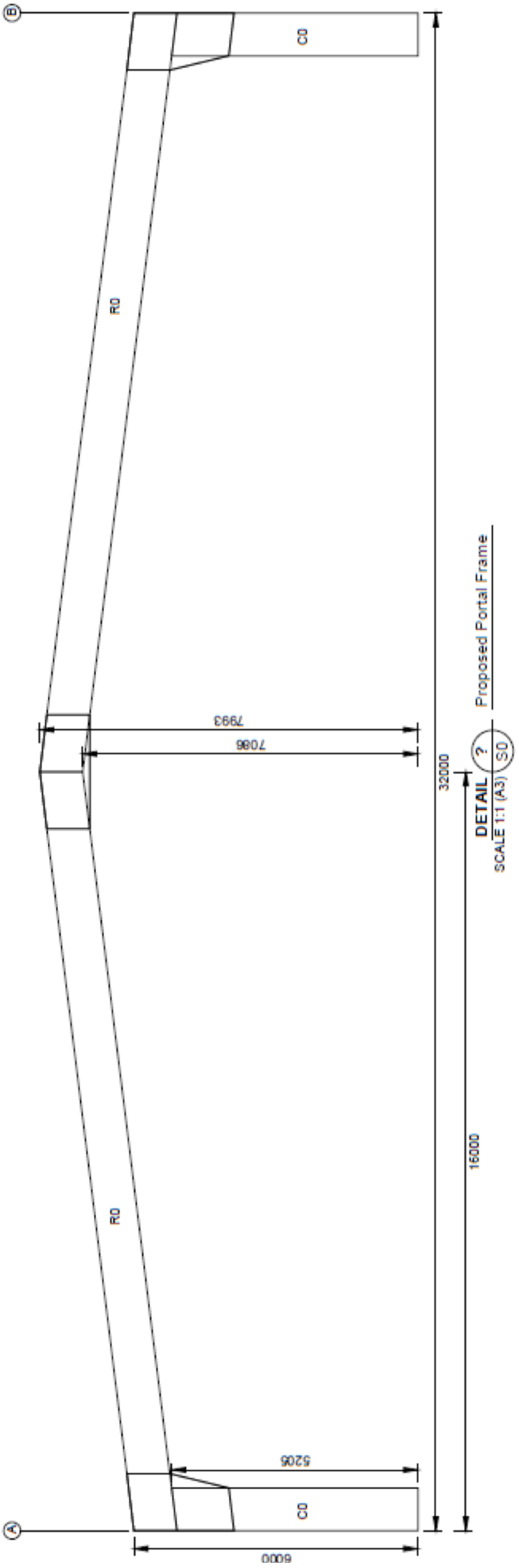
For Southern Wind Region:
4M20 8.8 theaded rod
12 spax 8 Dia. x 200
screws per block
total = 96 screws

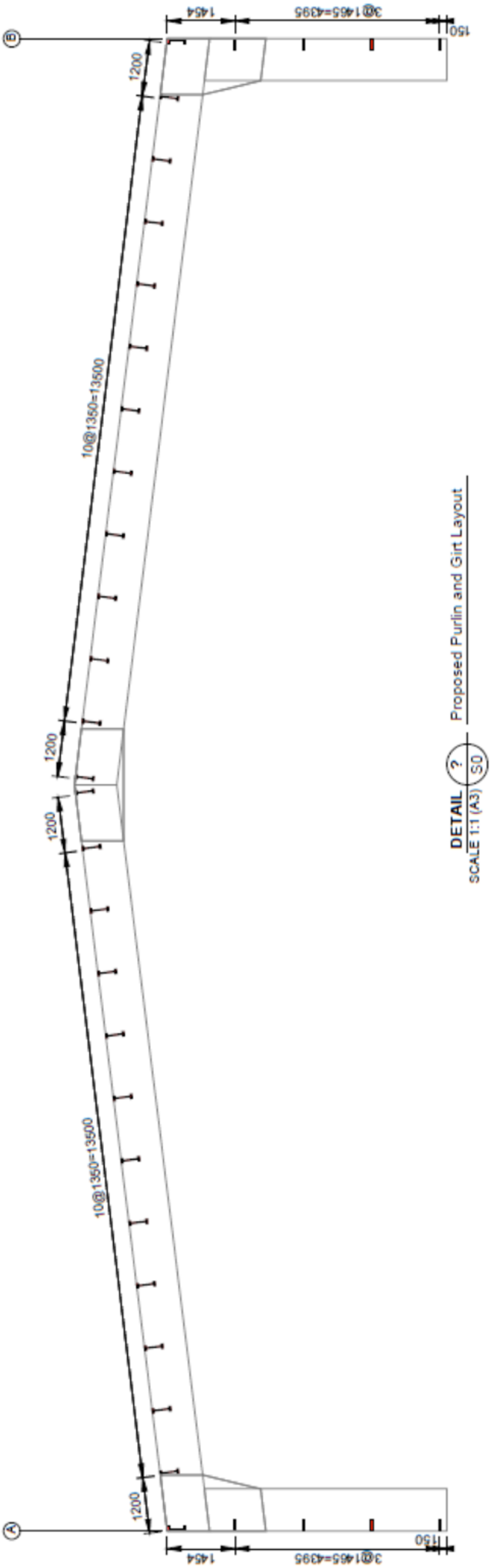
Detail 6

Scale : 1 : 20

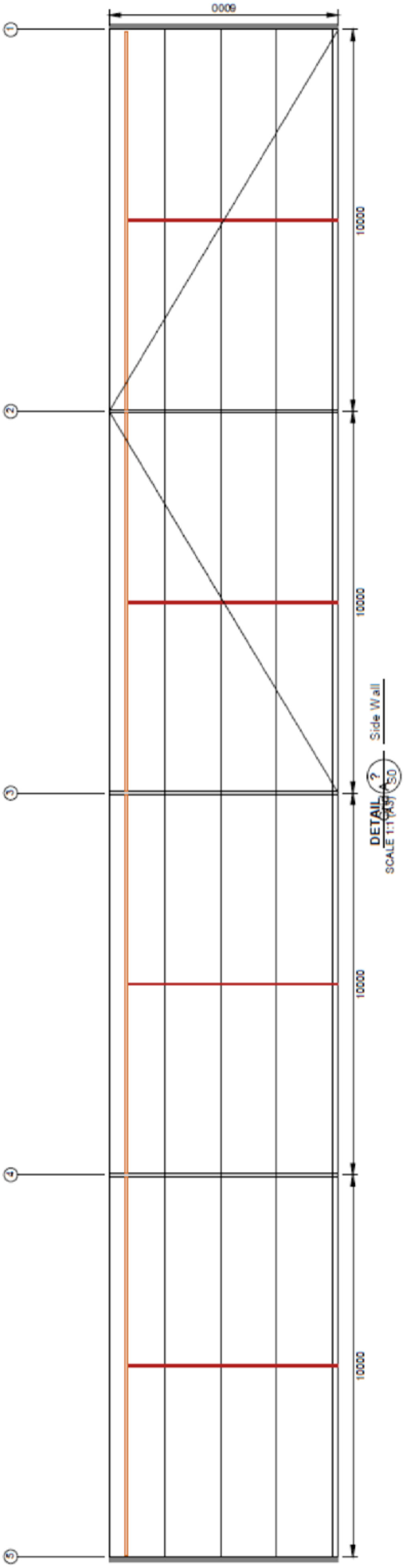
Appendix B: Timber Solution 2 – 10 m bay spacing

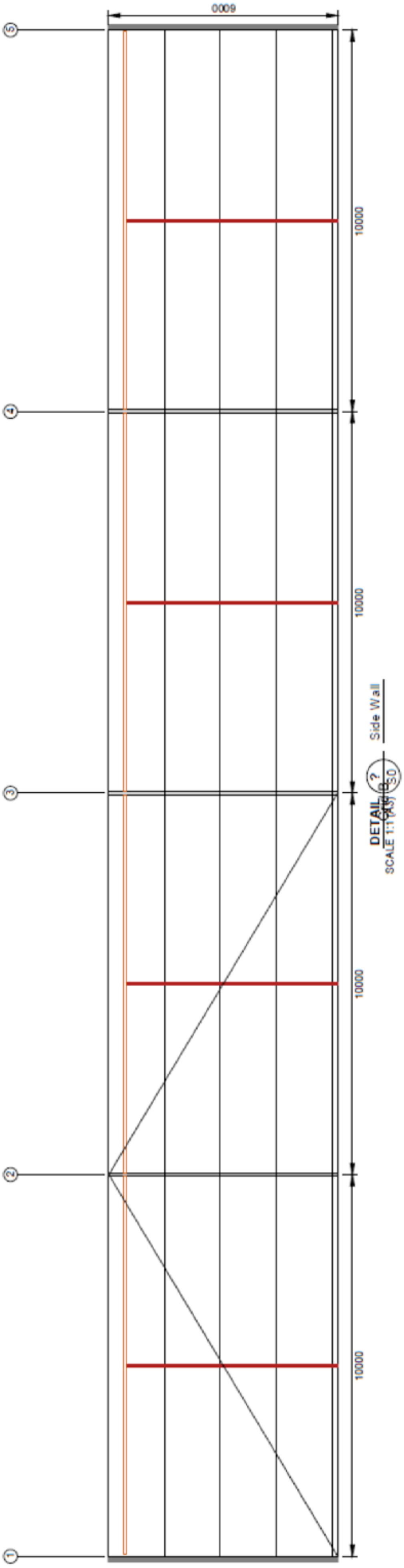


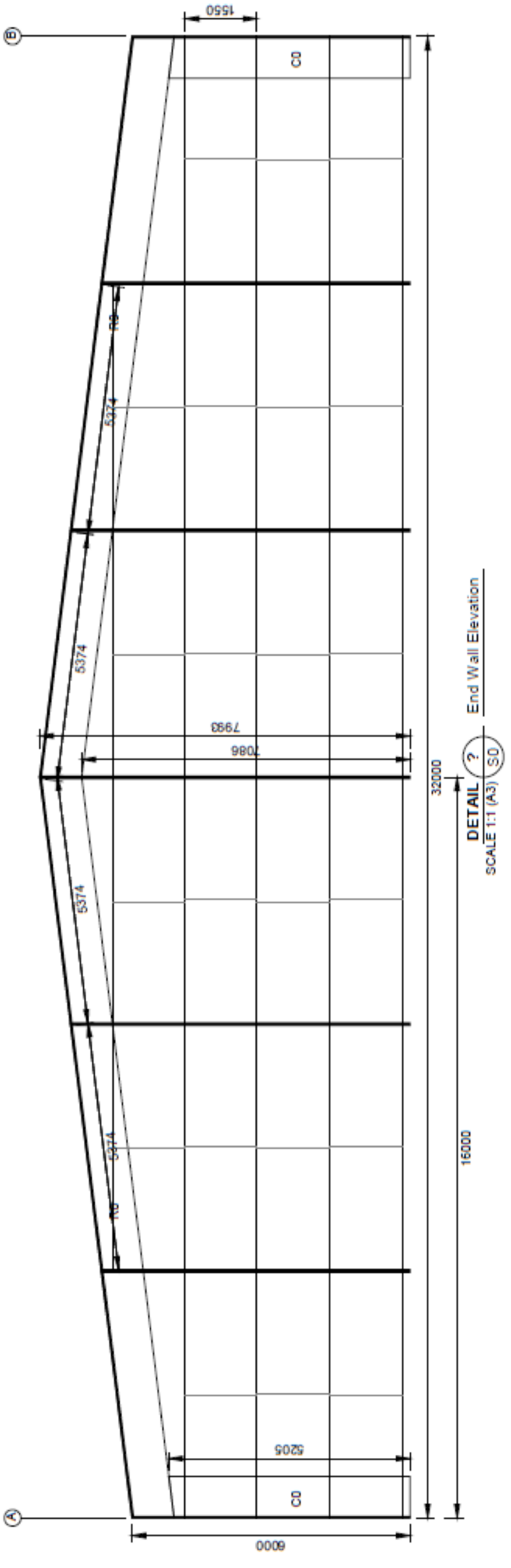

Proposed Portal Frame
DETAIL
SCALE 1:1 (A3)
?
S0
A
B
C0
C0
R0
R0
7993
7086
5206
6000
32000
16000

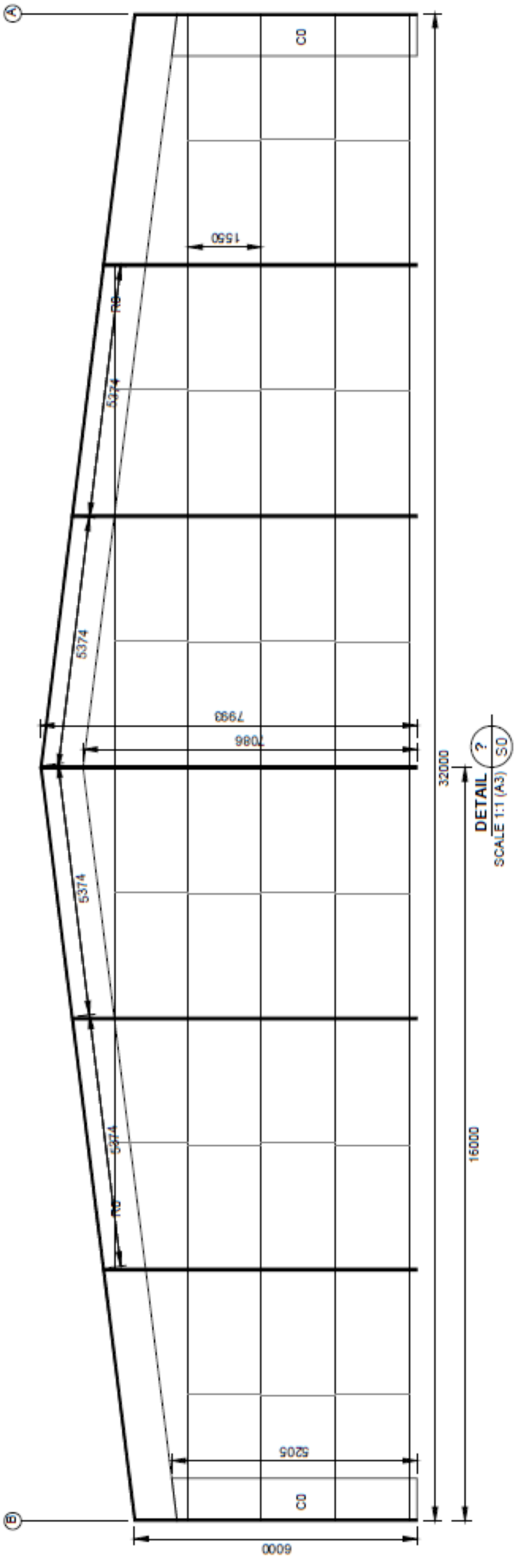


DETAIL ? S0 Proposed Purlin and Girt Layout
SCALE 1:1 (A3)

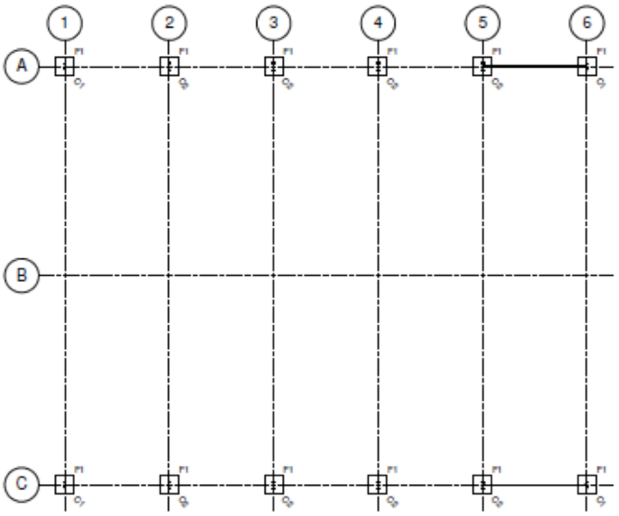

6000
10000
10000
10000
10000
Side Wall
DETAIL ?
SCALE 1:1 (A3)
30
1
2
3
4
5


6000
10000
10000
10000
10000
Side Wall
DETAIL ?
SCALE 1:1 (A3)
30
5
4
3
2
1

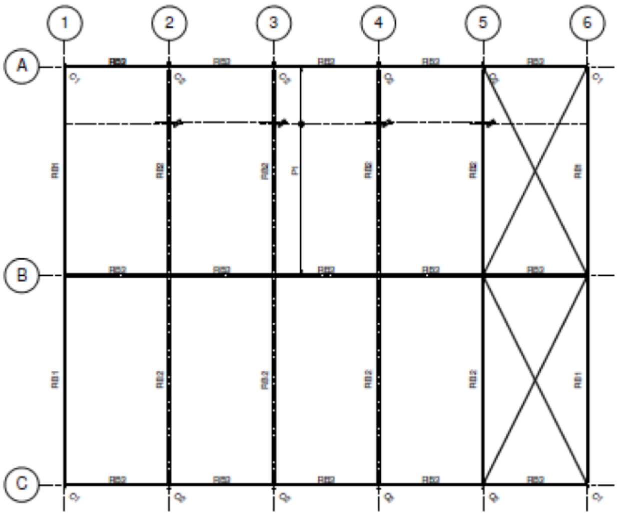

End Wall Elevation
DETAIL
SCALE 1:1 (A3)
?
S0
A
B
1550
C0
5374
5374
5374
5374
R0
R0
7993
7086
32000
16000
5205
C0
6000


DETAIL
SCALE 1:1 (A3)
?
S0
A
B
C0
1550
R0
5374
5374
5374
5374
R0
7993
7086
32000
16000
5205
C0
6000

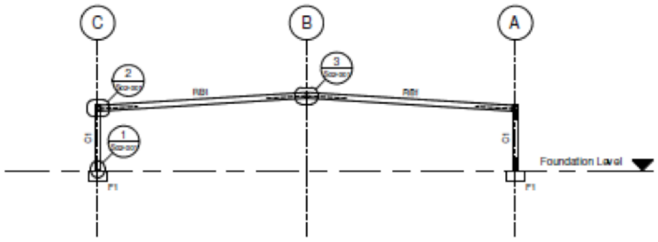
Appendix C: Steel Solution – 8 m bay spacing



