DESIGN, FABRICATION AND ASSEMBLY OF A TWO-STOREY POST-TENSIONED TIMBER BUILDING

Michael P. Newcombe\(^1\), Stefano Pampanin\(^2\), Andrew H. Buchanan\(^3\).

ABSTRACT: Recent structural timber innovations at the University of Canterbury have led to the design, construction and experimental testing of a large scale, 2 storey, post-tensioned timber frame and wall building. The building system, referred to as Pres-Lam\(^\circ\), aims to minimise on-site construction time and building cost, to compete with alternative construction materials (concrete and steel). Hence, construction and cost data was recorded for the test building with the aim that it can be applied to future buildings. The building was assembled in 17 hours. The rapid speed of construction is attributed to the simplicity of post-tensioned connections, the flexibility of the construction sequence, the manoeuvrability of the structural components and the strict tolerances specified for timber fabrication. It was determined that, even with limited manufacturing capabilities, high tolerances could be achieved which avoided the need for special detailing between beam and column connections. Approximately eighty percent of the cost of the building came from materials and pre-fabrication, verifying that on-site costs had been minimised. Further cost breakdown, established that wall systems are more cost effective than frames. Several beam-column reinforcing arrangements were considered, each with varied performance. External reinforcement for the beam-column interface was expensive and only slightly increased the strength of the frames. Internal reinforcement of the columns using screws had little effect on the initial and long term compressive deformation, and the seismic shear deformation, of the columns. Internal steel plate reinforcement was more effective than screws but, due to rotation of the plates, provided limited shear stiffness to column, reducing the structural efficiency of the frame. Overall, the building performed excellently under earthquake simulations, incurring trivial amounts of damage to the timber components and the concrete slab. Through interaction with the building industry several construction details for future buildings have been developed.

KEYWORDS: Pres-Lam\(^\circ\), post-tensioned, timber, Laminated Veneer Lumber, seismic, multi-storey building.

1 INTRODUCTION

New structural systems for multi-storey timber buildings are under development at the University of Canterbury in collaboration with the Structural Timber Innovation Company Ltd (STIC). These systems, referred to as Pres-Lam\(^\circ\), are suitable for a wide range of building types, including commercial structures. It has the potential to compete with existing forms of construction in Australia and New Zealand (concrete and steel) in terms of cost, flexibility of structural form and structural performance [1]. The Pres-Lam\(^\circ\) system incorporates large timber structural frames or walls, constructed of Laminated Veneer Lumber (LVL), connected by steel post-tensioning (see Figure 1). This timber connection technique [2] was adapted from post-tensioned pre-cast concrete systems [3; 4] specifically for seismic applications. The combination of timber and post-tensioning is particularly efficient since it avoids potential brittle failure modes that are problematic in traditional timber solutions [5]. In addition, Pres-Lam\(^\circ\) fits well into modern Performance-Based Seismic Engineering (PBSE) design [6] because residual deformations and structural damage are minimized.

Figure 1: The Pres-Lam\(^\circ\) system concept implemented into a beam-column frame connection

Although extensive seismic testing has been performed on the post-tensioned connections in the vertical structure (frames and walls), till recently little attention
has been given to the connection of floor diaphragms [7] and the interaction of the gravity systems with the vertical structure [8]. Connection details are currently under development, the seismic performance of which must be evaluated.

The cost of the structural system also requires further investigation. Timber fabrication within New Zealand is gradually becoming more mechanised. However, to-date most fabrication is performed by hand, which can result in significant labour costs. Hence, the fabrication process may result in structural elements that are more expensive than concrete and steel alternatives. Nevertheless, the in-place cost of Pres-Lam® buildings may be cheaper due to reduced erection time and ease of assembly [9].

This paper gives an overview of the design, assembly, cost and seismic performance of a two-storey post-tensioned timber building, shown in Figure 2 and provides recommendations for the progression of Pres-Lam® buildings within New Zealand and Australia.

2 BUILDING DESIGN

The building is a 2/3rd scale model and incorporates frames and coupled walls in each direction and Timber-Concrete Composite (TCC) floors [10]. To construct the building, a traditional procurement management structure was followed. Hence, design drawings and specifications were produced by STIC (acting as a consulting engineer) and the tender process, fabrication and construction process was project managed by Mainzeal Property and Construction Ltd (Mainzeal).

