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Feasibility of Multi Storey Post-Tensioned Timber Buildings: Detailing, Cost and Construction

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ABSTRACT

This thesis describes a feasibility study into the use of a new method of timber construction developed in New Zealand. This new method combines the use of an engineered wood product (Laminated Veneer Lumber) and post-tensioned ductile connections. Three case study buildings are presented in concrete, steel and timber all representing current design and construction practice. A fourth building, referred to as the "timber plus" structure, is also considered with the addition of timber architectural components. The case study timber building consists of two lateral resisting systems. In one direction post-tensioned LVL moment resisting frames are used, with post-tensioned cantilever walls in the orthogonal direction.

INTRODUCTION

Modern timber construction largely consists of residential structures. This is mainly due to the use of large wall panels being necessary for seismic resistance. Timber moment connections have previously been avoided due to difficulty of construction and significant costs. However, as global focus shifts towards sustainability and environmental concerns timber construction is an obvious choice for the future.

Research Objectives and Questions

The objective of this research is to investigate the feasibility of post-tensioned timber multi-storey buildings. This is carried out through the comparison of a case study building designed in concrete, steel and timber. Several research questions will be asked as detailed below:

How will a timber post-tensioned building be designed?

1. How will lateral seismic loading be calculated?
2. What type of flooring will be used?
3. How will lateral forces be resisted?
4. What type of connections will be used and how will these connections be designed?

How will these connections perform under lateral loading?

1. How will floor shear be transfer to the seismic frame?
2. How will the placement of armour at the beam to column interface influence the moment response of the section?
3. Is it necessary to place corbels under the seismic beams?

LITERATURE REVIEW

Timber Construction

Study into the performance of multi storey timber structures can be separated into two categories; light timber framing, and heavy timber construction. The use of light timber framing for housing in New Zealand has been well documented (Garret 1990). This research culminates in NSZ3604forthedesignoflight timber framed buildings, which covers non-specific design of buildings fitting within the scope of the standard. Considerable work has also been performed regarding the design of multi-storey ply shear walls (Stewart1987,Deam1997)and hysteretic loops and analytical model shave been developed.

The Hybrid Connection in Reinforced Concrete

Beginning in late 1985 a research project known as the U.S. PRESSS (Precast Seismic Structural Systems) program at the University of California, San Diego, initiated an extensive amount of research on precast concrete with jointed ductile moment connections. This research studied the combination of mild steel and/or full or partial bonded post-tensioning (Priestley 1991, 1996; Priestley et al., 1999).

The development of a Timber Hybrid Connection

In 2004 an extensive research program was launched at the University of Canterbury adapting the precast concrete ductile connection technology for use with Laminated Veneer Lumber (LVL). Shown in Figure 2.2a, LVL is an engineered wood product produced by reducing the raw log into 3mm thick veneers and gluing these veneers together under pressure in the same manner used to form plywood sections, however, the grain is laid parallel.

The existing design procedure for a jointed ductile precast concrete connection (NZS3101:2006 Appendix B) was modified by Newcombe (2008) making it applicable to the jointed timber connection. In the same contribution the use of Direct Displacement Based Design (DDBD) (Priestley et al. 2007) for post- tensioned timber connections was discussed and a design procedure was proposed.

Costing and Construction of Timber Structures

Tonks (1974) presented an architectural Ph.D thesis describing the feasibility of medium rise office building with glulam frames and plywood sheathed shear walls. The construction and cost of three storey motels has also been discussed and favourable comparisons to similar concrete and masonry structures have been shown (Tonks 1989). Several investigations into the feasibility of multi storey timber buildings were carried out early in the 1990's. Thomas (1991) discussed the design of multi-storey light timber framed buildings, the cost savings made possible though rapidity of construction are also discussed. The re-design of a six storey concrete building using plywood sheathed walls was also presented concluding that under half the construction time is required when compared to the original concrete building. Halliday (1991) discussed the design of 4 to 6 storey timber office buildings using both sheathed walls and large glulam members.

