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FULL-SCALE EXPERIMENTAL TESTING OF A RESILIENT, TWO-STOREY CROSS LAMINATED TIMBER WALL STRUCTURE

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ABSTRACT: Full-scale experimental tests on a two-story Cross-Laminated Timber (CLT) structure are conducted at the University of Auckland, constructed with a focus on low-damage and resiliency concept. The structure's design incorporates innovative wall-to-floor shear keys, among other resilient connections. The performance of the structure is tested in-plane, out-of-plane, and bi-directionally to obtain a realistic assessment of the system. The objective is to demonstrate that the structure can endure significant drifts while maintaining complete displacement and force compatibility, without any damage to the CLT members and without yielding any of the connections and fasteners. The lateral load-resisting system includes two CLT rocking walls (6 meters tall) utilizing spring friction dampers as hold-downs in the longitudinal direction, and tension bracing bars with spring friction dampers in the transverse direction. This paper presents the structural performance and examines the behavior of the innovative shear keys. The results demonstrate that the structure exhibits high levels of ductility and can sustain repeatable cycles without any loss of strength or stiffness. All structural members and connections remain elastic, while the resilient joints provide the required ductility.

KEYWORDS: cross laminated timber, resilience, ductility, rocking wall, self-centring, sustainability

1 INTRODUCTION

As industries worldwide continue to modernize, develop, and adopt innovative methods to advance toward a better future, the civil engineering and construction sectors are no exception. Structural designs are evolving beyond life safety, emphasizing resilience, cost-effective and ductile solutions, sustainability, and strategies to minimize downtime, ultimately aiming for immediate occupancy after events. This trend is even more pronounced in mass timber structures. From their inception in the construction sector, these materials have introduced advantages, including lightweight properties, sustainability, ease of construction, reduction in construction time, rapid and efficient assembly, and adaptability to various lateral load-resisting systems (LLRS). Extensive research and experiments have been conducted worldwide to explore and advance mass timber structures. Studies [1-3] have shown that conventional bracket and fastener connections, along with conventional hold-downs, provide limited ductility and result in extensive yielding and damage, leading to loss of stiffness and brittle failure of timber. This is also followed by relatively high overstrength factors required in the design of such buildings, especially when compared to other construction methods and materials. Experimental research [3, 4] have highlighted displacement incompatibility between walls and floors, while other studies [5-7] have demonstrated rocking-induced toe crushing of timber fibers. Additionally, experimental tests on balloon CLT walls [8, 9] have identified the limitations of current diaphragm connections. This paper presents the experimental testing of a full-scale, resilient, two-story CLT wall structure, with the objective to demonstrate its ability to exceed life safety requirements while achieving high levels of ductility and addressing the existing shortcomings of mass timber structures.

2 FULL-SCALE TWO-STOREY CLT WALL STRUCTURE

The test structure has a footprint of 6 meters in the longitudinal direction and 4 meters in the transverse direction while 6 meters tall, with each storey measuring 3 meters (Figure 1). The structure's LLRS are designed to take care of assumed tributary area of 30m^2. The structure is constructed entirely with CLT. The gravity frame consists of CLT floor panels, CLT beams, and CLT

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columns. Each floor is constructed with two 5-layered CLT floor panels connected together via steel plates and inclined engineered screws, creating rigid diaphragms, with openings in the middle to allow space for the rocking walls. The gravity load path transfers from the CLT panels to the CLT beams and is then carried through the columns to the foundation. The CLT columns extend continuously from the foundation to the top, with joints designed to permit sufficient rotation. This flexibility enables the gravity frame to accommodate the LLRS in all directions, achieving the required drifts while maintaining displacement compatibility. Similarly, small gaps are incorporated at column-beam connections to facilitate gap opening and closing, enabling the frame to accommodate large drifts in the transverse direction. The LLRS consists of two CLT rocking walls (6 meters tall) utilizing spring friction dampers as hold-downs in the longitudinal direction, and tension bracing bars with spring friction dampers in the transverse direction. For this phase of testing, the rocking walls are decoupled. The Resilient Slip Friction Join (RSFJ) [10] are used as the selected spring friction damper for the structure, ensuring resilience and enabling damage-free, repeatable cycles throughout the testing phases. Similarly, RSFJ tension joints are utilized in conjunction with ReidBrace tension braces in the transverse direction. To enhance and optimize damping and energy dissipation, symmetric friction dampers (FD) are installed at wall-to-floor connections to utilize wall uplift and improve overall damping performance. This implementation aims to demonstrate the effectiveness and functionality of the previously proposed system by authors [11]. Innovative shear keys are incorporated into the rocking walls to facilitate safe and synchronized rocking with the sway mechanism of the frame. To prevent toe crushing, steel rocking shoes are installed at the rocking corners.