Key aspects of the building design was the material, the fabrication requirements and the structural connections

2.1 MATERIALS

The structural material can be divided into timber components, steel components and the concrete slab.

2.1.1 Timber

The beams, columns, walls and edge beams (see Figure 2) are constructed of LVL provided from two suppliers (Carter Holt Harvey Ltd and Nelson Pine Industries Ltd). To ensure consistency throughout the structure, it was specified that the LVL must have a modulus of elasticity between 10 and 11 GPa and a moisture content of less than 15%.

Low grade 15mm plywood was used for a permanent formwork on the timber-concrete composite floor units

2.1.2 Steel components

Fabricated mild steel plates and SPAX screws were used to internally reinforce the columns at Level 2 and Level 3 respectively (see Figure 3a and b). Multiple high strength steel strands (0.5 inch, 7-wire strands) were used to post-tension the frames and walls. Additional mild steel reinforcement was positioned across the beam-column connections (see Figure 3c) and between the walls for some tests.

Type 17 woodscrews were used to fasten the walls to the edge beams (see Figure 2c) and attach timber corbels on the columns.

2.1.3 Concrete slab

A low strength (25 MPa), low shrinkage (less than 600 microstrain at 56 days) concrete mix was specified. Mild steel reinforcing mesh and reinforcing bars were used in the concrete topping.

2.2 FABRICATION

The fabrication of the timber components was divided amongst two manufacturers. The steel components were constructed first (to strict tolerances) and delivered to fabricators before timber work began.

The timber manufacture was in accordance with existing New Zealand Standards for Glulam [11]. Special consideration was given to dimensional tolerances, as shown in Table 1. The tolerances proved crucial to the construction speed (see section 3.1) and the structural stability of the system.


**Table 1: Dimensional tolerances**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of elements</td>
<td>+/- 2 mm</td>
</tr>
<tr>
<td>Squareness of column and wall bases</td>
<td>0.15 degree</td>
</tr>
<tr>
<td>Squareness of beam ends</td>
<td>0.15 degree</td>
</tr>
<tr>
<td>Squareness of column face</td>
<td>0.15 degree</td>
</tr>
<tr>
<td>Gap between internal steel plate and</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>timber</td>
<td></td>
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</tbody>
</table>

2.3 CONNECTIONS

The beam-column (B-C) connections for Pres-Lam® frames require many design considerations. High compressive forces are applied to the column by the post-tensioning perpendicular-to-grain, which can result in significant deformations during stressing and long term creep deformation. In addition, it has been documented [12] that perpendicular-to-grain bearing and shear deformation of the column can increase the flexibility of the frame systems.

To combat these issues an internal steel plates have been utilised on Level 2 (see Figure 3a). The internal box section avoids perpendicular-to-grain compression. End plates transfer the compression forces applied by the beam into the box section. Under seismic loading the beam rotates relative to the column; the end plates increase the bearing area on the column, stiffening the connection. The top and bottom of the box section are snug within the column; this reduces rotation of the steel plates relative to the column which further increases the stiffness of the beam-column connections.

On Level 3 (see Figure 3b), SPAX screws are used to reduce short and long term deformation of the column and to increase the shear stiffness of the column for seismic loading. The screws also reinforce anchorage pins (see Figure 3c) used to mount external bars.

The external bars (see Figure 3c) are used to strengthen the beam-to-column connection and are designed to yield at large displacements, dissipating earthquake energy (which reduces the response of buildings during earthquakes).

Floor diaphragm connections (see Figure 3d) were designed to transfer in-plane seismic forces from the concrete topping, through notches into an LVL joist and into a frame or wall system via woodscrews. This connection avoids cracking of the concrete slab by allowing small displacements (due to geometrical frame elongation) to occur in the timber-to-timber connections. The TCC floor units were supported with steel plates fastened to the top of LVL joints (see Figure 3e). This connection arrangement enables easy fixing (from the top of the floor unit) and allows rotation between the floor and the supporting corbel. If the floor were supported on the bottom of joists there would be a loss of bearing area as the supporting elements rotate.

