

# Design and Construction of Prestressed Timber Buildings for Seismic Areas\*

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## Abstract

This paper describes the structural design of low-rise multi-storey timber buildings using a new and exciting structural system. This system, originally developed for use with pre-cast concrete, combines un-bonded post-tensioning and additional energy dissipaters, providing a recentering capability after the earthquake, while greatly reducing the structural damage. This new structural system can be used in multi-storey buildings, with large structural timber members made from laminated veneer lumber (LVL) or glulam timber, with lateral loads resisted by prestressed timber frames or walls, separately or in combination. A case study of a six storey timber office building in a moderate seismic area is analysed and a virtual design is carried out, allowing investigation of different methods of structural analysis, and development of many construction and connection details for rapid construction. Total building cost is compared to equivalent steel and reinforced concrete options.

## 1. Introduction

Recent developments in seismic design have led to the development of damage control design philosophies and innovative seismic resistant systems. In particular, jointed ductile connections for precast concrete structures [7,8,9,10] have been implemented and successfully validated. These solutions rely on a discrete dissipative mechanism placed in specific locations in the structure.

A precast concrete seismic resisting system developed in the U.S.-PRESS program (PREcast Seismic Structural System), coordinated by the University of California, San Diego, for frame and wall systems has been shown to be particularly effective. This system, referred to as the hybrid system, combines unbonded post-tensioned tendons with grouted longitudinal mild steel bars or any form of dissipation device (Figure 1a). While the post-tensioning provides desirable recentering, the dissipation devices allow adequate energy release. During lateral movement, controlled rocking will occur at the beam-column (Figure 1b), wall-foundation or column-foundation interface, characterised by the so-called flag-shaped hysteretic behaviour displayed in Figure 1c.

The hybrid system is material independent, and similar solutions have been proposed for steel moment-resisting frames [2]. This paper describes the extension to low rise multi-storey timber construction [4]. Testing on subassemblies carried out at the University of Canterbury by Palermo *et al.* (2005, 2006a, b) and Smith *et al.* (2007) have proven to be very successful and to represent a viable option for multi-storey timber buildings. The new post-tensioned timber construction system is the subject of an international patent application.

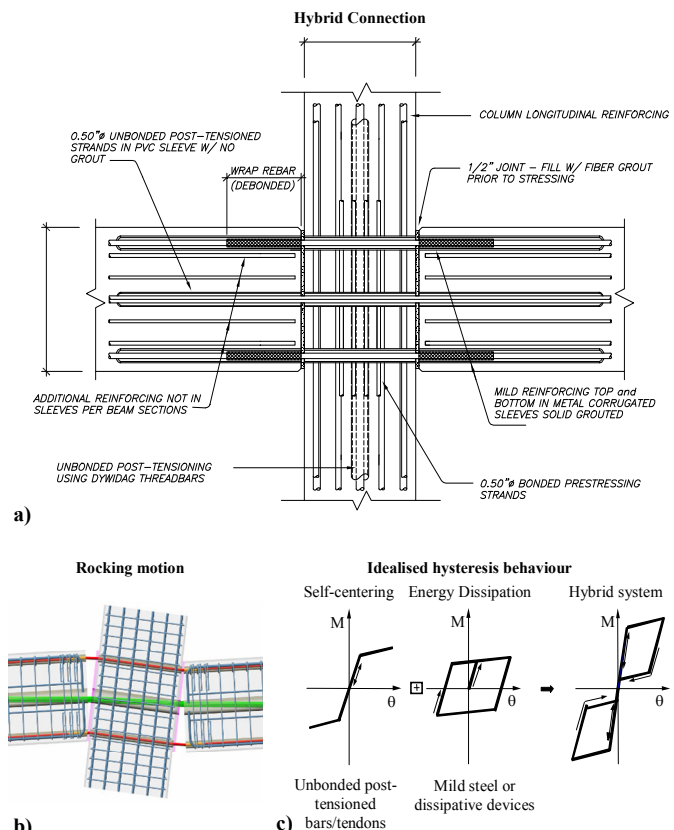


Figure 1: a) Hybrid connection [10]; b) rocking motion mechanism (courtesy of S. Nakaki); c) idealised flag-shaped hysteretic behaviour.