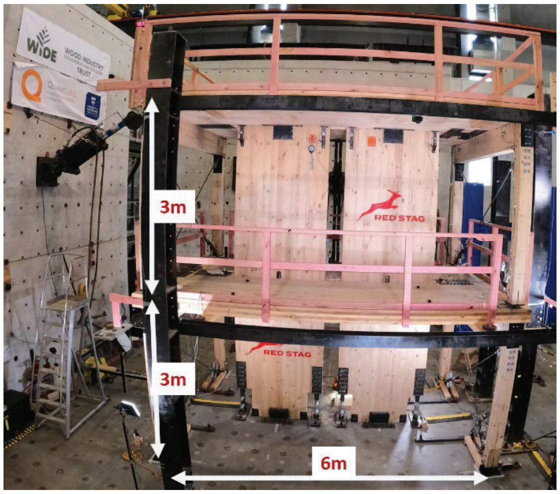

Figure 1a: Full-scale two-story CLT wall structure with resilient rocking walls and resilient tension bracing frame – resilient wall direction.

Figure 1b: Full-scale two-story CLT wall structure with resilient rocking walls and resilient tension bracing frame – resilient tension frame direction.

2.1 RESILIENT ROCKING HOLD-DOWN

The structure utilizes RSFJ hold-downs to provide energy dissipation, self-centering, and allow safe rocking movement of the wall (Figure 2). It functions as the primary energy dissipation device, governing the rocking mechanism and behavior of the CLT rocking walls while also providing self-centering and restoring forces to return the walls to their original position. RSFJ consists of grooved cap plates, grooved middle plates, disk springs and pre-stressed bolts. RSFJ is activated when force demand exceeds the slip force (resisting friction force between clamped plates). It is the friction between the grooved plates that dissipates energy as the cap plates slide onto the middle plates, while the pre-stressed bolts and disk springs are compressed together increasing the friction force required to slide the plates and thus forcing the grooved cap plates to return to their original position, which leads to self-centering behavior.

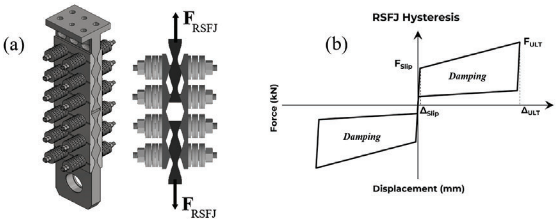

Figure 2: Resilient Slip Friction Joint (RSFJ): (a) hold-down assembly (b) flagged shaped hysteresis.

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2.2 SUPPLEMENTARY FRICTION DAMPER

Additionally, friction dampers are employed at floor levels to take advantage of the uplift and enhance the damping capacity of the structure. The symmetric slip friction joint is composed of sliding steel plates clamped together with bolts, Belleville disks, and nuts (no shims are used). Friction dampers dissipate energy through friction between clamped plates, with the inner steel plate incorporating a slot to facilitate free movement of the outer plates without damage while providing Isotropic loop hysteresis behaviour (see Figure 3).

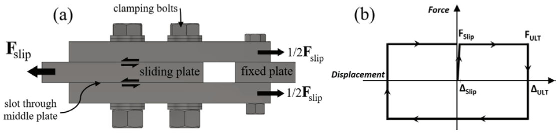

Figure 3: Symmetric slip friction joint: (a) joint assembly (b) idealized joint isotropic hysteresis

2.2 INNOVATIVE SHEAR KEYS

As a crucial component of the structure, innovative shear keys are installed at wall-to-foundation and wall-to-floor connections to facilitate effective shear transfer while accommodating the rocking motion of the CLT walls. Each shear key features profiled slotted holes with pins running through the wall thickness to accommodate controlled movement. Positioned at wall-to-floor, these shear keys ensure the effective transfer of horizontal forces to the walls while maintaining displacement compatibility with the floors. The wall-to-foundation shear key transfers horizontal forces, which originate from the frame and pass through the wall-to-floor shear keys, to the foundation.

