DUCTILE CONNECTIONS FOR CROSS-LAMINATED TIMBER STRUCTURES

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Abstract

Cross-Laminated Timber (CLT) is a new generation of Engineered Wood Product that 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. Preliminary results indicate the concept has good prospect and behavior of the connections can be predicted with analytical and numerical work. Experimental program is planned next for validation of the models. The ultimate goad is to develop guidelines and recommendations for practical applications through further analysis and testing.

Keywords: Timber Structures; Cross-Laminated Timber; Connections; Ductility; Post-tensioned Timber

1. Introduction

Cross-Laminated Timber (CLT) is 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 jointing 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. CLT Research with Ductility Consideration

Fragiacomo et al. [1] performed a study with the intention to suggest design overstrength factor for CLT connections based on connector test data. The study indicated that the main source of ductility in CLT buildings is the ductility in the connections, which should be used as the basis for calculating overstrength for all other parts of the building if ductile failure of the system is desired. The authors suggested designing floor panel connections using overstrength, i.e., limiting diaphragm damage during earthquakes. Based on cyclic loading tests a value of 1.3 was suggested for hold-downs and angle brackets for CLT walls. The study also applied a nonlinear static analysis approach to design an example four-story CLT building considering system ductility. The analysis revealed that ignoring ductile connections in the CLT system (by replacing nonlinear springs with rigid links) will greatly underestimate the natural period of the building and its displacement during earthquakes, and overpredict base shear. However, the authors also indicated that using only ductile springs to connect the panels may overestimate the building natural period if the effect of interpanel friction is ignored. A push-over analysis following the N2 procedure recommended by Eurocode 8 was conducted using the nonlinear model and proved the use of ductile connectors can increase the system ductility and seismic resistance.

Gavric et al. [2,3] summarized results of a series of panel connection tests including 20 different screwed panel configurations. These results provided information for CLT connection design where the design intent is that they remain undamaged under design seismic loads. It was concluded that the over strength factor for these connections ranges from 1.2 to 1.9, with an average value of 1.74.

Sustersic et al. [4] conducted a parametric study to investigate the effects of friction and vertical load on the dynamic behavior of panelized CLT system models. The numerical model was a four-story CLT building with a relatively simple floor plan (6.5×8.5 m) and regular story height (total height 11.2 m). A simplified model was also constructed for a single stacked wall line. The models were subjected to earthquake excitation with varying connector and friction parameters. The results indicate that both friction and vertical load have significant impact on the response of the CLT system as modeled. The study highlighted the modeling uncertainty that could be associated with CLT system when the friction mechanism within the system is not fully understood. It also indicated that neglecting vertical acceleration during nonlinear time history analysis may affect system response considerably.

Rinaldin et al. [5] developed a numerical model to estimate the dissipative capacity of a CLT building based on component calibration approach. This study focused more on detailed calibration of the nonlinear hysteretic and pinching behavior of these connectors. Accuracy of the model to predict the energy dissipation under reverse cyclic tests was confirmed through comparison of the numerical simulation results to panelized wall tests and a single-story building test.

In North America FPInnovations (FPI) first initiated a series of research projects on seismic design of CLT systems to address seismicity considerations in the British Columbia, Canada. Popovski et al. [6,7] conducted CLT wall tests on 32 shear walls with different aspect ratio, opening, and panel combinations. There were also two-story shear walls with stacked and single-panel configurations. A wide range of connector and bracket types was also investigated. Similar to the findings in European studies, the general conclusion from the tests was that interpanel joint and metal brackets are the main source of ductility in CLT walls, and thus should be implemented for CLT building in seismic regions.

With the objective to investigate the three-dimensional (3D) system behavior of CLT structures subjected to lateral loads, a two story full-scale model of a CLT house was tested under quasi-static monotonic and cyclic loading at FPInnovations [8,9]. Parameters such as direction of loading, number of hold-downs, and number of screws in perpendicular wall-to-wall connections were varied in the tests. The CLT structure performed according to the design objectives, with perpendicular walls having significant influence on the lateral load resistance of the house. Failure mechanisms were similar in all tests; shear failure of nails in the brackets in the first story as a result of sliding and rocking of the CLT wall panels. Half lap joints between the CLT wall panels allowed for relative slip during their rocking as predicted in the design. Despite the rigid connection between floor panels and wall panels, rocking of the wall panels was not fully restricted by the floor panels above. Relative slip between CLT floor panels in the diaphragms was negligible, as expected in the connection design. The deformed shaped also suggested that CLT slabs act as rigid diaphragms. Maximum story drift of 3.2% (inclusive of sliding) proved that CLT structures are capable of achieving relatively large story drifts with proper design and details such as connection types, positions and utilization of resistance considering the kinematic behavior of the structure.