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Structural design with displacement based design [11] uses the displacement spectrum rather than the acceleration spectra. This design method is used widely for concrete structures and can be utilised for hybrid LVL systems [12]. With timber's low embodied energy and ability to act as a carbon sink, this method of construction is also highly sustainable.

This paper, after a preliminary overview on previous subassembly testing, presents the design of a 6 storey hybrid timber framed building. The design of the members and connection details is described. The proposed construction technique is also presented. Further to this, the costs of the building are compared to similar concrete and steel buildings.

## 2. Development of Laminated Veneer Lumber Hybrid Systems

An extensive and ongoing experimental campaign is being carried out on *beam-to-column*, *column-to-foundation* and *wall-to-foundation* subassemblies for the implementation of LVL hybrid solutions [4,5,6,13]. The results of these tests, some of which are presented in Figure 2 below, have yielded extremely pleasing performances. Rocking connection options have considered internal and external attachment of the dissipation devices as well as post-tensioned only connections.

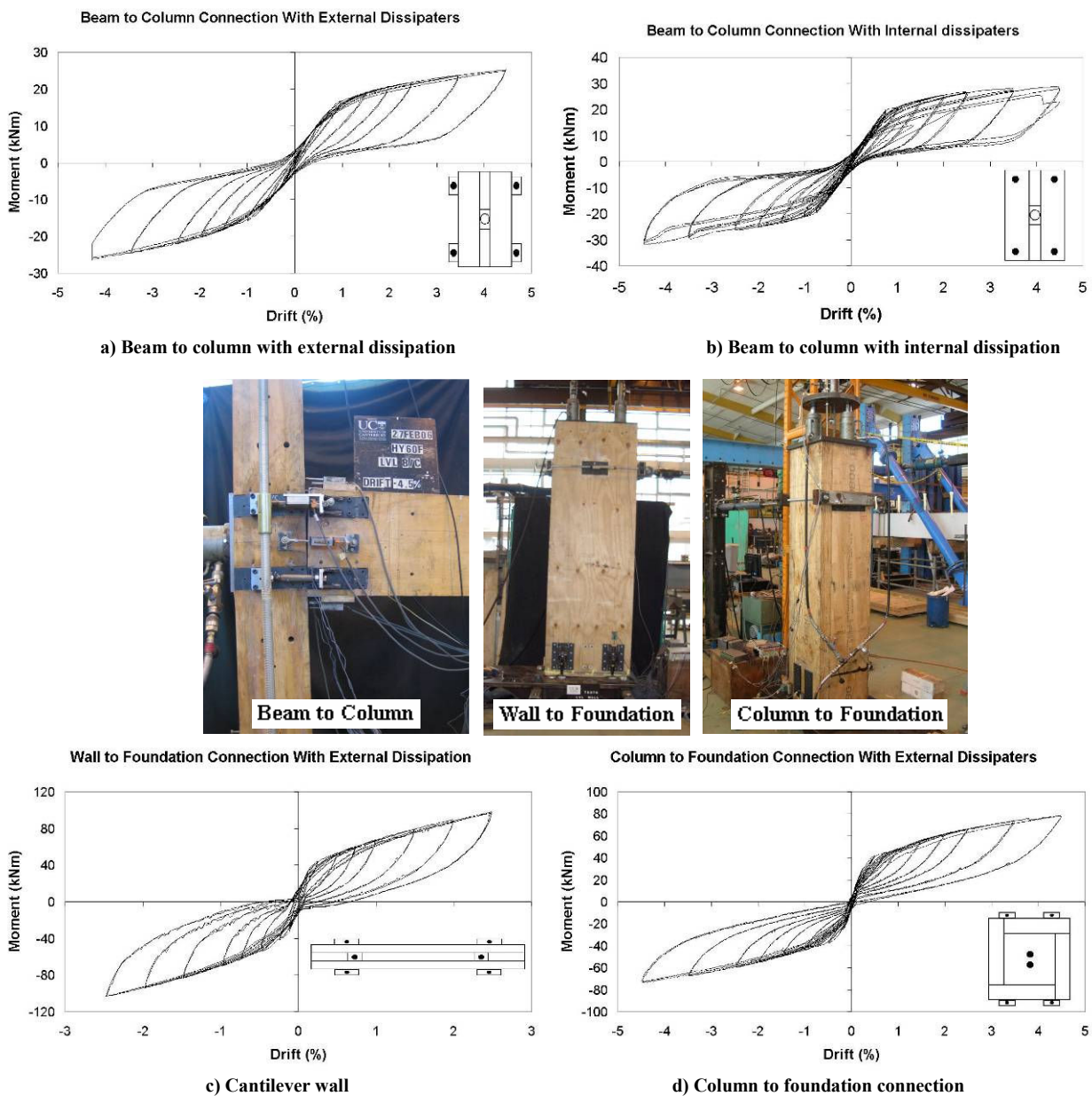


Figure 2: Hysteretic loops from sub-assembly testing of hybrid systems.

