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The Demountability, Relocation and Re-use of a High Performance Timber Building

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ABSTRACT: This paper outlines the deconstruction, redesign and reconstruction of a 2 storey timber building at the University of Canterbury, in Christchurch, New Zealand. The building consists of post tensioned timber frames and walls for lateral and gravity resistance, and timber concrete composite flooring. Originally a test specimen, the structure was subjected to extreme lateral displacements in the University structural testing laboratory. This large scale test of the structural form showed that post tensioned timber can withstand high levels of drift with little to no structural damage in addition to displaying full recentering characteristics with no residual displacements, a significant contributor to post earthquake cost. The building subsequently has been dismantled and reconstructed as offices for the Structural Timber Innovation Company (STIC). In doing this over 90% of the materials have been recycled which further enhances the sustainability of this construction system. The paper outlines the necessary steps to convert the structure from a test specimen into a functioning office building with minimal wastage and sufficient seismic resistance. The feasibility of recycling the structural system is examined using the key indicators of cost and time.

1 INTRODUCTION

First conceived in 2005, the innovative post tensioned timber (Pres-Lam) system combines reinforced concrete jointed ductile technology (Priestley et al. 1999) and engineered timber products to form a simple and effective moment resisting joint system for multi-storey timber buildings. Various small scale and large scale (Iqbal et al. 2010; Newcombe et al. 2010a) tests have established the stable and damage-free nature of the controlled rocking connection. During these tests additional methods of internal and external dissipation (Iqbal et al. 2008; Palermo et al. 2005; Smith et al. 2007) have been successful used. While the post tensioning is designed to remain elastic under even extreme seismic loading these devices will yield at a certain (chosen by the engineer) level of drift and can be replaced after the event. The recent large scale tests have meant that secondary effects of seismic loading such as beam elongation have been studied and shown to be negligible (Newcombe et al. 2010a).

Several recent projects have also studied the likely cost and construction times of buildings using this system. Smith (2008) compared a 6-storey Laminated Veneer Lumber (LVL) post tensioned timber building with prototype buildings in both precast concrete and steel. Concluding that the building would take a similar time to construct and cost roughly 5% more that the $NZD 9.5 million required to construct either the steel or concrete alternatives. The Pres-Lam test building, provided valuable cost data for the second study performed by Menendez (2010). This study compared an open plan 5 storey concrete building with a theoretical post tensioned timber alternative. One conclusion of this study was that the post tensioned timber building would have taken 40% less time to construct due to its fully prefabricated nature. The cost comparison of the two buildings showed an increase of $NZD 100,000 for the timber building, 8% of the total cost of the building. In this paper focus is given to the deconstruction and reconstruction of a 2 storey post-tensioned frame and wall building, the building is then analysed in terms of construction time and pre-commencement cost estimation.

2 THE PRES-LAM TEST BUILDING

The two storey Pres-Lam test building was a frame and wall open plan structure as shown in Figure 1. The building consisted of a lateral resisting post-tensioned timber frames in one direction and post-tensioned coupled shear walls in the opposite direction. The floor of the structure, which was of area 41m^2 on two levels (i.e. a total area of 82m^2 of the building), was a timber concrete composite flooring system developed at the University of Canterbury, consisting of LVL joists and 50mm of topping concrete connected with notch and coach screw discrete couplers (Yeoh 2010). Due to the structure being a research specimen the floors spanned in two different directions.

Post tensioning tendons were placed inside the beams and walls providing moment connections and thus lateral resistance. Additional moment capacity and energy dissipation was provided by two types of non-prestresssed reinforcement. The first was a fused type bar/dissipater attached externally, developed for use in concrete (NZCS, PRESSS Design Handbook, 2010) and adapted to timber. These devices were placed across interfaces between the beam-column and column-foundation. The second solution was given by U-shaped Flexural Plates (UFP) (Kelly et al., 1972) placed in the gap between the two wall elements and being activated by the relative movement of the adjacent walls during the rocking mechanism. Diaphragm action was achieved through the concrete topping which was attached to couplers connected to edge beams which were screwed to the frame and wall members. More information on the test building and its performance can be found in Newcombe et al. (2010a,b).