Using the FPI set of test data on CLT walls, Schneider et al. [10] applied an energy-based damage index to quantify the damage to CLT shear walls. Different failure modes for metal bracket connections were identified. Connection tests were analyzed to obtain the relationship between observed damage in the test and calculated damage index. This type of research is important for the performance-based seismic design philosophy expected to be adopted by the design community in the near future. Shen et al. [11] used hysteretic and pinched models to represent CLT bracket connections. The model parameters were calibrated based on connection test results. Then, these connections were incorporated into CLT wall models subjected under cyclic loading numerically. Comparison between the numerical model behavior and full-size CLT tests verified the accuracy of this connection-based modeling method. This study highlighted the feasibility of numerical simulation of CLT system behaviour.

Pei et al. [12] proposed a concept of alternating rigid CLT shear walls (using long panels) and ductile CLT shear walls (using short panel segments) in a multistory building at different story levels. It was confirmed through numerical analysis that lateral deformation was concentrated at the ductile layers and acceleration at higher stories was reduced significantly.

Similarly, Dolan et al. [13] proposed adding ductile components in tall CLT buildings to improve resiliency of the system under large earthquakes. The concept of inter-story isolation was applied to tall CLT construction, detailing the CLT floor diaphragms to be deformable with a slip plane with stiffness and damping elements. Through numerical simulation it was shown that for a 10-story building, one or two layers of deformable diaphragm at selected stories would effectively reduce floor accelerations and force demands on CLT connections.

The latest research effort in the United States on this topic deals with resilient tall CLT systems. An United States National Science Foundation sponsored NEES-CLT Planning project [14] is currently underway to design and test seismically resilient CLT lateral force resisting systems suitable for use in 8–20 story buildings. The objective of the project is to introduce ductility and resilience in tall CLT construction. Designs similar to that investigated by Pei et al. [12] and Dolan et al. [13] will be further developed and tested. The NEES-CLT project plans to develop and experimentally validate innovative CLT systems with a vision to enable tall CLT buildings in the Pacific Northwest region of the United States by 2020.

CLT production is gaining some interest in Japan as well. Okabe et al. [15] tested connections and panelized CLTwalls made from Sugi wood, a locally available softwood species. The anchor connection was tested in tension, wall-to-diaphragm connection was tested in shear, and interpanel connection was tested in shear as well. The wall tests were conducted under different levels of vertical load, but the difference in the observed strength for the walls was not very significant. It was also observed that rocking deformation is the predominant behavior for CLT walls, with the interpanel connection failing in shear and each individual panel engage in rocking motion on its own. Similar results were reported by Yasumura [16] and Yasumura and Ito [17].

Significant research efforts have been focused on low-rise CLT buildings. Matsumoto et al. [18] designed and performed time-history analysis on a 3-story building made of Sugi CLT panels. Results from FEM analysis showed that the building satisfied the Japanese seismic performance requirements. Miyake et al. [19] looked further into the connections of the model and concluded that analytical estimates of the seismic performance match test results with sufficient accuracy. Tsuchimoto et al. [20] compared the deformations during static and dynamic tests as well as that of the components and the full-sized specimen. Yasumura et al. [21] described experimental and numerical results of a low-rise CLT building subject to lateral loading.

Experimental studies on CLT connection and wall assembly behavior in different parts of the world over the past decade have exhibited some common treads and provided valuable information for analysis and design. Panelized CLTwalls develop their ductility primarily through connection deformation, while the panels remain elastic with local damage where connected. Panelized CLT walls tend to rock about their corners under lateral load when the boundary condition allows, which will engage the anchors in combined uplift and shear. On the other hand, very long wall panels (with small height-to-length ratio) will likely engage anchors primarily in shear. The boundary conditions and vertical loads all contribute to the strength and stiffness of the CLT shear walls. Numerical studies verified that component-based modeling of CLT wall assemblies using connection test data is a reasonable approach. However, modeling the nonlinear effects such as contact, friction, and connection hysteresis must be carefully considered as they influence the behavior significantly and test data are critical for CLT system model validation. Damage to CLTassemblies is concentrated at connections, which can be quantified through a damage index, but the work related to quantifying CLT system damage is very limited at this point.