CASE STUDY BUILDING

Actual Building

The case study building used for the project is a six storey structure that is to be built at the University of Canterbury for the Biological Sciences department. The building has two distinct lateral resisting systems in order to resist loading in both the north-south and east-west direction. In the long (east-west) direction a moment resisting frame will be used. In the short (north-south) direction structural walls will be used.

The structure has been designed to be in the Christchurch region in what can be considered to be a moderate seismic zone. The foundations are in reasonably good conditions considered to be a shallow soil.

New Concrete Structure

Overall the original concrete design will be used with a few minor changes, resisting lateral and vertical loading through the use of pre-cast concrete frames and walls.

Steel Structure

The frames and walls are removed and replaced with Eccentrically Braced Frames (EBF's) in both directions (Figure 3.4b). Four of these frames are used in the long and two in the short direction. The remaining members are designed to be only vertically loaded. The flooring will be a Comfloor steel concrete system which places 150mmor reinforced concrete on a0.9mm corrugated steel decking. The original structural design of this building was performed by Steel Construction New Zealand (SCNZ) (APPENDIX A) and later Holmes Consulting Group was employed to alter and check the lateral resistance design.

Timber Structure

The basic form of the Timber building (Figure 3.5a) will remain similar to that of the concrete structure with the use of frames and walls .The structural system will be altered to use a new method of connection currently under investigation at the University of Canterbury. This combines the use of un-bonded post tensioning cables and sacrificial mild steel in order to achieve force resistance.

This system is essentially damage free after a major event and will return to zero residual displacement; these are major advantages for any structural system. The floor units are timber-concrete composite with 65mm of reinforced concrete poured onto17mm ply sheets which are supported by LVL joists. Figure 3.5b shows a typical flooring plan for the timber structure.

STRUCTURAL DESIGN

Loading Calculations

The following section will describe the loading calculations for the six-storey case study building for all materials. Gravity loadings will first be presented followed by the lateral loadings. Finally the building internal moments and reactions will be displayed for the timber structure.

Timber Building Gravity Loadings

The architectural floor plan for the case study building is displayed in Figure 3.2 above. This shows a total floor plan of 36m x 20m. The corridor and lift shaft area will add additional mass contributing to the total gravity loading in each floor. The building will be classified as an 'office for general use' type structure in accordance with AS/NZS1170.1; therefore a 3kPa live load will be applied. The dead loading from the flooring units is assumed to be 3kPa and a superimposed dead load of 1.0kPa is also added This loading is used to calculate the demand on a flooring unit, the design of this is shown in Section 4.2.1.1. Tributary areas are used to calculate the proportion of this loading that will be transmitted via axial loading in the seismic and gravity columns.The Direct Displacement Based Design (DDBD) (Priestley et al. 2007) method has been proposed for the calculation of lateral forces arising from earthquake ground motion. A damping ratio and displacement reduction factor is then calculated depending of the type of structure used and based on ductility (Figure 4.1c). This damping ratio is used to modify the displacement spectra to account for hysteretic energy release.

Gravity Loadings

Timber-Concrete Composite Floor Panels Presently at the University of Canterbury a new form of timber-concrete composite flooring is being developed. This consists of prefabricated timber panels fabricated 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 (Figure 4.4). 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. 10mm steel mesh at 200 centres is placed inside the concrete to control shrinkage cracking. This composite behaviour allows a significant increase in stiffness of the system. The concrete topping also improves the acoustic separation between intertenancy floors. For further information regarding this system, and the design of it, refer to Buchanan et al. (2008) and Yeoh et al. (2008).

Gravity Beam and Column Design

The flooring is connected to four large LVL gravity beams in the centre of the structure. In order to enable the reduction of the size of these beams these are tied into the floor slab through the use of notched coach screws placed in the top of the beam member. This allows composite action to form and reduces deflection by increasing the stiffness of the member.