The “flag shaped” hysteretic loop observed in Figure 2 has negligible residual displacement, confirming the self-centering characteristics. The equivalent yield point corresponds to the actual yielding of the dissipaters, while the total moment capacity increases with increasing drift due to tendon elongation. There was no degradation of stiffness and no structural damage was observed. A maximum drift level of 4.5% was achieved during all the tests apart from the column test which was stopped due to the tendon approaching yield. This rapid increase in tendon tension would not occur in a real building where the unbonded length is greater.

Further to this testing, *coupled and parallel wall systems* have been investigated. In this case the dissipation is caused by the relative motion between the two walls, not the gap formed between the member and the foundation. Different methods of dissipation have been investigated. The most effective of these was the use of U Shaped Flexural Plate (UFP) dissipaters, shown in Figure 3a.

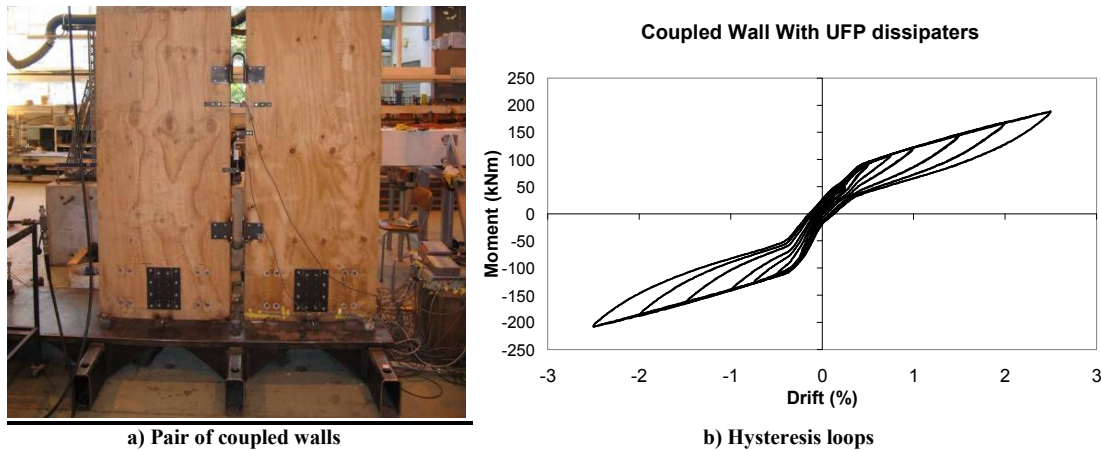


Figure 3: Result from coupled walls with UFP dissipation

### 3. Seismic Design of a Virtual Six Storey Building

The feasibility study is an alternate timber design for a 6-storey building currently being built at the University of Canterbury in reinforced concrete, as shown in Figure 4. The structural system has been altered slightly from that of the original concrete structure. Seismic forces will be resisted by frames along the building and by walls across it. The floor will span in the long direction and will be seated on four gravity beams across the shorter axis, which sit on central columns and exterior columns.