Near collapse performance was used and defined using connection damage and uplift since real collapse of a CLT building has not been realized experimentally to this point. It is possible to design a multistory CLT building using an existing design methodology with appropriate seismic design parameters adopted for life-safety. However, the building will have considerable risk of significant connection damage due to motion of the panels. A performance-based seismic design (or no damage design) philosophy should be adopted for tall CLT buildings in high seismic regions in order to ensure resiliency.

Based on the findings from past research efforts, suggested critical studies include performance-based seismic design methodology for multistory CLT construction, and innovative CLT-based lateral force-resisting systems that can achieve resiliency under major earthquakes.

3. 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 [22, 23]. Conventional post-tensioning is combined with timber structures made of engineered wood products to produce highly efficient systems. The 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. 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.

In the “Hybrid” structures replaceable ductile elements protects the structural members from serious damage through absorbing energy during seismic events (Fig. 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.

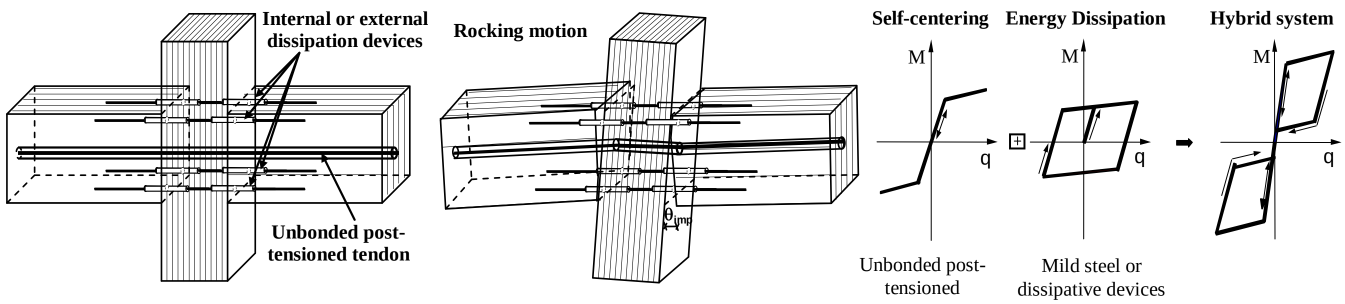

Fig. 1 – Application of Hybrid concept to LVL frame system and idealized flag-shape hysteresis loop

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-storey LVL buildings at the University of Canterbury, Christchurch, New Zealand [24]. Initially beam to column, column-to-foundation or wall to foundation connections were tested with and without energy dissipation devices (Fig. 2). The flag-shaped hysteresis plots of beam-column joint and wall specimens are shown in Fig. 3. The research was extended [25-26] to shear walls coupled with energy dissipating elements and interior beam column joints which were followed up by tests on a two-storied building model (Fig. 4).

The tests confirmed the behavior of the assemblies as well as feasibility of adopting the system in multi-storied building structures [27]. 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 [28].