The connection between the walls and edge beams consisted of a dense group of 36 woodscrews (see Figure 2c). These screws were designed to act as pins that transferred shear forces and allow rotation. The dimension of the screw pattern was limited to avoid screw fracture under cyclic loading.

*Figure 3: Connections a) Internal column reinforcing Level 2 b) Internal column reinforcing Level 3 c) External bars d) Floor connections Level 2 e) Floor connections Level 3*
3 BUILDING CONSTRUCTION

All prefabricated timber components were delivered and stacked on site (see Figure 4a). The timber components were assembled by professional contractors (from Mainzeal) whom have experienced in the construction of concrete and steel buildings. The post-tensioning was applied to the frames and walls by specialist contractors (BBR Contech Ltd). Subsequently, a subcontractor (Allied Concrete Ltd) cast the concrete slab in-situ.

3.1 SPEED OF CONSTRUCTION

The assembly of the timber components (see Figure 4a and b) took 15 hours (2 working days) using 4 construction workers. For a full scale building, the floor coverage rate equates to approximately 480m²/hour. Floor units were light and could be positioned manually, reducing crane usage per floor unit.

The post-tensioning was completed in 2 hours (approximately 15% of the assembly time). The concrete pouring, levelling and floating took 1 day. Propping was not required.

Half of the prefabricated timber components were delivered to site one day late. Notably, this had little impact on the construction time. The modularity and simplicity of the structural system allowed many alternative construction sequences.

The fabrication tolerances (see section 2.2) significantly effected the speed of construction. Equivalent buildings in precast concrete require building tolerances be taken up by grout pads between the beam and column faces. This can be labour intensive, requires skilled labour and strict quality assurance on site. By specifying strict tolerances and performing an accurate foundation setout, these measures can be avoided. In addition, strict tolerances ensure that the frames remain straight and the walls remain plumb during stressing.

3.2 HEALTH AND SAFETY

Compared to concrete and steel construction, onsite safety was significantly improved with Pres-Lam®. Handrails could be attached easily to beams before they were lifted in position. Structural elements are significantly lighter, compared to concrete, reducing the risk of injury when positioning elements. Floor units created a safe working platform and were fastened to beams from the top, avoiding the need for ladders. Using prefabricated elements reduced onsite clutter and minimised the number of workers on-site.

4 BUILDING COSTS

A cost analysis of the test building is performed to identify which structural elements and details are cost effective and should be used for future buildings.

The total cost of the building ($70,139NZD) is divided into material and fabrication, assembly, post-tensioning and the concrete slab (see Figure 5a). Note, building foundations are not considered. As a prefabricated system, the aim for Pres-Lam® is to minimise expenditure on-site. As shown in Figure 5a, this is achieved since 78% of the total cost is associated with materials and off-site fabrication.

Figure 4: Construction progress a) Start b) At 1 day (Refer to Figure 2a for progress at 2 days) c) Applying post-tensioning d) Concrete pour
4.1.1 Materials and fabrication (delivered cost)
The total cost of the building delivered to site was $54,971NZD. Labour contributed to 28% of the delivered cost; this is expected to reduce over time as manufacturing processes improve.
The cost of each structural system can be separated and further analysed as shown in Figure 5b. Firstly, the frame system is 55% of the delivered cost (including labour). The external bars (see Figure 3c), which are non-essential (see section 5.1), contributes to 17% of the delivered cost. The internal steel plates (see Figure 3a) contributes 10%, ten times the cost of the SPAX screws (see Figure 3b). The steel plates complicated the fabrication of the columns resulting in significant labour costs (contributing 4%). The wall system, while having a similar strength to the frames, is only 17% of the delivered costs. Hence, the wall systems provide more strength per dollar. The additional reinforcement between the walls only contributes only 3%.
The floor units are 23% of the delivered cost. They are the most labour intensive of all the structural components. Labour on the floors contributes 10%. The cost of a basic frame (excluding external bars and using SPAX screws), in-place equates to $3450/m³. The wall system (including edge beams) is slightly more expensive at $3953/m³ but is structurally more efficient, so less volume will be required.
For equivalent reinforced concrete frames the in-place cost is expected to be between $2,400/m³ to $2500/m³ [13]. Considering the high labour content and low timber volumes for the test building, the delivered cost of the Pres-Lam® frames and walls appears cost competitive.