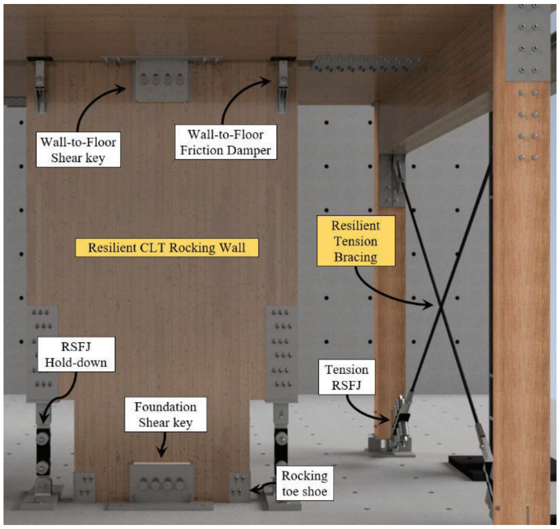

Figure 4: Components of the resilient rocking wall, tension bracing, and shear key locations.

3 TESTING PROTOCOL

This paper demonstrates the quasi-static cyclic testing of the structure which are tested unidirectionally and bidirectionally. The testing protocols are adopted from FEMA 461 section 2.91 for the unidirectional tests and section 2.9.2 for the bidirectional testing. In both unidirectional and bidirectional testing, the structure undergoes a step-by-step increase in induced drift at the end of each cycle, as illustrated in Figure 5. For each unidirectional test (along the direction of the wall and tension bracing), the structure was pushed to a 2.5% drift. During bidirectional testing, the structure was subjected to 2.5% drift in the longitudinal direction (walls) and 1.5% drift in the transverse direction (tension bracing). The structure is instrumented with spring string potentiometers to monitor the global displacement of the structure at all four corners and floors, and linear potentiometers are used to monitor the displacement of hold-downs and friction dampers.

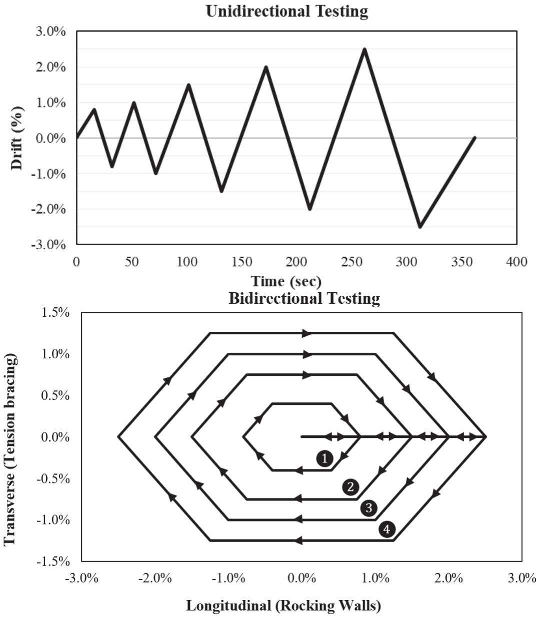

***Figure** 5: Testing protocol for the unidirectional and bidirectional loading.*

4 STRUCTURAL PERFORMANCE

The load-deformation response of the structure demonstrates its repetitive and resilient characteristics. In both loading directions, the structure exhibited repeatable cycles at various induced drift levels without any loss of strength or stiffness (Figure 6). In the rocking wall direction, the shear keys enabled complete force-displacement compatibility between the walls, floors, and the overall frame. The displacement measurements of the hold-downs and wall-to-floor friction dampers closely match, confirming that the shear keys effectively facilitated the free uplift of the wall relative to the floors. Figures 7 and 8 illustrate the rocking wall motion and the transition between push and pull cycles at the foundation level and the second floor, respectively. The structure achieved a ductility factor of $\mu=3$ at approximately the ultimate limit state (ULS) design drift of 1.5% for both LLRS. Following each test, the structure was thoroughly examined for any signs of damage or change. Beyond the test phase presented in this paper, approximately 60 cyclic tests (cycles defined as a complete push and pull round) have been conducted on the structure, with no observed damage to the CLT members, connections, or fasteners. A simple method for monitoring damage in mass timber connections involves marking the outline of the connections. Any fastener yielding or withdrawal would cause a visible shift in the connection relative to the marked lines. Observations confirm that none of the connections exhibited movement beyond these outlines, indicating that the structure successfully achieved its resilience objectives. The connections remained elastic, while the ductility is provided by the resilient hold-downs and friction dampers.

