Experimental Investigation of a Two-Storey Full-Scale CLT Structure with Resilient Rocking Walls

S.R. Agarwal, A. Hashemi & P. Quenneville

The University of Auckland, Auckland, New Zealand.

ABSTRACT

A two-story full-scale structure is being constructed and tested at the University of Auckland lab to investigate its performance with resilient rocking walls. The structure is 6 meters high with CLT floors spanning 6 meters. It is entirely built from CLT columns, beams, and floors, with CLT walls serving as the primary lateral load-resisting system in the longitudinal direction. A resilient tension-only brace acts as the lateral load-resisting system in the transverse direction.

The investigation focuses on the performance of the lateral load-resisting system and its deformation compatibility with the gravity system. The behavior of the beam-column joints, floor beam rotations, sway or rocking behavior of the gravity frame, and the lateral load-resisting system will be assessed. The structure will undergo a series of tests, including a snapback test to determine structural properties and estimate inherent damping, static tests at high drifts to determine displacement compatibility and verify damage-free drift limits, and dynamic loading at high drifts. Performance enhancement using additional dampers to couple walls will also be evaluated.

This paper will present the results and recommendations for mass timber design, as the tests are integral to determining seismic behavior factors for resilient rocking walls. Additionally, it will provide relevant information and recommendations to engineers regarding mass timber connections subjected to high drifts.

1 INTRODUCTION

Mass timber is increasingly preferred for engineered buildings for its sustainability, eco-friendly characteristics, lightweight properties, and efficient construction capabilities. Cross Laminated Timber (CLT), with its low cost and bidirectional properties, has been extensively researched in the last two decades (Dujic, et al., 2004), (Popovski, et al., 2010) and (Lindt, et al., 2020). CLT offers the integrated benefits of a vital structural component, particularly as a biophilic cladding system, and a Lateral Load-Resisting System (LLRS).

CLT wall as LLRS behaves rigidly with ductility and damage restricted to the base/connections (Ceccotti, et al., 2013). Various conventional and Low Damage Design (LDD) options have been researched with few relevant to this paper discussed here.

The conventional systems include CLT walls with conventional hold-downs and couplers prone to damage and results in pinching hysteresis and stiffness degradation (Ceccotti, et al., 2013), (Popovski & Gavric, 2016)and (Amini, 2018). Further, these systems can have either rocking or sliding mechanisms, with most pragmatic, high ductile wall aspect ratios tending to be dominated by rocking behavior. Furthermore, the rocking behavior has displacement compatibility issues with connecting diaphragms (Palermo, et al., 2005).

LDD design concept in CLT walls includes walls with Post-tensioned (PT) cables (Sarti, et al., 2016 and Iqbal, et al., 2015) and wall systems with resilient dampers and couplers (Hashemi, et al., 2016, Chan, et al., 2020 and Agarwal, et al., 2023).

Several studies that have investigated rocking CLT walls with post-tensioned (PT) cables, including full-scale experimental programs include Sarti et al., 2016; Pei et al., 2012, 2018 and Blomgren et al., 2019.The NEHRI tall wood projects (Dowden et al., 2025 and Pei et al., 2024) have further contributed notably to compliant design procedures for rocking CLT walls with PT cables.

Most of these full-scale tests involved PT cables. Rocking CLT walls with PT cables requires CLT to be machined for PT cables to pass through and may need monitoring of PT force (long-term creep in timber), which may reduce the system's competitiveness (Blomgren, et al., 2019). Further most of these tests and test by Amer, et al., 2023 indicated toe damage at the rocking toe with loss of initial stiffness.

1.1 Research Plan

To address the research gap in full-scale testing of CLT walls with self-centering hold-downs (without PT cables), this research investigates the holistic behaviour of a complete CLT structural system. For the first time, a full-scale CLT structure, including columns, beams, and floors, was constructed and tested (Figure 1).