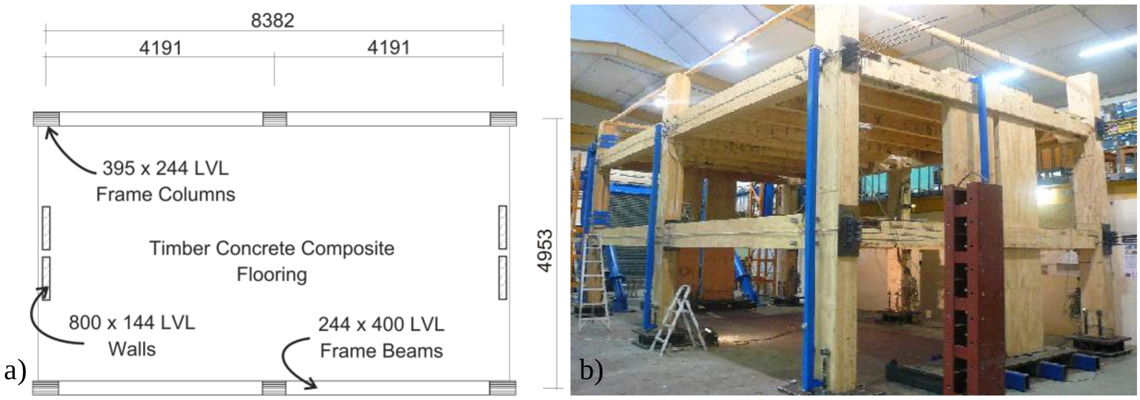

Figure 1. Pres-Lam Test Building a) Floor Plan and b) Constructed Test Building

3 SEISMIC PERFORMANCE OF PRES-LAM TEST BUILDING

A very brief description of the lateral performance of the test building is presented. Quasi-static cyclic testing was performed in both the frame and wall directions separately as well as simultaneously. The test building displayed excellent seismic performance with complete recentering and no significant damage up to 2% drift (Newcombe et al. 2010a). It was noted that the simultaneous bi-directional loading had no major effect on the in-plane resistance of either the frames or walls. Testing was also performed with and without the addition of the concrete topping slab. Compressive deformation of the timber beam-connections limited the overall frame elongation and therefore the damage to the concrete slab. This limited the interaction of floor slab with the building in the frame direction, providing an increase in base moment of only 15%. Due to some displacement incompatibilities, an increase of base moment of 25% in the wall direction was noted along with slight flexural damage to the concrete floor topping (Newcombe et al. 2010b).

4 DECONSTRUCTION OF THE PRES-LAM TEST BUILDING

Deconstruction is the selective dismantlement of building components, specifically for reuse, recycling and waste management. The requirement for this to be an option in construction has increased due to the increased ability to recycle materials (thus reducing landfill and carbon emissions) through the implementation of demountable buildings. The post tensioned timber system has been shown to be sustainable (John et al. 2009). In addition, due to the nature of the system, deconstruction of the structure should be feasible in terms of both time and cost.

4.1 Deconstruction Procedure

The first stage deconstruction was performed by Mainzeal Construction Ltd, the same contractor that assembled the Pres-Lam test building. Members were then demounted by University technical staff after the floors were decoupled and the tendons released. The major aim of the deconstruction was the removal of all members safely with minimal damage. Structural consultants were engaged before the deconstruction to ensure that reconstruction would be efficient. A major concern was the removal of the floor system and the consequent loss of diaphragm action provided by the concrete topping. This would have to be recreated in the reconstructed building. The deconstruction sequence is displayed in Figure 2. More information on the deconstruction can be found in Wong (2010).

Figure 2. Deconstruction Sequence of Pres-Lam Test Building (Wong 2010)

4.2 Deconstruction Time and Cost of the Pres-Lam Test Building

The deconstruction process took a total of 122 manhours to complete (Wong 2010). Most of the onsite work was performed by two labourers with more required during certain stages. 6 days were needed to completely dismantle the structure. While little time was spent dismantling the structural elements the removal of the floor was time intensive. This was due to the use of discrete connectors from the floor to the frames or edge beams within the slab to provide load transfer between each floor unit. This choice meant that considerable labour was required to decouple the slab from the beam and edge-beam members. The remaining time was spread evenly amongst the other structural elements The total estimated cost of the deconstruction was $NZD 10,420 (Wong 2010). This was 15% of the total cost of the building and half the cost of the original construction. All other costs were evenly distributed among the other elements. In practical application it is envisaged that this cost will be more than offset by the sale of the building members or money saved in materials for a new structure.