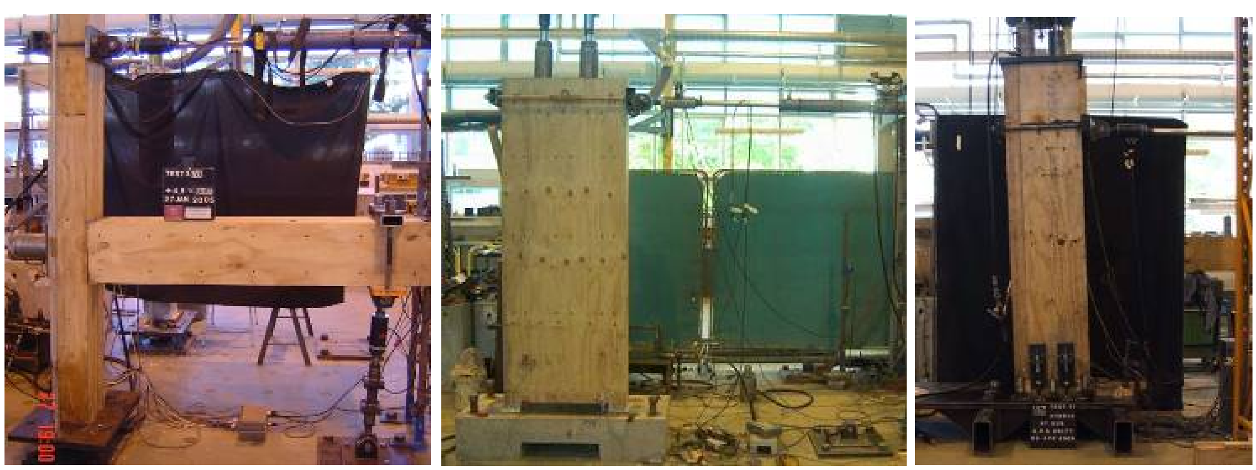

Fig. 2 - Exterior beam-column joint, wall-foundation, column-foundation test specimens [24]

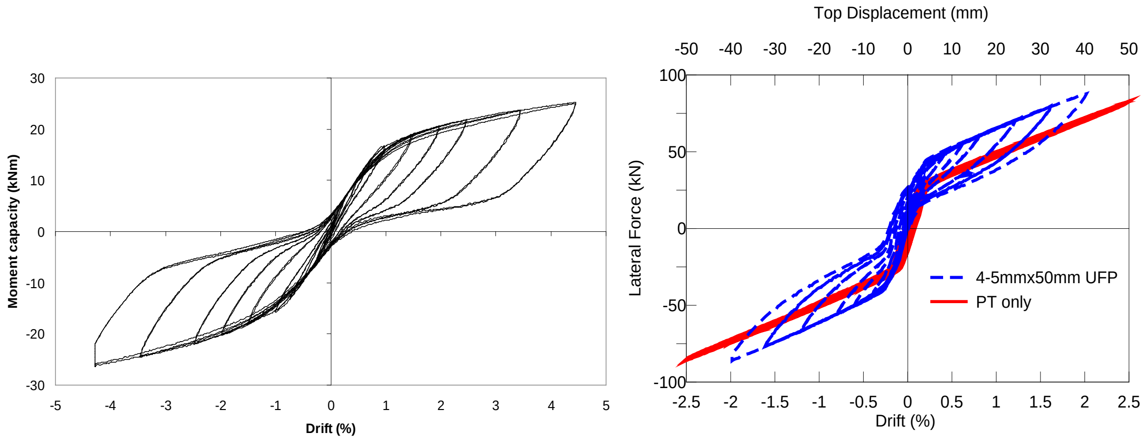

Fig. 3 - Beam-column joint and shear walls load-deflection plots [24, 25]

Fig. 4 - Coupled walls and two-storied building model [25, 27]

After the significant developments with LVL and Glulam an initiative was taken to extend the research into CLT. Dunbar et al. [29] tested core walls made of CLT panels (Fig. 5). 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 [30]. 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.

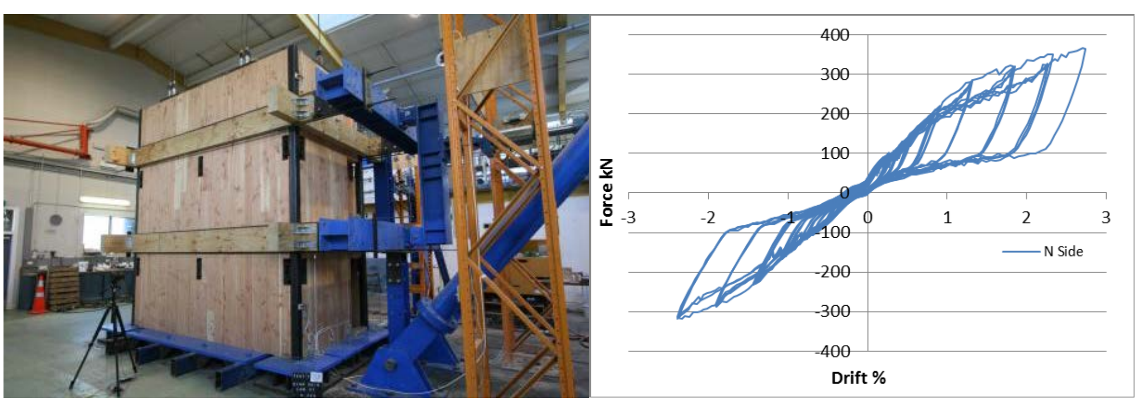

Fig. 5 - CLT shear wall test specimen and load-deflection plot [29]