4.1.2 Assembly
The building was assembled at cost by Mainzeal. Including labour the expected assembly cost is $8,020NZD. A crane and scaffolding was provided free of charge. Market estimates [13] indicate that crane costs for the building assembly would be approximately $2,130NZD. Hence, the total assembly cost is approximately $10,150NZD.

4.1.3 Post-tensioning
BBR Contech Ltd performed the post-tensioning at no cost. However, the expected cost, as quoted by Contech, is $1794NZD.

4.1.4 The concrete slab
The concrete slab, including reinforcement, was constructed by Mainzeal and Allied Concrete Ltd for $3,224NZD at market rates.

Figure 5: Cost breakdown for test building a) Total b) Material and fabrication (delivered cost) c) Frames d) Wall systems
5 EARTHQUAKE PERFORMANCE

The building was subjected to uni-directional and bi-directional (quasi-static) earthquake simulation. Displacement-controlled cyclic loading was applied to the structure using hydraulic actuators and steel reaction frames, as shown in Figure 6. More detailed information on the seismic performance of the building can be found in companion papers [8; 14].

Figure 6: Test apparatus for seismic loading

5.1 Frame response

The frames remained elastic up to design displacements (2% column rotation or drift). There is no significant loss in strength or stiffness for repeated cycles. The concrete slab had little effect on the strength of the building in the frame direction.

The external rods (see Figure 3c) had little effect on the strength of the frame (contributing only an additional 10% base shear). The elastic deformation of the frames delayed the connection opening between the beam and column, and consequent activation of the rods until over 1% drift. The rods began to yield at approximately 1.5% drift, so that the yielding (and energy dissipation) remained low. Some deformation in the anchorage of the external mild steel devices meant that there was no increase in the initial stiffness of the frame.

The internal steel reinforcement (see Figure 3a) minimised axial deformation of the column due to the post-tensioning. However, gaps between the steel plates and column timber, allowed rotation which resulting in a limited increase in column shear stiffness (only double the shear stiffness of the unreinforced column). To improve the structural efficiency of the frame, higher shear stiffness is required.

The SPAX screws (see Figure 3b) were essentially ineffective at increasing the axial or shear stiffness of the column. More screws or alternative reinforcing details are required.

5.2 Wall response

The wall elements remain elastic up to 2% drift. The strength of the wall system was significantly increased by the interaction of the concrete slab and edge beams. Coupling reinforcement between the walls (see Figure 7c) was effective at further increasing the strength and stiffness of the wall system (by 28%). However, the reinforcement did not active until beyond service level displacements (0.33% drift).

5.3 Damage observation

Up to drifts of 2%, there was no significant damage to the building. The timber surrounding all beam-column connections remained elastic (see Figure 7a and b). For cyclic testing in the frame direction, minor cracking occurred in the concrete slab, none of which was due to geometrical frame elongation or would require repair. Localized cracking was observed adjacent to the walls due to displacement incompatibility because the floor remained flat as the walls rotated out-of-plane. The total elongation of the slab at 2% drift was 1.3mm, with a residual elongation of 0.4mm, all concentrated around the walls. Slightly more cracking occurred under cyclic testing in the wall direction, with maximum crack widths of 0.2mm at 2.0% drift. The level of cracking in the wall direction was magnified by the short span between columns and walls.

Figure 7: B-C connections at 2% drift a) Level 2 b) Level 3, c) Wall coupling reinforcement at 2% drift
6 FUTURE BUILDINGS

Key outcomes for the project were recommendations for future buildings. These are divided into design and construction considerations.

6.1 DESIGN

For a given design strength, wall systems are more economical than frames. However, the choice between frames and walls will depend strongly on architectural requirements.

Beam-column connection reinforcement using external bars (see Figure 3c) is costly and provides little increase in strength under design level earthquake loads. It would be more cost effective to use an independent wall system than to add beam-column reinforcement to a frame. Unless a more efficient detail is available this type of reinforcement should be avoided.