Seismic Loadings

Development of the Concrete Hybrid Connection

As described in Section 2.2 recent developments in the field of seismic design have lead to the development of damage control design philosophies and innovative seismic resistant systems. In particular, jointed ductile connections for precast concrete structures (Priestley 1991, 1996; Priestley et al., 1999; Pampanin, 2005) have been implemented and 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 the use of unbonded post- tensioned tendons with grouted longitudinal mild steel bars or any form of dissipation device. While the post-tensioning provides a desirable recentering characteristic, the dissipation devices allow adequate energy absorption by the system.

Connection Design

The beam to column connection was designed to have a moment capacity greater than 213kNm at the design drift of 1.4%. The finalised design is a 600 x 378 LVL beam with varying post-tensioning up the building. The first two floor levels require twelve 0.5 inch tendons will be use in the next two levels, and three 0.5 inch tendons used in the last two levels (Figure 4.09a). Steel armouring is placed at the face of each connection to reduce the effect of the low perpendicular to grain stiffness of LVL. As it is likely that the frame will remain nearly elastic with minimal gap opening during the design seismic event, dissipation will not be used in the connection. The wall base moment is considerably larger than that of the columns with a moment demand of 8242 kNm. 4000mm x 252mm walls will be used. 50mm Mac Alloy bars are placed in two. 32mm diameter fused internal dissipation is also used with a fuse length of 500mm.

Foundation Design

As mentioned in Section 3.2 the foundation level of the case study building was altered from the original design of the concrete structure. This meant that a re- design of the foundation level was required.

For the timber building beam foundations are placed under both the seismic frame and walls, with pad foundations under the four central gravity columns (Figure 4.13). This layout was also used for the concrete building however a slight increase in the capacity of the foundations was necessary. Calculations of the foundation size for the timber and concrete buildings found that the size of the foundations required are comparable. This is unexpected due to the lightness of the timber building intuitively leading to a reduction in foundation size. However, the foundation size was principally governed by the overturning moment applied by vertical members during a seismic event, and not gravity loading. It can be expected that a significant reduction in foundations between the timber and concrete structures will occur if a building is gravity dominated or is situated in soft soil.

Connection Design of Case Study Timber Building

On completion of the seismic design of the six storey biological sciences building attention was turned to the connection detailing of the structure. The combination of the timber-concrete composite flooring system and the innovative post-tensioned timber system enables considerably larger spans to be achieved compared to traditional timber construction. These longer spans cause increased gravity loadings to be placed onto members and therefore connections. Although the increase in the characteristic strength of LVL means that these larger loadings can be accommodated, the connection details are required to reach capacities that have previously not been achieved in timber structures.

Joist Hanger Design

The use of joist hangers for timber construction is common practice for both residential and low rise commercial timber construction. The application of joist hangers allows quick construction and the ability for mass production of the product means that the cost of a single element can be kept to a minimum.

Corbels for Gravity Beam Seating

The use of corbels is common practice for structural engineering applications. Due to the sizable gravity loadings present in the structure gravity bearing was the most appropriate method of transferring the gravity loadings of the structure. The corbel is glued onto the face of the column during the construction of the member. The seating arrangement will act as a pin support, meaning that only a small amount of moment will be transferred to the gravity frame from the eccentricity of the loading.

This method involves the calculation of a ratio between the Modulus of Elasticity of the timber and that of the tension steel. This method can be used to determine the amount of tension strength required in the top of the timber corbel. Once the required tension strength is found the amount of Type 17 screws and the required penetration can be found using characteristic pull out strength of the screw (Gaunt and Penellum 2007).

Seismic Seating

Although it is possible that the friction at the face of the beam to column connection is adequate, the current New Zealand code states that it is not possible to consider in the transfer of the ultimate gravity loading to the column. It is therefore important to have a corbel at the connection. The major issue with the attachment of these corbels is that they can cause the beam to rise up during rocking leading to increased un-necessary damage to the floor.

