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ANALYTICAL STUDY OF DUCTILE CONNECTIONS FOR CROSS-LAMINATED TIMBER STRUCTURES

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Abstract: Cross-Laminated Timber (CLT) has been gaining increased interest within the construction industry over the last two decades. It is already well accepted in Europe and has been coming into the North American market in the last few years. There are a growing number of applications for CLT around the world including regions of high seismicity. It is therefore essential to develop design guidelines and standards to reduce the risk of potential serious problems in the future, particularly in respect of jointing for seismic applications. Significant research has been completed in Europe and North America on properties, structural behavior and sustainability aspects of CLT. But the research on the seismic considerations particularly on joining of the structural members to ensure ductile performance has been limited. This paper focuses on a detailed investigation of CLT joint design. The primary focus is to develop appropriate jointing methods for CLT panels in order to provide a system that will accommodate expected loads particularly seismic forces, conforms with building code requirements and suitable for the construction environment. Experience from similar engineered wood products is drawn into the current research. A new type of with jointed ductile connections through combination of post-tensioning and energy dissipating elements has been implemented for CLT members. The post-tensioning ensures self-centering in addition to the ductility provided by additional energy dissipating elements within the connections. Extensive experimental and numerical investigation is currently underway to develop and test appropriate connections types for CLT building structures. The results confirm the behavior of the connections can be predicted with analytical and numerical work. Experimental program is planned next for validation of the models. The ultimate goal is to develop guidelines and recommendations for practical applications through further analysis and testing.

1 Introduction

Cross-Laminated Timber (CLT) has already been used for significant number of structures particularly in Europe and has been gaining acceptance in the North American market over the last few years. There are a growing number of applications for CLT around the world including regions of high seismicity. It is therefore essential to develop design guidelines and standards to reduce the risk of potential serious problems in the future, particularly in respect of joints for seismic applications. Considerable amount of research has been completed in Europe and North America on properties, structural behavior and sustainability aspects of CLT. An overview of research on seismic considerations particularly with considerations of ductility underlines the need for further information. A new research initiative is with the primary focus is to develop appropriate joining methods for CLT panels is described here. Drawing experience from similar engineered wood products extensive experimental and numerical investigation is currently underway to develop and test appropriate connections types for building structures.

2 Developments in New Zealand

An innovative structural system for timber with jointed ductile connections has been developed through extensive research in New Zealand over the last decade (Buchanan 2008, 2011). Conventional post-tensioning is combined with timber structures made of engineered wood products to produce highly efficient systems. The “Hybrid” moment connections are particularly useful in structures designed for seismic regions. The post-tensioning ensures self-centering in addition to ductility provided by additional energy dissipating elements within the connections (Figure 1). Extensive experimental and numerical studies have confirmed the expected performance of the systems and design procedures have been developed for practical applications. The concept has already been applied in design of a number of structures within and outside New Zealand.

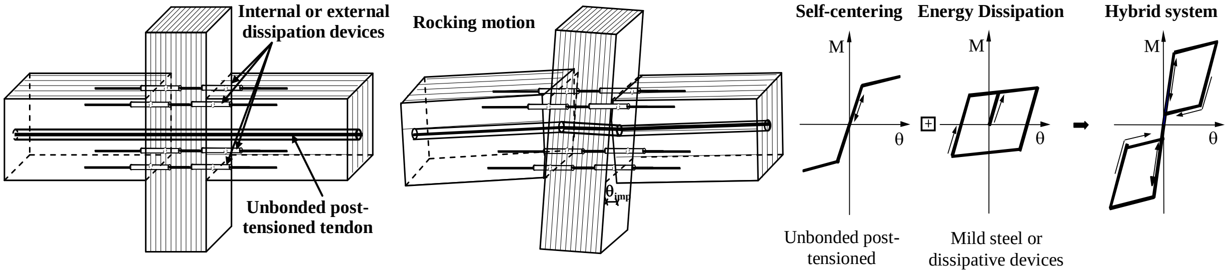

Figure 1: Application of Hybrid concept to LVL frame system and idealized flag-shape hysteresis loop