More effective techniques are required to increase the shear stiffness of the column in beam-column connections. For screw reinforcement, much higher reinforcement content is required. For internal steel plates, their effectiveness would be improved if they were epoxied in position as shown in Figure 8a. In addition, steel reinforcement should be fixed to the columns after they are constructed, to avoid complication during the timber fabrication. Alternatively, carbon fibre or grout reinforcement could be employed (see Figure 8b and c) which would activate instantly as the column deforms in shear. If column shear deformations are accepted in the building design, parallel-to-grain timber can be employed to resist axial shortening of the column. This could be achieved by rotating and gluing the outer laminations of the column. Similarly, stiffer wall reinforcement is required so that it activates at service level displacements.

With the current capabilities of timber manufacturers, it may be more cost effective use floor systems with lower labour costs than TCC floors. Stress-skin panels would generally require less labour to fabricate. In addition, using stress-skin panels avoids the need for joist hangers since they can be flange hung.

Due to reduced moment demands at exterior columns, internal post-tensioning anchorages can be used (see Figure 9a). A timber cap can provide fire protection to the tendons. For the walls, the post-tensioning can be anchored in a concrete basement level in two ways (see Figure 9b). A void can be cast into the concrete to allow mechanical anchorage of the tendons. A section of wall should be removable to allow the tendons to be positioned correctly into ducts. Another option is to cast proprietary post-tensioning anchorages into the concrete wall and use couplers at the base of the walls.

For medium-rise buildings the columns and walls will need to be spliced at every 3rd or 4th level due to transportation limitations. Finger jointed column splices could be used at the half height of the floor (where there is low moment demand) to transfer column shear, as shown in Figure 10a. For the walls, post-tensioning tendons will need to be coupled at the splicing locations, as shown in Figure 10b. The post-tensioning force is sufficient provide moment fixity between each wall element and generate enough friction to transfer shear forces, preventing relative in-plane movement of the walls. The wall laminations are finger jointed to allow location of the walls and prevent out-of-plane movement.

Figure 8: Potential beam-column connection details a) Epoxied internal steel plate b) Carbon fibre c) Grout

Column base connections can be moment-resisting or pinned, as shown in Figure 11. For moment-resisting connections, shear keys are required to transfer shear. For pinned connections dowels can be used.

6.2 CONSTRUCTION

The timber components should be fabricated to strict tolerances to increase construction speed. However, this requires accurate set-out of column and wall bases.
Grout pads should be used to precisely locate columns and walls (see Figure 9b and Figure 11). Several alternative construction sequences are possible for frame and walls systems. One approach is to accurately plumb and brace a corner column, and construct each bay moving out from the corner column. Structural elements will be light enough to be manually manoeuvred into position and lifted by low capacity cranes. An alternative is to construct a segment of frame horizontally on the ground and tilt the entire segment into position.

Each floor unit should be fabricated with specifically designed lifting connections to increase the speed of construction.

To reduce time for tensioning, frame and walls systems should be fabricated with internal ducts that will guide each tendon from one anchorage to the other. If steel tendons are used they should be protected by a grease-filled sheath for durability. Otherwise carbon-fibre tendons would be appropriate. Each tendon in a group should be stressed repeatedly until the design level post-tensioning force is achieved in all tendons. This may require up to three cycles of stressing.

7 CONCLUSIONS

The test building has demonstrated that Pres-Lam® is a cost-competitive, high performance structural system, with enormous potential for future buildings.

- The assembly of the structural components on-site is simple, flexible and rapid.
- Approximately eighty percent of the building cost was associated with material and fabrication, verifying that on-site time has been minimised.
- The wall systems were more cost effective than frames for resisting lateral loads.
- Beam-column connection reinforcement using external rods was found to be expensive and structurally inefficient.
- Internal reinforcement using screws was essentially ineffective (see Figure 4b) at increasing the axial and shear stiffness of the columns. Reinforcement using parallel-to-grain timber, close-tolerance steel plates, carbon fibre or grout is recommended.
- Under earthquake loading, negligible damage occurred in the timber components and the concrete slab.
- Through interaction with the construction industry, numerous connection details were developed for future Pres-Lam® buildings.

ACKNOWLEDGEMENTS

The project was funded by the Structural Timber Innovation Company Ltd.

Services and industry knowledge provided by Mainzeal Construction and BBR Contech is greatly appreciated.

SPAX Screws are thanked for supplying their products free-of-charge.

Contributions from the members of the STIC research team at the University of Canterbury are gratefully acknowledged. Especially Tobias Smith whom assisted with cost analysis for the test building.
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