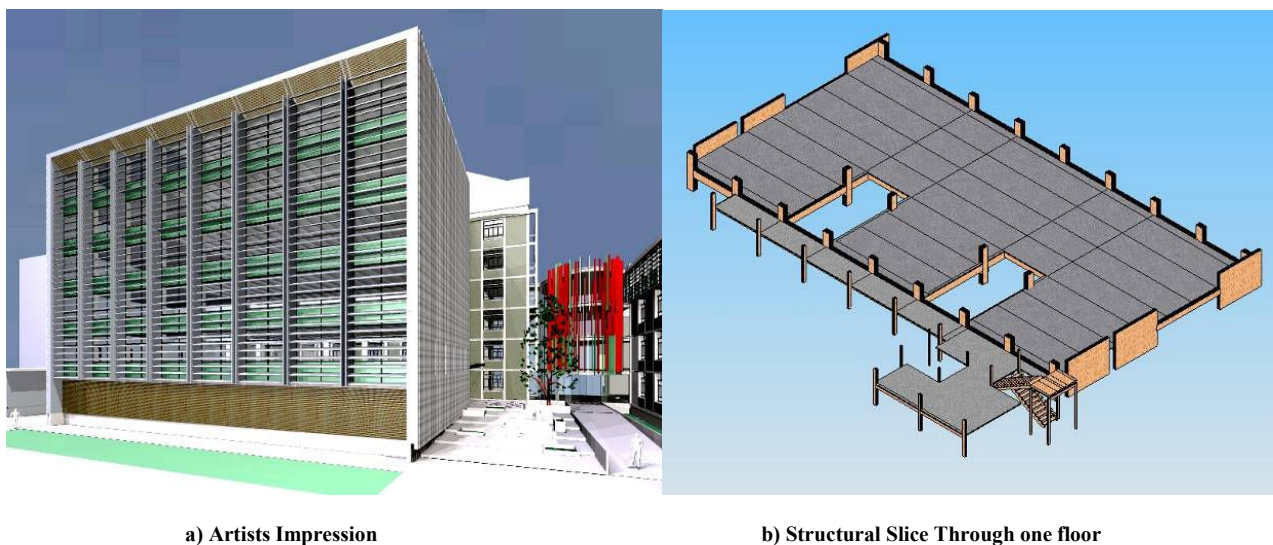


Figure 4: Biological Sciences Building

## Member design

The applied lateral forces were calculated with Direct Displacement Based Design (DDBD) [11,12]. Drift limits were 2% inter storey drift in the frame direction and 1% in the wall direction. Conservative equivalent viscous damping value was 5% although experimental testing gave values of 10% to 12%. Base shear forces in both directions were distributed up the building in accordance with the assumed first mode displacement of the structure.

Linear elastic internal actions were calculated. With DDBD principles [11] the base shear was evenly distributed along the building and the moments were applied at the base for design of column, beam and wall members with geometry shown in Figure 5.