As part of a comprehensive research investigation for the development of innovative seismic resisting systems for timber construction, a number of different hybrid solutions for frame and wall systems have been successfully tested for implementation in multi-story LVL buildings at the University of Canterbury, Christchurch, New Zealand (Newcombe 2008). Initially wall to foundation connections were tested with and without energy dissipation devices (Figure 2). The research was extended (Iqbal 2007, 2010) to shear walls coupled with energy dissipating elements (Figure 3).

The tests confirmed the behavior of the assemblies as well as feasibility of adopting the system in multi-storied building structures (Newcombe et al. 2010). The two-storied model suffered little damage and was re-used as a practical structure providing office space after some modifications. Design procedures were developed based on the research findings and design guidelines were published for practitioners (Expan 2013).

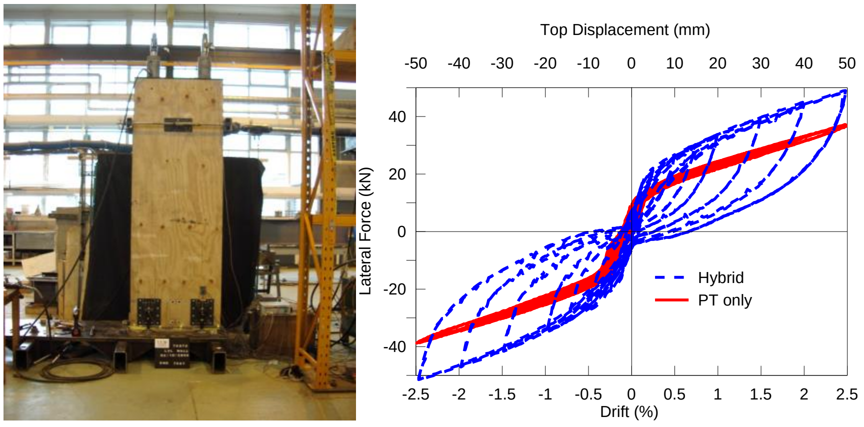

Figure 2: Wall-foundation test specimen and load-deflection plot (Smith et al. 2007)

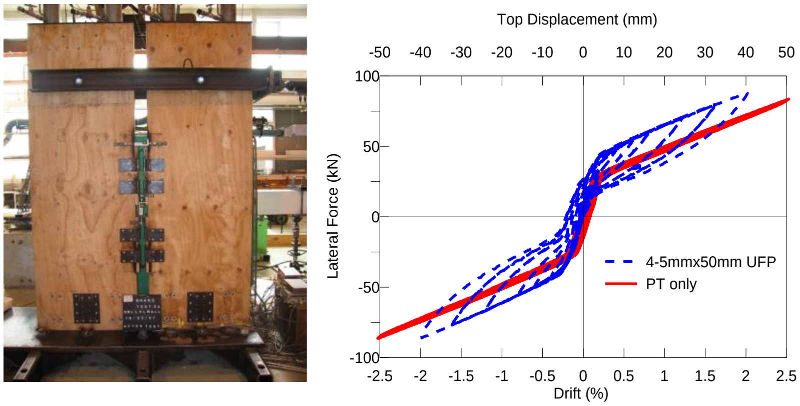

Figure 3: Coupled walls specimen and load-deflection plot (Iqbal et al. 2007)