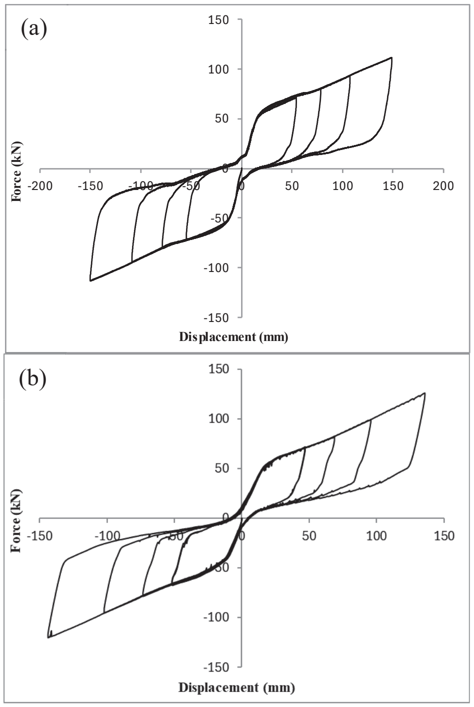

Figure 6: Load deformation response of the structure (a) Resilient CLT rocking walls – longitudinal direction (b) Resilient tension bracing frames – transverse direction

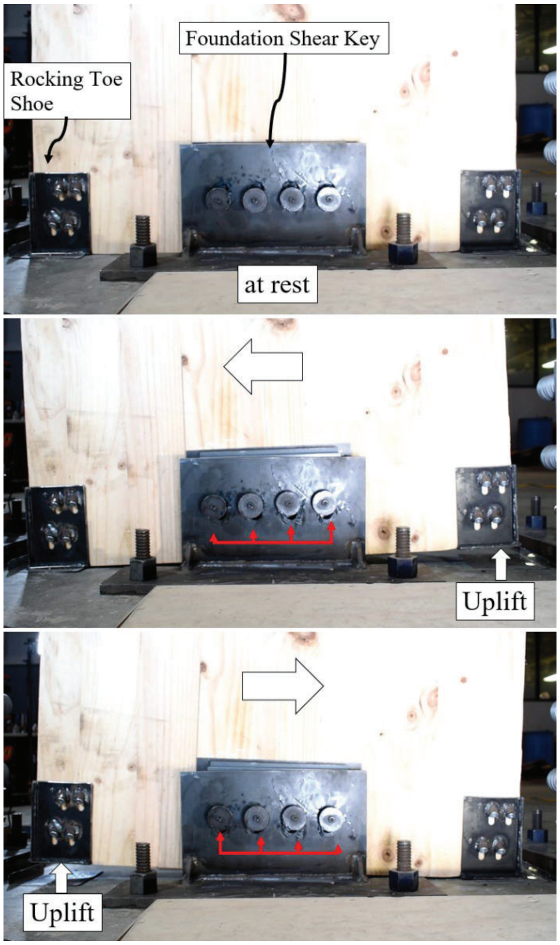

Figure 7. Rocking wall motion and transition between push and pull cycles at foundation level