Wall Foundation Attachment

The energy dissipation of the Hybrid connection described in Chapter 4 is a crucial part of the system performance. The detailing of this connection is discussed in the following paragraphs.

Internal Attachment of Dissipater into Member

Internal attachment of these dissipation devices has been performed successfully using epoxy (Palermo et al. 2005, 2006). The design procedure of this attachment is a slight modification of that suggested in the Timber Design Guide (Buchanan 2007) which is as follows: This equation has been verified to be accurate for embedment lengths 50 – 400mm (Van Houtte 2003) however due to the lack of further information this has been applied to the connections above this length. This equation was used to calculate the embedment length required for the bonded length of the dissipater.

Column Foundation Attachment

An issue arose during the detailing of the building regarding the attachment of the columns epoxied bars into the foundation. The 25mm diameter bars required a considerable development length causing an increase in the depth of the foundation.

These restriction lead to the development of a steel shoe which will be attached to the base of the column .In order to gain the required bending strength in the section vertical steel plates are added. It is important to ensure adequate clearance is left around the specimen so that the controlled rocking motion is not hindered. The plate will be bolted to the foundation using high strength bolts.

Shear Transfer for the Slab into the Frame
As the length of the area that the frame system in contact with the diaphragm is longer than that of the wall, a connection of lower strength that is simpler to attach is used.

Further Connection Details
Although the above connection details were used for the design of the six storeycase study, during the design process several other options were consided. These further options are outlined below.

Corbel for Joist Seating
The main issue with the use of the joist hangers is that they must be attached in an exact location meaning that this attachment must also occur on site. One possible way to negate this situation is the use of a corbel seating.

Use of U Shaped Plate for Energy Dissipation
The use of U shaped flexural plates (UFP's) for energy dissipation was first proposed by Kelly et al. in 1972. Later, during the PRESSS testing programme (Conley et al. 2002) this element was used with great success when coupling two rocking wall members. Testing at the University of Canterbury has shown that similar results can be achieved when the UFP's are used to couple two LVL walls (Iqbal etal. 2007).

Coupling Walls with Plywood Sheets
Testing performed at the University of Canterbury has also investigated the use of nailed plywood for the coupling of wall members (Smith et al. 2007). These sheets were attached to each face of the wall using nailed perimeters. The nail spacing was then altered changing the amount of hysteretic dissipation in the system.

Connection Testing
The following chapter outlines tests performed to assess the performance of key connections adopted in the design of the timber case study building. The first tests assess methods to resist shear at the base of a wall or column member due to lateral loading. Secondly a series off our simple push out tests is performed to find an initial indication of characteristic strength of the beam to floor diaphragm connection suggested in Section 5.7.

A beam to column subassembly was then used to investigate the interaction of key factors in the systems performance. A series of test were performed aiming to answer the following questions:

- What is the effect of placing steel armouring on the column face in the beam to column connection?
- Whatistheeffectofalteringtheinitialposttensioningforceinthetendonon moment response of the connection?
- How accurately does the design procedure out line din New combe et al.2008 predict the key characteristics (Moment response, tendon force, and neutral axis depth) during lateral movement of the column?
- What effect does the placement of corbels on the column face under the beam have when a shear load is placed on the beam?
- What effect does the placement of a timber-concrete composite floor unit have on the moment response of the beam to column connection?

Testing of Angle Shear Keys
During the testing of the single LVL hybrid wall (Smith 2006b) a major issue relating to the attachment of shears keys to resist seismic shear at the base of the wall was recognized. This will be an issue for both wall to foundation and column to foundation members. It was originally stated that the use of circular shear keys is preferable to the stiffer angular shear key previously used as movement and rolling over the keys is allowed. Although this is adequate for short term seismic testing it is necessary to revisit this idea if serviceable loading is to be considered.