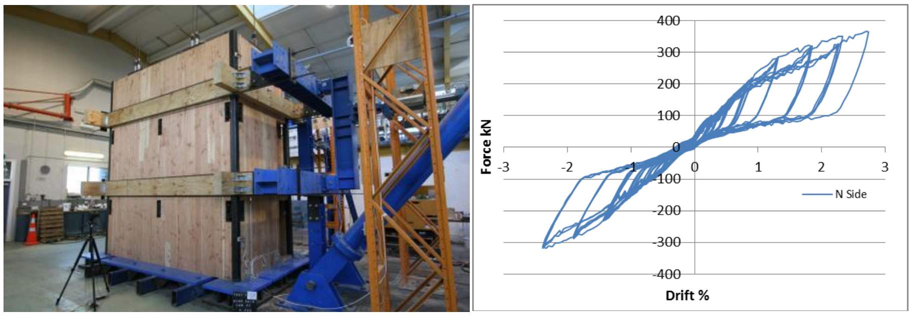

Figure 4: CLT Core and load-deflection plot (Dunbar et al. 2014)

After the significant developments with LVL and Glulam an initiative was taken to extend the research into CLT. Dunbar et al. (2014) tested core walls made of CLT panels (Figure 4). Utilizing information from the research the new Kaikoura District Council building in New Zealand has been designed to be the first in the world with post-tensioned CLT structure (DesignBASE 2014). CLT shear walls have been used alongside LVL beams and columns and wooded floors. A number of other structures are currently at different stages of design or construction in New Zealand.

3 Concept and Theory

In the Hybrid structures replaceable ductile elements protects the structural members from serious damage through absorbing energy during seismic events (Figure 1). Engineered wood products have been found to be particularly suitable for this type of applications because of their superior strength characteristics compared to rough sawn timber and the concept has been applied to different engineered wood products such as Laminated Veneer Lumber (LVL) and, Glue Laminated Timber (Glulam). One of the common energy dissipating connection consisted of axially loaded deformed bars, encased in steel tubes to prevent buckling. A high level of deformation can be achieved by the ‘fuse’ with possibility of replacement after yielding.

Presence of unbonded post-tensioning and energy dissipaters allows for gap opening at a hybrid connection. This means the strain in the concrete becomes unknown in addition to the position of the neutral axis. Strain compatibility thus does not apply at a section level. To address this issue, a global strain compatibility relationship between the parameters has been derived from an analogy (Figure 5) between the precast and a monolithic connection referred to as Monolithic Beam Analogy (Pampanin et al. 2001).

In the monolithic cantilever the total displacement is given by the sum of elastic deformation and plastic rotation about the centroid of the plastic hinge. In case of the precast beam, in addition to the elastic deformation, there is an opening of a gap at the beam-column interface due to imposed rigid rotation about a zero-length plastic hinge at the joint interface similar to the monolithic beam.

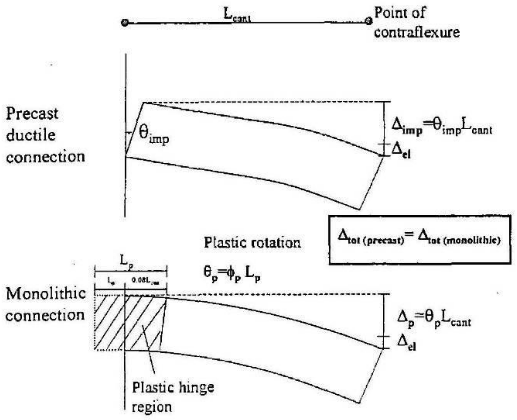

Figure 5: The Monolithic Beam Analogy (Pampanin et al. 2001)

For the same total imposed displacement, the elastic deformations are the same in the two beams with identical geometry and reinforcement. Then the plastic deformations in the two beams can be equated and the following relationship between concrete strain and neutral axis position is derived:

$$\varepsilon_c = \left[\frac{(\theta \cdot L_{cant})}{\left(L_{cant} - \frac{L_p}{2}\right) L_p} + \phi_y \right] \cdot c$$

A section analysis procedure to calculate the moment capacities of the subassemblies was implemented using the connection moduli suggested by the numerical models.