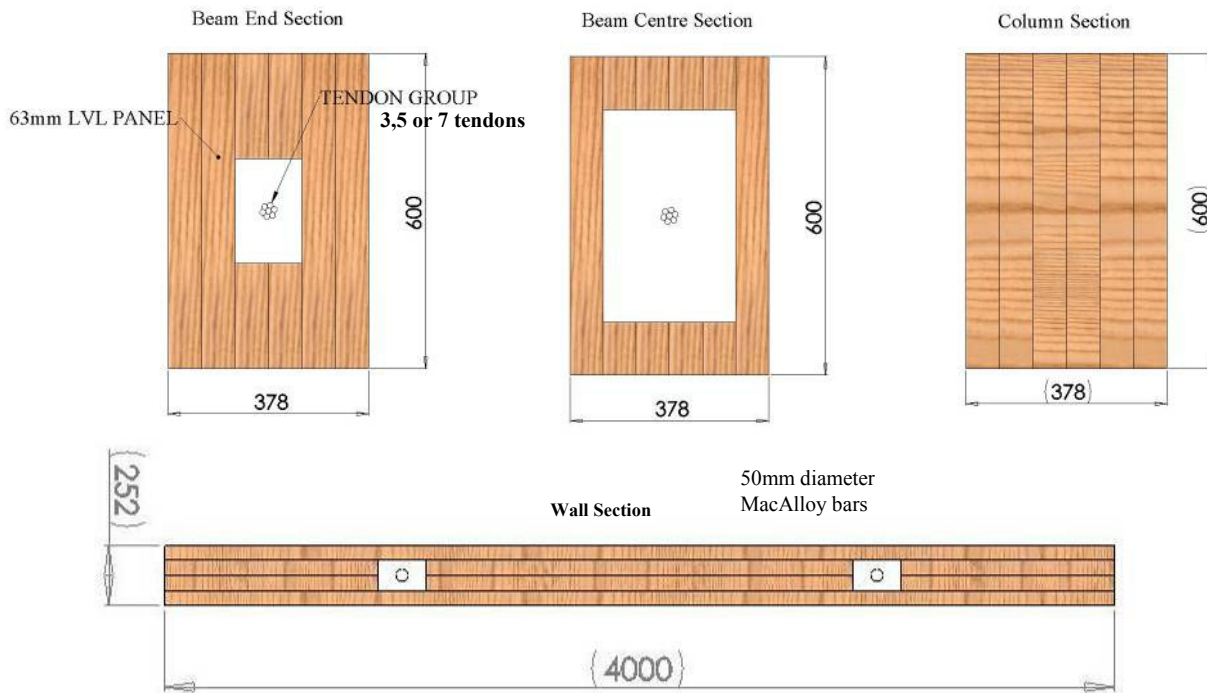


Figure 5: Structure members for Hybrid Timber building

The timber member sizes are comparable to those of the original concrete structure. As the beam sizes are controlled by the moment demand at the interface of the connection it is possible to remove a large portion of wood from the centre of the beam at mid-span, reducing the amount of LVL required, therefore, reducing the weight and cost of the member. It is recommended that the columns and walls remain as solid timber in order to reduce the flexibility of the system. Figure 5 also shows that there are no tendons required in the solid timber column member. This is due to adequate re-centring force being provided by the gravity loading on the columns plus the moment induced by the post-tensioned beams.

## Connection design

Due to the anisotropic nature of timber the connection detailing for the building has presented a challenging problem in the design of this system. In general it is desirable to load wood in compression parallel to the grain, rather than in compression perpendicular to the grain, to obtain greater strength and stiffness. This is even more important if wood is loaded in tension, in order to prevent weak and brittle splitting failures. The following paragraphs outline some of the proposed connection details.

### Timber-Concrete Composite Floor

Timber flooring being developed at the University of Canterbury consists of prefabricated timber panels prefabricated off-site with 65 mm concrete topping cast on site. The timber panels are made from two adjacent 63×400 mm LVL joists spaced at 1200 mm centres with a nailed plywood sheet. Notches cut from the joists will be filled by concrete, reinforced by one coach screw at the centre of each notch, to give composite behaviour. This composite behaviour allows a significant increase in stiffness of the system. The concrete topping also improves the acoustic separation between inter-tenancy floors. For further information refer to Buchanan et al. (2008) and Yeoh et al. (2008).

### Joist Connection from Flooring to the Gravity Beam

One major aim in the connection design was to ensure that the modular system enables rapid construction. A joist hanger, shown in Figure 6, was devised such that gravity forces in the joist are carried to the beam through bearing and Tek-screws are used to fasten the hanger to the face of the gravity beam.