Push out Testing of Floor to Beam Shear Connection
One of the crucial connections in the any building is that of the floor diaphragm into the seismic resisting system. In most seismic designs it is assumed that the floor diaphragm acts as a rigid block and that the connection between this floor and the frames and walls always remains elastic. Both of these tests displayed the sudden shear failure, and again this failure was accompanied by a large cracking noise. Test one displayed the same level of ultimate strength as that of the two parallel tests, however, the second test displayed significantly lower ultimate strength. Visual inspection of the test indicated that local crushing of the concrete around the coach screw due to inadequate cover may have been responsible for this significantly lower strength. The failure mode of the two specimens (Siebold and modified) is compared.

CONCLUSIONS

This thesis aimed to assess the feasibility of post-tensioned timber building. This assessment was performed with the use of case study buildings designed in timber, concrete and steel. The structural design of the timber building was presented with emphasis placed of the connection design. Subassembly testing was performed to investigate the performance of a selection of critical connections. Finally, the costs, construction technique and construction time was compared between the case study buildings and a business case was presented suggesting the way forward to ensure adoption of post-tensioned timber buildings in the construction market place.

These questions can be divided into two major categories: questions about the design of post-tensioned timber structures, and questions about comparative performance between the timber system and other common systems in steel and concrete. The answers to these questions are detailed below:

MEMBER AND CONNECTION DESIGN OF TIMBER BUILDING

How will a timber post-tensioned building be designed?

- **How will lateral seismic loading be calculated?**
  The lateral seismic loading of the building is assessed using a modified version of the Direct Displacement Based Design Procedure. Simple modifications can be made to allow for both the an isotropic and flexible nature of timber.
- **What type of flooring will be used?**
  Timber-concrete composite flooring is used. These units consist of concrete topping poured onto plywood sheets which sit on plywood joists. Notches are cut into the joist units providing composite behaviour. Diaphragm action is achieved through the concrete topping.
- **How will lateral forces be resisted?**
  Lateral resistance is provided using the ductile post-tensioned timber connection. This system combines the use of post-tensioned steel elements with the use of sacrificial yielding elements. Design of these connections follows the procedure for the design of a concrete ductile post-tensioned connection. A few modifications are necessary to allow for the differing stiffness values in the LVL perpendicular and parallel to the grainWhat type of connections will be used and how will these connections be designed?
  The principle aim of the connection design was simplicity. Joist hangers are currently common in practice and can also be used for the composite flooring. Bearing is used for gravity load transfer due to its simplicity and ease of design. The floor diaphragm is connected to the seismic elements through the use of discrete connectors cast into the topping. The design of these connections largely follows current code previsions.

The conclusions from these tests are listed below:

- **How will shear at the base of a beam to column or wall to foundation connection be resisted without effecting the rocking motion of the member?**
  The shear sliding at the base of a wall or column is resisted using shear keys. Angled shear keys at the base of a wall or column are preferable to half circular shear keys as they reduce stress concentrations and damage. These do not affect the moment capacity of the wall or column.
- **How will floor shear be transfer to the seismic frame?**
  The floor diaphragm is connected to the frames and wall using discrete connectors. The coach screw connection used in the frame direction was tested. A minimum characteristic strength is suggested for the connection, however, larger values may occur if a sudden slip failure occurs.
- **How will the placement of armour at the beam to column interface influence the moment response of the section?**
  The placement of steel armour at the beam to column interface causes a significant increase in the moment capacity of abeam to column connection by reducing the effect of the perpendicular to grain stiffness.
- **Is the predicted performance of a beam to column connection using current design procedures accurate?**
  The design procedure suggested in New combe et al. (2008) describes the method used to calculate the moment capacity of a post-tensioned connection subjected to a given drift. Testing has shown that this procedure adequately predicts the moment capacity of a beam to column connection.
  Comparisons between Timber and Other Construction Materials
- **How will member size compare between the timber and concrete structures?**
  Timber member sizes are comparable to that of the concrete case study building. As timber is less dense than concrete, the timber members are significantly lighter.

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