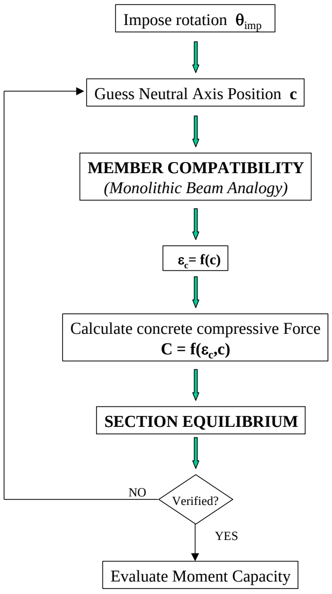

Figure 6: Section Analysis procedure flowchart (Pampanin et al. 2001)

The iterative procedure based on Monolithic Beam Analogy (Figure 6) was followed for section analysis for ultimate limit state. The subassemblies were assumed to go through rigid body motion during rocking at the interface as it has been found that generally it would be conservative in terms of moment capacities to ignore the elastic deformations in the subassemblies. The additional tension in the prestressing tendons due to elastic deformations contribute to the moment capacity of the overall system, so the moment capacity is slightly underestimated if that is not accounted for in the final calculations. But caution has to be exercised in checking the prestressing tendon against yielding because will be non-conservative to ignore the elastic deformations due to additional stresses in the tendons. One way of taking care that is to keep a safe margin of safety to prevent any possible yielding of tendons and provisions for this margin should be included in the calculations with a reasonable estimate of the elastic deformations.

4 Section Analysis

Axial dissipaters were added to the PT-only double walls. Two (one in either side) 8mm diameter dissipaters were attached at the centre of each wall. The other details remained the same. The arrangements are as shown in Figure 7.

For Hybrid walls with axial energy dissipators:

Elongation in energy dissipator,

$\Delta_s = \theta_{imp}\left(\frac{l_w}{2} - c\right)$ where c is the depth of neutral axis and θ_{imp} Imposed rotation at the rocking interface

Strain in the dissipater,

$\varepsilon_s = \frac{\Delta_s}{l_{ub,d}}$ where l_{ub} is the unbonded length of post-tensioning tendons

For connection equilibrium:

$$C_t = T_{pt} + N + T_s$$

Where, tension force in post-tensioning tendons $T_{pt} = T_{pt,i} + \Delta T_{pt} = \rho_{pt} f_y A_{pt} + \varepsilon_{pt} E_{pt} A_{pt}$

And tension force in energy dissipators $T_s = f_y A_s$

The moment capacity

$$\phi M_n = \phi\left[T_{pt}\left(\frac{l_w}{2} \pm x_{pt} - \frac{c}{3}\right) + N\left(\frac{l_w}{2} - \frac{c}{3}\right) + T_s\left(\frac{l_w}{2} - \frac{c}{3}\right)\right]$$

The re-centering ratio, $\lambda = \frac{M_{pt} + M_N}{M_s}$

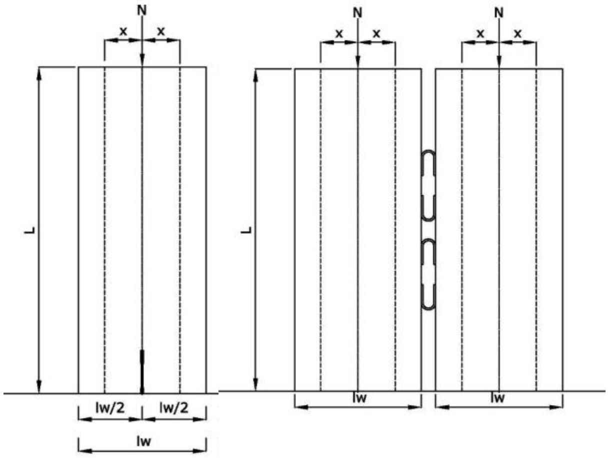

Figure 7: Details of Hybrid walls with axial dissipaters

For Hybrid walls with UFP dissipaters:

UFP force contributions:

$$V_s = n * 0.5 \frac{bt^2}{D} F_y$$

Wall axial forces:

$$N_1 = N - V_s$$

$$N_2 = N + V_s$$

Connection equilibrium conditions:

$$C_{t1} = T_{pt11} + T_{pt12} + N_1$$

$$C_{t2} = T_{pt21} + T_{pt22} + N_2$$

Where,

$$T_{pt} = T_{pt,i} + \Delta T_{pt} = \rho_{pt} f_y A_{pt} + \varepsilon_{pt} E_{pt} A_{pt}$$

The moment capacity

$$M_{pt1} = T_{pt11}\left(\frac{l_w}{2} - x_{pt} - \frac{c_1}{3}\right) + T_{pt12}\left(\frac{l_w}{2} + x_{pt} - \frac{c_1}{3}\right) + N_1\left(\frac{l_w}{2} - \frac{c_1}{3}\right)$$

$$M_{pt2} = T_{pt21}\left(\frac{l_w}{2} - x_{pt} - \frac{c_2}{3}\right) + T_{pt22}\left(\frac{l_w}{2} + x_{pt} - \frac{c_2}{3}\right) + N_2\left(\frac{l_w}{2} - \frac{c_2}{3}\right)$$

$$M_{pt} = M_{pt1} + M_{pt2}$$

$$M_{pt} = \frac{l_w}{2}\left(T_{pt11} + T_{pt12} + T_{pt21} + T_{pt22} + N_1 + N_2\right) - x_{pt}\left(T_{pt11} - T_{pt12} + T_{pt21} - T_{pt22}\right)$$

$$-\frac{c_1}{3}\left(T_{pt11} + T_{pt12} + N_1\right) - \frac{c_2}{3}\left(T_{pt21} + T_{pt22} + N_2\right)$$

$$M_s = M_{s1} + M_{s2} = V_s\left(\frac{c_1}{3}\right) + V_s\left(l_w - \frac{c_2}{3}\right) = V_s\left(l_w + \frac{c_1 - c_2}{3}\right)$$

5 Current Research

In continuation of the research in New Zealand a new research program has been launched recently in British Columbia, Canada to facilitate use of CLT in the local building industry. The project focuses on new developments and testing of connection details for seismic applications leading towards development of guidelines for practical applications.

Analytical and numerical studies are currently underway under the research program. The initial stage focuses on connections for CLT walls panels with the foundation and floor panels. A single panel with post-tensioning and energy dissipation elements (Figure 8) has been investigated. Figure 9 shows plots of the analytical study. Arrangements and details similar to earlier studies with LVL walls (Iqbal 2011) were followed. The calculation procedure had to take the representative properties and consequent implications into account. The backbone curve of the monotonic load-deflection behavior indicates yielding of the energy dissipators as expected. Variations in tendon forces and neutral axis locations are also similar to those observed in earlier research. The plots also indicate that no yield in the post-tensioning tendons or any damage to the panel is anticipated.