4. 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 (Fig. 6) has been investigated. Fig. 7 shows plots of the analytical study. Arrangements and details similar to earlier studies with LVL walls [31] 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.

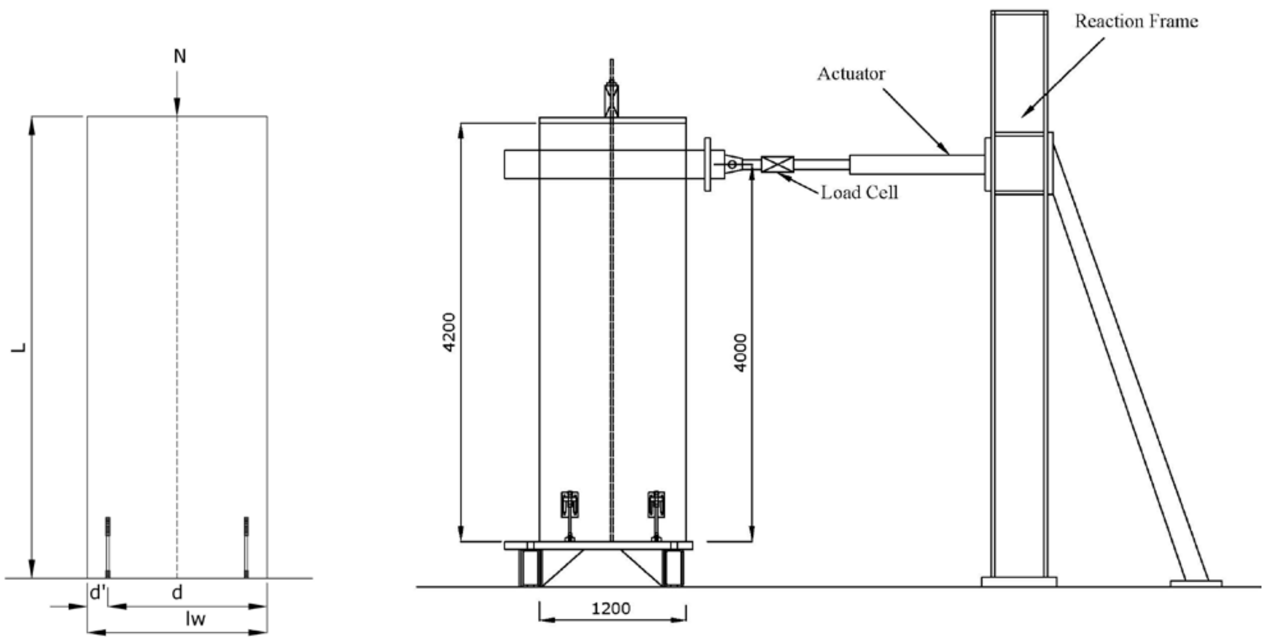

Fig. 6 – CLT Wall panel and wall-foundation test specimen

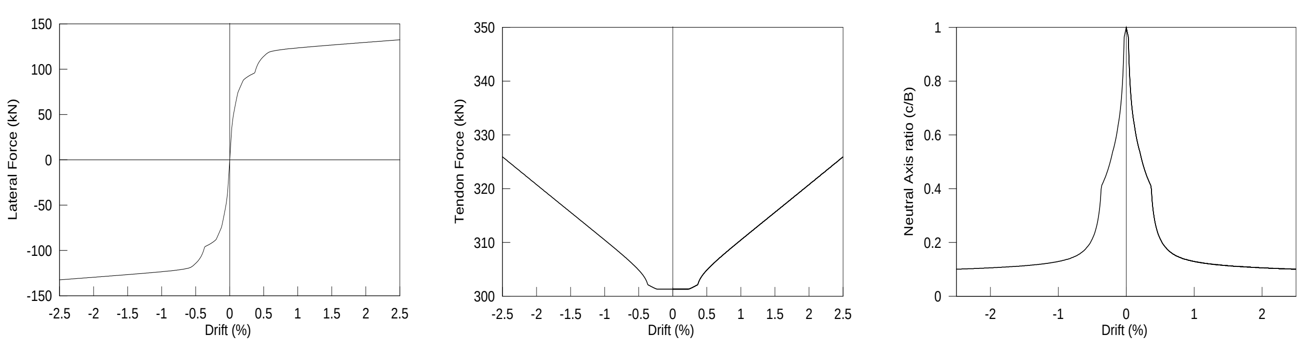

Fig. 7 – Load-deflection (left), tendon forces (middle) and neutral axis (left) plots of CLT wall-foundation model

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 Fig. 8, 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.

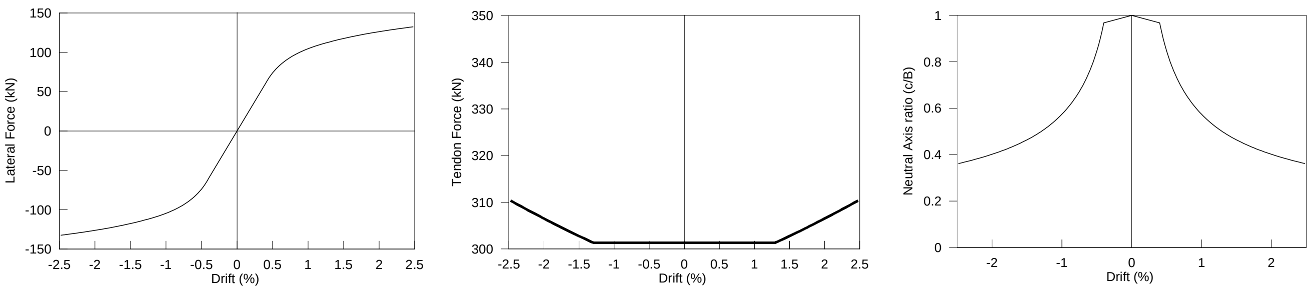

Fig. 8 - Load-deflection, tendon forces and neutral axis plots of CLT wall-floor model