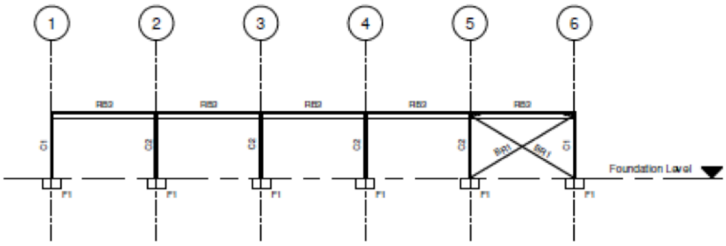
Foundation Plan
Scale : 1 : 200



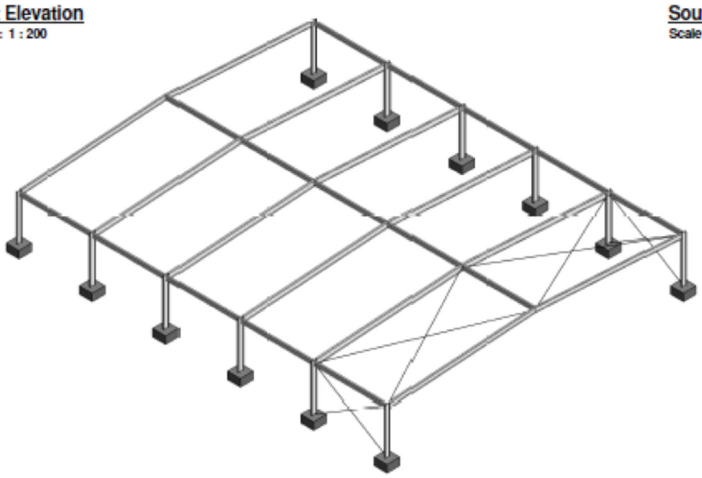
Roof Plan
Scale : 1 : 200



East Elevation
Scale : 1 : 200



South Elevation
Scale : 1 : 200

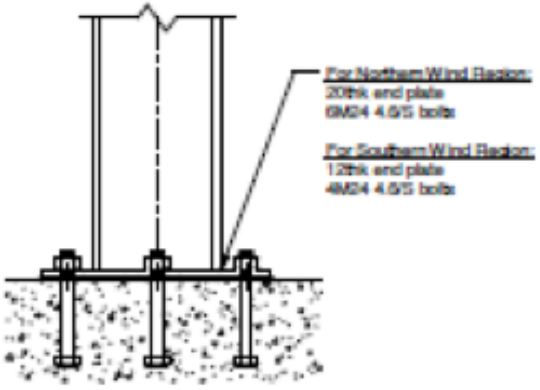


3D View

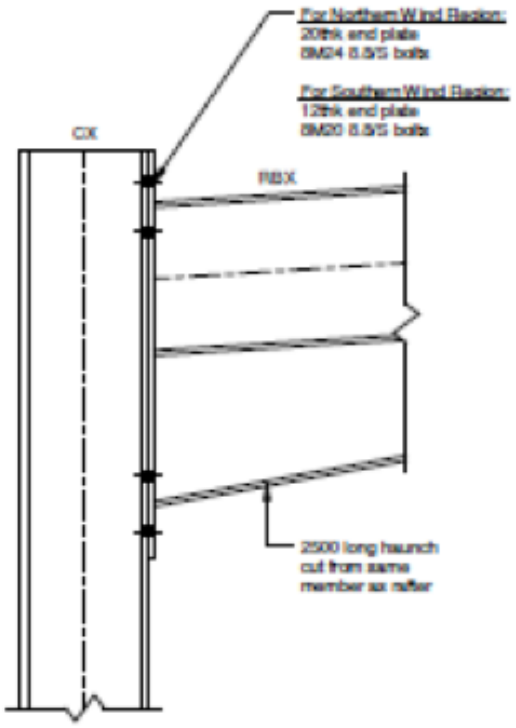
Member Schedule		
Type Mark	Northern Wind Region	Southern Wind Region
BR1	25 Dia. Rod (hung from purlins)	25 Dia. Rod (hung from purlins)
C1	460UB67	610UB101
C2	530UB82	610UB125
F1	1400x1400x800dp	1750x1750x1000dp
RB1	460UB67 x 3 rows of fly bracing	610UB101 x 3 rows of fly bracing
RB2	530UB82 x 3 rows of fly bracing	610UB125 x 3 rows of fly bracing
RB3	410UB54 x 3 rows of fly bracing	530UB82 x 3 rows of fly bracing

Note:

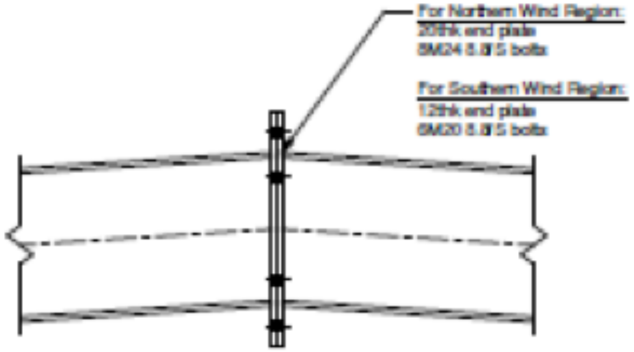
For Type Mark P1:
- For Northern Region – 250Z24/19 Purlins at 1600 crs. plus 1 row of bridging
- For Southern Region – 200Z24/19 Purlins at 1600 crs. plus 1 row of bridging



Detail 1
Scale : 1 : 10



Detail 2
Scale : 1 : 10



Detail 3
Scale : 1 : 10

Appendix D: Detailed Cost Information

Project Name: Industrial Building – Timber Frame 6.67 m Bays - Timber Solution 1

Element		$/m^2 GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
Industrial Steel Frame 8 m Bays			**1,280**	**m^2**	**$244.32**	**$312,728**
Substructure		**$17.31**				**$22,160**
1	1,200 x 1,200 x 800 Column base, including excavation, concrete, reinforcement	$16.31	14	no.	$1,400	$19,600
2	Holding down bolt assembly comprising 4M24 bolts cast into concrete with cages	$1.70	14	no.	$155	$2,170
3	20 mm grout under base plates	$0.30	6	m^2	$65	$390
Columns		**$42.09**				**$53,873**
1	1,220 x 135 LVL13 block bonded columns; 10 No.	$22.97	60	m	$490	$29,400
2	800 x 135 LVL13 block bonded columns; 4 No.	$8.01	24	m	$410	$10,250
3	Knee gusset; Quick Connect LVL13	$1.13	20	no.	$72	$1,440
4	Knee gusset; Quick Connect Screws 22 x 8 Dia x 200 mm per block, total 88 screws	$1.56	20	no.	$100	$2,000
5	Knee gusset; Quick Connect M20 threaded rod, bearing plate and nut	$4.69	40	no.	$150	$6,000
6	24 mm diameter rod bracing	$3.69	105	m	$45	$4,725
7	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$0.05	0.4	t	$144	$58.00
Roof		**$150.06**				**$192,083**
1	1,220 x 135 LVL13 block bonded roof beams; 10 No.	$62.02	162	m	$490	$79,380
2	800 x 135 LVL13 block bonded roof beams; 4 No.	$20.82	65	m	$410	$26,650
3	400 x 135 LVL13 block bonded roof beams; 18 No.	$19.22	120	m	$205	$24,600
4	Purlins P1 @ 1,250 centres; 300 x 45 LVL13; 104 No.	$24.07	693	m	$44.45	$30,804
5	Purlins P2 @ 1,500 centres; 300 x 45 LVL13; 48 No.	$11.11	320	m	$44.45	$14,225
6	Ridge gusset; Quick Connect LVL13	$1.58	28	no.	$72	$2,016
7	Ridge gusset; Quick Connect Screws 12 x 8 Dia x 200 mm per block, total screws 48	$2.19	28	no.	$100	$2,800
8	Ridge gusset; Quick Connect M20 threaded rod, bearing plates and nuts	$6.56	56	no.	$150	$8,400
9	24 diameter galvanised roof bracing	$2.46	70	m	$45.00	$3,150
10	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$0.05	0.4	t	$144	$58
External Walls		**$34.85**				**$44,612**
1	Mullions End Wall; 400 x 63 LVL13; 10 No.	$3.26	68	m	$61.30	$4,168
2	Mullions Side Wall; 400 x 63 LVL13; 12 No.	$2.87	60	m	$61.30	$3,678
3	Girts P1 @ 1250; 300 x 45 LVL13; 40 No.	$9.27	267	m	$44.45	$11,868
4	Girts P2 @ 1500; 300 x 45 LVL13; 84 No.	$19.45	560	m	$44.45	$24,898
Preliminaries Adjustment		**$0**				**$0**
1	Provision of time-related preliminaries based on the duration of structure construction time	0	0	weeks	-	0
2	Preliminaries based on reduced Construction duration of:	0	0	weeks	-	0
Total Cost						**$312,728**

Notes

1. The cost estimates are priced in March 2020 and based on construction in the Sydney Region.
2. Concrete and steel rates are based on the Australian Institute of Quantity Surveyors, Building Cost Index, March 2020.
3. Excavation rates include for backfilling and removal of surplus material from the site a distance of about 10 kilometres. Excavation rates do not include for shoring or planking and strutting.
4. All concrete is N20 unless otherwise stated.
5. Rates for reinforcement include for bending, tying, supports and placing, rolling margin and bending schedules.
6. The timber costs have been obtained from the market place, through Meyer Timber.
7. All timber elements are H2S termite treated.
8. All fabricated timber element have been sanded finish, simple CNC fabrication, CAD shop drawings provided, one coat of finish for construction period weather protection, and wrapped for transport.
9. The cost comparison of steel and timber frames uses the steel frame construction program duration as the base, and subsequently, there is no adjustment to the preliminaries.
10. The steelwork is assumed to be pre-fabricated and bolted together on-site with minimum welding required.
11. Provision has included for 5% steelwork fittings.
12. Structural steel includes rolling margin, hand cleaning shop priming, erection complete with all necessary temporary bracing and an allowance of 8% of the fabricated cost to cover shop detailing.
13. The crane costs are assumed equivalent for all models.
14. Contractor's margin is not included.

Project Name: Industrial Building – Timber Frame 10 m Bays - Timber Solution 2

Element		\$/m^2 GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
Industrial Timber 10 m Bay			**1,280**	**m^2**	**$203.27**	**$260,180**
Substructure		**$13.81**				**$17,810**
1	1,600 x 1,600 x 800 mm Column base, including excavation, concrete, reinforcement	$12.50	10	no.	$1,600	$16,000
2	Holding down bolt assembly comprising 4M24 bolts cast into concrete with cages	$1.21	10	no.	$155	$1,550
3	20 mm grout under base plates	$0.20	4	m^2	$65	$260
Columns		**$18.61**				**$23,815**
1	1,050 x 105 LVL16 columns; 10 No.	$14.87	52	m	$366	$19,032
2	24 mm diameter rod bracing	$3.69	105	m	$45	$4,725
3	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$0.05	0.4	t	$144	$58
Roof		**$116.81**				**$181,352**
1	1,050 x 105 LVL16 columns; 10 No.	$46.61	163	m	$366	$59,658
2	Knee gusset; 63 4x-band LVL13	$10.39	20	no.	$665	$13,300
3	Ridge gusset; 63 4x-band LVL13	$5.20	10	no.	$665	$6,650
4	Purlins; HJ400 90 I-beam	$40.22	1,040	m	$49.50	$51,480
5	Eaves beam; 400 x 63 LVL13; 8 No.	$3.93	82	m	$61.30	$5,027
6	Fly braces; 90 x 45 LVL13 screwed to rafter and purlin	$2.31	80	no.	$37.00	$2,960
7	Lateral restraint; 90 x 45 LVL nailed to underside of purlins 1,350 mm long	$2.19	56	no.	$50.00	$2,800
8	Lateral restraint; 90 x 45 LVL blocking piece to fix purlins	$4.10	210	no.	$25.00	$5,250
9	24 diameter galvanised roof bracing	$1.83	52	m	$45.00	$2,340
10	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$0.03	0.4	t	$144	$58
External Walls		**$29.06**				**$37,203**
1	Mullions End Wall; 400 x 63 LVL13; 10 No.	$3.54	74	m	$61.30	$4,536
2	Mullions Side Wall; 400 x 63 LVL13; 8 No.	$2.30	48	m	$61.30	$2,942
4	Girts Side Wall; 200 x 45 LVL13; 32 No.	$11.88	400	m	$38.00	$15,200
5	Girts End Wall; 240 x 45 LVL13; 10 No.	$9.65	305	m	$40.50	$12,352
6	24 mm diameter rod bracing	$1.65	47	m	$45.00	$2,115
7	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$0.05	0.4	t	$144	$58
Preliminaries Adjustment		**$0**				**$0**
1	Provision of time-related preliminaries based on the duration of structure construction time	0	0	weeks	-	0
2	Preliminaries based on reduced Construction duration of:	0	0	weeks	-	0
Total Cost						**$260,180**

Notes

1. The cost estimates are priced in March 2020 and based on construction in the Sydney Region.

2. Concrete and steel rates are based on the Australian Institute of Quantity Surveyors, Building Cost Index, March 2020.

3. Excavation rates include for backfilling and removal of surplus material from the site a distance of about 10 kilometres. Excavation rates do not include for shoring or planking and strutting.

4. All concrete is N20 unless otherwise stated.

5. Rates for reinforcement include for bending, tying, supports and placing, rolling margin and bending schedules.

6. The timber costs have been obtained from the market place, through Meyer Timber.

7. All timber elements are H2S termite treated.

8. All fabricated timber element have been sanded finish, simple CNC fabrication, CAD shop drawings provided, one coat of finish for construction period weather protection, and wrapped for transport.

9. The cost comparison of steel and timber frames uses the steel frame construction program duration as the base; and subsequently, there is no adjustment to the preliminaries.

10. Knee and Ridge gussets include a nailing allowance.

11. The steelwork is assumed to be pre-fabricated and bolted together on-site with minimum welding required.

12. Provision has been included for 5% steelwork fittings.

13. Structural steel includes rolling margin, hand cleaning shop priming, erection complete with all necessary temporary bracing and an allowance of 8% of the fabricated cost to cover shop detailing.

14. The crane costs are assumed equivalent for all models.

15. The contractor's margin is not included.

Project Name: Industrial Building – Steel Frame 8 m Bays - Steel Solution

Element		$/$m^2$ GFA	Quantity	Unit	Unit Rate ($)	Cost ($)
Industrial Steel Frame 8 m Bays			**1,280**	**m^2**	**$249.57**	**$319,461**
Substructure		**$28.51**				**$36,490**
1	1,750 x 1,750 x 1,000 Column base, including excavation, concrete, reinforcement	$26.95	12	No.	$2,875	$34,500
2	Holding down bolt assembly comprising 4M24 bolts cast into concrete with cages	$1.45	12	No.	$155	$1,860
3	20 grout under base plates	$0.10	2	m^2	$65	$130
Columns		**$41.17**				**$52,693**
1	460UB67 Column; 4 No.	$9.94	1.61	t	$7,900	$12,719
2	530UB82 Column; 8 No.	$24.32	3.94	t	$7,900	$31,126
3	165 x 5 CHS bracing	$4.94	40	m	$158	$6,320
4	Allowance for steel plates and bolts fittings of 5% on structural steelwork	$1.98	0.32	t	$7,900	$2,528
Roof		**$145.81**				**$186,640**
1	310UB40 Roof beam; 4 No.	$15.92	2.58	t	$7,900	$20,382
2	460UB67 Roof beam; 8 No.	$53.33	8.64	t	$7,900	$68,256
3	165 x 5 CHS Roof beam; 15 No.	$14.57	2.36	t	$7,900	$18,644
4	50 x 50 x 5 steel angle in fly bracing	$6.20	122	no.	$65	$7,930
5	165 x 5 CHS bracing	$15.18	123	m	$158	$19,434
6	Allowance for plates and bolts fixings 5% on structural steelwork	$5.06	0.82	t	$7,900	$6,478
7	200Z24/19 Galvanised purlins	$30.86	1,056	m	$37.40	$39,494
8	Bridging between 200Z24/19 Galvanised purlins	$4.70	161	m	$37.40	$6,021
External Walls		**$34.09**				**$43,638**
1	200Z24/19 Galvanised girts	$20.80	712	m	$37.40	$26,629
2	Sag rod between 200Z24/19 Galvanised girts	$4.46	112	m	$51.00	$5,712
3	250UB31 Mullion including zinc silicate treatment; 6 No	$8.39	1.36	t	$7,900	$10,744
4	Allowance for plates bolts and connections 5% on structural steelwork	$0.43	0.07	t	$7,900	$553
Preliminaries Adjustment		**$0**				**$0**
1	Provision of time-related preliminaries based on the duration of structure construction time	0	0	weeks	-	0
2	Preliminaries based on reduced Construction duration of:	0	0	weeks	-	0
Total Cost						**$319,461**

Notes

1. The cost estimates are priced in March 2020 and based on construction in the Sydney Region.
2. Concrete and steel rates are based on the Australian Institute of Quantity Surveyors, Building Cost Index, March 2020
3. Excavation rates include for backfilling and removal of surplus material from the site a distance of about 10 kilometres. Excavation rates do not include for shoring or planking and strutting.
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10. The crane costs are assumed equivalent for all models.
11. The contractor’s margin is not included.


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Timber Concrete Composite Floors

Technical Design Guide issued by Forest and Wood Products Australia

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Introduction

Timber concrete composite (TCC) floor systems are relatively new to Australia and satisfactory performance requires a rigorous design procedure addressing both ultimate and serviceability limit states. TCC structures have a degree of complexity, since they combine two materials that have very different mechanical properties and respond in different ways to their environment. In addition, most TCC structures exhibit partial (not full) composite action.

There are several design procedures for TCC structures. Among these, the Eurocode 5 (EC5) procedure[1] is relatively straightforward and has been successfully implemented in Europe. It uses a simplification for modelling the complex timber–concrete interaction known as the 'Gamma coefficients' method, which manipulates properties of the concrete member to predict the cross-section characteristics of the structure.

This Guide presents a design procedure for TCC floor structures that is based on the Gamma method and *AS 1720.1 Timber structures Part 1: Design methods.*

The Eurocode 5 approach has been adopted as the underlying basis for the design procedures presented in this document; modified to comply with current design codes and practices in Australia. It comprises normative parameters for the strength and safety (ultimate limit state) and informative guidelines for appearance, deflection limits and comfort of users (serviceability limit states). While the latter must be defined by designers to meet the specific functional requirements of the floor under consideration, it is recommended that the serviceability guidelines in this document should be adopted as a minimum standard for TCC floors.

At the time of publication of this Guide, there is still uncertainty about some aspects of long-term deflection of TCC floors. As such, it is recommended that designers exercise caution when applying the design procedures contained in this document to floors exceeding 8 m in span, utilising the notched connections and crossed screws. This caveat restriction is due to a lack of research data at this stage to support the behaviour of floors and connections for spans exceeding 8 m. Some general considerations for manufacturing the notched connections are presented in this Guide.

Design of floor diaphragms for wind loading has been described in detail in WoodSolutions Technical Design Guide *#35: Floor Diaphragm.*

Fire resistance design is not covered in this Design Guide, for further information on Fire Design, please refer to WoodSolutions Technical Design Guide *#15: Fire Design.*

2

Design Requirements

The design procedure addresses performance requirements for the strength (normative) and serviceability (advisory or informative) limit states. Load type and intensity, load combinations and modification factors for both the ultimate and the serviceability limit states have been defined in accordance with the AS 1170 Structural Design Action series (AS 1170).

The limit states that require checking are:

1. **Short-term ultimate limit state**, where the response of the structure to the maximum load is analysed. It generally corresponds to short-term exertion of the structure.
2. **Long-term ultimate limit state**, where the analysis focuses on the response of the structure to a quasi-permanent loading and avoiding failure due to creep of the timber member in particular. (Checking the end-of-life ultimate limit states corresponds to analysis and assessment of the durability/reliability of the structure.)
3. **Short-term serviceability limit state**, which corresponds to the instantaneous response of the structure to an imposed load.
4. **Long-term serviceability limit state** analysis considers time-dependent variations of the material properties; particularly creep, to identify the service life behaviour.
5. **1.0-kN serviceability limit state**: the instantaneous response to and imposed load of 1.0 kN at mid-span provides an indication of dynamic behaviour.

3

Design Procedure

The design procedure has three fundamental stages:

1. Identifying the characteristics of the TCC cross-section.
2. Evaluation of the strength capacity of the structure.
3. Assessment of the serviceability limit states.

3.1 Cross-section Characteristics

The free body diagram of a T-shape TCC module with partial composite action including internal and external loads is illustrated in Figure 3.1.

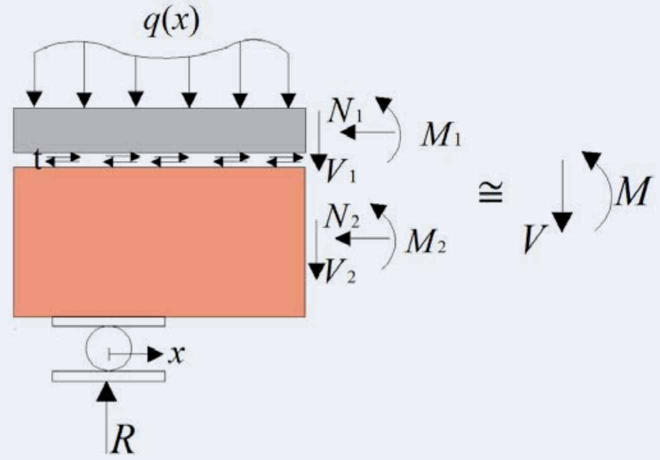


Figure 3.1: Internal and external loads applied on TCC system. *Source: Moshiri, F*[2]*.*

The Gamma method in Eurocode 5 (part 1 annex B) has been recognised as the only specific design provision used to analyse TCC structures, with reasonable accuracy in determining the resultant stresses and deformations.