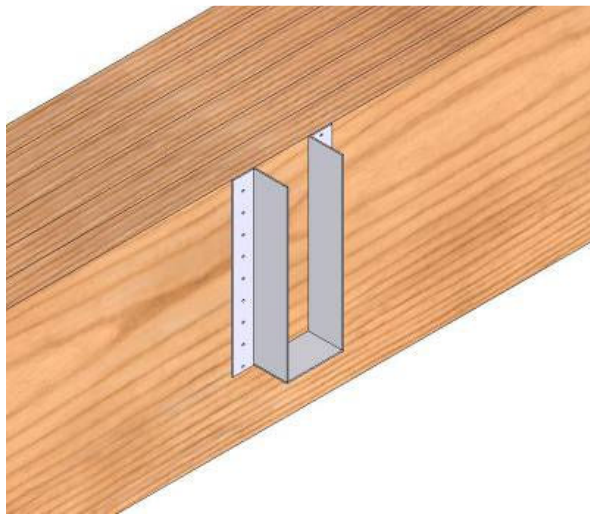


Figure 6. Joist Hanger

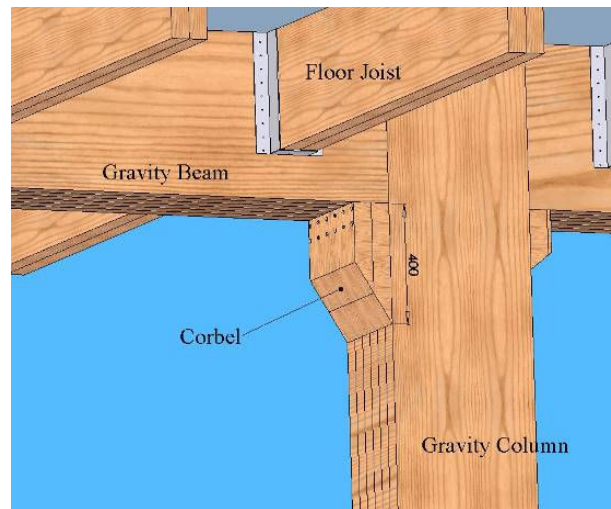


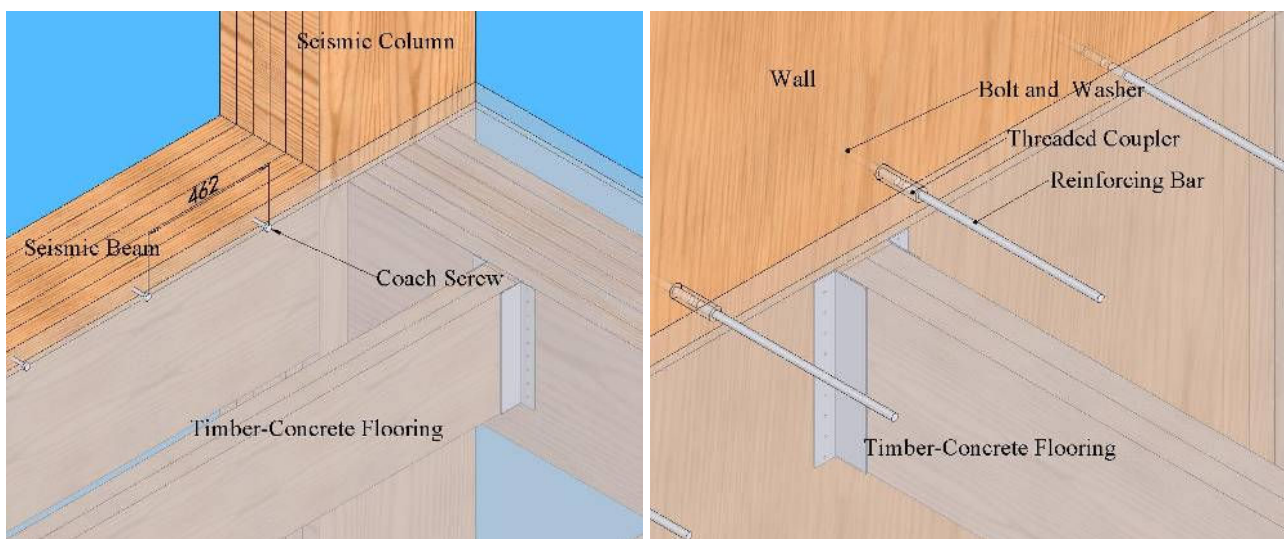
Figure 7. Corbel Connection

### Gravity Beam Corbel

The interior beams resist only gravity load, and span 12 m. Due to the large span of these floor beams considerable gravity loading must be transferred into the adjacent columns. Corbels, shown in Figure 7, were designed to carry the combined factored dead and live load of 320 kN. As Figure 7 shows, it was necessary to place screws in the top of the corbel to resist tensile stresses arising from the bending moment induced by the high offset bearing load coming from the beam.