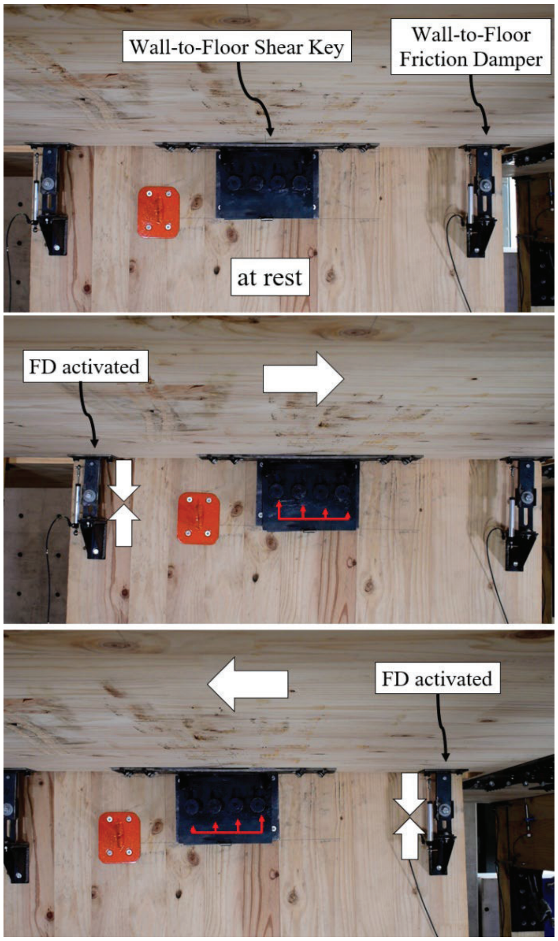

Figure 8. Rocking wall motion and transition between push and pull cycles at second level.

5 CONCLUSIONS

This paper presents the experimental testing of a full-scale resilient, two-story cross laminated timber wall structure. Structures LLRS includes resilient CLT rocking walls in the longitudinal direction and resilient tension bracing frames in the transverse direction. The structure was tested both unidirectionally and bidirectionally, with drift levels reaching 2.5% in both directions. The load-deformation response remained consistent across cycles without any loss of stiffness or strength, demonstrating the structure's resilience and ductility. The connections remained elastic throughout the tests, while the resilient hold-downs and friction dampers effectively provided the required ductility. The innovative shear keys have enabled complete force-displacement compatibility between the rocking walls and the gravity frame, both in-plane and out-of-plane.

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REFERENCES

[1] Ceccotti, A., C. Sandhaas, M. Okabe, et al., *SOFIE project - 3D shaking table test on a seven-storey full-scale cross-laminated timber building.* Earthquake engineering & structural dynamics, 2013. **42**(13): p. 2003-2021.

[2] Gavric, I., M. Fragiacomo, and A. Ceccotti, *Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures.* Materials and structures, 2015. **48**(6): p. 1841-1857.

[3] Popovski, M. and I. Gavric, *Performance of a 2-Story CLT House Subjected to Lateral Loads.* Journal of structural engineering (New York, N.Y.), 2016. **142**(4).

[4] Yasumura, M., K. Kobayashi, M. Okabe, et al., *Full-Scale Tests and Numerical Analysis of Low-Rise CLT Structures under Lateral Loading.* Journal of structural engineering (New York, N.Y.), 2016. **142**(4).

[5] Amer, A., R. Sause, and J. Ricles, *Experimental Response and Damage of SC-CLT Shear Walls under Multidirectional Cyclic Lateral Loading.* Journal of Structural Engineering, 2024. **150**(2): p. 04023215.

[6] Ganey, R., J. Berman, T. Akbas, et al., *Experimental Investigation of Self-Centering Cross-Laminated Timber Walls.* Journal of Structural Engineering, 2017. **143**(10): p. 04017135.

[7] Moroder, D., T. Smith, A. Dunbar, et al., *Seismic testing of post-tensioned Pres-Lam core walls using cross laminated timber.* Engineering structures, 2018. **167**: p. 639-654.

[8] Moroder, D., S. Pampanin, A. Palermo, et al., *Diaphragm Connections in Structures with Rocking Timber Walls.* Structural engineering international : journal of the International Association for Bridge and Structural Engineering (IABSE), 2017. **27**(2): p. 165-174.

[9] Shahnewaz, M., C. Dickof, and T. Tannert, *Seismic Behavior of Balloon Frame CLT Shear Walls with Different Ledgers.* Journal of structural engineering (New York, N.Y.), 2021. **147**(9).

[10] Zarnani, P. and P. Quenneville, *Resilient Slip Friction Joint (Patent)*, N.I. Office, Editor. 2015: New Zealand.

[11] Assadi, S., A. Hashemi, and P. Quenneville, *Innovative High Performance Seismic Resilient Timber Wall Structures with Low Damage Floor Connections*, in *World Conference on Timber Engineering (WCTE 2023)*. 2023: Oslo, Norway.

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