Design and Construction of Prestressed Timber Buildings for Seismic Areas

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Summary

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 [8,9,10,7] 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.-PRESSS 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 (Fig. 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 (Fig. 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 proved 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.

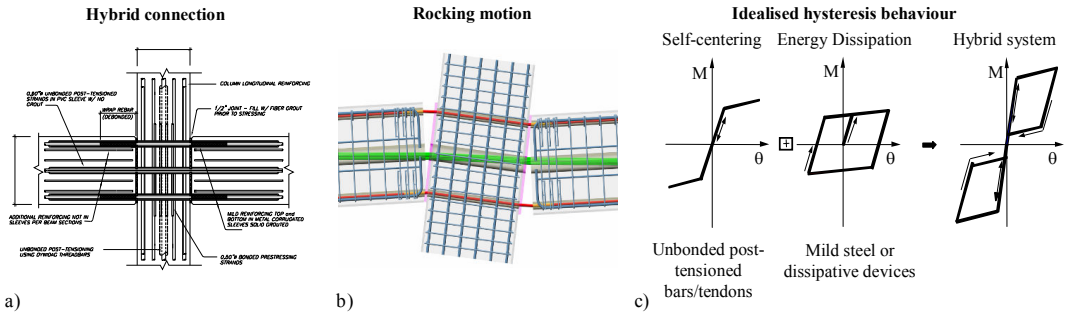


Figure 1: a) Hybrid connection [10]; b) rocking motion mechanism (courtesy of S. Nakaki); c) idealised flag-shaped hysteresis behaviour.

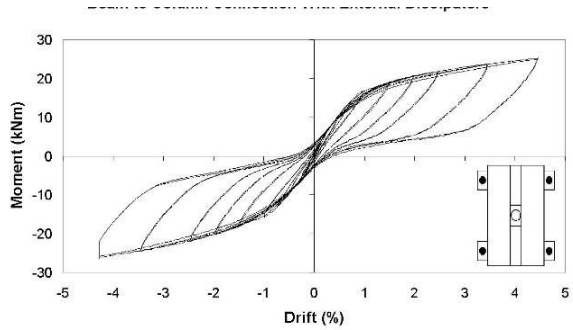
Structural design with displacement based design [11] uses the displacement spectrum rather than the acceleration spectra. This design method is used widely for concrete structures and can be utilised for hybrid LVL system [12].With timber's low embodied energy and ability to act as a carbon sink, this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

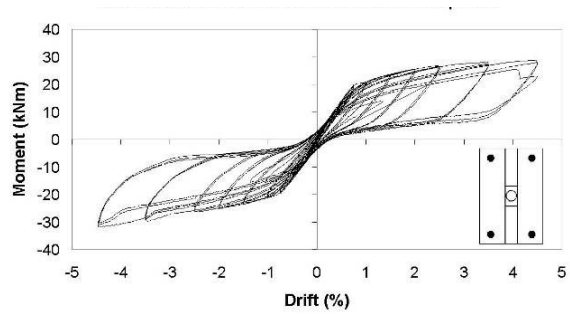
2. Development of Laminated Veneer Lumber Hybrid Systems

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], as shown in Figure 2. The results of these tests, some of which are presented in Figure 3, have yielded extremely pleasing results. An extensive number of rocking connection options have considered internal and external attachment of the dissipation devices as well as post-tensioned only connections have been investigated.

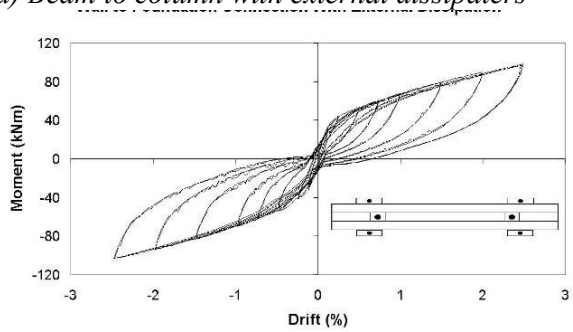
(a) Beam to column *(b) Wall to foundation* *(c) Column to foundation*