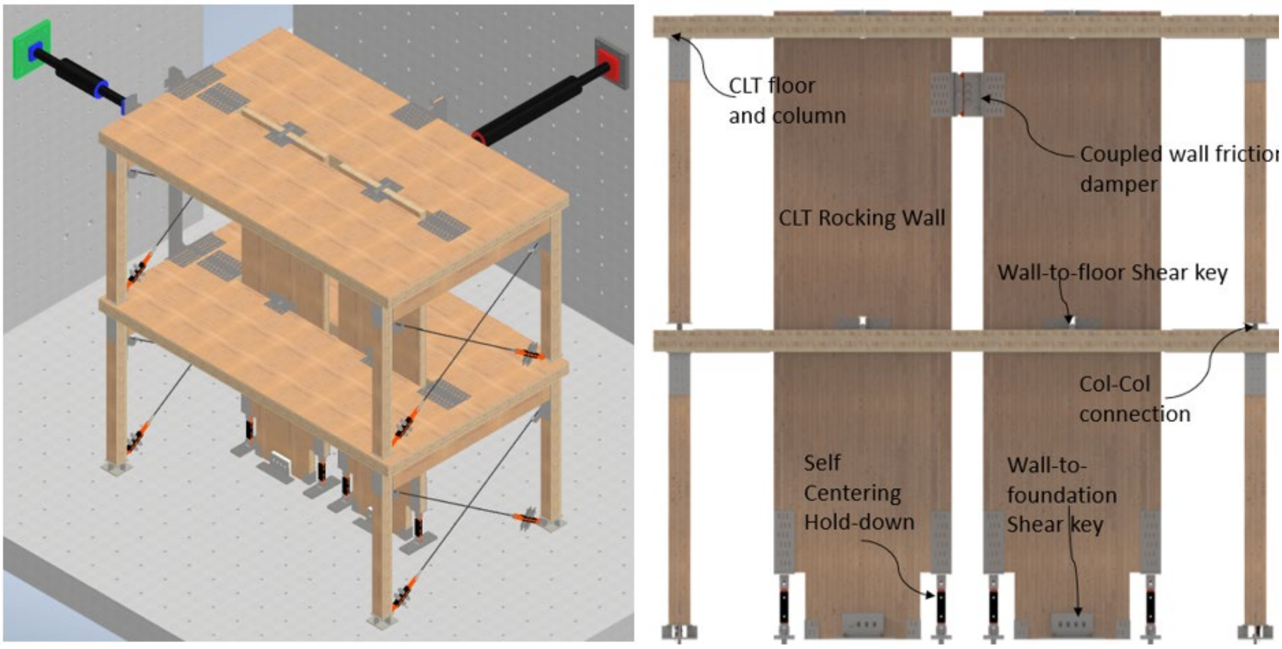

Figure 1 Test Setup for Two story Full-scale CLT Building.

The two-story test setup consists of two CLT walls in the longitudinal direction as the primary LLRS. Although a single CLT wall would have sufficed structurally, two walls were intentionally incorporated to investigate the coupled wall behaviour with conventional friction dampers. Tension-only X-bracing provided lateral stability in the transverse direction. The CLT walls were decoupled from the gravity system for the initial two test phases and transfers only lateral forces. The overall dimensions of the test structure are 6 meters long, 6 meters high, and 4 meters wide.

The performance of Column -column / Column beam/ Column brace connection, Column with Top connector plate, column base connection was evaluated under high drift (Figure 2 and). Moreover, the design of the structure specifically addressed challenges encountered in previous research, such as toe damage and loss of initial stiffness. The CLT walls were further tested coupled using conventional friction dampers in combination with self-centering resilient hold-downs

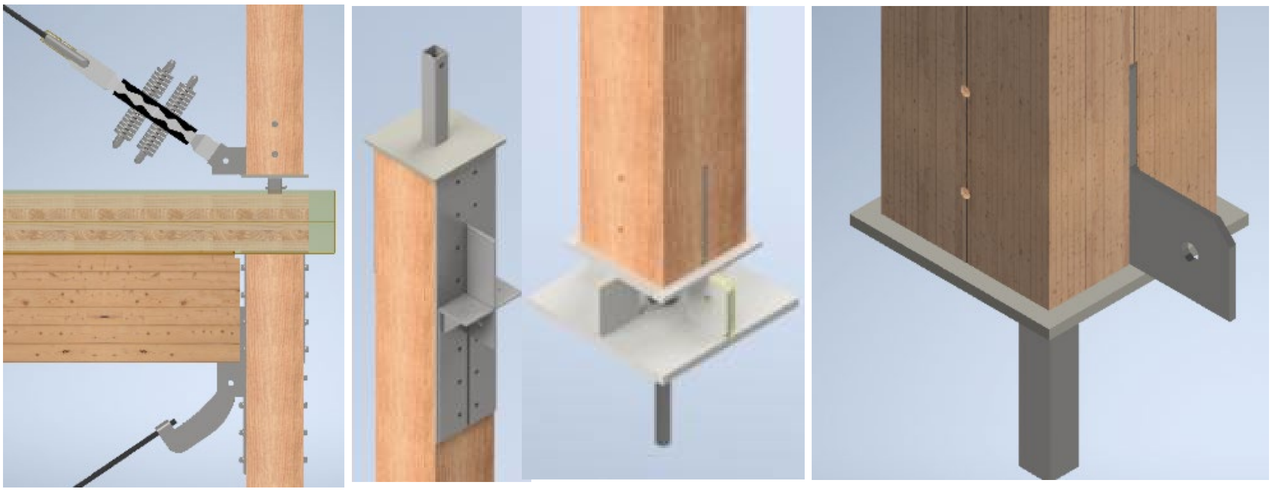

Figure 2 Left to right: Column -column / Column beam/ Column brace connection, Column with Top connector plate, column base connection.