### In-Plane Floor Shear Transfer

In a timber concrete composite flooring system the in-plane shear due to diaphragm action will be transferred through the topping concrete. To connect this topping concrete into the seismic resistant system two details were used as shown in Figure 8: coach screws inserted in the lateral face of the beam; and reinforcing bars connected to fasteners in the solid wall using threaded couplers.



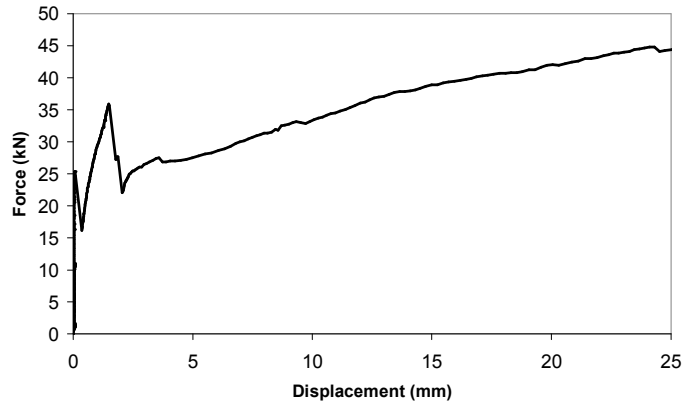
a) Connection of timber concrete topping to beam

b) Connection of concrete topping to timber wall

Figure 8: In-Plane Shear Transfer Mechanisms

Experimental testing (Figure 9) has shown that the coach screw can reach a minimum of 20 kN before any slip occurs. Once this slip does occur, the concrete fails and ductile behaviour is exhibited.

To calculate the shear capacity of the coach screw or steel dowel a modified version of Johansson's yield theory was used. It was assumed that the bar inside the concrete topping would act as a fastener in a rigid medium and failure in the timber would occur. It is possible to manufacture these attachments easily in a factory and assemble them on site.



a) Force displacement graph



b) Plan view of test specimen

Figure 9: Shear Testing of Single Coach Screw for Diaphragm Connection

#### Column to Foundation Connection

To reach the desired moment capacity at the base of the column, steel dissipating bars were used. These bars are 32 mm diameter and due to the large axial forces generated by the system it was decided to use an internal epoxied solution.

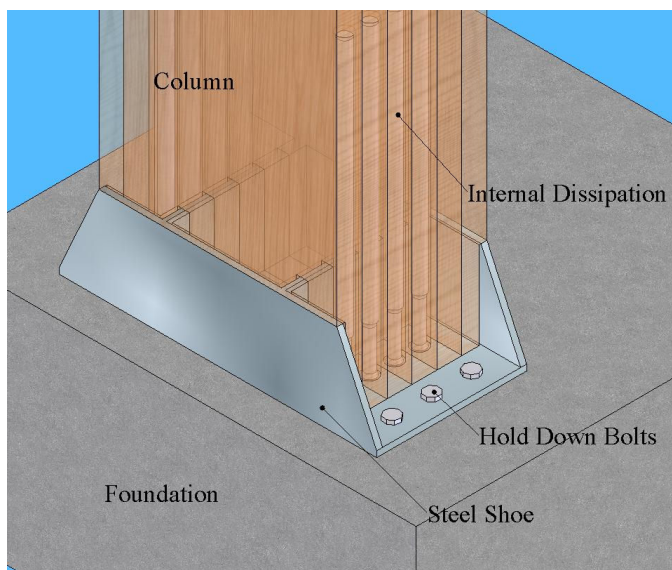


Figure 10. Column Foundation Connection

This is designed using the equations devised by Van Houtte (2003) for the axial strength of epoxied rods into LVL. The attachment of these bars into the foundation also required careful consideration. To avoid an unnecessary increase in the required depth of the foundation the steel 'shoe' shown in Figure 10 was devised. This is able to be attached during the manufacture of the column and simply bolted to the foundation on site with hold down bolts to anchor in the concrete.