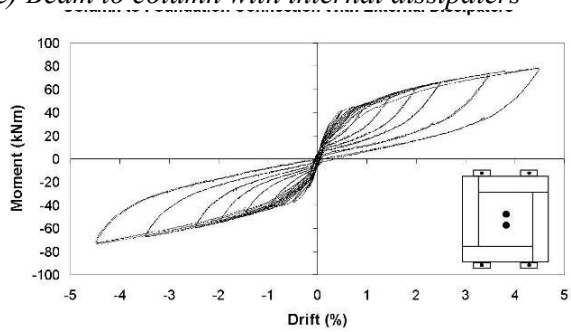
d) Beam to column with external dissipaters



e) Beam to column with internal dissipaters



f) Cantilever wall to foundation connection



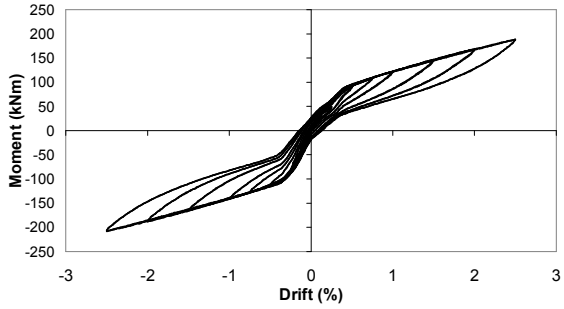
g) Column to foundation connection

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. No degradation of stiffness and no structural damage are observed and a maximum drift level of 4.5% is achieved during all the tests apart from the column test which was stopped due to the tendon approaching yield. This rapid increase in tension will not occur in a real building where the un-bonded tendons are much longer.

Further to this testing, coupled and parallel wall systems have been investigated. The difference in the application in this system is 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 3.

a) Pair of coupled walls

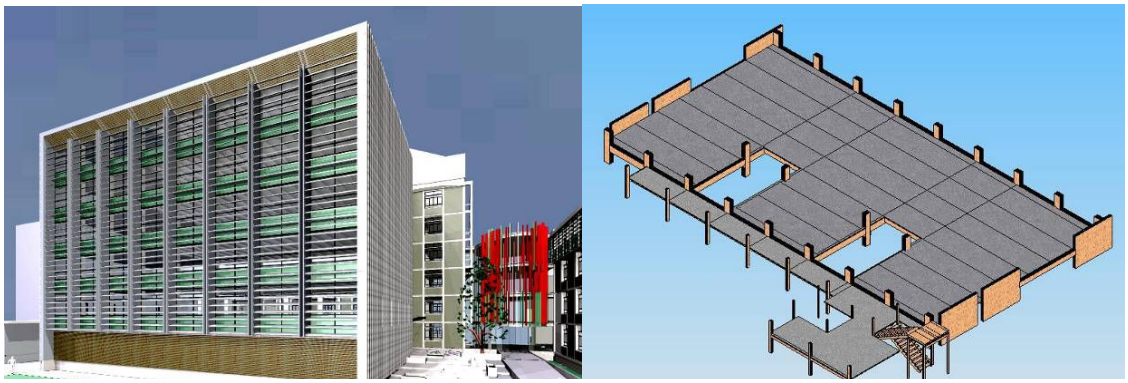


b) Hysteresis loops for coupled walls

Figure 3: Pair of coupled timber walls with UFP dissipaters

3. Seismic Design of a Virtual Six Storey Building

The feasibility study is a timber design of a 6-storey reinforced concrete building being built at the University of Canterbury, as shown in Figure 4.



a) Artists impression of concrete building *b) One floor slice of timber alternative*

Figure 4: Six storey building at University of Canterbury

The structural system has been altered slightly from that of the original concrete structure. Seismic forces will be resisted by frames in the east-west direction and by walls in the north-south direction. The floor will span in the east to west direction and will be seated on four gravity beams which sit on central columns and exterior columns.

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. A conservative equivalent viscous damping value was taken as 5% although 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 is evenly distributed along the building and the moments are applied at the base, for design of column, beam and wall members with geometry shown in Figure 5.

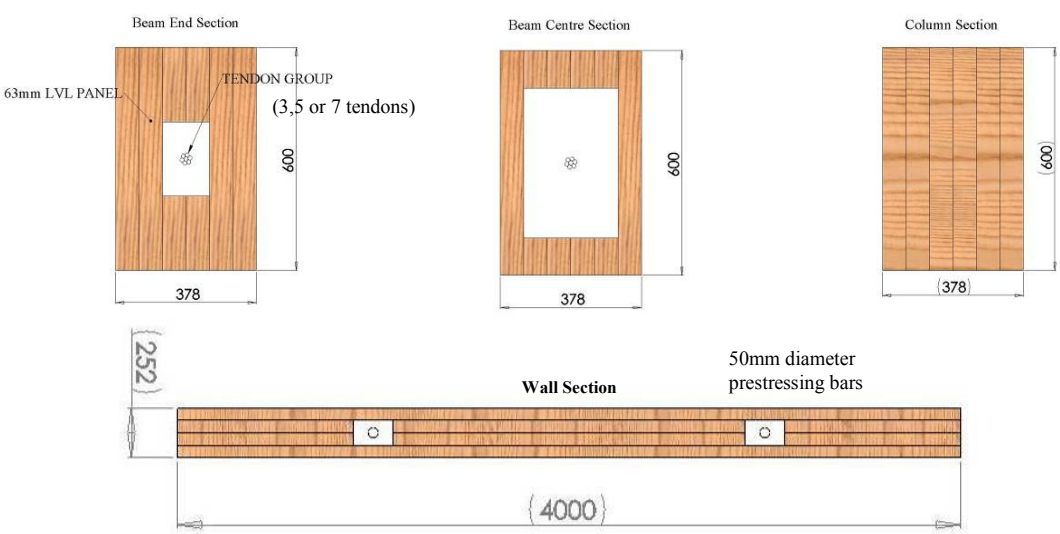


Figure 5: Structural members for hybrid timber building (dimensions in mm)