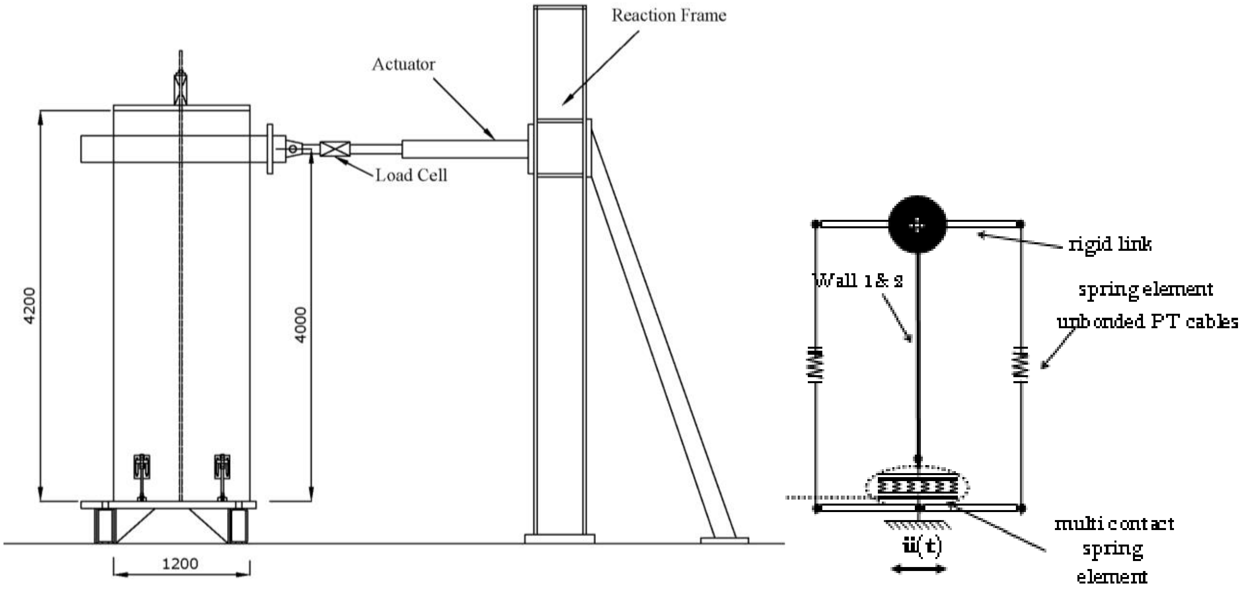

Figure 8: CLT wall-foundation test specimen (left) and numerical model (right)

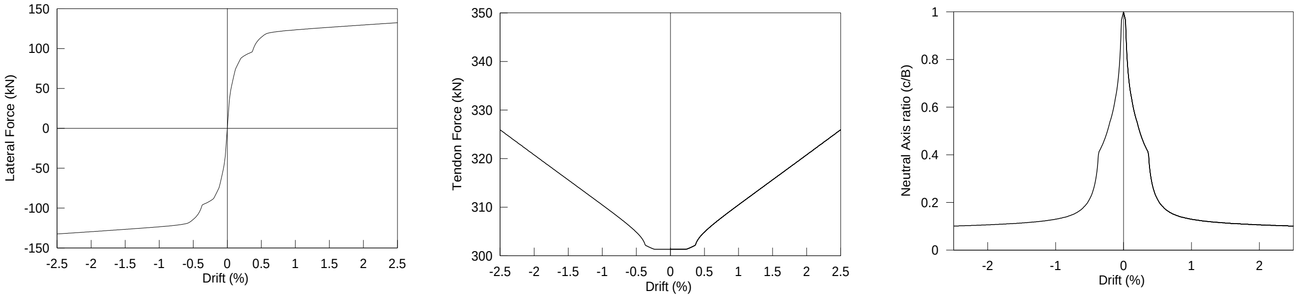

Figure 9: Load-deflection (left), tendon forces (middle) and neutral axis (right) plots of CLT wall-foundation

A variation of the wall-foundation model was developed to represent wall-floor panel connections. The rigid foundation was replaced by another CLT panel loaded in perpendicular-to-grain direction. The energy dissipators were omitted which made it a post-tensioned only connection. The results are shown in Figure 10, that are similar to the previous plots. Noticeably, the lower increase in the tendon forces and higher locations of the neutral axis indicate crushing in the floor panel.