5 EXPAN OFFICE BUILDING

Once the Pres-Lam test building was completed a proposal was made to recycle the structural components to form a new office structure for the Structural Timber Innovation Company (Figure 3).

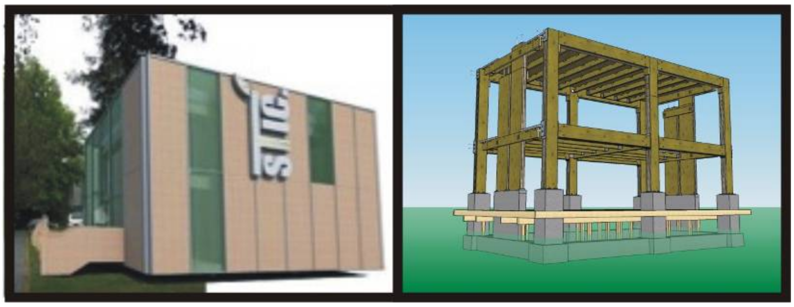

Figure 3. Rendering of the EXPAN Office Structure (Courtesy of Thom Craig Architects Ltd.) and of Internal Structure

To transform the experimental building into a new office building, most components of the existing experimental building would be fully utilised. In total over 90% of the structural components were able to be reused, however due to the original purpose as a 2/3 scale test specimen, some changes had to be made as follows:

- The interstorey heights of the first and second levels were increased to 2.7 and 2.8m, respectively meaning:
  1) The bases of the columns were placed on 0.8m high plinths,
  2) The upper beams were moved up to become flush with the tops of the columns, and new cavities for the tendons were drilled, and
  3) One wall at each end was extended to match the height of the columns. This was done using 4 grade 8.8 Ø20mm threaded bars epoxied into the walls (Figure 4a).
- Prefabricated steel shoes were placed at the base of each column, these were attached to the bases of the columns with epoxied bars which were epoxied onsite (Figure 4b)
- Face hung joist hangers were used, replacing the top hung system used in the Pres-Lam test Building (Figure 4c)
- One and a half floor panels on Level Two were removed to accommodate a spiral staircase
- Two 25mm diameter 1030 MacAlloy bars were used in the beams replacing the four 7 wire tendons (12.7mm diameter) used in the Pres-Lam test Building.

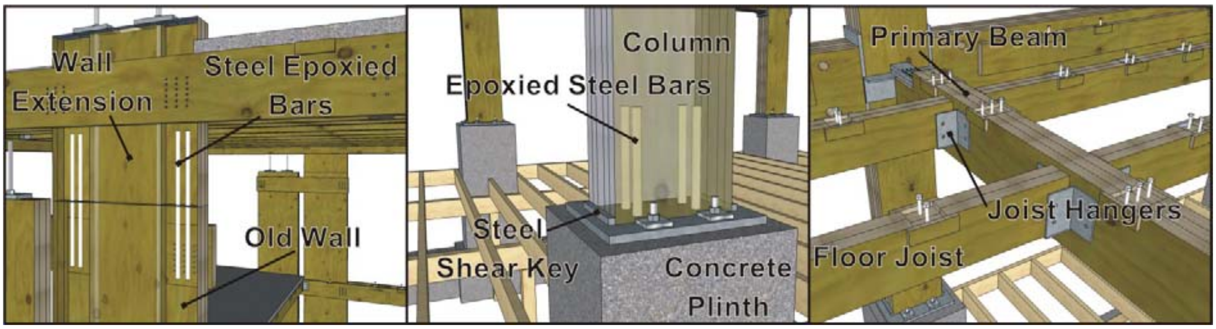

Figure 4. a) Wall Extension b) Column Base Connection and c) Face Hung Joist Hangers for EXPAN Office