Quasistatic testing is underway, using the FEMA 461 reversed cyclic loading protocol to achieve up to 4% drift. Currently, testing is complete up to 2.5% drift. Dynamic tests, following the ASCE-07 loading protocol, are planned. Researchers are actively seeking collaborations and funding for shake table testing of the setup.

2 CONNECTIONS FOR CLT BUILDING

The connection design for the experimental setup aimed to provide the flexibility needed to test various configurations while simultaneously addressing capacity design requirements, ensuring displacement compatibility, incorporating findings from existing research (Ringhofera, et al., 2018 and Franke & Quenneville, 2011), and complying with relevant code provisions (Eurocode-5, 2008). The structure utilized a combination of bolted connections and inclined self-tapping screws. Column base connections employed knife plates with 12 mm diameter bolts (Figure 2 and Figure 3). A complex connection was designed at the column-to-column interface to transfer forces between columns, from beams to columns, and from the transverse bracing system. This connection also incorporated a mechanism to disengage beam support from the CLT slab selectively and to transfer gravity to four columns and the ledge beam from the CLT wall during later phases of the testing program. The complexity of these requirements led to the selection of external steel-plated connections over a potentially more aesthetically pleasing knife plate arrangement.

Figure 3 Clockwise from top left: Column base connection, Column Beam and brace connection, Rocking shear wall with shear key and rocking toes, Coupling Damper connection between walls

2.1 Self-tapping screws

The capacity design was implemented using overstrength factors (OSF) of 1.35 for the hold-down connections and 1.2 for the friction couplers. Additional screw holes were included to accommodate potential screw withdrawal, but no such withdrawal has been observed up t 2.5% drifts, confirming full displacement compatibility (Figure 3).

The inclined screws were installed using custom-made jigs and welding inclined cut CHS sections to connection plates, resulting in screw angles ranging from 40 to 50 degrees, thereby simulating the variations expected in field conditions.

3 CLT BUILDING TESTING

The structure was subjected to 2.5% drift following the FEMA 461 reversed cyclic loading protocol and subsequently examined for damage. The results indicated that the low-damage design performed as expected, with no damage, screw withdrawal, or movement observed in any connection plate. The connections between the gravity-resisting system and the LLRS exhibited synchronized behaviour, confirming full displacement compatibility. A selection of bolted base plate connections was opened for inspection, revealing no timber crushing.

3.1 Selected of Key Results

The hysteretic behaviour of the structure, which incorporates resilient hold-downs and coupled wall dampers, is presented in this study (Figure 4).

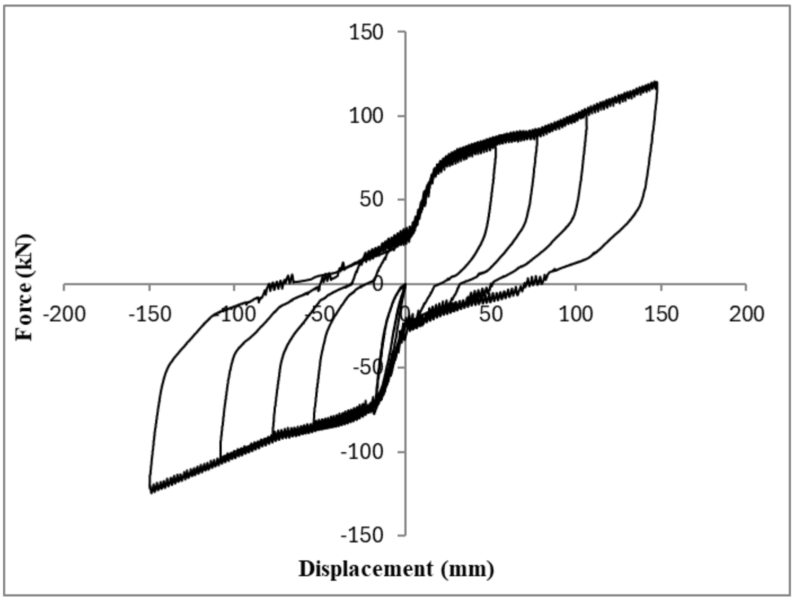

Figure 4 Structure hysteresis for 2 Storey Full scale CLT structure with Coupled rocking wall with conventional friction dampers and Self-centering Hold-downs

The structure achieved a displacement ductility of approximately 7.5. The hysteresis loops demonstrate no noticeable stiffness or strength degradation with repeated cycles, even up to 2.5% drift. Furthermore, the hysteresis plots reveal an increased damped response when the walls were coupled using friction dampers, with damping estimated to be in the range of 25%.