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 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 action, which gives a significant increase in stiffness of the system. The concrete topping also improves acoustic separation between floors. For further information refer to Buchanan et al. (2008) and Yeoh et al. (2008).

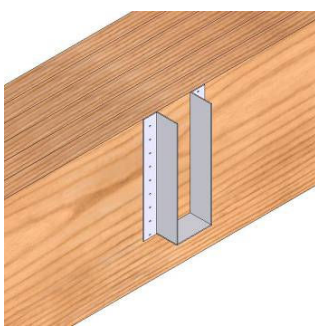


Figure 6: Joist Hanger

Joist connection from flooring to the gravity beam

One major aim in the connection design was to ensure that the modular system allows rapid construction. A simple steel joist hanger (Figure 6) allows gravity forces in the joist to be carried to the beam through bearing, with Tek-screws fastening the hanger to the face of the beam.

Gravity beam corbel

The interior timber beams, of span 12m, resist only gravity load. Due to this large span, considerable gravity loading must be transferred into the supporting columns. Timber corbels, shown in Figure 7, were designed to carry the factored dead and live load of 320kN. Figure 7 shows screws in the top of the corbel which are necessary to resist tensile stresses due to the bending moment induced by the gravity load coming from the beam.

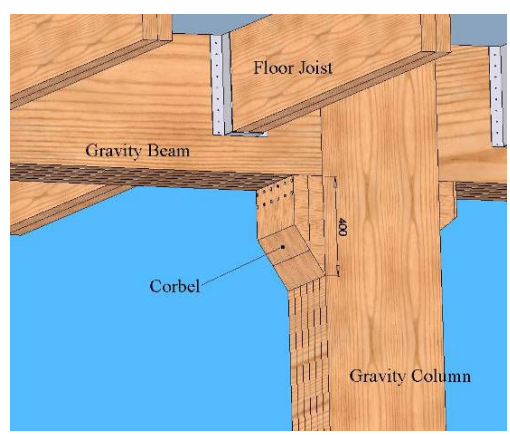
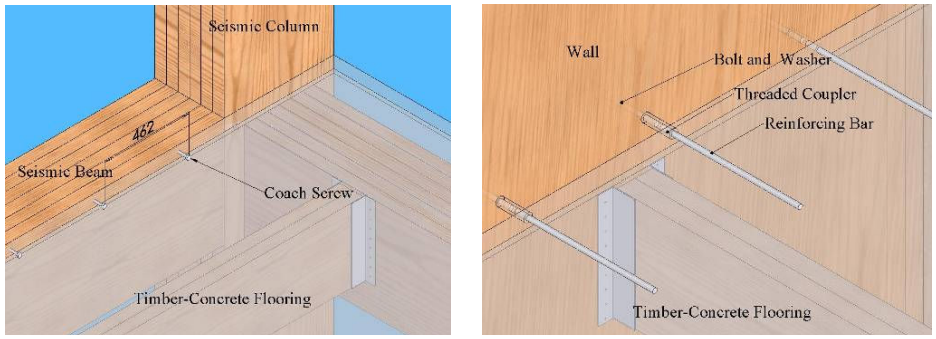


Figure 7: Corbel Connection

In-plane floor shear transfer

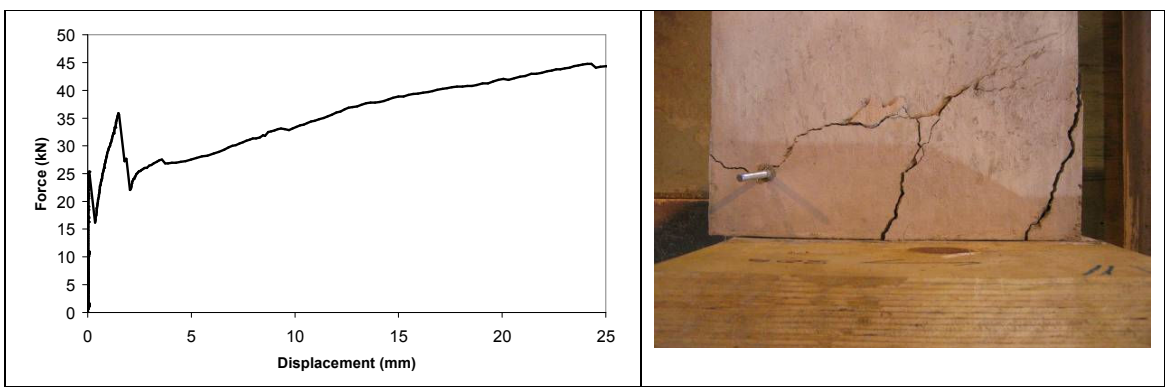
In a timber concrete composite flooring system, the in-plane shear due to diaphragm action will be transferred through the topping concrete. It is therefore necessary to connect this topping concrete into the seismic resistant system. Two systems are used as shown in Figure 8, using coach screws inserted into the lateral face of the beam; and reinforcing bars connected to fasteners in the solid wall using threaded couplers. Experimental testing, shown in Figure 9, has shown that the coach screw can reach a minimum of 20kN before any slip occurs. Once this slip does occur, the concrete fails and ductile behaviour is exhibited.