6 SEISMIC DESIGN OF THE EXPAN OFFICE

The building was designed following current design practice to have an importance level of 2 and a design life of 10 years. The seismic analysis for the building used a displacement-focused design with the final design being checked using forced based design (equivalent static) principles, in accordance with the appropriate standard (AS/NZS 1170.5:2004). Using Rayleigh’s method the building was estimated to have an initial-elastic period of T = 0.34s. The test building utilised a reinforced concrete diaphragm reinforced with ductile 430 – 200 mesh (MDT) which was cut into sections during deconstruction. This concrete diaphragm was not re-established as the loads in the diaphragm were low enough for the plywood to develop full diaphragm action, the existing plywood was re-nailed to the joists where the concrete topping had been removed during deconstruction, and an adequate connection was provided using bolts (M12 at 300 c/c Level 1 and 400 c/c Level 2) through the joists, without needing to re-activate the reinforced concrete diaphragm. This bolted connection was only necessary where the floor units had been decoupled during deconstruction and it replaced a screwed connection between the floor units which was used in the Pres-Lam test building.

The design brief was to allow for the building to be deconstructed again in 3 to 5 years time. Safe deconstruction requires a certain amount of tendon or bar to remain protruding from the frame for the stressing jacks to connect to for re-stressing or de-stressing. MacAlloy bars require a shorter active end distance beyond the anchorage in order to de-stress, which fitted within the proposed cladding envelope. All post-tensioned bars were MacAlloy 1030, 26.5mm diameter bars with 2 bars in each beam, and 2 bars in each wall. The force in the bars will be monitored over time to ensure they do not drop below 80% of the original specified force, and long term monitoring of the tensile losses due to compression stresses in the timber will be ongoing. Although the base connection of the moment resisting frames could have been designed as “pinned” due to the estimated nominal damping values for a post-tensioned only frame with no dissipaters (e.g. no additional non-prestressed reinforcement), the design-level damping was increased by allowing for yielding in the steel base plates and some foundation movement thus reducing lateral load through additional damping in the case of an extreme seismic event.

7 CONSTRUCTION OF THE EXPAN OFFICE

This section focuses on the reconstruction of the test building, up to the completion of the structural components; hence, the assembly of the structural elements (frames, walls, and floors) and the application of the post tensioning. From the beginning of the erection of the timber frame until the completion of the post tensioning took a total of 9 working days, and 2 of these days were required to place scaffolding onsite allowing access for post tensioning crews.

7.1 Post Tensioned Timber Frames and Walls.

The erection of the post tensioned timber frame was begun on the 16th of November, 2010. The frames were assembled on the ground, MacAlloy bars were hand tightened and then frames were lifted into place. Once in position, adjustable props were placed and secured. The total time of erection for the first frame was 3 hours. Of this time approximately 1 hour was spent on each of the tasks of; the frame assembly, hand stressing/plumbing and the erection/securing with propping. The assembly of the second frame was performed on the ground beside the structure and then lifted into place in the same manner as the first frame. Less time was required for the second frame erection as workers became familiar with the necessary procedures. The frame was assembled on slightly uneven ground demonstrating the versatility of the building system and the way it can be adapted easily to onsite conditions. Pictures displaying frame erection are shown in Figure 5. During the erection of the frames a total of 8 workers were used onsite. A total of 40 man hours were used in the erection of both Post Tensioned Timber Frames.

Figure 5. Erection of Second Post Tensioned Timber Frame

Erection of the walls took place one day after the erection of the timber frames. The two parallel walls were placed on trestles, the edge beams were attached and the whole end section was lifted into place and secured. External props were not used as the walls were supported by temporary braces attached to the frames along with the hand tightened MacAlloy Bars. The total time taken to assemble the first set of walls was 3.5 hours. The assembly of the second set of walls was more rapid than the first set (2.75 hours) as the workers became more familiar with the necessary procedures. The erection sequence and time of the erection of the wall systems are shown in Figure 6. A total of 37.5 man hours were required for the erection of the two walls.

Figure 6. Erection of Post Tensioned Timber Walls

7.2 Primary Beam and Floor Units

Immediately upon completion of the structural frames and walls, work commenced on the placement of the 1st floor primary beam which would act to further increase the stability of the structure. Once the primary beam was placed the flooring units were lowered into position. The floor units were placed on the already existing top mounted joist hangers before the face mounted joist hangers were installed on site. Figure 7 shows the placement and time required for the floor units.

Figure 7. Placement of Floor Units

During the placement of the floor units handrails were nailed to column members on the first floor to comply with site safety requirements. The placement of the first floor took a total of almost 5 hours. As with the frames and the walls the second part (i.e. Level 2) took less time, requiring only 3.5 hours.