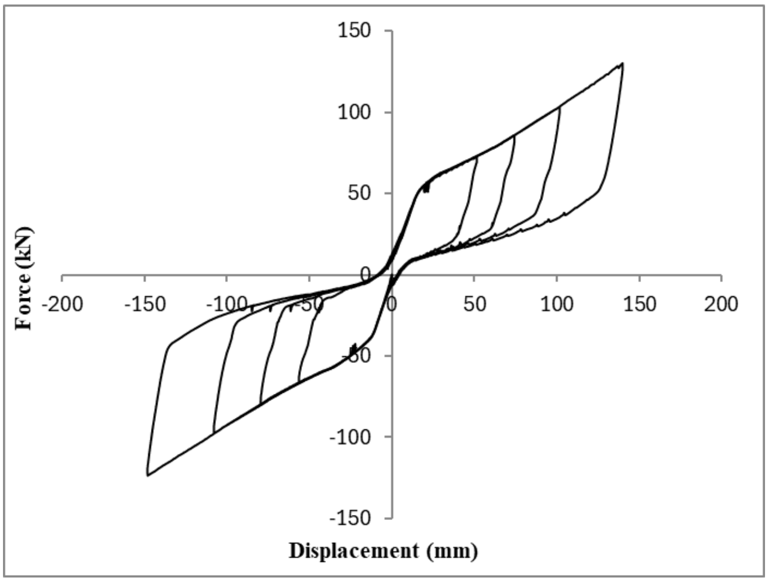

Figure 5 Structure hysteresis for 2 Storey Full-scale CLT structure with self-centering Tension-only Braces.

The structure has been subjected to more than 30 cycles in this phase of testing, demonstrating the repeatability and resilience of the designed system. The hysteresis loops, characterized by low static residual force, suggest a high probability of self-centering. This self-centering capability will be thoroughly investigated in a separate, dedicated study.

The transverse hysteretic behaviour of the structure is also examined in this study (Figure 5). Notably, without the addition of any supplemental friction dampers, the self-centering resilient brace system achieved static self-centering even at high ductility (greater than 7.5). The inherent self-centering mechanisms provided damping in the range of 15-17%, exhibiting full repeatability and no observed damage.

Finally, this study confirms the displacement compatibility between the lateral load-resisting system (LLRS) rocking in one direction and the resilient tension-only bracing system in the orthogonal direction.

More detailed information for the test will be provided as the part of Thesis of the main Author.

4 CONCLUSIONS

This paper presents the preliminary results of an ongoing experimental program that investigates the seismic performance of a two-story, full-scale CLT structure at the University of Auckland. The structure, constructed entirely from CLT, features rocking walls with resilient hold-downs as the primary longitudinal LLRS and tension-only bracing in the transverse direction. The research focuses on the seismic behaviour of the LLRS, its compatibility with the gravity system, and the performance of key connections. Initial testing, conducted up to 2.5% drift following the FEMA 461 reversed cyclic loading protocol, demonstrated the full effectiveness of the low-damage design philosophy. The structure exhibited stable hysteretic behaviour with no signs of stiffness or strength degradation, screw withdrawal, or connection damage. The connections between the gravity system and the LLRS maintained full displacement compatibility.

The results also highlight the potential of resilient rocking CLT walls with friction dampers and self-centering hold-downs for achieving high displacement ductility (exceeding 7.5) and significant levels of supplemental damping (up to 25%). Furthermore, the transverse system, utilizing resilient tension-only braces, also demonstrated excellent performance, achieving high ductility and providing inherent damping in the range of 15-17% without any additional damping devices. The successful integration of the longitudinal and transverse LLRS confirms the feasibility of this structural system for seismic applications.

These initial findings provide valuable insights for the development of seismic design guidelines for resilient mass timber structures and their behaviour factors. The ongoing research, including planned dynamic testing and shake table experiments, will further refine these recommendations and contribute to the broader adoption of sustainable and resilient mass timber construction.

5 ACKNOWLEDGEMENT

This research was conducted at the University of Auckland, and the authors express their sincere gratitude for the use of their state-of-the-art laboratory facilities. The authors would also like to extend their appreciation to the University's staff and technicians for their invaluable assistance and expertise throughout the experimental program. The Wide Trust is gratefully acknowledged for their generous financial support, which made this research possible.