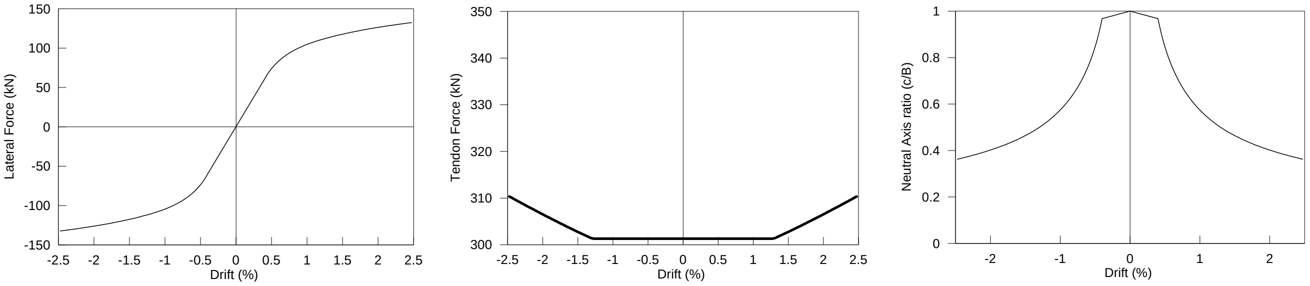

Figure 10: Load-deflection, tendon forces and neutral axis plots of CLT wall-floor model

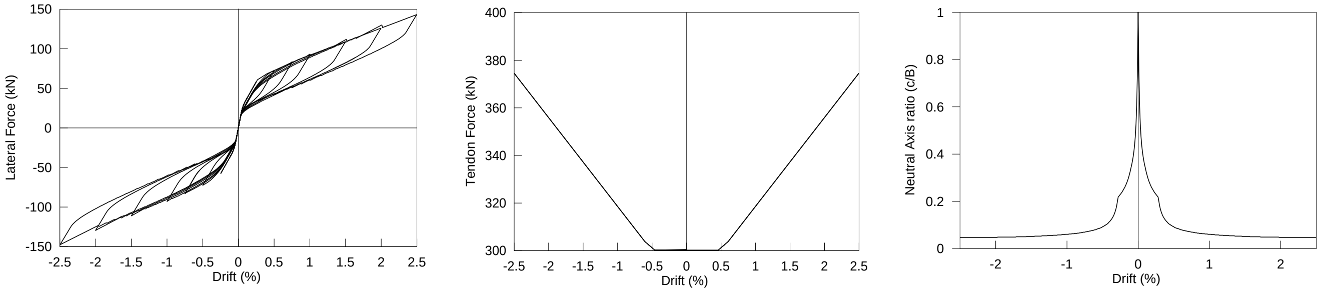

Figure 11: Load-deflection, tendon forces and neutral axis plots of CLT wall-floor finite-element model

Utilizing results from the analytical work further analysis has been performed to predict the cyclic behavior of the models. A finite-element software (Carr 2016) model (Figure 8, right) capable of representing the behavior with special elements (Palermo et al. 2005) has been utilized. Figure 11 shows the results of the wall-foundation model. They are generally close to the analytical results presented in Figure 9.

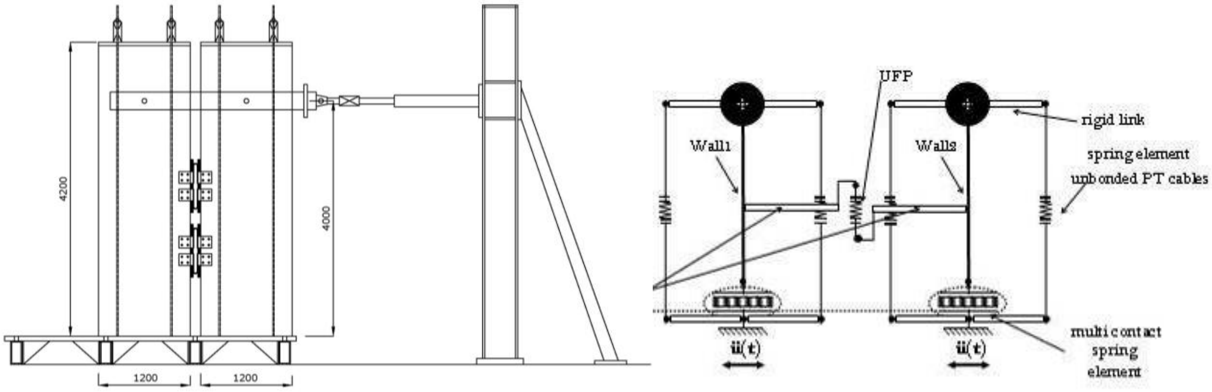

Figure 12: CLT coupled wall-foundation test specimen (left) and numerical model (right)