In the Gamma method, it is assumed there is no vertical separation between concrete slab and timber joist and plane sections remain plane, except for the discontinuity at the connection interface.

The Gamma method evaluates effective bending stiffness (EI_{ef}) using the shear bond coefficient (Y). The effective bending stiffness is used to check the design resistance of the connector and the stress values in the timber and concrete.

The effective bending stiffness depends on the shear bond coefficient of the concrete, where the shear bond coefficient of the concrete depends on the spacing and slip modulus of the connectors. Usually, the shear bond coefficient of regular connection is within the range of 0.1–0.4. A shear bond coefficient of 0 represents the layers which behave independently with no force couple resisted by the composite section ($EI_{ef}=EI_{min}=E_cI_c+E_tI_t$), while a shear bond coefficient of 1 indicates a fully composite beam with no slip in the interface ($EI_{ef}=EI_{max}=4EI_{min}$).

The effective (apparent) stiffness of the composite cross-section is calculated by:

$$(EI)_{ef} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 \tag{3-1}$$

The subscripts *c* and *t* refer to concrete and timber, respectively, unless otherwise specified. The contribution of the formwork (if present) is neglected in the design.

The second moment of area for concrete and timber components is:

$$I_c = \frac{b_c h_c^3}{12} \tag{3-2}$$

$$I_t = \frac{b_t h_t^3}{12} \tag{3-3}$$

where *b* and *h* are width and height of composite members, respectively. The tributary width of the concrete member (b_c) is assessed using Equations (3-4) and (3-5), which are derived from *AS 3600:2009 Concrete structures, Section 8.8:*

$$b_c = b_t + 0.2a \quad \text{(for T- beams)} \tag{3-4}$$

$$b_c = b_t + 0.1a \quad \text{(for I - beams)} \tag{3-5}$$

where *a* is distance between points of zero bending moment, which for continuous beams may be taken as 0.7*L*.

The shear bond coefficients of concrete and timber components are:

$$\gamma_c = \frac{1}{1 + \frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}} \tag{3-6}$$

$$\gamma_t = 1 \tag{3-7}$$

where E_c and A_c are modulus of elasticity (MOE) and section area of the concrete; s_{ef} represents effective spacing of the connectors; K_i is slip modulus of the connector; and *L* is span length of the beam.

The section areas of concrete and timber are:

$$A_c = b_c h_c \tag{3-8}$$

$$A_t = b_t h_t \tag{3-9}$$

The spacing for the commercially available connectors in Europe is within the range of 100 to 500 millimetres[3]. Based on the values for shear force at the interface, the spacing of connectors can be variable and an effective constant spacing (s_{ef}) can be assumed during calculation of shear bond coefficient[4]. The minimum, maximum and effective spacing for notched and screws connections (refer to Figure 3.2 and Figure 3.3) of the connections is given by:

$$s_{ef} = 0.75 s_{\min} + 0.25 s_{\max} \tag{3-10}$$

where s_{min} and s_{max} are the spacing at the beam ends and mid-span, respectively[4]. All connectors are evenly spaced within the end quarter spans, as indicated in Figure 3.2.

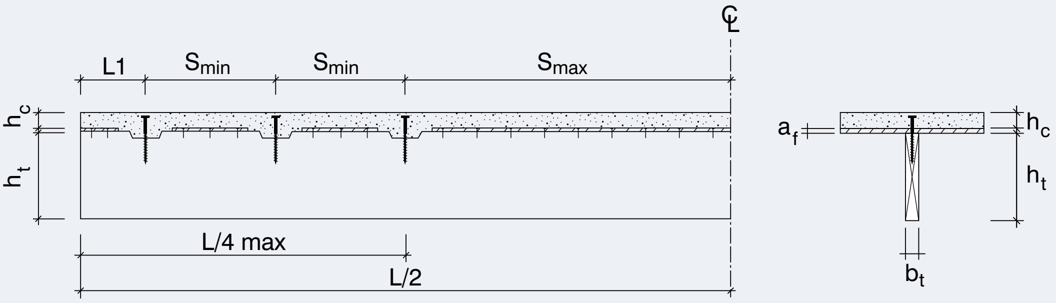


Figure 3.2: Connection-related distances and spacing for notched connections.

The notch shapes can be trapezoidal or triangular and should comply with the fabrication provisions and geometry specified in Section 5. The recommended minimum number of notches is three, at each end of the beam.

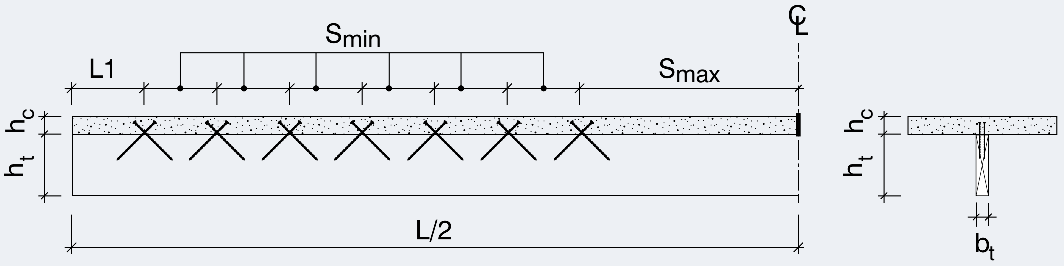


Figure 3.3: Connection-related distances and spacing for SFS connections.

The details of the connections are listed in Table 3.1.

Type of Connection:	***L_1 (mm)***	***S_{min} (mm)***	***S_{max} (mm)***
trapezoidal	300 + length of bearing	$S_{min} \geq 300$	L_1+S_{min}*no. connections ≥ L/4
triangular	280 + length of bearing	$S_{min} \geq 280$	L_1+S_{min}*no. connections ≥ L/4
SFS - VB-48-7.5x165	300	$100 \leq S_{min} \leq 300$	L/2-L_1+S_{min}*no. connections

Table 3.1: Details of the connections.

For a T-shape TCC module as shown in Figure 3.4, the distance between centroid of timber component and centroid of TCC section (a_t) and the distance between centroid of concrete component and centroid of TCC section (a_c) are given by:

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \qquad (3\text{-}11)$$

$$a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \qquad (3\text{-}12)$$

The height factor (H) is defined by:

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} \qquad (3\text{-}13)$$

where h is the height of timber and concrete members and a_f is thickness of the formwork (if present).

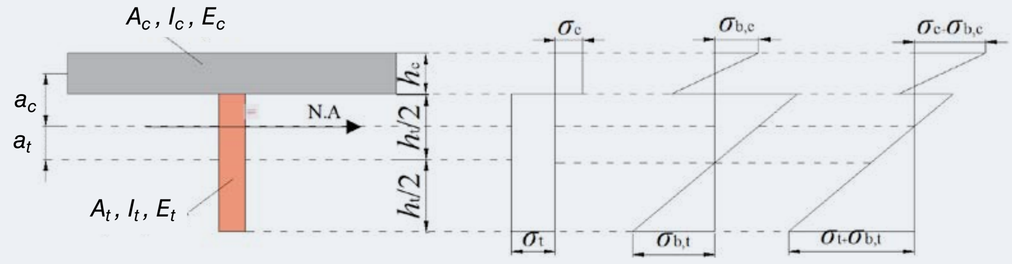


Figure 3.4: T shape TCC section - parameters and stress distribution of a partially composite beam. *Source: Moshiri, F²*.

The stiffness values for each connection are derived from:

$$K_{ser} = \frac{0.4R_m}{v_{0.4}} \tag{3-14}$$

$$K_{ef} = \frac{K_{ser}}{j_2} \tag{3-15}$$

$$K_u = \frac{0.6R_m}{v_{0.6}} \tag{3-16}$$

This design guide uses three connection types that have been extensively tested to derive characteristic properties for both strength and stiffness. Two of these connection types require the fabrication of a notch in the timber beam (Figure 3.5), which are referred to as 'trapezoidal' and 'triangular' notched connections reinforced with vertical coach screw. The third type is un-notched, and uses proprietary SFS screws (Figure 3.6).

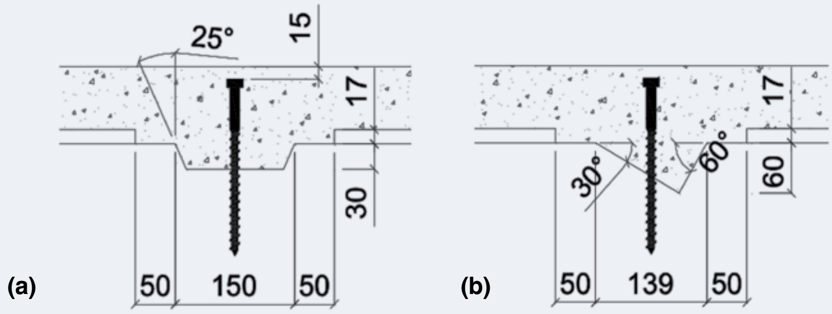


Figure 3.5: Notched connections – trapezoidal (a) and triangular (b).

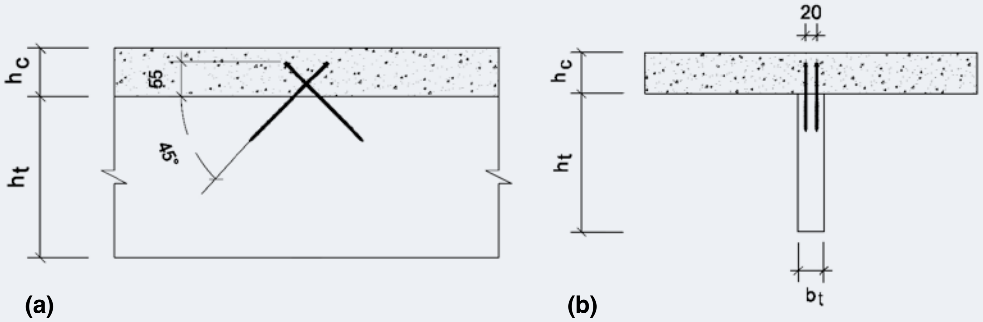


Figure 3.6: Cross SFS screw connection detail – profile (a) and cross-section (b).

The SFS screw connector developed in 1992 is recognised as a proprietary system for TCC structures, either in the construction of new flooring systems or the rehabilitation of existing timber floors in Europe. The double-headed screw consists of two parts with a diameter of 6 mm as an anchor in the concrete, and another threaded 165 mm long with a diameter of 7.5 mm as an anchor in the timber (total length of 220 mm).

The use of SFS screws is prescriptive and limited to the specific type of screws tested, which were VB-48-7.5x165, inclined at 30° to 45° as shown in Figure 3.6. The characteristic properties for SFS screws (per connection – one screw pair) are as follows:

SFS screws inclined at 45°

Q_k = 33 kN
K_{serv} = 70 kN/mm
K_{ult} = 44 kN/mm

SFS screws inclined at 30°

Q_k = 37 kN
K_{serv} = 55 kN/mm
K_{ult} = 44 kN/mm

Details of the equations used to generate these values are given in Appendix A2.

The characteristic strength of notched connections is the same and can be derived from Figure 3.7.

Although the creep behaviour of TCC floors is quite complex, the 'creep component' for long-term defections is modelled using the j_2 factor. This is consistent with AS 1720.1, which uses a simplified multiplier on the initial short-term deflection. A value of j_2 between 3.0 (controlled) and 4.0 (variable environment) is currently recommended for indoor applications (Table 3.2) where j_2 represents stiffness modification factor – load duration.

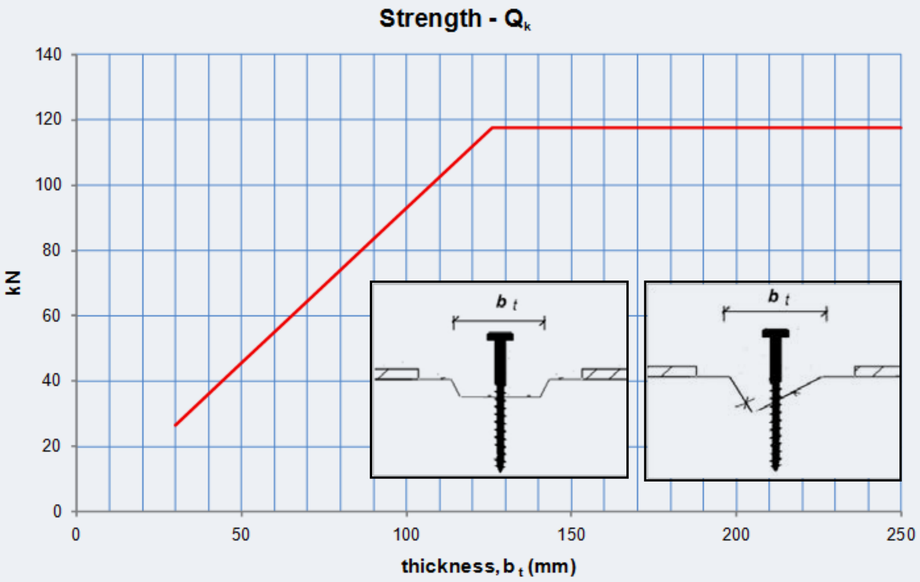


Figure 3.7: Characteristic strength of notched connections.

The characteristic stiffness of notched connections for serviceability and ultimate limit states can be derived from Figure 3.8 and Figure 3.9, respectively. Details of the equations used to generate these figures are presented in Appendix A2.

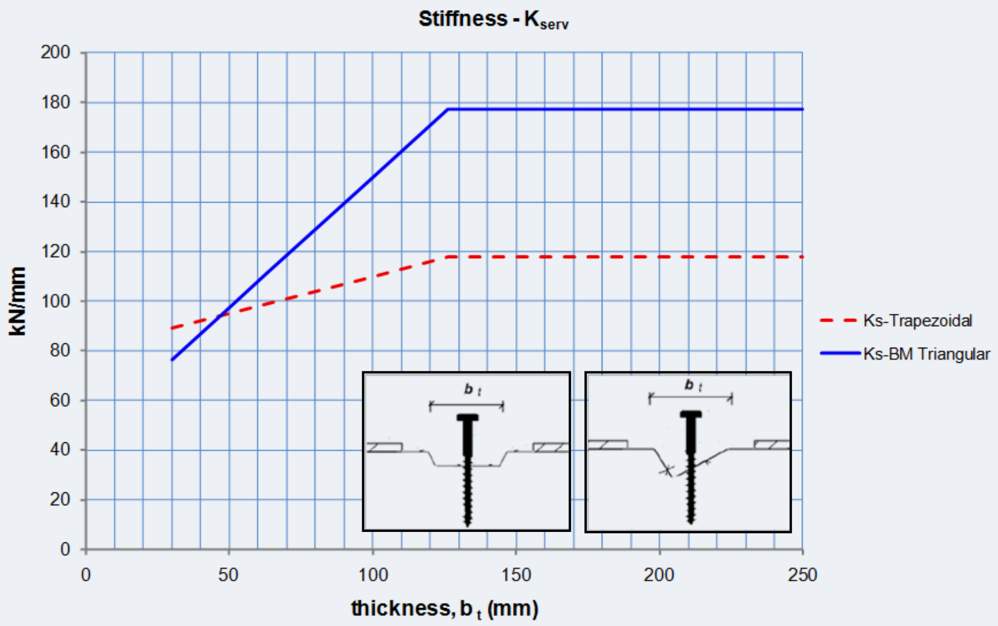


Figure 3.8: Characteristic stiffness (K_{serv}) of notched connections.

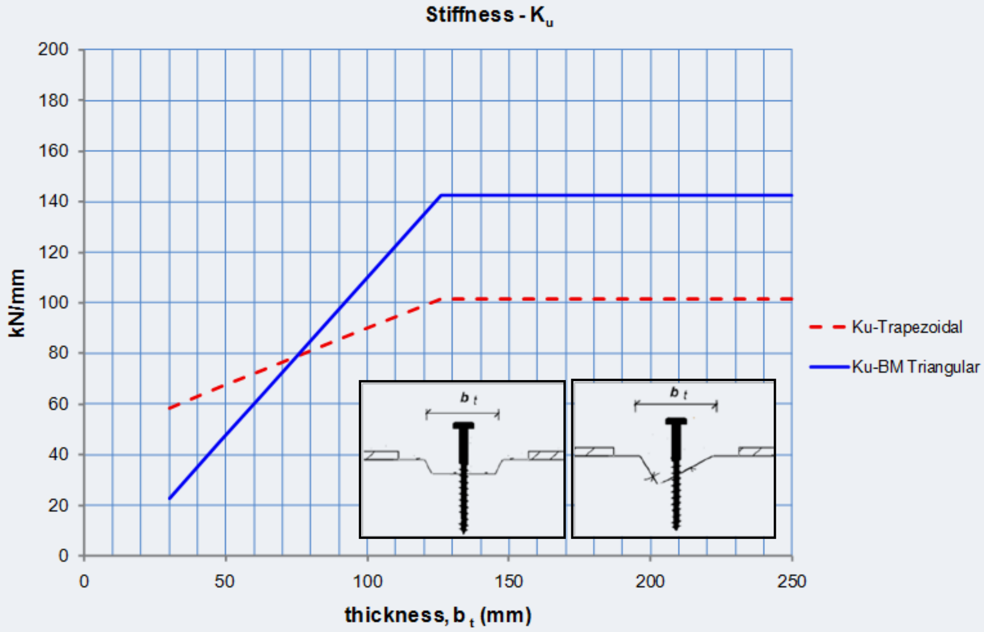


Figure 3.9: Characteristic stiffness (K_u) of notched connections.

Since the test data is not yet available for the thicknesses exceeding 126 mm, the characteristic properties are assumed to be constant beyond this point.

3.2 Strength of the TCC section – Concrete and Timber Members

3.2.1 Strength Requirements for Flexural Action

The load combinations and factors for the ultimate limit state (ULS) must comply with the relevant provisions of AS 1170. The checks imposed on a structure under flexural action or flexural and axial actions are described in Sections 3.2 and 3.5 of AS 1720.1, respectively. These requirements apply to TCC floor structures as follows:

- Bending strength – the concrete and timber members resist a combination of bending moment and/or axial force.
- Flexural shear strength – the timber member resists the flexural shear force.
- Bearing strength – the timber member resists the support action/reactions.
- Strength of the connection interface

3.2.2 Bending Strength

At the extreme fibres, upper and lower, the concrete and timber members experience compression and tension stresses which result in combined bending and axial stresses as defined in Figure 3.4. Equation (3-16) should be checked for the upper and lower fibres of the concrete member and for the lower fibre of the timber member.

An efficient design of a TCC cross-section occurs when the concrete member is fully under compressive stress and the timber member is mainly subjected to tensile stress. If some portion of the concrete member experiences tension stress, this contribution is ignored in the design. It is also possible for the timber beam to experience compression, but this is not critical because the timber material exhibits adequate compression capacity.

$$\frac{\sigma_n}{f_n} + \frac{\sigma_b}{f_b} \leq 1.0 \tag{3-17}$$

where f_n and f_b are axial (tensile or compressive) and bending strength of composite members (timber and concrete), respectively, while σ_n and σ_b represent effective axial and bending stresses, respectively.

The general expression for bending stress of composite member (timber or concrete) is defined in:

$$\sigma_{b,i} = \pm\frac{1}{2}\frac{E_i h_i M^*}{(EI)_{ef}} \tag{3-18}$$

Specifically, the bending stresses in the concrete and timber members, $\sigma_{b,c}$ and $\sigma_{b,t}$, respectively, are:

$$\sigma_{b,c} = \pm\frac{1}{2}\frac{E_c h_c M^*}{(EI)_{ef}} \tag{3-19}$$

$$\sigma_{b,t} = \pm\frac{1}{2}\frac{E_t h_t M^*}{(EI)_{ef}} \tag{3-20}$$

where M^* is the design moment due to factored load and $(EI)_{ef}$ is the effective bending stiffness of composite section.