Utilizing results from the analytical work further analysis has been performed to predict the cyclic behavior of the models. A finite-element software [32] model capable of representing the behavior with special elements [33] has been utilized. Fig 9 shows the results of the wall-foundation model. It is generally in good agreement with the analytical results presented earlier. Further analysis and refinement of the parameters is ongoing for other models.

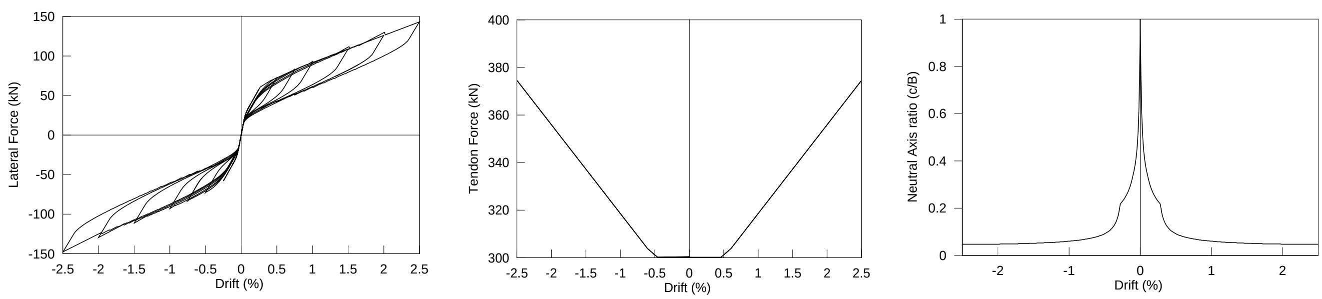

Fig. 9 - Load-deflection, tendon forces and neutral axis plots of CLT wall-floor finite-element model

5. 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 and behavior of the connections can be predicted with analytical and numerical work. 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.

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