7.3 Post Tensioning of the Frames and Walls

The post tensioning of the frame and wall elements took place on the 26th of November. Three workers were required and the recently erected scaffolding was used to access the building. The time taken to post tension the two frames and four walls was approximately two hours. To apply the post tensioning to the shorter walls, a steel extension was fabricated giving the jack adequate space to pull the bar from above while the nut was tightened. The post tensioning of the wall is shown in Figure 8, with the extension used for the shorter wall shown on the far right. 3 workers were required for the safe application of the post tensioning.

Figure 8 Post Tensioning of the Wall

7.4 **Reconstruction Cost Estimate**

The total cost of the reconstruction of the test building (Figure 9) was estimated before construction commenced to be \$NZD 250,000 (3,000 \$NZD/m^2 of floor area) which included the \$NZD 42,000 cost for the original structure and a 13% margin (intended to cover additional risk in the project cost and set at the current standard rate) but did not include the reworking of the members necessary for their new application (performed at the University of Canterbury free of charge). This estimation was made from a combination of quotations from suppliers and the Rawlinsons Construction Hand Book (Rawlinsons & Co. 2009).

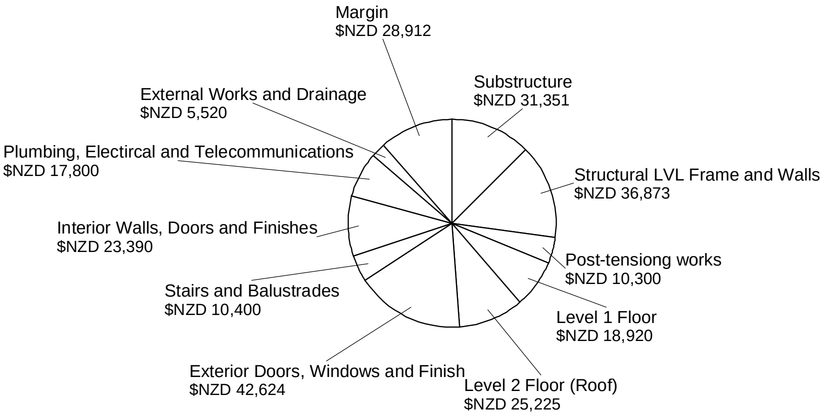

Figure 9. Estimated Cost of EXPAN Office Building

It can be seen above that the structural system (substructure, frames, walls, post-tensioning, Levels 1 and 2) makes up \$NZD 122,000 (1,470 \$NZD/m^2 of floor area) which is approximately 50% of the total cost of the structure. Of this, the foundation makes up \$NZD 31,000 (26%), slightly less than the frames and walls which cost a total of \$NZD 37,000 (30%). The level one and two floors are estimated at \$NZD 19,000 (16%) and \$NZD 25,000 (20%) respectively. The post tensioning works cost \$NZD 10,300 including materials, a significant portion (70%) of which is the cost of materials. The remaining cost was for architectural components such as cladding and interior finishes.

8 **CONCLUSIONS**

This paper documented the deconstruction and reconstruction of a high seismic performance post tensioned timber building. It was effectively divided into two parts: the deconstruction of the Pres-Lam test building and the building reconstruction as a 2 storey office structure. Testing of the building in the University of Canterbury laboratory demonstrated the excellent, damage free, seismic performance of the structure, the building was then demounted and remounted quickly and economically to become a fully functional office structure.

The deconstruction of the Pres-Lam test structure took a total of 122 man hours to complete over a period of 6 days. The total time (and therefore cost) was dominated by the separating and removal of the timber-concrete flooring system. This was due to the fact that the diaphragm action of the building was ensured through the use of an in situ concrete slab which had to be decoupled in a way that the floor units could be reused and effectively re-coupled. In the future, if demounting will be required a new method of coupling which requires less time in demounting may be necessary. Once the floors were removed the system proved to be highly demountable requiring little time and personnel.