The bending moment capacities for concrete (*ΦM$_u$*) and timber (*ΦM*) can be written as, respectively:

$$\phi M_u = \phi f_c' \frac{2(EI)_{ef}}{\gamma_c E_c h_c} \tag{3-21}$$

$$\phi M = \phi k_1 k_4 k_6 k_9 k_{12} f_b' \frac{2(EI)_{ef}}{\gamma_t E_t h_t} \tag{3-22}$$

where *f'$_c$* is characteristic strength of concrete in compression while k factors and ***Φ*** are modification and capacity factors as defined in AS 1720.

Each capacity determined for concrete and timber (*ΦM* and *ΦM$_u$*) must be greater than the design moment, *M**. The design moment, *M** is derived from loading requirements and boundary conditions of the TCC structure.

$$\phi M_u > M^* \text{ and } \phi M > M^* \tag{3-23}$$

The axial (in-plane) stress of concrete or timber is predicted by:

$$\sigma_{c/t,i} = \pm \frac{\gamma_i E_i a_i M^*}{(EI)_{ef}} \tag{3-24}$$

Specifically, the stresses in the concrete and timber member, respectively, are:

$$\sigma_{c,c} = -\frac{\gamma_c E_c a_c M^*}{(EI)_{ef}} \tag{3-25}$$

$$\sigma_{t,t} = \frac{\gamma_t E_t a_t M^*}{(EI)_{ef}} \tag{3-26}$$

Assessment of the axial stress is derived from the flexural action. However, the (corresponding) design axial force can be determined from:

$$N_c^* = \sigma_{c,c} A_c \tag{3-27}$$

$$N_t^* = \sigma_{t,t} A_t \tag{3-28}$$

and the allowable axial forces of concrete (*ΦN$_u$*) and timber (*ΦN*) are defined as:

$$\phi N_u = \phi f_c' A_c \tag{3-29}$$

$$(\phi N) = \phi k_1 k_4 k_6 k_{11} f_t' A_t \tag{3-30}$$

where *f'$_c$* and *f'$_t$* are characteristic axial strength of concrete and timber in compression and tension, respectively, while *k* factors and ***Φ*** are modification and capacity factors as defined in Section 4, AS 1720.1.

If the depth of the timber member exceeds 150 mm, the characteristic tension strength must be reduced or modified in accordance with the Manufacturer's specifications.

3.2.3 Flexural Shear Strength

In the absence of structural reinforcement in the concrete member, the flexural shear strength (*ΦV*) is provided by the timber member, therefore:

$$\left(\phi V\right) \geq V^* \tag{3-31}$$

where for rectangular sections:

$$\left(\phi V\right) = \phi k_1 k_4 k_6 k_{11} f_s' \frac{2A_t}{3} \tag{3-32}$$

where f'_s is characteristic shear strength timber parallel to the grain while *k* factors and ***Φ*** are modification and capacity factors as defined in AS 1720.1.

Some conditions (for example, use of a deep notch at the support of a beam) may require reducing the shear plane area by using the net area of the (beam) cross-section. AS 1720.1 has specific requirements for such conditions.

3.2.4 Bearing Strength

The bearing strength is provided by the timber member, therefore:

$$\left(\phi N_p\right) \geq N_p^* \tag{3-33}$$

in which:

$$\left(\phi N_p\right) = \phi k_1 k_4 k_6 k_7 f_p' A_p \tag{3-34}$$

3.3 Strength of the Composite Cross-Section – Connection Capacity

The connection (a machined notch containing a screw fastener or cross SFS screws) transfers the shear force occurring between the concrete and timber elements when loaded under flexure. Since the actual mechanics of this force transfer are relatively complex, a prescriptive approach that defines connection capacities (based on empirical test data) is specified in Section 5.1.

3.3.1 Shear Strength of the Connection

Assessment of the connection strength (*Nj*) includes assessment of the strength of the first connection due to V^*_{max} near to the support, and the connection located at the quarter-span area due to $V^*_{L/4}$.

$$\left(\phi N_j\right) \geq Q^* \tag{3-35}$$

where Q^* is lateral shear force and the connection strength (N_j) is calculated by

$$\left(\phi N_j\right) = \phi k_1 k_4 k_6 Q_k \tag{3-36}$$

where Q_k is characteristic capacity of a fastener while k_i and ***Φ*** are modification and capacity factors as defined in AS 1720.1.

The effective shear force in the connection located near the support is:

$$Q^*_{\left(V^*_{\max}\right)} = -\frac{\gamma_c E_c A_c a_c s_{\min}}{(EI)_{ef}} V^*_{\max} \tag{3-37}$$

where S_{min} is the minimum spacing of shear connections and the effective shear force in the connection located at the 'quarter' span:

$$Q^*_{\left(V^*_{L/4}\right)} = -\frac{\gamma_c E_c A_c a_c s_{\max}}{(EI)_{ef}} V^*_{L/4} \tag{3-38}$$

3.3.2 Shear Strength of the Timber

The shear strength of the timber (ΦN_V) and tangential shear action in the area located between the support and the first connection (V^*) is checked as follows:

$$\left(\phi N_V\right) \geq V^* \tag{3-39}$$

where:

$$\left(\phi N_V\right) = \phi k_1 k_4 k_6 f_s^{'} \left(b_t l_s\right) \tag{3-40}$$

where f'_s is characteristic shear strength timber parallel to the grain while b_t and l_s are width and length of the horizontal shear plane for the timber member.

3.4 Serviceability – Deflection

The load combinations and factors for the serviceability limit states (SLS) are defined in AS 1170. Serviceability of the TCC structure is assessed by checking the deflections against the limits defined to suit the functional requirements of the building being designed. In the absence of any specific limits, the following are recommended:

- Short-term 0.7Q only, limited to *L* / 300
- Short-term Point load deflection (Q), limited to 2.0mm
- Long-term G + 0.4Q, limited to *L* / 250
- Long-term G only, limited to *L* / 300

where Q and G are and imposed and permanent actions while *L* is the span.

The effective stiffness $(E_I)_{ef}$ of the structure is defined earlier. Where deflection is deemed to be critical, a 5th percentile estimate of *E*, should be used.

The mid-span deflection under uniformly distributed load (Δ) is assessed using:

$$\Delta = \frac{5\left(\mathrm{G}^* + \varphi\, \mathrm{w}^*_{\mathrm{imp}}\right) L^4}{384\left(EI\right)_{ef}} \tag{3-41}$$

where w^*_{imp} and G^* are imposed design load and design self-weight while φ is creep coefficient of timber.

The mid-span deflection under a point load is assessed by:

$$\Delta = \frac{P^* L^3}{48\left(EI\right)_{ef}} \tag{3-42}$$

where p^* is design action for point load action.

The value of φ and $(EI)_{ef}$ are defined to suit the loading condition and duration. The creep component for long-term defections is modelled using the j_2 factor, which is stiffness modification factor of connection for load duration. This is consistent with AS 1720.1, which uses a simplified multiplier to the initial short-term deflection.

3.4.1 Instantaneous Short-Term Deflection

a) Imposed load only – deflection check under uniformly distributed load using Equation (3-41).

b) 1.0 kN load (vibration check) – deflection check under point load using Equation (3-42).

The unit point load deflection criterion should be applied to the light-frame floors design when the vibration due to walking is an issue[5]. The unit point load deflection criterion is shown in Figure 3.10. For floors with spans below 3 m, the limit for unit load deflection is ≤2 mm and the deflection limit for span ≥3 m decreases exponentially as shown Figure 3.10. The deflection of about 0.6 mm under the application of 1 kN point load is acceptable to all floor spans.

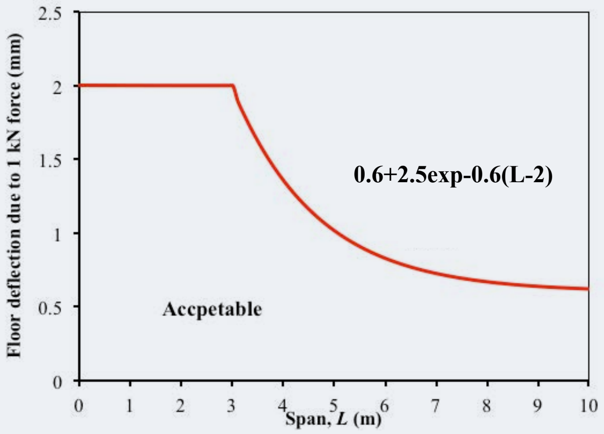


Figure 3.10: Design criterion for light-frame floors.

The shrinkage and creep effect of the concrete member and the creep of the timber are neglected. Thus, $\varphi = 1.0$ and $(EI)_{ef}$ is approximated as defined in Equations (3-1).

3.4.2 Long-Term End-of-Life Deflection

a) Permanent (G) and imposed load (Q) – deflection check under uniformly distributed load using Equation (3-41)

b) Permanent load only – deflection check under uniformly distributed load using Equation (3-41)

The shrinkage and creep of the concrete member and the creep of the timber are accounted for. There are two approaches for predicting the long-term deflection due to creep effects.

Method 1 (simplified method) is based upon empirical data obtained from long-term deflection measurements of TCC floor beams collected by researchers at the University of Technology Sydney (UTS). This estimates the gross deflection behaviour and involves multiplying the short-term EI_{ef} by a j_2 factor from Table 3.2.

Instantaneous Live load	1.0
Long-term loads in a controlled environment	3.0
Long-term loads in a variable environment	4.0

Table 3.2: Simplified Method – Recommended values of the creep factor j_2.

Method 2 (rigorous method) involves consideration of both the concrete shrinkage and timber creep separately (using the j_2 factors in Table 3.3), as noted in Equations (3-43) to (3-46), below.

Load	j_2
Instantaneous Live load	1.0
Long-term loads in a controlled environment	2.0
Long-term loads in a variable environment	3.0

Table 3.3: Rigorous Method – Recommended values of the creep factor j_2.

The effective (apparent) stiffness *(EI)*$_{ef}$ of the composite cross-section is given by:

$$(EI)_{ef} = E_{c,lts}I_c + E_{t,lts}I_t + \gamma_{c,lts}E_{c,lts}A_c a_c^2 + \gamma_{t,lts}E_{t,lts}A_t a_t^2 \qquad (3\text{-}1)$$

where the term *lts* refers to modified value for long-term service. and I_t refer to Equations (3-2) and (3-3) and the gamma functions modified for long-term service are given by Equations (3-6) and (3-7):

$$\gamma_{c,lts} = \frac{1}{1 + \dfrac{\pi^2 E_{t,lts} A_c s_{ef}}{K_{eff} L^2}} \qquad (3\text{-}6)$$

$$\gamma_{t,lts} = 1 \qquad (3\text{-}7)$$

a_c and a_t are obtained from Equations (3-11) and (3-12) as:

$$a_c = \frac{\gamma_{t,lts} E_{t,lts} A_t H}{\gamma_{c,lts} E_{c,lts} A_c + \gamma_{t,lts} E_{t,lts} A_t} \qquad (3\text{-}11)$$

$$a_t = \frac{\gamma_{c,lts} E_{c,lts} A_c H}{\gamma_{c,lts} E_{c,lts} A_c + \gamma_{t,lts} E_{t,lts} A_t} \qquad (3\text{-}12)$$

where:

$$E_{c,lts} = \frac{E_c}{\left(1+\varepsilon_{cs}\right)\left(1+\phi_{cc}\right)} \qquad (3\text{-}43)$$

$$E_{t,lts} = \frac{E_t}{j_2} \qquad (3\text{-}44)$$

And:

$$\varepsilon_{cs} = k_1 \varepsilon_{cs.b} \qquad (3\text{-}45)$$

$$\phi_{cc} = k_2 k_3 \phi_{cc.b} \qquad (3\text{-}46)$$

where

Φ_{cc}	is design creep factor (concrete)
$\Phi_{cc,b}$	is basic creep factor (concrete)
ε_{cs}	is design shrinkage strain (concrete)
$\varepsilon_{cs,b}$	is basic shrinkage strain (concrete)

for *H* refer to Equation (3-13) and for b_c refer to Equations (3-4) and (3-5).

3.5 Serviceability – Dynamic Behaviour

In addition to the 1 kN point load vibration check above, a more rigorous dynamic assessment can be carried out based on the fundamental frequency of the TCC floor – noting that this formula predicts the behaviour of single span beams with different types of boundary conditions and continuous beams having a maximum of three spans. The formula will generally be conservative as a prediction of the floor system behaviour. Prediction of the first fundamental frequency of simply supported TCC floor beam is based on an empirically derived methodology, which is summarised in the formula below:

$$\text{Nat Freq (Hz)} = C_B \times \left(\frac{EI_{ef}}{L^4 \times m}\right)^{0.5} \qquad (3\text{-}47)$$

where *m* is the mass per unit length (t/m if *EI* is in kNmm^2, or kg/m if *EI* is in Nmm^2), *L* is the clear span in metres (for continuous beams, the longest span should be used) and C_B is the frequency coefficient, which depends upon the number of spans and boundary conditions.

Table 3.4 lists the values of C_B for a single span. Frequency coefficient (C_B) is the same for both pin–pin and pin–roller boundary conditions whereas higher frequency is expected for pin–pin compared to pin–roller boundary condition.

No. of Spans	End condition	*Values of* C_B
Single	Pinned/pinned (simply supported)	1.57
	Single Fixed/pinned	2.45
	Fixed both ends	3.56
	Fixed/free (cantilever)	0.56

Table 3.4: Values of CB for a single span. *Source: Wyatt, T*[6]*.*

It is essential that designers define the serviceability limits for deflection and dynamic performance to meet the intended functional requirements of the floor under design. Currently accepted design methods for timber floors, such AS 1684 Residential timber-framed construction Part 1 Design Criteria, are generally based upon the assumption that acceptable performance of the floor is considered to occur when the fundamental frequency exceeds 8 Hz. However, this is a simplification and recent studies such as Hamm[7] indicate that lower frequencies in the 3.5 to 5.5 Hz range may also be acceptable. Several modules coupled together would most likely have greater natural frequencies when several units are coupled together in a two-way system.

A more comprehensive assessment of the dynamic performance of the floor where the dynamic performance is deemed to be critical can be undertaken based on quantifying a 'Response Factor'[8] . This method is based on concrete and steel-concrete composite floor design, but is considered to be equally applicable to TCC floors. However, the method will normally require the use of finite element modelling to establish the dynamic parameters of the floor such as natural frequencies, mode shapes and damping.

4

Acoustic Performance

From a review of existing knowledge on acoustic performance of timber floors, it is clear that both airborne and impact sound insulation requirements can be fulfilled by applying suitable treatments and proper detailing to the timber floors. It is important to understand the difference in the factors affecting the airborne and impact sound insulation to address the acoustic performance of a floor.

A number of best practice guidelines based on existing knowledge of acoustic performance of timber floors are summarised below:

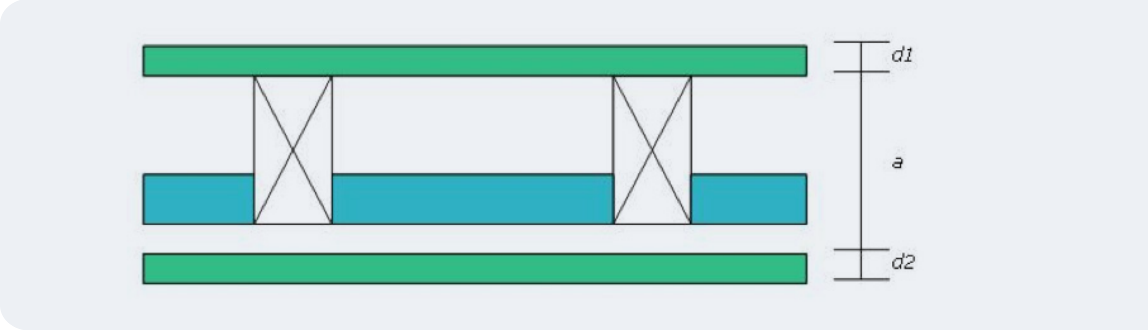


Figure 4.1: Double layer floor with good acoustic properties.

4.1 Guidance on Improving the Airborne Sound Insulation

1. Larger spacing and separated layers of double layer floor: The ceiling boards should not be directly connected to the floor joists. Ceiling should be separated from the floor joists (distance 'a' in Figure 4.1) by either providing resilient support for the ceiling board or separate joists for ceiling boards supported on the walls.
2. The ceiling boards should have a minimum density of 10 kg/m^2. Although single layer ceiling boards provide adequate airborne sound insulation, it is preferable to use two ceiling boards with staggered joints for better sound insulation performance.
3. The floor cavity between the subfloor and ceiling should be filled with sound absorbing material (mineral fibre). The material's type and density is dependent on the floor's construction. The BCA may require the mineral wool to be non-combustible.
4. Increasing the mass of the joist may not improve the airborne sound insulation of timber floors. The thickness of sound absorbing material, arrangement of resilient channels and depth and spacing of joist has some effect in the airborne sound insulation behaviour but it is not as significant as the effect of having ceiling boards separated from the joists.
5. A combination of sub-floor with a mass of 20 kg/m^2 and 150 mm thick sound absorbing material with ceiling boards supported on resilient metal channels have been reported to give good airborne sound insulation for timber floors.
6. Thin, heavyweight, and non-rigid layers, or asymmetric construction (d_1/d_2 = approximately 2) options, are suitable to get satisfactory acoustic properties[9].

4.2 Guidance on Improving the Impact Sound Insulation

1. Increasing the mass or by separating the ceiling from the floor joists can impact sound insulation of timber floors.
2. Good impact sound insulation can be achieved for floors constructed with a sub-floor layer (e.g. particle board, gypsum board), separated ceiling using resilient channels and sound absorbing material in the floor cavity. The requirements for the density of floor boards and insulation material are same as that for airborne sound insulation.

3. A floor with a mass of at least 200 kg/m^3 has been reported to have adequate impact sound insulation. However, mass alone may not be sufficient and attention also needs to be given to the floor finish and ceiling treatment
4. Providing soft floor topping can reduce high frequency impact sound transmission. Hard floor toppings such as concrete, marble, tile and hardwood lead to problems with high frequency impact noise. If a hard floor topping is unavoidable, a floating floor on a resilient layer should be used.
5. A top floor layer should be installed with a resilient under layer and should not be screwed directly to the timber joist (Figure 4.2).
6. Addition of transverse stiffeners can improve the high frequency impact insulation of the floor, but reducing the joist spacing may not always improve this.

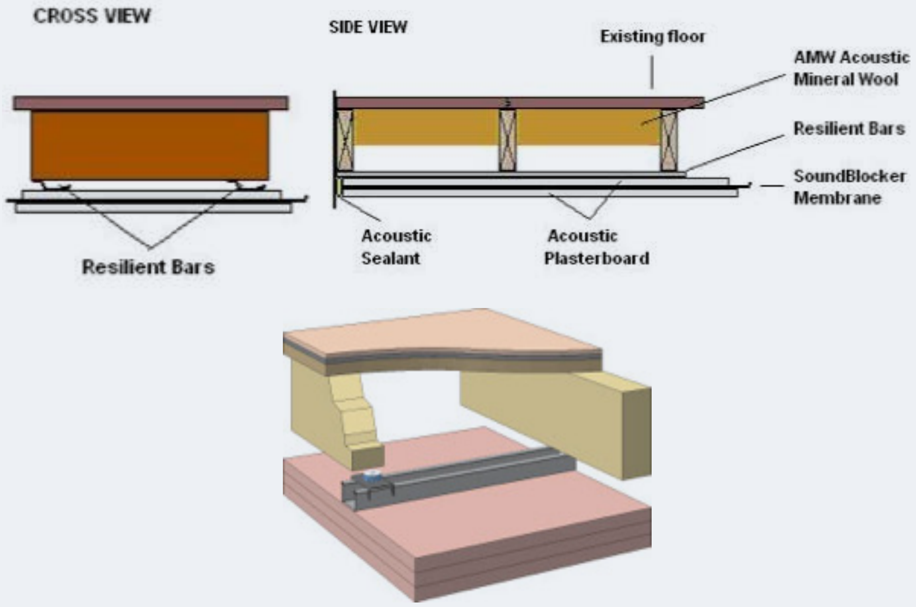


Figure 4.2: Acoustic improvement methods.