#### Wall to Foundation Connection

The wall to foundation connection requires a very large moment capacity of 8.3 MNm. To meet this demand a large amount of dissipater steel was required. Two 50 mm MacAlloy bars were placed inside cavities in the wall and the foundation depth was established at 1.5 m deep, large enough for the dissipation steel to be grouted into the foundation on site.

#### **Construction**

Various construction options are being discussed for the system. Due to its modular nature and the low mass of the structural members it will be possible for construction to be fast and inexpensive. The proposed construction sequence for the main structure is as follows:

- Pouring of foundation
- Erection of columns and walls for first three and a half stories in height
- Placement of beams in first three floors, stressing of beams in one operation
- Placement of timber flooring panels and pouring of concrete topping

- Exterior cladding of bottom three floors
- Erection of next three floors columns and walls
- Placement of beams in top three floors
- Stressing of beams in top three floors and stressing of walls
- Placement of timber flooring panels and pouring of concrete topping
- Construction of roof, and exterior cladding of top three floors

This sequence of construction will ensure that the cost associated with the post-tensioning procedure is kept to a minimum.

### Timber Building Total Cost: \$10,021,274

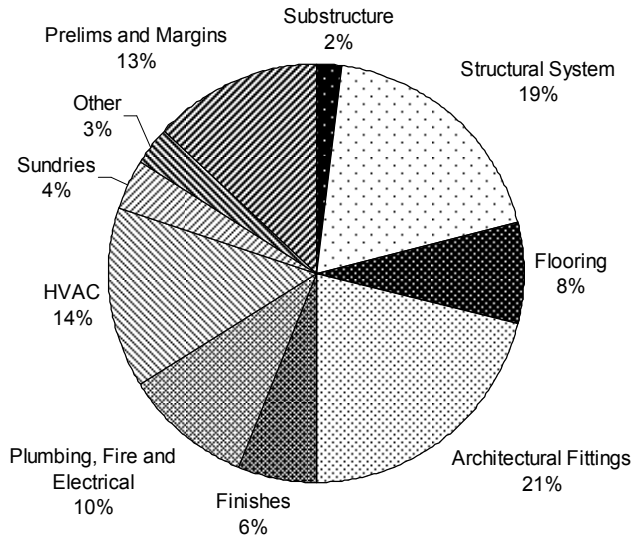


Figure 11. Cost Breakdown of Case Study

### Cost- Analysis

An initial cost analysis for the building has compared the timber building to steel and concrete structures that have been designed to the same seismic and architectural standards. The total cost of these buildings is shown below in Table 1, with cost breakdown in Figure 11.

Table 1: Total cost of the case study building options

	Timber	Steel	Concrete
Total Cost	\$10,020,000	\$9,370,000	\$9,430,000

As shown above the steel and concrete building options cost approximately \$500,000 (5%) less than that of the timber option. Although the structural timber system costs considerably more than that of the steel or concrete systems it represents a small portion of the buildings overall cost ensuring the total cost difference is modest. Further to this the cost of construction is likely to be offset by the rapid construction time using light pre-fabricated sections on site. It is also expected that the cost over time will decrease as the technology matures. Actual costs will come available as real buildings are constructed.

## 4. Conclusions

A new and exciting method of timber construction has been presented. A 6-storey building design has frames in one direction and walls in the other. Post-tensioned prefabricated LVL timber beams, columns and walls are similar sizes to the original concrete design. Composite timber flooring is pre-fabricated. Gravity loading on the columns provides desirable re-centering, and energy dissipaters at wall and column bases give excellent seismic behaviour.

Construction will be fast with costs kept to a minimum. The overall building costs are comparable to steel and concrete options. Based on testing and analysis to date, the feasibility of the post tensioned hybrid solution is evident.

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## Structural Design of Timber and Composite Floors Seminar



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**Monday 4<sup>th</sup> February 2009**  
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*This one-day course is designed for practising structural engineers who wish to expand their ability to design a range of floor systems for multi-storey timber buildings.*

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The course will be delivered by academics and experts from industry and consulting offices, in order to provide the participants with the best mixture of theory and practice.

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