a) Connection to face of beam *b) Connection to timber wall*

Figure 8: In-plane shear transfer mechanisms from concrete topping to timber members

In order 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 will act as a fastener in a rigid medium and failure in the timber will 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

In order to provide the necessary large moment capacity at the base of the column, mild steel energy-dissipating bars are used, 32mm diameter, attached to the timber column with an internal epoxied connection. This is designed using the equations devised by Van Houtte (2003) for epoxied rods in LVL. An alternative would have been external replaceable dissipaters. The attachment of the dissipaters into the foundation required careful consideration. Grouting the bars into the concrete would have required an unnecessary increase in the depth of the foundation, so the steel 'shoe' shown in Figure 10 was devised. This can be attached to the columns during the manufacture, and be simply bolted to the foundation on site with hold down bolts to high-strength anchors in the concrete.

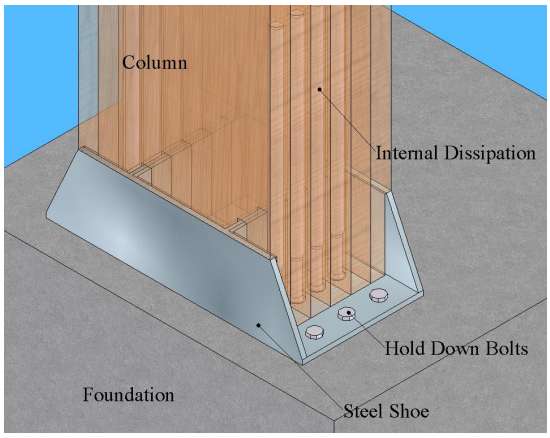


Figure 10: Column Foundation Connection

Wall to Foundation connection

The wall to foundation connection requires a very large moment capacity of 8.3MNm. This demand is met with two 50mm prestressing bars placed inside cavities in the wall, and mild steel dissipaters similar to those in the columns. This large bending moment requires a 1.5m deep foundation which is large enough for the dissipation steel to be grouted into the foundation on site.

Construction

Various construction options are being discussed for the proposed system. Due to its modular nature and the low mass of the structural members it will possible for construction to be fast and inexpensive. The planned 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, and the building is closed in as construction proceeds. Weatherproofing of timber members on site will require careful attention.

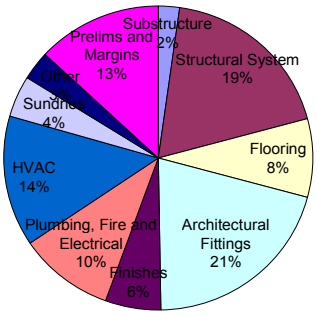


Figure 11: Cost Breakdown of the case study

Cost- Analysis

A preliminary cost estimate for the building has compared the timber building to steel and concrete alternatives designed to the same seismic and architectural standards. The total cost of these buildings is shown below in Table 1, with cost breakdown for the timber building in Figure 11.

Table 1: Total cost of the case study building options ($NZ)

	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 cost estimate is considerably more than that of the steel or concrete systems it represents a small portion of the overall building cost, ensuring the total cost difference is modest. This is only an estimate, and actual costs will come available as real buildings are constructed. Any additional cost of construction is likely to be offset by the rapid construction time using light pre-fabricated sections manufactured off site for easy transportation. It is also expected that the cost of this new technology will decrease over time as the technology matures.

4. Conclusions

A new and exciting method of timber construction has been presented. A six storey building design has frames in one direction and walls in the other. Post-tensioned LVL timber beams, columns and walls are of similar sizes to the original concrete design. These members and the composite timber flooring panels are pre-fabricated off site. The internal post-tensioning, together with energy dissipaters at wall and column bases will ensure that the building has only small displacements during an earthquake, with no residual structural deformations.

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 and sustainability of the post tensioned hybrid solution is evident.

5. References

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