5

Manufacturing Provisions

5.1 Coach Screw and Notch Connection

The characteristic properties for the notched connections specified in this Design Guide (Section 3.1) apply to notched connections with screw fasteners manufactured in accordance with the specified geometries and dimensions in Table 5.1. The connections tested to characterise their properties used laminated veneer lumber (LVL) as the timber joist; however, any timber product with joint group classification of at least JD4 as per AS 1720.1 can be used. Where two pieces of timber are vertically laminated to make a thicker beam, each piece must include a coach screw at each notch (See Figure 4.1). A wide beam made from two pieces of timber must have two coach screws as specified in Table 5.1.

(a) l_p refers to the depth of penetration of the threaded portion of the coach screw into the timber joist.

(b) The pre-drill holes for the coach screws should be a diameter of 1 mm less than the root diameter of the coach screw and not exceed the root diameter of the screw.

(c) The pre-drill holes should extend to the penetration depth l_p only.

5.2 Coach Screws

Coach screws suitable for TCC floors would come in lengths of around 100, 120, 130, or 150 mm. The length of coach screw that is clear of the timber is to be about 55 mm. Coach screws are hot dipped and galvanised, and their protection type and application as a corrosive resistant fastener are specified in WoodSolutions Design Guide *#5: Timber service life design – design guide for durability* (Section 8).

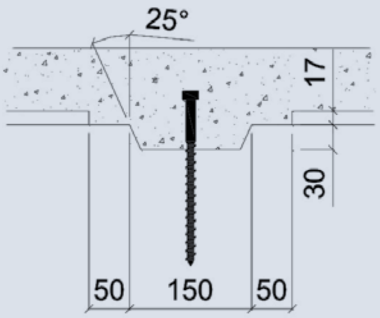
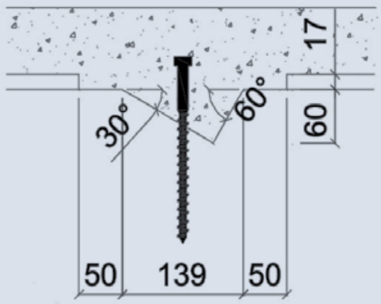
Connection types with geometry and dimensions (mm)	***For beam thickness 50 mm or less***	***For beam thickness more than 50 mm***
	Coach screw Ø: 12 mm (shank diameter) and l_p: 80 mm or at least the length of the thread.	Coach screw Ø: 16 mm and l_p: 100 mm or at least the length of the thread.
		

Table 5.1: Manufacturing provisions for notches.

5.3 Cross SFS Screws

The characteristic properties for the cross SFS screws inclined at 30° to 45° specified in this Design Guide (presented in Section 3.1) apply to SFS screws connections manufactured in accordance with the specified geometries and dimensions in Figure 5.1.

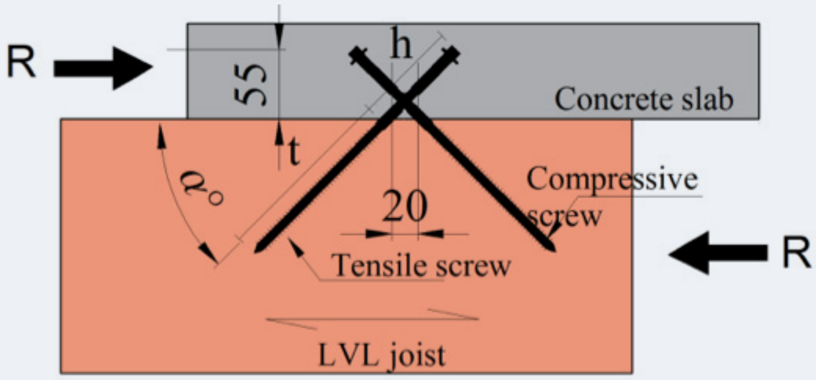


Figure 5.1: Manufacturing provisions for cross SFS screws inclined at 45°.
Source: Moshiri, F[2].

Screws were inserted so that the thread was in the timber. This meant a vertical length of approximately 55 mm was embedded in the concrete. (In the case of presence of the interlayer between timber and concrete members, screws have less length within the timber as screws also had to penetrate through the interlayer.)

The threaded part of a pair of screws should be installed laterally reversed at an angle of ±30° and ±45° with embedding length of 120 and 142 mm as shown in Figure 5.2. The inclination angles were measured from the horizontal.

The connections tested to characterise their properties used laminated veneer lumber (LVL) as the timber joist; however, any timber product with joint group classification of at least JD4 (as per AS1720.1) can be used. Where two pieces of timber are vertically laminated to make a thicker beam, each piece must include a pair of screws. A wide beam made from two pieces of timber must have two pairs of screws as specified in Figure 5.1.

Figure 5.2: SFS screws installed at an angle of ±30° (left) and ±45° (right).
Source: Moshiri, F[2].

SFS screws are made of mild carbon steel and their protection type and application as a corrosive resistant fastener are specified in WoodSolutions Design Guide #5: *Timber service life design – design guide for durability* (Section 8).

6

Provisions for Holes in Timber Joists

Installation of building services may require introduction of holes or penetrations through the timber joists. The following limits on details of the holes are prescriptive and are based on AS 1684. In situations where a larger penetration is required, advice must be sought from the manufacturer of the timber beam products being specified.

6.1 Size

a) For span/depth ratio greater than 10, the maximum hole diameter shall be limited to 50 mm.

b) For span/depth ratio less than or equal to 10, the maximum hole diameter shall be limited to 25 mm.

c) Additionally, when depth (height) of the timber joist (h_t) is less than 200 mm, in addition to the limits prescribed in a) and b), the diameter of holes must not exceed $h_t/4$.

6.2 Spacing

The clear spacing between adjacent holes must be not more than 3 holes per 1.8 m.

Edge Distance

a) The clear distance of a hole from the joist edge should be at least 50 mm when the depth of the timber joist (h_t) is greater than or equal to 200 mm.

b) For timber joist where $h_t < 200$ mm, the clear distance to the hole from the edge should be at least $h_t/3$.

The depth of the timber joist only should be used to calculate the span/depth ratio.

7

Concluding Notes

The design procedure presented in this report is adapted from the design procedure of Eurocode 5 and is modified to suit local practices and reflect research and development recently undertaken in Australia and New Zealand.

The design methodology adequately addresses the complexity of TCC structures, including the partial composite action provided by the connection, and imposes a comprehensive series of strength checks on the cross-section components and serviceability checks with consideration of dynamic response and the long-term performance of the structure.

Adapting the design procedure to suit Australian practices has been a challenging exercise and, where assumptions have had to be made due to uncertainties, these have erred towards being conservative.

A

Appendix A

A1 Commentary & Background Information

A1.1 Introductory Comments

The design procedure presented in this report is based on an extensive review of the published research combined with numerical investigation and laboratory testing.

This Appendix presents further information to improve understanding of some of the considerations and assumptions made in the design procedure.

The informative material discussed in the Appendix addresses:

- Loading conditions
- Connection behaviour
- Tributary width of the concrete
- Behavioural assessment of a notched connection.

A1.2 Loading Conditions

To comply with the loading provisions of the AS 1170 series, any TCC structure must be designed to resist a series of combined uniformly distributed loadings. Figure A1.1 depicts the free-body diagram for a beam under such loading action.

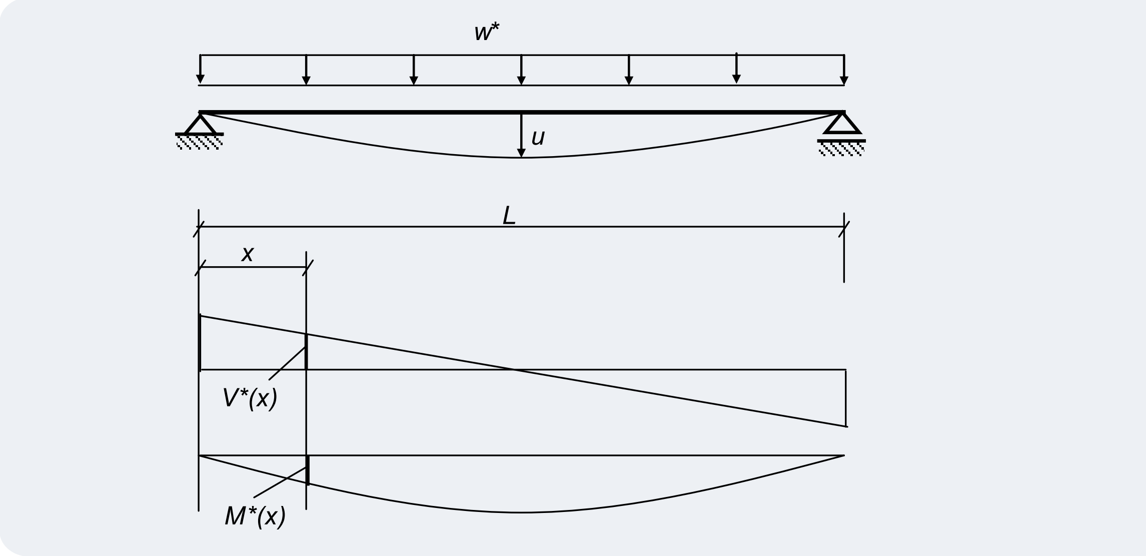


Figure A1.1: Free-body diagram of the TCC beam. Source: Yeoh, D, et al.[10]

Further design requirements may include checking the structural behaviours of TCC structures under pad or point loading.

A1.3 Connection Behaviour

The behaviour of the connection is important for the design of composite sections such as TCC structures and both the strength and flexibility of the connection must be considered. In Figure A1.2, possible states or extents of composite action are depicted:

a) full - no slip between the member
b) partial - some slip impediment
c) zero composite action.

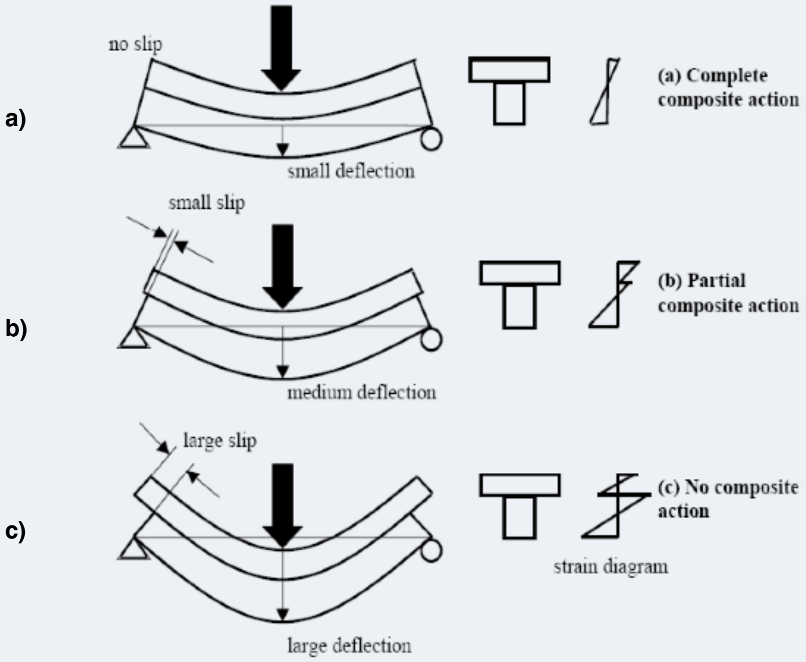


Figure A1.2: State of the composite action. Source: Yeoh, D.[11]

TCC structures constructed with notched and coach screw connections exhibit partial composite action, since some measure of slip occurs between the layers of the cross-section[12,13]. By optimisation of the section proportions (timber–concrete depth ratio), the concrete member can be sized to remain completely under compression stresses.

In an attempt to account for partial composite action, Möhler[14] devised a series of formulae for linear-elastic inter-layers. Unfortunately, such assumptions do not accurately model the non-linear behaviour of TCC connections. A more accurate method was proposed by Cecotti[15], which characterises the connection behaviour with two values of the stiffness modulus – respectively at 40% and 60% of the ultimate load capacity of the connection (refer to Figure A1.3) – which approximates both the performance at the serviceability and ultimate limit states.

To date, the structural properties of the connection types specified in this document rely on databases established by comprehensive laboratory investigations[16]. To increase the level of reliability of the design of TCC structures, more testing will be required on specific selected types of connection. This future work will contribute to increasing the confidence in the design and will maximise use of available connection structural properties.

The connection transfers the shear force between the members under flexure. This transfer is relatively complex and has been characterised to some extent by experimental investigations undertaken in 2009 at the University of Technology Sydney (UTS) by Agus, Gerber and Crews 2009[17]. The stiffness parameters for design are:

- K_{ser} for short-term serviceability
- K_{ef} for long-term serviceability
- K_u for the ultimate state.

Note: Refer to Section 3 for characteristic properties of connections.

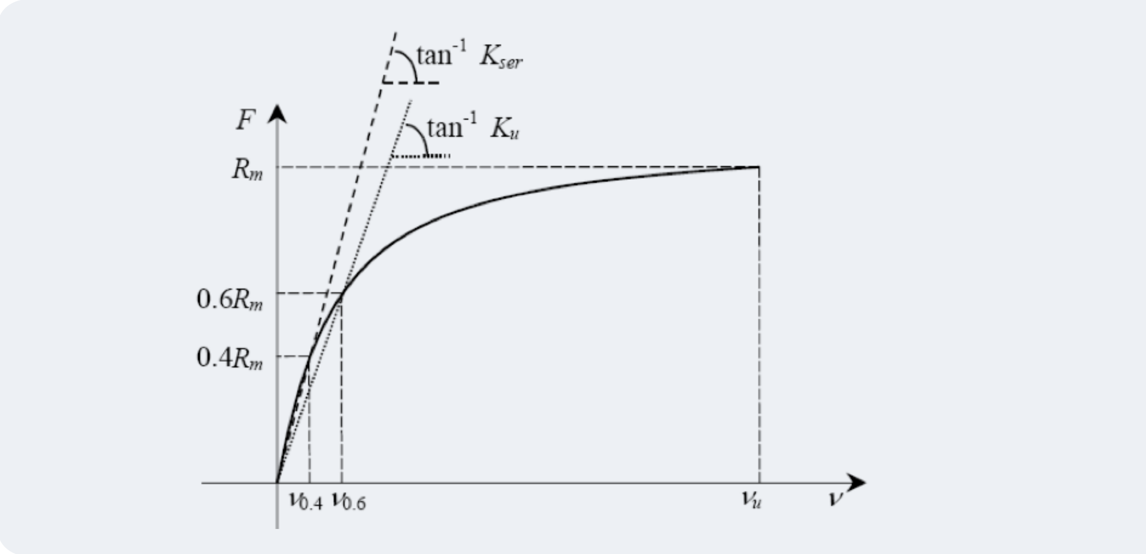


Figure A1.3: Slip moduli of the connections for limit states. Source: Yeoh, D., et al.[11]

A1.4 Tributary Width of the Concrete Member

A T-beam (Figure A1.4) structural form is commonly used for TCC floors. The tributary width models the effects of shear lag. An accurate estimation for this is essential to fully use the properties of the concrete member and to achieve a safe design.

In Australia, two evaluations are proposed, one in AS 3600 and the other in *AS 2327.1 2003 Composite structures – Part 1: Simply supported beams*. For constructions that do not comply with the shape and dimension requisites of AS 3600 and AS 2327.1, the tributary width must be assessed to suit the construction technique used and include aspects such as the geometry, dimensions, proportion. In particular, the shear lag effect and buckling stability must be investigated.

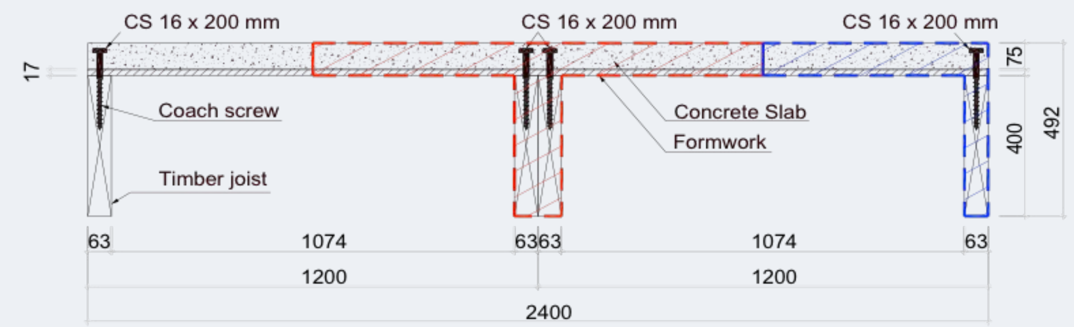


Figure A1.4: Division and tributary width of TCC element.

In AS 3600, the tributary width of the concrete member shall comply with (3-4) for T-beams and (3-5) for L-beams. Also, the tributary width must not exceed the beam spacing.

An alternative to AS 3600 for the assessment of the tributary width of the concrete member can be found in AS 2327.1.

- the tributary width:

$$b_c = b_{e1} + b_{e2} \qquad \text{(A1-1)}$$

in which, for an edge beam, b_{e1} and b_{e2} are:

$$b_{e1} = \min\left\{\left(\frac{L_{ef}}{8}\right) or \frac{b_1}{2} or \left(\frac{b_{sf1}}{2} + 8D_c\right)\right\} \qquad \text{(A1-2)}$$

$$b_{e2} = \min\left\{\left(\frac{L_{ef}}{8}\right) or\ b_2 or \left(\frac{b_{sf1}}{2} + 6D_c\right)\right\} \qquad \text{(A1-3)}$$

and for an internal beam, b_{e1} and b_{e2} are:

$$b_{e1} = \min\left\{\left(\frac{L_{ef}}{8}\right) or \frac{b_1}{2} or \left(\frac{b_{sf1}}{2} + 8D_c\right)\right\} \qquad \text{(A1-4)}$$

$$b_{e2} = \min\left\{\left(\frac{L_{ef}}{8}\right) or\ b_2 or \left(\frac{b_{sf1}}{2} + 8D_c\right)\right\} \qquad \text{(A1-5)}$$

where

b_{e1} and b_{e2} are measured effective on each side of the centre-line of the timber beam.

L_{ef} is the effective span of the beam calculated in accordance with Clause 5.3.3, AS 2327

b_{sf1} is effective width of composite beam top flange (0 for timber beam)

D_c is the overall depth of the concrete slab

b_1, b_2 are centre-to-centre spacing of adjacent beams or distance from centre of timber beam to edge of slab outstand.

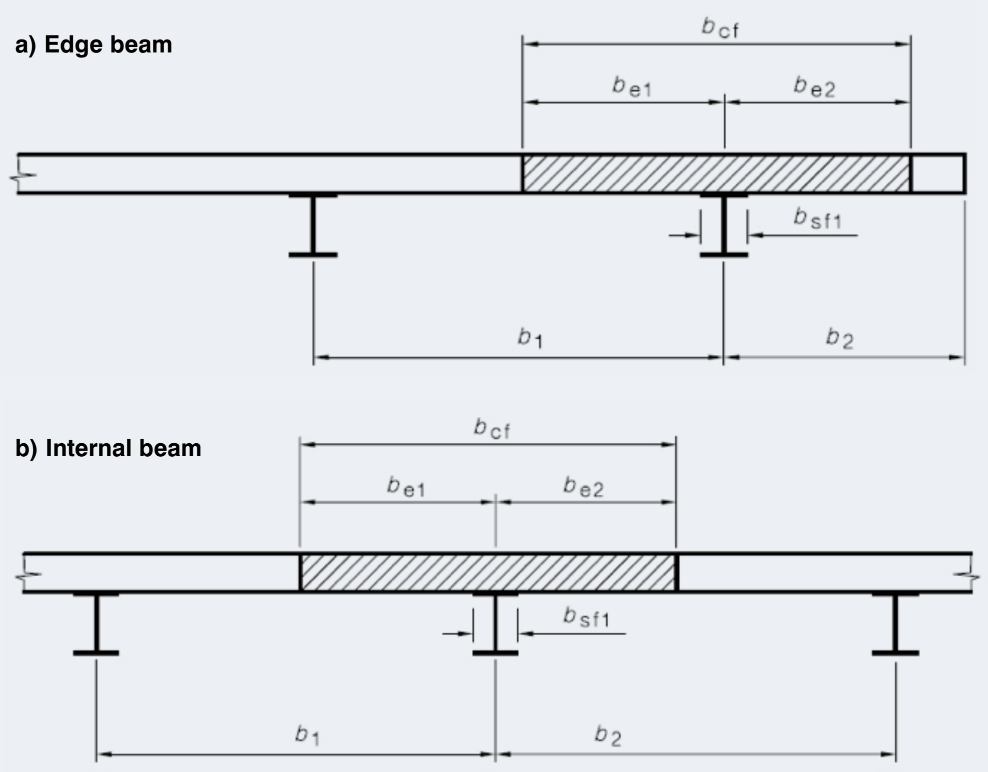


Figure A1.5: Tributary width of the concrete.