6 REFERENCES

Agarwal, S., Hashemi, A. & Quenneville, P., 2023. *Effect of uncertainties in collapse assessment of coupled CLT walls with energy dissipators as couplers and resilient hold-downs.*. Auckland, New Zealand, New Zealand Society for Earthquake Engineering Annual Technical Conference.

Amer, Alia, S. & Richard, 2023. *Multidirectional Experimental Performance of a Seismically Resilient Self-Centering Cross-Laminated Timber Shear Wall System,* s.l.: s.n.

Amini, M. O., 2018. *Determination of seismic performance factors for cross laminated timber shear wall system based on FEMA P695 methodology.* s.l., Dept. of Civil and Environmental Engineering,Colorado State Univ.

Blomgren, H.-E.et al., 2019. Full-Scale Shake Table Testing of Cross-Laminated Timber Rocking Shear Walls with Replaceable Components. *Journal of Structural Engineering,* 145(10).

Blomgren, H.-E.et al., 2019. Full-Scale Shake Table Testing of Cross-Laminated Timber Rocking Shear Walls with Replaceable Components. *J. Struct. Eng.*.

Ceccotti, A. et al., 2013. SOFIE project—3D shaking table test on a seven storey full-scale cross-laminated timber building. *Earthquake engineering & structural dynamics,* Volume 42(13).

Chan, N. et al., 2020. Pinching-Free Connector for Timber Structures. *Journal of Structural Engineering,* 147(5).

Dowden, et al., 2025. Shake-Table Test of a Seismically Resilient 10-Story Mass Timber Building with Supplemental Uplift Friction Dampers. *J. Struct. Eng,* 151(1).

Dujic, B., Pucelj, J. & Zarnic, R., 2004. *Testing of racking behavior of massive wooden wall panels.* Rotterdam, Netherlands., Proceedings of 37th CIB-W18 Meeting, International Council for Building Research and Innovation.

Eurocode-5, 2008. *Design of timber structures.* Brussels: EUROPEAN COMMITTEE FOR ST ANDARDIZATION.

FEMA P695, .., 2009. *Quantification of Building Seismic Performance Factors.* Redwood City, California, USA, Federal Emergency Management Agency.

FEMA-461, 2007. *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components.* Redwood City California, Federal Emergency Management Agency.

Franke, B. & Quenneville, P., 2011. Numerical Modeling of the Failure Behavior of Dowel Connections in Wood. *Journal of Engineering Mechanics,* 137(3).

Hashemi, A. et al., 2016. *Ductile cross laminated timber (CLT) platform structures with passive damping.* Vienna, Austria, WCTE2016.

Iqbal, A., Pampanin, S., Palermo, A. & Buchanan, A. H., 2015. Experimental performance and structural analysis of plywood-coupled LVL walls. *Journal of Structural Engineering,* p. 142(2).

Lindt, J. W. V. D. et al., 2020. Seismic Performance Factors for Cross-Laminated Timber Shear Wall Systems in the United States. *Journal of Structural Engineering,* 146(9).

Palermo, A., Pampanin, S., Buchanan, A. & Newcombe, M., 2005. *Seismic Design of Multi-Storey Buildings using Laminated Veneer Lumber (LVL).* Taupo, New Zealand, New Zealand Society for Earthquake Engineering.

Pei, et al., 2024. Shake-Table Testing of a Full-Scale 10-Story Resilient Mass Timber Building. *J. Struct. Eng.,,* 150(12).

Pei, S. et al., 2018. *Full-scale shake table test of a two-story mass timber building with resilient rocking walls..* Thessaloniki, Greece, 16th European Conference on Earthquake Engineering.

Pei, S., Lindt, V. d. & J.W., P. M., 2012. Approximate R-Factor for Cross Laminated Walls in Multi-Story Buildings.. *ASCE Journal of Architectural Engineering.*

Popovski, M. & Gavric, I., 2016. Performance of a 2-Story CLT House Subjected to Lateral Loads. *Journal of Structural Engineering,* 142(4).

Popovski, M., Schneider, J. & Schweinsteiger, 2010. *Lateral Load Resistance of Cross-Laminated Wood Panels.* Trento, Italy, Proceedings of World Conference on Timber Engineering, p. 20–24.

Ringhofera, A., Reinhard, B. & Blaßb, H. J., 2018. Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections. *Engineering Structures,* Volume 171, pp. 849-861.

Sarti, F. et al., 2016. Determination of the seismic performance factors for post-tensioned rocking timber wall systems. *EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS,* pp. 181-200.