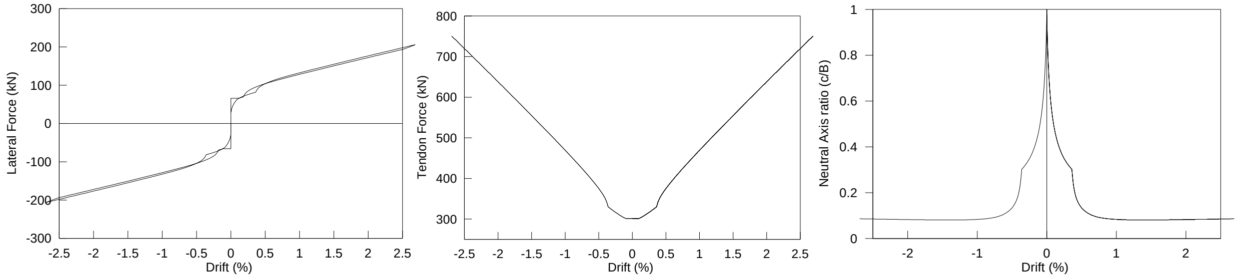

Figure 13: Load-deflection, tendon forces and neutral axis plots of CLT coupled walls

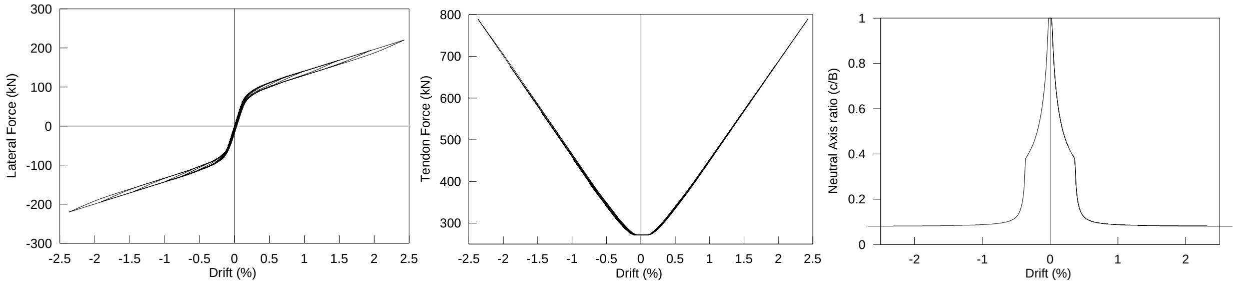

Figure 14: Load-deflection, tendon forces and neutral axis plots of CLT coupled walls finite element model

Similar to the single wall-foundation specimen, a couple wall specimen was investigated with U-shaped flexural plates between the panels (Figure 12). Figure 13 shows the results from the analytical study. Results from the finite-element model are shown Figure 14 shows the results of the wall-foundation model. As in the case with the single-wall, it is clear that the results from the two models are in good agreement.

6 Conclusions and Future Work

There has been significant research on CLT members for seismic application over the last two decades. The ongoing research presented here follows a ductility-based approach compatible with the performance-based design philosophy. Preliminary results indicate the concept has good prospect for calculating behavior of connections. However, validation of the models and further analysis are necessary before guideline for practical application can be proposed with full confidence. An extensive experimental program aimed at achieving that goal is currently under planning.

Acknowledgements

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