Source: AS 2327.1, *Composite structures, in Part 1: Simply supported beams.* 2003, Standards Australia: Australia.

A1.5 Behavioural Assessment of a Notched Connection

The behavioural response of a connection is very complex and in-depth analysis may provide a better understanding about the actual force transfer and flow in the connection. However, at the present time, a prescriptive approach has been adopted for design inputs of the connection types specified in Table 5.1 of this Guide.

The information in this section of the appendix is background to research that will improve understanding of the connections behaviour. Meanwhile, the experimental results presented in the body of the report are sufficient to carry out safe designs.

A1.5.1 Strength Requirements for the Connections

Analysis of connection behaviour must address critical areas such as the shear strength at the base of the concrete bulge, the shear strength of wood preceding the first notch and the crushing strength of the facet area (Figure A1.6).

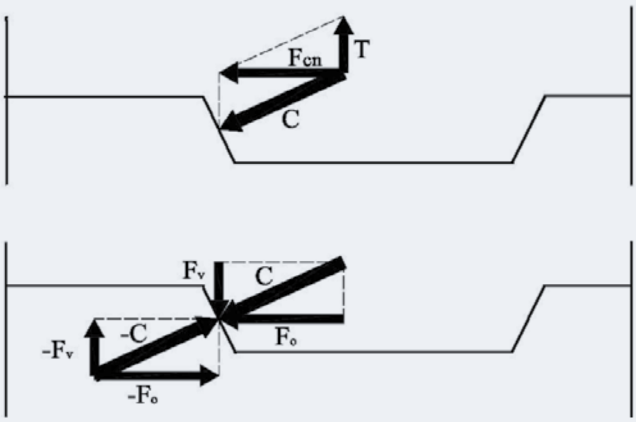


Figure A1.6: Local forces acting in a rectangular notch.

The investigation conducted at UTS[17] identified that the shear strength (in-plane shear) of the concrete bulge and the wood portion behind the (first) shear key are critical for ensuring a safe design. The study has also identified that only the connection resisting the largest load action needs to be checked.

A1.5.2 Shear Strength of the Concrete Bulge (AS 3600)

The shear strength at the baseline of the concrete bulge (Figure A1.6) must be assessed:

$$\phi V_{uc} \geq V^* \tag{A1-6}$$

where

$$\phi V_{uc} = \phi \beta_1 \beta_2 \beta_3 b_v d_o \left(\frac{A_{st} f'_c}{b_v d_o} \right)^{\frac{1}{3}} \tag{A1-7}$$

where

$$\beta_1 = 1.1\left(1.6 - d_o/1000\right) \geq 1.1 \tag{A1-8}$$

$$\beta_2 = 1.0 \tag{A1-9}$$

$$\beta_3 = 1.0 \tag{A1-10}$$

A_{st} = cross-sectional area of the coach screw.

b_v is width of the notch concrete

d_o is length of the notch concrete

A1.5.3 Shear Strength of the Timber

This check has been included in the design guidelines.

A1.5.4 Bearing Strength of the Timber

The bearing strength of the notch facet – compression contact area in the connection and location of the maximum shear force (refer to Figure A1.1) – must also be verified:

$$\left(\phi N_\theta\right)\cos\left(90-\theta\right) \geq V^* \tag{A1-11}$$

where:

$$\left(\phi N_\theta\right)\cos\left(90-\theta\right) = \frac{\left(\phi N_l\right)\left(\phi N_p\right)}{\left(\phi N_l\right)\sin^2\theta + \left(\phi N_p\right)\cos^2\theta}\cos\left(90-\theta\right) \tag{A1-12}$$

and the parallel and perpendicular components are:

$$\left(\phi N_l\right) = \phi k_1 k_4 k_6 f'_l A_l \tag{A1-13}$$

where

ΦN_l	is design capacity in bearing parallel to the grain (timber)
ΦN_p	is design capacity in bearing perpendicular to the grain (timber)
ΦN_θ	is design capacity in bearing at an angle to the grain (timber)
θ	is angle of the notch facet under compression,
f'_l	is characteristic strength in bearing parallel to the grain
A_l	is bearing area for loading parallel to the grain (timber)

for $\left(\phi N_p\right)$ refer to (Equation 3.34).

A2 General Background Information on TCCs

A2.1 Connection Behaviour and Classification

The structural behaviour of the connection is a significant parameter in the design of a TCC floor. The elastic properties of the connection are used for both limit states and accounted for in the identification of the Gamma coefficients in the design procedure. An extensive (literature) review of shear connectors used in timber concrete composite structures, covering the period from 1985 to 2004, has been undertaken by Dias[18]. Elsewhere, Ceccotti[4] also presents an overview of the timber-concrete connectors (Figure A2.7) that are most commonly used to achieve composite action between the concrete and the timber members.

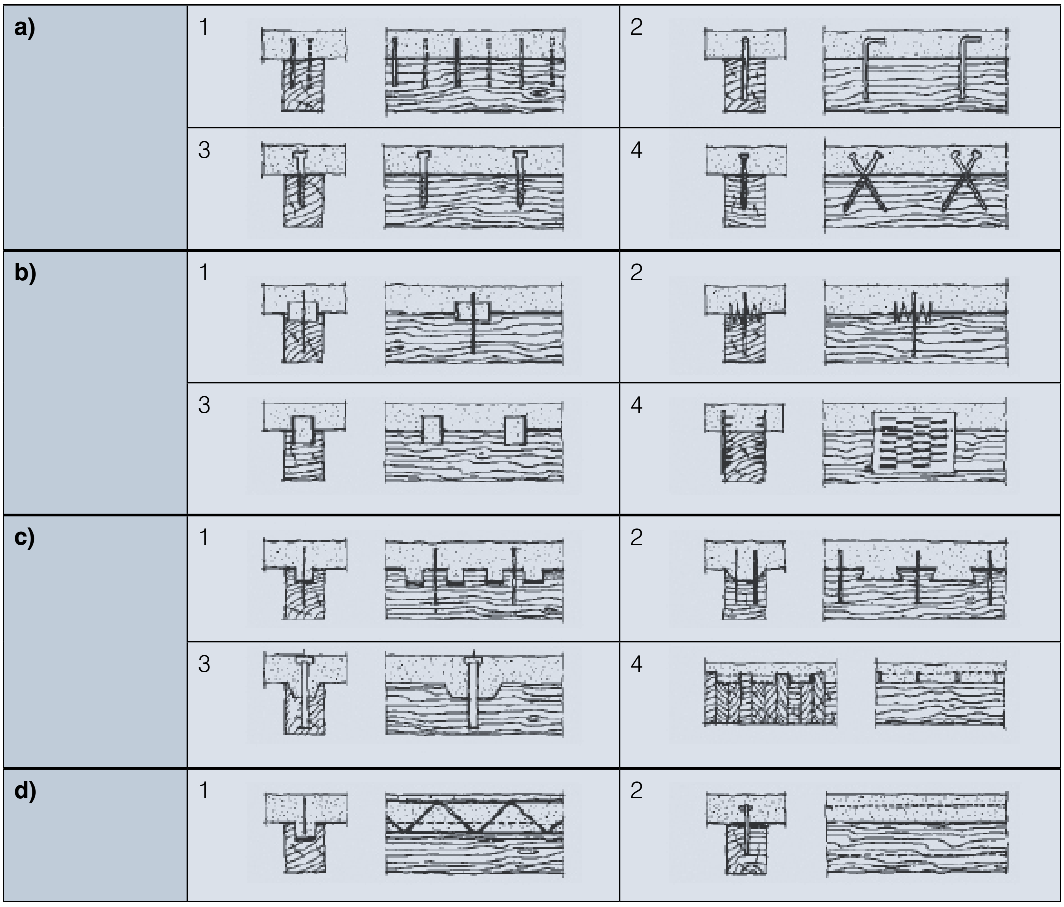


Figure A2.7: Range of TCC connections.

Different connections shown in Figure A2.7 are as follows:

(a1) nails; (a2) glued reinforced concrete steel bars; (a3, a4) screws; (b1, b2) connectors (split rings and toothed plates); (b3) steel tubes; (b4) steel punched metal plates; (c1) round indentations in timber, with fasteners preventing uplift; (c2) square indentations, with fasteners preventing uplift; (c3) cup indentation and prestressed steel bars; (c4) nailed timber planks deck and steel shear plates slotted through the deeper timber planks; (d1) steel lattice glued to timber; (d2) steel plate glued to timber.

The stiffness characteristics of some of the shear connectors presented in Figure A2.7 are plotted in Figure A2.8. The load-slip plot indicates that for this group of connector types, the stiffest connections are those in group (d), while the least stiff are in group (a). Connections in groups (a), (b) and (c) allow relative slip between the timber element and the concrete member, that is, the cross-sections do not remain planar under load and the strain distribution is not continuously linear in the composite cross-section. Only connections in group (d) exhibit a planar behaviour, corresponding thus to fully composite action between timber member and the concrete slab. It can be assumed that TCC structures assembled with connectors from group (a) achieve 50% of the effective bending stiffness of TCC systems constructed with connectors from group (d)[15].

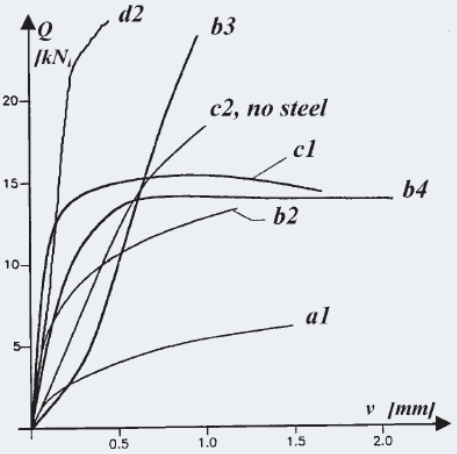


Figure A2.8: Schematic of load-slip behaviour of types of connection.
Source: Ceccotti, A., ed.[15]

A2.2 Connection Characterisation

The behaviour and effectiveness of the tested shear connections were assessed based on their strength (failure load or maximum load), stiffness and failure mode. The strength of the connection specimens was defined as the maximum load that can be applied in the push-out tests before failure. Depending upon the failure mode, the connection specimens may have some load carrying capacity following the maximum load resulting in a ductile behaviour. The failure modes were therefore carefully documented in all tests. The connection stiffness or slip modulus, which represents the resistance to the relative displacement between the timber joist and the concrete slab, is one of the key parameters defining the efficiency of a shear connection. Stiffness for the serviceability limit state (SLS) and ultimate limit state (ULS) are essential to characterise a shear connection. The stiffness for SLS (K_{ser}) corresponds to the inclination of the load-slip curve between the loading start point (generally taken as 10% of failure load to overcome 'settling in') and the 40% of the failure load. The stiffness for ULS (K_u) corresponds to the inclination of the load-slip curve between the loading start point and the 60% of the failure load. As a general rule, it can be assumed that $K_u = (2/3)\ K_{ser}$.

A2.3 Laboratory investigation at UTS – Observations and Steps Towards Suitable Connections

A number of shear connections have been tested using push-out tests on full scale specimens and load-deflection plots and stiffness for these connections have been determined. Parameters such as the type of connector, shape of notches, use of mechanical anchors and concrete properties have been investigated and analysis of this data has led to number of conclusions.

- Early research showed that the use of nail plates alone as shear connectors did not prove to be effective, while a combination of nail plates with either screws or concrete notches was more effective – especially incorporation of concrete notches.
- A number of concrete notch type shear connections were then tested such as trapezoidal, triangular type and polygonal notch and parameters such as slant angle, use of either coach screw or normal wood screw as mechanical fastener, inclination of the mechanical fastener, inclination of the slanting face and use of low shrinkage concrete were studied.
- Use of coach screws has the advantage of deeper penetration depth inside the concrete slab in comparison to normal wood screws due to their longer length. This resulted in a single coach screw providing higher shear capacity than a combination of four wood screws.
- Interesting results were obtained from the triangular type connections as these connections generally exhibited higher strength and stiffness than the trapezoidal notch connections and especially so for triangular connections using 70–20 and 60–30 angle combinations.
- Polygonal notch connections were also found to be superior to the trapezoidal notch connections; however, the complex angle sequence makes such connections difficult to fabricate.

- Triangular type connections are much easier to fabricate with a simple cutting sequence and do not need special tools for fabrication. Use of a slanted coach screw configuration in the triangular notch connections provided higher stiffness; however, the effect on characteristic strength was not significant, while steel plate placed on top of the coach screw did not provide any additional strength or stiffness. It should however be noted that the coach screws in the triangular notch provided only limited post peak plastic behaviour when compared to trapezoidal notch connections.
- The depth of the notch has a significant effect on both the stiffness and strength of the connections. Connections with 60 mm deep notch had superior strength and stiffness compared to the connections with 90 mm deep notch.
- The effect of the ratio of coach screw diameter to timber joist thickness is one of the parameters that need to be further investigated. Table A2.1 highlights the effect of the ratio of coach screw diameter to LVL thickness and suggests that there is no advantage in using 16 mm diameter screws in 48 mm thick LVL beams.

While the variability of maximum load (strength) is considered to be acceptable, the variability of the characteristic stiffness properties highlights some of the uncertainty inherent in the performance of notched connections for TCC constructions. It is proposed to use the data generated to date, to refine connection performance and attempt to reduce stiffness variability to lower levels that could lead to more efficient design of these types of floor structures.

A2.4 Empirical Characterisation of Notched Connections

The main results for both connection types are presented in Table A2.1.

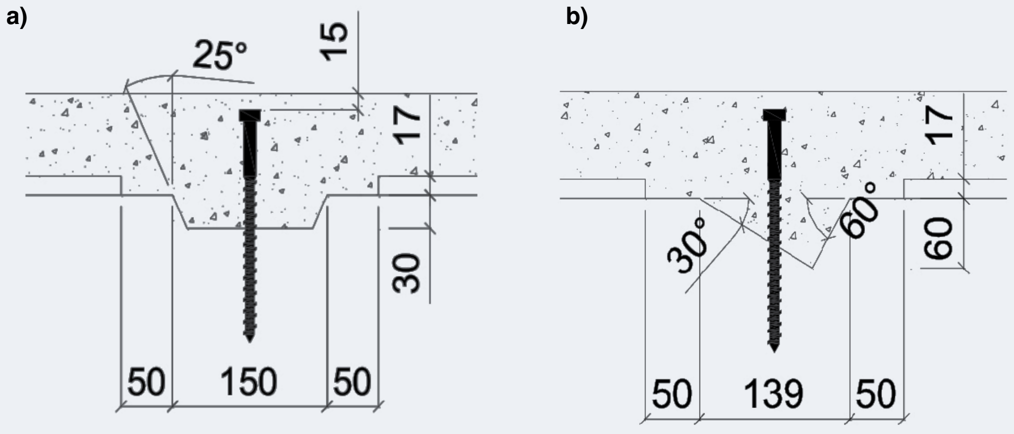


Figure A2.9: Notched connections – trapezoidal a) and triangular b) (45 and 63 mm thick LVL with 12 and 16 mm coach screw, respectively).

Connection Description	Strength Q_k (kN)	K_{ser} (kN/mm)	K_u (kN/mm)
T1 – 48 mm LVL, 16 mm coach screw	46 – 8.7%	87 – 20.5%	60 – 13.0%
T2 – 48 mm LVL, 12 mm coach screw	46 – 6.6%	106 – 15.0%	87 – 17.9%
T3 – 63 mm LVL, 16 mm coach screw	78 – 6.4%	109 – 19.3%	81 – 24.7%
T4 – 96 mm LVL, 12 mm coach screw	89 – 10.0%	110 – 34.8%	93 – 39.3%
T5 – 126 mm LVL, 16 mm coach screw	134 – 4.8%	124 – 41.3%	103 – 30.2%
B1 – 48 mm LVL, 16 mm coach screw	55 – 8.1%	37 – 12.4%	36 – 15.2%
B2 – 48 mm LVL, 12 mm coach screw	51 – 8.4%	115 – 48.4%	46 – 54.0%
B3 – 63 mm LVL, 16 mm coach screw	66 – 7.7%	98 – 12.9%	74 – 27.7%
B4 – 96 mm LVL, 12 mm coach screw	91 – 5.5%	156 – 19.8%	119 – 20.8%
B5 – 126 mm LVL, 16 mm coach screw	120 – 11.6%	213 – 34.2%	150 – 22.7%

Table A2.1: Characteristic properties of notched connections – trapezoidal (T-Series) and triangular (B-Series) notch shapes.

Integer = capacity; % = CV
Strength – 5th percentile based on a log normal distribution
Stiffness – 50th percentile

A2.5 Equations for Characteristic Properties of Connections

These Equations describe the sloping sections of the curves in Figures 3.7 to 3.9.

Trapezoidal Notch and Coach Screw:

$$Q_k = 0.95 \text{ x (thickness)} - 2 \quad \text{(A2-1)}$$

$$K_{serv} = 0.3 \text{ x (thickness)} + 80 \quad \text{(A2-2)}$$

$$K_u = 0.45 \text{ x (thickness)} + 45 \quad \text{(A2-3)}$$

Triangular Notch and Coach Screw:

$$Q_k = 0.95 \text{ x (thickness)} - 2 \quad \text{(A2-4)}$$

$$K_{serv} = 1.05 \text{ x (thickness)} + 45 \quad \text{(A2-5)}$$

$$K_u = 1.25 \text{ x (thickness)} - 15 \quad \text{(A2-6)}$$

where thickness is in mm, and must be between 30 mm and 126 mm.

The maximum values for Q_k, K_{serv} and K_u for trapezoidal notch are 118 kN, 118 kN/mm and 102 kN/mm while the same for the triangular notch are 118 kN, 177 kN/mm and 143 kN/mm, respectively.

It is noted that the test data is not yet available for thicknesses exceeding 126 mm.

A3 Worked Example – 8 m TCC Floor Span by 5 m Bearer

TCC work example prepared by Arup, Sydney Building Structure.

Calculation of timber concrete composite floor capacity in accordance with the Design Guide

The calculations were initially carried out by spreadsheet but have been presented here, written in full, to demonstrate the calculation process.

A3.1 Material Input

Timber type: LVL 11

Timber modulus	E_t = 11000 MPa
Timber density	ρ = 620 kg/m^3
Timber bending strength	f'_b= 48 MPa
Timber tensile strength	f'_t= 30 MPa
Timber shear strength	f'_s= 6.0 MPa
Concrete modulus	E_c = 31000 MPa
Concrete density	ρ_c = 2500 kg/m^3
Concrete compressive strength	f'_c = 32 MPa
Concrete thickness	h_c = 80 mm
Plywood thickness	a_f = 15 mm

A3.2 Loading Input

Super imposed dead load	SDL = 1.0 kPa
Live load	LL = 4 kPa
Acceleration due to gravity	g = 9.81 m/s^2
Concrete selfweight	$C_w = h_c \times \rho_c \times g$ = 1.96 kPa
Formwork selfweight	$F_w = a_f \times \rho \times g$ = 0.09 kPa

A3.3 Geometric Input

Joist Span	L = 8 m
Spacing	S = 600 mm
Beam Depth	h_t = 400 mm (Therefore 3 No. fit into a 1200 mm billet without wastage)
Beam Width	b_t = 90 mm
Concrete Thickness	h_c = 80 mm
Beam Selfweight	$B_w = b_t \times h_t \times g \times \rho$ = 0.219 kN/m
Concrete Effective Width	$b_c = \min(S, b_t + 0.2 \times L)$ = 600 mm

A3.4 Joist Ultimate Strength Checks

A3.4.1 Required capacity

W^*= 1.2 x ($B_w/S + C_w + F_w$+ SDL) +1.5 x LL= 10.10 kPa

$M^* = w^* \, b_c \, L^2/8$ = 48.5 kNm

$V^* = w \times S \times L/2$= 24.2 kN

A3.4.2 Section properties

h_c=75.9 mm; (Reduced effective concrete thickness due to concrete tension at Ultimate Limit State, ULS)

$A_c = h_c \text{ x } b_c$ = 45540 mm^2

$A_t = h_t \text{ x } b_t$ = 36000 mm^2

$$I_c = \frac{b_c h_c^3}{12} \quad 21.86\text{x}10^6 \text{ mm}^4$$

$$I_t = \frac{b_t h_t^3}{12} = 480.0\text{x}10^6 \text{ mm}^4$$

A3.5 Worked Example (a): 8 m Floor with Trapezoid Notches

The *K* factor below has been determined from Figure 3.8 of the Design Guide

K_i =100 kN/mm

Refer to Section 3 of the Design Guide for further details.