Once structural members were altered to become adequate for their new life as part of a two storey office structure, 9 working days and a total of 118 man hours were required in construction. However this does not include the time between the completion of the frame and the application of the post tensioning. Due to the lightness of timber it was possible to assemble the frame on the ground and erect it intact using a Hiab truck which saved considerable cost and the necessity for a higher capacity or fixed crane to be present on site. The structural walls were erected in the same manner and external propping was not necessary due to the ability to support the walls from the frame structure and hand tighten the MacAlloy bars. The placement of the floors required approximately one day and again, due to their lightness, a Hiab truck was used. The structural cost makes up almost half of the total cost of the building of which a quarter is in the cost of the foundation. The frames and walls comprise $NZD 37,000 (30%) of the total cost with the largest contributor being the floors with a combined cost of $NZD 44,000. (36%) Work is ongoing on verification of these initial estimates.

Overall the demounting and reconstruction of the post tensioned building has been found to be economical in both time and cost. These facts, along with the system's excellent seismic performance, make it a sustainable option for the future of seismic resistant buildings in New Zealand.

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REFERENCES:

Amigo, J. M. M. (2010). "Feasibility of Multi-Storey Pres-Lam Timber Buildings: Design, Construction and Cost," Edinburgh Napier University, Edinburgh, Scotland.

Kelly, J. M., Skinner, R. I. and Heine A. J. [1972]. Mechanisms of Energy Absorption in Special Devices for use in Earthquake Resistant Structures, Bulletin of NZSEE, 5(3):63-88.

Iqbal, A., Pampanin, S., and Buchanan, A. H. (2008). "Experimental Study of Prestressed Timber Columns under Bi-directional Seismic Loading." 2008 New Zealand Society for Earthquake Engineering Conference, Wairakei, Taupo, New Zealand.

Iqbal, A., Pampanin, S., Palermo, A., and Buchanan, A. H. (2010). "Seismic Performance of Full-scale Post-tensioned Timber Beam-column Joints." 11th World Conference on Timber Engineering, Riva del Garda, Trentino, Italy, 10.

John, S., Nebel, B., Perez, N., and Buchanan, A. (2009). "Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials." New Zealand Ministry of Agriculture and Forestry.

Newcombe, M. P., Pampanin, S., and Buchanan, A. H. (2010a). "Experimental Testing of a Two-Storey Post-Tensioned Timber Building." 9th US National & 10th Canadian Conference on Earthquake Engineering, Toronto, Canada, 8.

Newcombe, M. P., Pampanin, S., and Buchanan, A. H. (2010b). "Global Response of a Two Storey Pres-Lam Timber Building." 2010 New Zealand Society for Earthquake Engineering Conference, Wellington, New Zealand, 8.

NZCS, 2010, PRESSS Design Handbook (Ed. S. Pampanin). New Zealand Concrete Society, Wellington, New Zealand

NZS 1170.5:2004. Standards New Zealand, "Structural Design Actions Part 5 : Earthquake Actions - New Zealand." Standards New Zealand, New Zealand.

Palermo, A., Pampanin, S., Buchanan, A., and Newcombe, M. (2005). "Seismic Design of Multi-Storey Buildings using Laminated Veneer Lumber (LVL)." 2005 New Zealand Society for Earthquake Engineering Conference, Wairakei Resort, Taupo, New Zealand.

Priestley, N., Sritharan, S., Conley, J., and Pampanin, S. (1999). "Preliminary Results and Conclusions From the PRESSS Five-Story Precast Concrete Test Building." PCI Journal(November-December 1999), 42-67.

Rawlinsons & Co., (2009). Rawlinsons New Zealand Construction Handbook, Rawlhouse Publishing, Auckland, New Zealand.

Smith, T. (2008). "Feasibility of Multi Storey Post-tensioned Timber Buildings," University of Canterbury, Christchurch, New Zealand.

Smith, T., Ludwig, F., Pampanin, S., Fragiacomo, M., Buchanan, A., Deam, B., and Palermo, A. (2007). "Seismic Response of Hybrid-LVL Coupled Walls Under Quasi-Static and Pseudo-Dynamic Testing." 2007 New Zealand Society for Earthquake Engineering Conference, Palmerston North, New Zealand, 8.

Wong, C.-W. R. (2010). "Construction Time and Cost of Multi Storey Post Tensioned LVL Timber Structures Compared with Concrete and Steel," University of Canterbury, Christchurch, New Zealand.

Yeoh, D. (2010). "Timber-Concrete Composite Floor System," University of Canterbury, Christchurch, New Zealand.