A3.5.1 Ultimate Limit State Checks

Assuming that there are 4 shear connectors in each half beam span, as shown in the Figure A3.1.

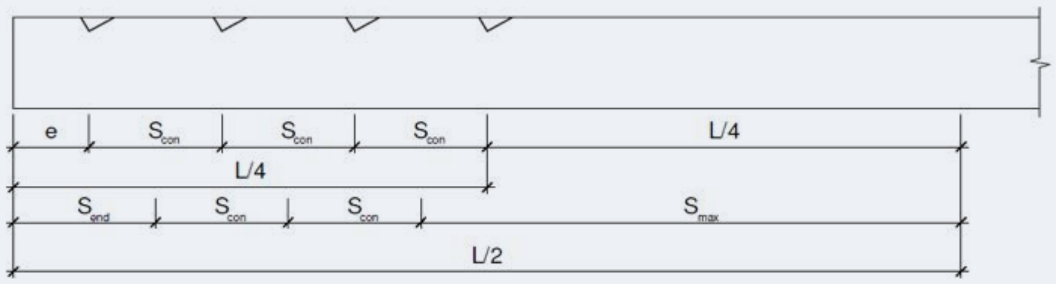


Figure A3.1: Notched connection arrangement.

Number of Connectors; n = 4

e = 320 mm

s_{con} = $(L/4 - e)/(n-1)$ = 560 mm

s_{end} = $s_{con}/2+e$ = 600 mm

s_{min} = $\min(s_{end}, s_{con})$ = 560 mm

s_{max} = $L/4 + s_{con}/2$ = 2280 mm

s_{ef} = 0.75 x s_{min} + 0.25 x s_{max} = 990 mm

$$\gamma_c = \frac{1}{1+\frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}} = 0.317$$

$\gamma_t = 1$

h_c = 80 mm

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} = 255 \text{ mm}$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 120 \text{ mm}$$

$$a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 135 \text{ mm}$$

$$(EI)_{ef} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 = 19.62 \text{ x } 1012 \text{ Nmm}^2$$

Bending Strength Limited by Concrete capacity

h_c=75.9 mm

$\phi = 0.6$

$\phi M_u = \phi f'_c \frac{2(EI)_{ef}}{\gamma_c E_c h_c}$ =1010 kNm

Concrete axial capacity

$\sigma_{c.c} = \frac{\gamma_c E_c a_c M^*}{(EI)_{ef}}$ 2.91 MPa

$N^*_c = \sigma_{c.c} \times A_c$ = 132.40 kN

$\Phi N_u = \Phi \times f'_c \times A_c$ = 874.37 kN

Combined compression and bending check

$\frac{N_c^*}{\Phi N_u} + \frac{M^*}{\Phi M_u} =$ 0.2; < 1 ;Therefore section is OK

Bending strength limited by timber capacity

$\Phi = 0.9$

$k_1 = 0.8$; (live load i.e. 5 month load duration)

$k_4 = 1.0$; (equilibrium moisture content less than 15%)

$k_6 = 1.0$; (normal temperature range)

$k_9 = 1.0$

$k_{11} = (300 \text{ mm}/h_t)^{0.167} = 0.95$

$k_{12} = 1.0$

$\phi M_u = \phi k_1 k_4 k_6 k_9 k_{11} k_{12} f'_b \frac{2(EI)_{ef}}{\gamma_t E_t h_t}$ = 294 kNm

Timber axial capacity

$\sigma_{t.t} = \frac{\gamma_t E_t a_t M^*}{(EI)_{ef}}$ = 3.68 MPa

$N_t = \sigma_{t.t} \times A_t$ = 132.40 kN

$k_{11} = (150 \text{ mm}/ h_t)^{0.167} = 0.85$

$\Phi N_u = \Phi \times k_1 \times k_4 \times k_6 \times k_{11} \times f'_t \times A_t$ = 660.11 kN

Combined bending and tensile check

$\frac{N_t^*}{\phi N_u} + \frac{M^*}{\phi M_u} =$ 0.37; < 1 ;Therefore section is OK

Flexural shear strength

At the floor joist to bearer detail, a 125 mm deep notch is assumed. Therfore the notch geometry must to be checked in accordance with AS 1720.1, Appendix E9 (not shown here) and the flexural shear strength must be checked for the net area, as shown below.

$A_t = (h_t - 125 \text{ mm}) \times b_t = 24750 \text{ mm}^2$

$\Phi V = \Phi k_1 k_4 k_6 f'_s \frac{2A_t}{3}$ = 71.28 kN

$\Phi V \geq V^*$; Therefore section is OK

Shear connector strength

Assuming 4 shear connectors per half span

From Figure 3.2 of the Design Guide:

Q_k= 85 kN

Connector capacity

$\Phi = 0.9$

$k_1 = 0.8$

$\Phi N_j = \Phi k_1 k_4 k_6 Q_k$ = 54.4 kN

Under a uniformly distributed load, the shear force can be taken in the centre of send respectively s_{max}, as shown in Figure A3.2.

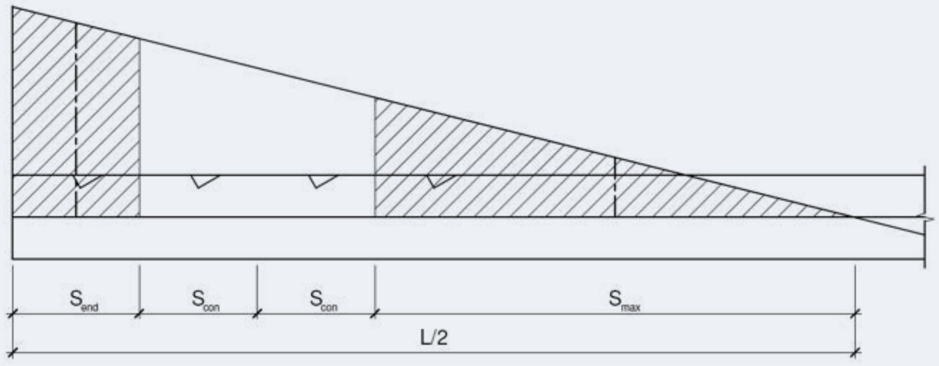


Figure A3.2: Shear force distribution along the beam.

At the support location:

$V^* = (L/2 - s_{end}/2) \times S \times w^*$ = 22.4 kN

$$Q^* = \frac{\gamma_c E_c A_c a_c s_{end}}{(EI)_{ef}} V = 36.7 \text{ kN}$$

At quarter point location:

$V^* = s_{max}/2 \times S \times w^*$ = 6.9 kN

$$Q^* = \frac{\gamma_c E_c A_c a_c s_{\max}}{(EI)_{ef}} V \quad 43.0 \text{ kN}$$

$\Phi N_j \geq Q^*$ Therefore connectors are OK

Tangential shear strength of the timber

Tangential Shear action in the area located between the support and the first connection:

$\Phi = 0.9$

Generally:

$\Phi N_V = \Phi k_1 k_4 k_6 f_s^{'} (b_t l_s)$

At the support location:

$\Phi Nv = \Phi \times k_1 \times k_4 \times k_6 \times f'_s \times (b_t \times e)$ = 124.42 kN

$\Phi N_V \geq Q^*$ Therefore connectors are OK

A3.5.2 Serviceability Checks

This section outlines the serviceability checks that have been done on the floor joist. Table A3.1 lists the cases considered in the calculations.

Case	Load Applied	Creiteria
1	Short-term (0.7Q)	Span /300
2	1 kN point Load	2 mm
3	Long-term (G+0.4Q)	Span/250
4	Long-term Only (G)	Span/300

Table A3.1: Deflection criteria for different load cases.

$G = (B_w/b_c + C_w + F_w + SDL) \times S = 2.05$ kN/m

$Q = LL \times S = 2.4$ kN/m

$h_c = 80$ mm; (Assume all the concrete is in compression, therefore use the full thickness)

$A_c = h_c \times b_c = 48000$ mm^2

$A_t = h_t \times b_t = 36000$ mm^2

Case 1(Short-term)

Calculate the serviceability stiffness with short-term load parameters.

From Figure 3.3 of the Design Guide:

$K_i = 140$ kN/mm

$$\gamma_c = \frac{1}{1 + \frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}} = 0.38$$

$\gamma_t = 1$

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} = 255 \text{ mm}$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 105 \text{ mm}$$

$$a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 150 \text{ mm}$$

$$I_c = \frac{b_c h_c^3}{12} = 25.60 \times 10^6 \text{ mm}^4$$

$$I_t = \frac{b_t h_t^3}{12} = 480.0 \times 10^6 \text{ mm}^4$$

$(EI)_{ef} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 = 21.24 \times 10^{12}$ Nmm^2 Calculate the short-term deflection:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(0.7Q)L^4}{384(EI)_{ef}} = 4.2 \text{ mm}$$

$L/\Delta = 1896 > 300$ Section Meets Short-term Deflection Limits;

Case 2 (Point load)

$$\Delta = \frac{PL^3}{48(EI)_{ef}}$$

$P = 1$ kN

$\Delta = 0.5$ mm ;< 2 mm Therefore OK

Case 3 (Short-term)

Calculate the serviceability stiffness with long-term load parameters.

ε_{CS} = 880x10^{-6}

Φ_{CC} = 3.62 ; (From Table 3.1.8.3 of AS 3600)

$$E_{c.lts} = \frac{E_c}{(1+\varepsilon_{cs})(1+\Phi_{cc})} = 6704 \text{ MPa}$$

j_2= 2; (Adopt j_2 of 2 as currently developed by the UTS research work)

$$E_{t.lts} = \frac{E_t}{j_2} = 5500 \text{ MPa}$$

$$K_{i.lts} = \frac{K_i}{j_2} = 70 \text{ kN/mm}$$

$$\gamma_{c.lts} = \frac{1}{1+\frac{\pi^2 E_{c.lts} A_c s_{ef}}{K_{i.lts} L^2}} = 0.59$$

γ_t = 1

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} = 255 \text{ mm}$$

$$a_c = \frac{\gamma_t E_{t.lts} A_t H}{\gamma_c E_{c.lts} A_c + \gamma_t E_{t.lts} A_t} = 130 \text{ mm}$$

$$a_t = \frac{\gamma_c E_{c.lts} A_c H}{\gamma_c E_{c.lts} A_c + \gamma_t E_{t.lts} A_t} = 125 \text{ mm}$$

$$(EI)_{ef} = E_{c.lts} I_c + E_{t.lts} I_t + \gamma_c E_{c.lts} A_c a_c^2 + \gamma_t E_{t.lts} A_t a_t^2 = 9.101\text{x}10^{12} \text{ Nmm}^2$$

Calculate the long-term deflection under G + 0.4Q:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(G+0.4Q)L^4}{384(EI)_{ef}} = 17.6 \text{ mm}$$

L/Δ=453 >250 Therefore OK

Section Meets Long-term Deflection Limits;

Case 4 (Long-term)

Calculate the long-term deflection under G:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(G)L^4}{384(EI)_{ef}} = 12.0 \text{ mm}$$

L/Δ= 666 ;>300 Therefore OK

Section Meets Long-term Dead Load Only Deflection Limits;

If the initial deflection due to shrinkage of the concrete is not offset during construction, it should be included in the cases 1, 3 and 4. It can be calculated using:

$$\Delta_{ini} = \frac{\varepsilon_{cs(28)} L^2}{8(h_c + a_f + h_t)}$$

A3.5.3 Bearer Design

The calculation below is for the internal bearer in the floor system. Although the edge bearer supports half the floor area of a typical bearer it may be required to carry facade loads. Given this, all the bearers have been assigned the same section in this design. This also simplifies fabrication. It would be expected that the design would be repeated for both elements.

Note that the testing done by UTS does not include members as thick as required for this bearer design and extrapolation of the available data does not give sufficient shear connector capacity to achieve composite action. At this stage the bearer has therefore been designed as non-composite, but with further testing or the use of a different connector system to achieve composite action the depth of the bearer could be reduced to approximately 600 mm.

The side pieces have been included to provide a bearing surface for joist connections.

Bearer ultimate strength checks

Geometric Input

Joist span;	$L = 6$ m
Spacing;	$S = 8$ m
Beam depth;	$h_t = 700$ mm
Beam width;	$b_t = 180$ mm
Side piece depth;	$h_s = 425$ mm
Side piece width;	$b_s = 90$ mm
Plywood thickness;	$a_f = 15$ mm
Concrete thickness;	$h_c = 80$ mm
Floor joists self-weight;	$J_w = 90\text{ mm} \times 400\text{ mm} \times g \times \rho / b_c = 0.37$ kPa
Concrete self-weight;	$C_w = h_c \times \rho_c \times g = 1.96$ kPa
Bearer self-weight;	$B_w = (b_t \times h_t + 2 \times b_s \times h_s) \times g \times \rho = 1.23$ kN/m

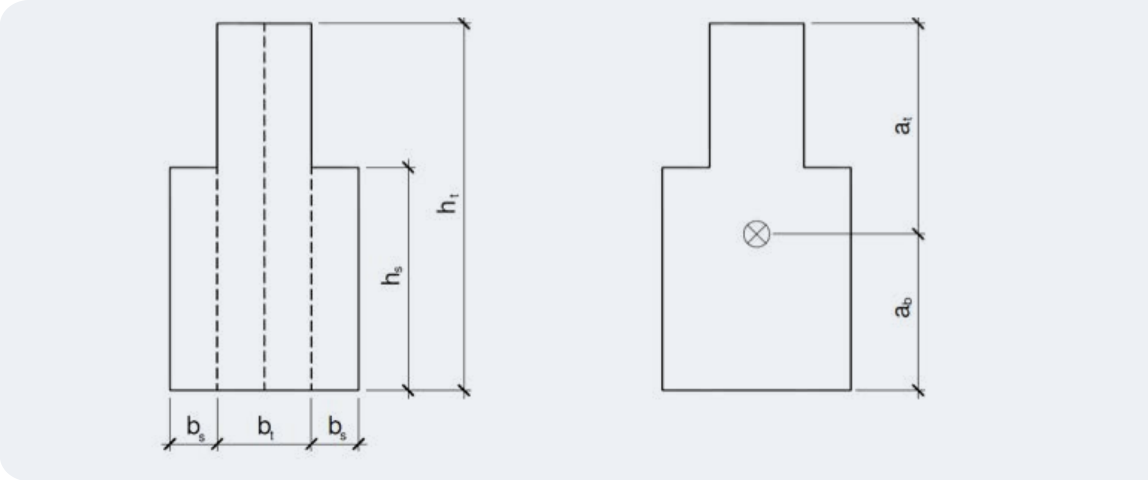


Figure A3.3: Bearer configuration.

Required Capacity

$\psi_a = 0.73$; (Area reduction factor, refer to AS 1170.1 clause 3.4.2)

$w = 1.2 \times (B_w/S + C_w + F_w + J_w + SDL) + 1.5 \times LL \times \psi_a = 8.7$ kPa

$M = w^* \times S \times L^2/8 = 312.6$ kNm

$V = w^* \times S \times L/2 = 208.4$ kN

Section Properties

$A_t = h_t \times b_t + 2 \times h_s \times b_s = 202500\text{ mm}^2$

$a_b = (b_t \times h_t \times h_t/2 + 2 \times b_s \times h_s \times h_s / 2) / A_t = 298$ mm

$a_t = h_t - a_b = 402$ mm

$I_t = \sum I_i + \sum\left((a_i - a_b)^2 \times A_i\right) = 7.2 \times 10^9\text{ mm}^4$

$Z_b = I_t / a_b = 24.14 \times 10^6\text{ mm}^3$

$Z_t = I_t / a_t = 17.90 \times 10^6\text{ mm}^3$

$(EI)_{ef} = E_t I_t = 79.16 \times 10^{12}\text{ Nmm}^2$

Bending Strength Limited by Timber capacity

$$\phi M_u = \phi k_1 k_4 k_6 k_9 k_{11} k_{12} f_b^{'} Z$$

Φ = 0.85

k_1 = 0.8; (live load i.e. 5 month load duration)

k_4 = 1.0; (equilibrium moisture content less than 15%)

k_6 = 1.0; (normal temperature range)

k_9 = 1;

k_{11} = $(300\text{ mm}/h_t)^{0.167}$ = 0.868

k_{12} = 1;

$M_{d,b} = \Phi \times k_1 \times k_4 \times k_6 \times k_9 \times k_{11} \times k_{12} \times f'_b \times Z_b$ = 724 kNm

$M_{d,t} = \Phi \times k_1 \times k_4 \times k_6 \times k_9 \times k_{11} \times k_{12} \times f'_b \times Z_t$ = 537 kNm

$$M_d \geq M^*$$

Capacity greater than *M**, Section OK;

Flexural Shear Strength

Check the flexural shear strength at the half height of the bearer (Section 1) and at the reduced width (Section 2).

Beam depth; h_t = 700 mm

Beam width; b_t = 180 mm

Side piece depth; h_s = 425 mm

Side piece width; b_s = 90 mm

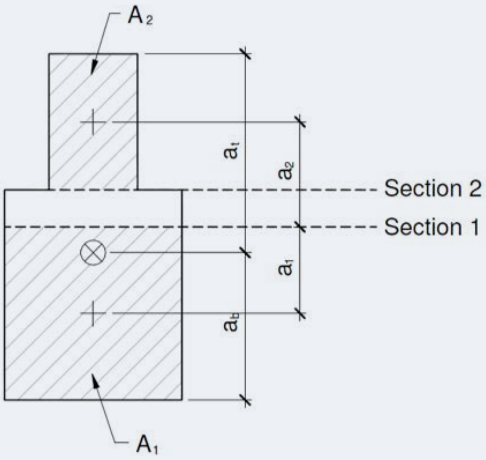


Figure A3.4: Bearer section.

$A_1 = h_t/2 \times (b_t + 2 \times b_s)$ = 126000 mm^2

$a_1 = a_b - h_t/4$ = 123.06 mm

$S_1 = A_1 \times a_1 = 15.50 \times 10^6$ mm^3

$A_2 = (h_t - h_s) \times b_t$ = 49500 mm^2

$a_2 = a_t - (h_t - h_s) / 2$ = 264.44 mm

$S_2 = A_2 \times a_2 = 13.09 \times 10^6$ mm^3

Calculate the shear capacity

$$V_{d,1} = \frac{\phi k_1 k_4 k_6 f_s^{'} I_t b_1}{S_1} = 721.8\text{ kN}$$

$$V_{d,2} = \frac{\phi k_1 k_4 k_6 f_s^{'} I_t b_2}{S_2} = 427.5\text{ kN}$$

$$V_d \geq V^*$$

Capacity greater than *V**, Section OK;

Serviceability checks

Case	Load Applied	Creiteria
1	Short-term (0.7Q)	Span /300
2	1 kN point Load	2 mm
3	Long-term (G+0.4Q)	Span/250
4	Long-term Only (G)	Span/300

Table A3.2: Deflection Criteria for different load cases.

$G = (B_w/S + C_w + F_w + J_w + \text{SDL}) \times S = 28.6$ kN/m

$Q = LL \times S = 32.0$ kN/m

Case 1: Short-term (0.7Q)

Calculate the short-term deflection:

$(EI)_{ef} = E_t I_t = 79.16 \times 10^{12}$ Nmm^2

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(0.7\text{Q})L^4}{384(EI)_{ef}} = 4.8 \text{ mm}$$

$L/\Delta = 1257 > 300$

Section Meets Short-term Deflection Limits

Case 2: 1 kN point Load

$$\Delta = \frac{PL^3}{48(EI)_{ef}}$$

$P = 1$ kN

$\Delta = 0.1$ mm < 2 mm Therefore OK

Case 3: Long-term (G+0.4Q)

Calculate the long-term deflection under G + 0.4Q.

$$E_{t.lts} = \frac{E_t}{j_2}$$

$j_2 = 2$; (From Table 2.1 of AS 1720.1 [2])

$E_{t.lts} = E_t/j_2 = 5500$ MPa

$(EI)_{ef} = E_{t.lts} I_t = 39.58 \times 10^{12}$ Nmm^2

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(\text{G}+0.4\text{Q})L^4}{384(EI)_{ef}} = 17.6 \text{ mm}$$

$L/\Delta = 340 > 250$

Section Meets Long-term Deflection Limits

Case 4: Long-term Only (G)

Calculate the long-term deflection under G.

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(\text{G})L^4}{384(EI)_{ef}} = 12.2 \text{ mm}$$

$L/\Delta = 492 > 300$

Section Meets Long-term Dead Load Only Deflection Limits

A3.5.4 Vibration Checks

The vibration performance can be assessed by various methods.

1. Deflection under a 1 kN point load
2. 8Hz frequency limit
3. Direct calculation of vibration performance in accordance with CCIP-016, A Design Guide for Footfall Induced Vibration of Structures by The Concrete Centre

For this structure checks using all three methods have been undertaken.

Deflection checks

The results of Method 1 are presented earlier in the deflection results section. The structure meets this requirement.

Frequency check

The design guide proposes a first fundamental frequency check is undertaken using the formula below.

Joists:

$$f = \frac{9.87}{2\pi}\left(\frac{9800EI_{ef}}{L^4\mathrm{G}}\right)^{0.5}$$

Where G is the self-weight

$G = (B_w/b_c + C_w + F_w) \times S = 1.45$ kN/m

$$f = \frac{9.87}{2\pi}\left(\frac{9800EI_{ef}}{L^4\mathrm{G}}\right)^{0.5} = 9.3 \text{ Hz}$$

Where all values are expressed in Nmm.

Bearer:

Where G is the self-weight

$G = (B_w/S + C_w + J_w + F_w) \times S = 20.6$ kN/m

$$f = \frac{9.87}{2\pi}\left(\frac{9800EI_{ef}}{L^4\mathrm{G}}\right)^{0.5} = 8.5 \text{ Hz}$$

Where all values are expressed in Nmm.

The frequency calculated by this method is only appropriate if it is beams in one direction that are very active. For floors spanning in two directions this may not be correct. More accurate results can be obtained by hand calculation using methods proposed for steel composite floors or by using an analysis program to model natural frequencies.

It should also be noted that for a frequency prediction of the floor in service, the floor will have additional in-service mass due to fit out and the effective stiffness will be for small amplitude displacements.

The first vertical mode of the structure predicted using Finite Element modelling and the assumptions below is 8.3 Hz.

Direct Calculation of Vibration Performance

The vibration performance of the structure has been calculated in accordance to best practice document CCIP-016 referenced above. This method calculates the vibration response of the floor as a multiplier (or response factor) on the floor due to a single person walking. Acceptability criteria recommended for offices is R = 4-8 depending on the quality of office space required.

The following assumptions were made in the assessment:

- Under the small amplitude vibrations of footfall loading the joists were considered fully composite with the concrete floor.
- The bearers were assumed to have no composite action.
- Under the small amplitude vibrations of footfall loading the facade was assumed to provide a vertical restraint around the edge of the floor.
- The full super imposed dead load and 10% live load was assumed to be present.
- The floor plate was assumed to be an open plan office therefore a maximum walking frequency of 2.0 footfalls/second was assumed.
- 3% critical damping was assumed for all modes.

The resulting response factor was calculated to be below 6 throughout the office. Therefore, the floor meets the recommended performance target for a typical office, but not premium office space.

Considering a central corridor section along the long axis of the building – where walking up to 2.5 footfalls/second may occur – resulted in response factors up to $R = 11$ but these higher responses were limited to the corridor zone. The office areas on either side achieve a response factor of R=4 for this scenario.

Conclusions and Comments

The calculations for a simple TCC floor have been presented.

The depth of the joists could be reduced slightly and still work structurally, but this would cause wastage in the production of the joists out of the usual 1200 mm billets and therefore was not considered worthwhile. Reducing the joist depth would also result in a decrease in the vibration performance.

The research done by UTS does not include members as thick as required for the bearer design and extrapolation of the available data does not give sufficient shear connector capacity to achieve composite action. At this stage, the bearer has therefore been designed as non-composite, but with further testing or the use of a different connector system to achieve composite action the depth of the bearer could be reduced to approximately 600 mm.

The floor meets the recommended vibration performance target for a typical office, but not premium office space.

A3.6 Worked Example (b): 8 m Floor Using Cross SFS Screws

The serviceability and ultimate slip moduli below have been determined from the tested data utilising one pair of cross SFS screws inclined at 45° connection:

$K_s = 70$ kN/mm

$K_u = 44$ kN/mm

Refer to Section 3 of the Design Guide for further details.

The detail of screw spacing is as below:

A3.6.1 Ultimate Limit State Checks

Type of Connection:	L_1 (mm)	S_{min} (mm)	S_{max} (mm)	S_{ef} (mm)
SFSVB - 48-7.5 x 165	300	280	N/A	314

Table A3.3: Details of cross SFS screws.

$$ULS: \gamma_c = \frac{1}{1+\frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}} \quad 0.42$$

$\Upsilon_t = 1$

$h_c = 80$ mm

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} \quad = 192 \text{ mm}$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \quad = 71.9 \text{ mm}$$

$$a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \quad = 120.3 \text{ mm}$$

$$(EI)_{ef} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 \quad = 9.74 \times 10^{12} \text{ Nmm}^2$$

Bending strength limited by concrete capacity

$h_c = 75.9$ mm (Reduced effective concrete thickness due to concrete tension at Ultimate Limit State, ULS)

$\phi = 0.6$

$$\phi M_u = \phi f'_c \frac{2(EI)_{ef}}{\gamma_c E_c h_c} \quad = 378.8 \text{ kNm}$$

Concrete axial capacity

$$\sigma_{c.c} = \frac{\gamma_c E_c a_c M^*}{(EI)_{ef}} \quad = 7.78 \text{ MPa}$$

$N^*_c = \sigma_{c.c} \times A_c = 354.1$ kN

$\Phi N_u = \Phi \times f'_c \times A_c = 874.37$ kN

Combined

$$\frac{N_c^*}{\Phi N_u} + \frac{M^*}{\Phi M_u} = 0.61 < 1$$; Therefore section is OK

Bending strength limited by timber capacity

$\Phi = 0.9$

$k_1 = 0.8$; (live load i.e. 5 month load duration)

$k_4 = 1.0$; (equilibrium moisture content less than 15%)

$k_6 = 1.0$; (normal temperature range)

$k_9 = 1.0$

$k_{11} = (300 \text{ mm}/h_t)^{0.167} = 0.95$

$k_{12} = 1.0$

$$\Phi M_u = \Phi k_1 k_4 k_6 k_9 k_{11} k_{12} f'_b \frac{2(EI)_{eff}}{\gamma_t E_t h_t} \quad = 145.8 \text{ kNm}$$

Timber axial capacity

$$\sigma_{t.t} = \frac{\gamma_t E_t a_t M^*}{(EI)_{eff}} \quad = 10.44 \text{ MPa}$$

$N^*_t = \sigma_{t.t} \times A_t = 376.16$ kN

$k_{11} = (150 \text{ mm}/h_t)^{0.167} = 0.85$

$\Phi N_u = \Phi \times k_1 \times k_4 \times k_6 \times k_{11} \times f'_t \times A_t = 660.11$ kN

Combined

$$\frac{N_t^*}{\Phi N_u} + \frac{M^*}{\Phi M_u} \approx 1 < 1$$; Therefore section is OK

Flexural shear strength

At the floor joist to bearer detail, the flexural shear strength must be checked for the net area, as shown below.

$A_t = (h_t) \times b_t = 36000\ \text{mm}^2$

$$\Phi V = \Phi k_1 k_4 k_6 f_s' \frac{2A_t}{3} = 103.7\ \text{kN}$$

$\Phi V \geq V^*$ 103.7 kN > 39.2 kN Therefore section is OK

Shear connector strength

$Q_k = 32$ kN

Connector capacity

$\Phi = 0.8$

$k_1 = 0.8$

$\Phi N_j = \Phi k_1 k_4 k_6 Q_k = 54.4$ kN

At the support location:

$V^* = L/2 \times w^* = 3.7 \times 4 = 14.8$ kN

$$Q^* = \frac{\gamma_c E_c A_c a_c s_{end}}{(EI)_{ef}} V^* = 20.05\ \text{kN}$$

$\Phi N_j \geq Q^*$ 32kN > 20.05 kN Therefore connectors are OK

Tangential shear strength of the timber

Tangential Shear action in the area located between the support and the first connection

$\Phi = 0.9$

Generally:

$$\Phi N_V = \Phi k_1 k_4 k_6 f_s' (b_t l_s)$$

At the support location:

$\Phi Nv = \Phi \times k_1 \times k_4 \times k_6 \times f'_s \times (b_t \times e) = 124.42$ kN

$\Phi N_V \geq Q^*$ Therefore connectors are OK

A3.6.2 Serviceability checks

This section outlines the serviceability checks that have been done on the floor joist. Table A3.4 lists the cases considered in the calculations.

Case	Load Applied	Creiteria
1	Short-term (0.7Q)	Span /300
2	1 kN point Load	2 mm
3	Long-term (G+0.4Q)	Span/250
4	Long-term Only (G)	Span/300

Table A3.4: Deflection Criteria for different load cases.

$G = (B_w/b_c + C_w + F_w + \text{SDL}) \times S = 2.05$ kN/m

$Q = LL \times S = 2.4$ kN/m

$h_c = 80$ mm; (Assume all the concrete is in compression, therefore use the full thickness)

$A_c = h_c \times b_c = 48000\ \text{mm}^2$

$At = h_t \times b_t = 36000\ \text{mm}^2$

Case 1 (Short-term)

Calculate the serviceability stiffness with short-term load parameters.

From Figure 3.3 of the Design Guide:

K_i = 70 kN/mm

$$\gamma_c = \frac{1}{1+\frac{\pi^2 E_c A_c s_{ef}}{K_i L^2}} = 0.54$$

$\gamma_t = 1$

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2} = 189.95 \text{ mm}$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 61.5 \text{ mm}$$

$$a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} = 128.5 \text{ mm}$$

$$I_c = \frac{b_c h_c^3}{12} = 25.60 \times 10^6 \text{ mm}^4$$

$$I_t = \frac{b_t h_t^3}{12} = 480.0 \times 10^6 \text{ mm}^4$$

$$(EI)_{eff} = E_c I_c + E_t I_t + \gamma_c E_c A_c a_c^2 + \gamma_t E_t A_t a_t^2 = 10.4 \times 10^{12} \text{ Nmm}^2$$

Calculate the short-term deflection:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(0.7\text{Q})L^4}{384(EI)_{ef}} = 8.6 \text{ mm}$$

L/Δ = 930.3 > 300 Section Meets Short-term Deflection Limits

Case 2 (Point load)

$$\Delta = \frac{PL^3}{48(EI)_{ef}}$$

P=1kN

Δ= 1.03 mm ;< 2 mm Therefore OK

Case 3 (Long-term)

Calculate the serviceability stiffness with long-term load parameters.

$\varepsilon_{cs} = 880 \times 10^{-6}$

$\Phi_{cc} = 3.62$; (From Table 3.1.8.3 of AS 3600)

$$E_{c.lts} = \frac{E_c}{(1+\varepsilon_{cs})(1+\Phi_{cc})} = 6704 \text{ MPa}$$

j_2= 2; (Adopt j_2 of 2 as currently developed by the UTS research work)

$$E_{t.lts} = \frac{E_t}{j_2} = 5500 \text{ MPa}$$

$$K_{i.lts} = \frac{K_i}{j_2} = 35 \text{ kN/mm}$$

$$\gamma_{c.lts} = \frac{1}{1+\frac{\pi^2 E_{c.lts} A_c s_{eff}}{K_{i.lts} L^2}}$$

$\gamma_t = 1$

$$H = \frac{h_c}{2} + a_f + \frac{h_t}{2}$$

$$a_c = \frac{\gamma_t E_{t.lts} A_t H}{\gamma_c E_{c.lts} A_c + \gamma_t E_{t.lts} A_t}$$

$$a_t = \frac{\gamma_c E_{c.lts} A_c H}{\gamma_c E_{c.lts} A_c + \gamma_t E_{t.lts} A_t}$$

$$(EI)_{ef} = E_{c.lts} I_c + E_{t.lts} I_t + \gamma_c E_{c.lts} A_c a_c^2 + \gamma_t E_{t.lts} A_t a_t^2$$

the serviceability stiffness with short-term load parameters.

Calculate the long-term deflection under G + 0.4Q:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(\mathrm{G}+0.4\mathrm{Q})L^4}{384(EI)_{ef}} \quad = 35.9 \text{ mm}$$

$L/\Delta = 250 \approx 250$ Therefore OK

Section Meets Long-term Deflection Limits;

Case 4 (Long-term)

Calculate the long-term deflection under G:

$$\Delta = \frac{5(W^*)L^4}{384(EI)_{ef}} = \frac{5(\mathrm{G})L^4}{384(EI)_{ef}} \quad = 24.4 \text{ mm}$$

$L/\Delta = 330.6 > 300$ Therefore OK

Section Meets Long-term Dead Load Only Deflection Limits;

If the initial deflection due to shrinkage of the concrete is not offset during construction, it should be included in the cases 1, 3 and 4. It can be calculated using:

$$\Delta_{ini} = \frac{\varepsilon_{cs(28)} L^2}{8(h_c + a_f + h_t)}$$

B

Appendix B – Notation

The symbols and letters used in the Guide are listed below:

A_c	cross-sectional area of the concrete member
A_t	cross-sectional area of the timber member
A_l	bearing area for loading parallel to the grain (timber)
A_p	bearing area for loading perpendicular to the grain (timber)
A_{sl}	shear plane area for shear action parallel to the grain (timber)
A_{st}	cross-sectional area of the coach screw (TCC only)
a	distance between points of zero bending moment
a_c	distance for the concrete member
a_f	thickness of the formwork
a_t	distance for the timber member
b_c	tributary width of the concrete member
b_{e1} & b_{e2}	measured effective on each side of the centre-line of the timber beam
b_{sf1}	effective width of composite beam top flange (0 for timber beam)
b_1, b_2	centre-to-centre spacing of adjacent beams or distance from centre of timber beam to edge of slab outstand
b_t	width (thickness) of the timber member
b_v	width of the notch (concrete)
d	timber density at a moisture content of 12% in kg/m^3
d_o	length of the notch (concrete)
D_c	overall depth of the concrete slab
E_c	value of the modulus of elasticity of the concrete member
$E_{c,lts}$	value of the modulus of elasticity of the concrete member for long-term serviceability
E_t	value of the modulus of elasticity of the timber member
$E_{t,lts}$	value of the modulus of elasticity of the timber member for long-term serviceability
EI_{ef}	effective (apparent) stiffness of the TCC cross-section
f_n	axial (tensile or compressive) strength
f_b	bending strength
f'_b	characteristic strength in bending
f'_c	characteristic strength in compression
f'_l	characteristic strength in bearing parallel to the grain
f'_p	characteristic strength in bearing perpendicular to the grain
f'_s	characteristic strength in shear
f'_t	characteristic strength in tension
G^*	design self-weight
H	factor for the height of the TCC cross-section
h_c	thickness of the concrete member
h_t	depth (height) of the timber member
I_c	second moment of area (moment of inertia) of the concrete member

I_t	second moment of area (moment of inertia) of the timber member
j_2	stiffness modification factor – load duration
K_{eff}	connection (shear key) stiffness for design of the Service Limit State – long-term deflection
K_i	connection (shear key) stiffness
K_{ser}	connection (shear key) stiffness for design of the Service Limit State – short-term deflection
K_u	connection (shear key) stiffness for design of the Ultimate Limit State
k_1	duration of load (timber)
k_{c1}	shrinkage strain coefficient (concrete)
k_{c2}	creep factor coefficient (concrete)
k_{c3}	maturity coefficient (concrete)
k_4	moisture condition (timber)
k_6	temperature (timber)
k_7	length and position of bearing (timber)
k_9	strength sharing between parallel members (timber)
k_{11}	size factor (timber)
k_{12}	stability factor (timber)
L	span of the structure
L_{ef}	effective span of the beam calculated in accordance with Clause 5.3.3, AS 2327
l_s	length of the horizontal shear plane (timber)
M^*	design action effect in bending
ϕM_u	design capacity in bending (concrete)
(ϕM)	design capacity in bending (timber)
N^*	design action effect produced by axial force
N^*_p	design action effect in bearing produced by reaction at a support
ϕN_u	design capacity in axial stress (concrete)
(ϕN)	design capacity in axial stress (timber)
(ϕN^j)	design capacity of the connection in shear
(ϕN_l)	design capacity in bearing parallel to the grain (timber)
(ϕN_p)	design capacity in bearing perpendicular to the grain (timber)
(ϕN_v)	design capacity in shear parallel to the grain (timber)
(ϕN_θ)	design capacity in bearing at an angle to the grain (timber)
P^*	design action for point load action (Service Limit State)
$Q^*_{V^*_{L/4}}$	design action effect in shear in the connection
$Q^*_{V^*_{\max}}$	design action effect in shear in the connection (at L / 4)
Q^*	design action effect in shear in the connection (at a support)
Q_k	design action for shear in the connection
	characteristic strength of the connection in shear
R_m	mean characteristic strength of the connection in shear (test data)
s_{ef}	factor for the connection spacing
s_{max}	distance of the first connector from mid-span
s_{min}	distance between the connectors (inside the external quarter-spans)
t	period of time, in minutes 90 mins
V^*	design action effect in flexural shear (also tangential shear)

$V^*_{L/4}$	design action effect in flexural shear (also tangential shear) at L / 4
V^*_{max}	design action effect in flexural shear (also tangential shear) at a support
(ϕV)	design capacity in flexural shear (timber)
ϕV_{uc}	design capacity in shear (concrete)
w^*_{imp}	imposed design load(s)
$\beta_{1,2,3}$	*coefficients (concrete)*
Δ	*deflection at mid-span*
γ_c	*partial factor for material properties of the concrete member*
$\gamma_{c,lts}$	*partial factor for material properties of the concrete member – long-term serviceability*
γ_t	*partial factor for material properties of the timber member*
$\gamma_{t,lts}$	*partial factor for material properties of the timber member – long-term serviceability*
ε_{cs}	*design shrinkage strain (concrete)*
$\varepsilon_{cs.b}$	*basic shrinkage strain (concrete)*
$v_{0.4}$	*mean slip of the connection measured at 0.4* R_m *(test data)*
$v_{0.6}$	*mean slip of the connection measured at 0.6* R_m *(test data)*
ϕ	*capacity factor*
ϕ_{cc}	*design creep factor (concrete)*
$\phi_{cc.b}$	*basic creep factor (concrete)*
φ	*creep coefficient (timber)*
θ	*angle of the notch facet under compression,*
σ_b	*effective bending stress*
σ_c	*effective compression stress*
σ_t	*effective tension stress*
σ_n	*effective axial stress*
$\sigma_{t,N}$	*axial stress of timber*
$\sigma_{t,M}$	*bending stress of timber*
$\sigma_{b,t}$	*tensile stress of timber*
$\sigma_{b,c}$	*bending stress of concrete*

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