Low damage wall to floor connections for seismic resilient timber structures

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ABSTRACT

Rocking timber walls provide superior seismic performance in comparison with conventional light timber structures. Nevertheless, there is an uplift movement at the base of the wall that is translated as vertical displacement and rotation demands at the floor levels. With current conventional approach, not only floors and connections are prone to damage, but also the rocking movement is compromised. This paper presents a new wall-to-floor and beam-to-floor connection for mass timber wall structures that not only transfer the lateral loads but also dissipates the seismic energy without damage while providing full self-centering. This new system provides few advantages such as increased damping capacity of the system, eliminate bulky and expensive fastener connections, reduce size and capacity of wall hold-downs, and the potential to reduce the size and number of the walls amongst others. A new shear key like system including friction dampers is proposed, to both safely allow wall uplift relative to floor and at the same time dissipate energy.

In order to explore and investigate the benefits and advantages of the aforementioned concept, numerical modelling and dynamic time history analyses of different case studies have been carried out and the results and findings has been discussed. A few key performances of the system include a reduction of drift and seismic base shear, as well as an increase in damping and seismic energy dissipation. This study shows that the system has substantial potential to be further developed and implemented in real structures.

1 INTRODUCTION

Considering mass timber (engineered) elements' advantages over conventional light timber, such as speedy and efficient construction, reduced seismic demands due to their lighter weight, and sustainability, their application in structures has noticeably increased over the past decade. Worldwide over the past decades, structural wall systems have gained an excellent reputation as Lateral Load Resisting Systems (LLRS). One of the easiest and most economical LLRSs to construct are timber walls, furthermore, rocking timber walls provide superior seismic performance compared to conventional light timber and timber shear wall structures. In recent years, Cross Laminated Timber (CLT) rocking walls have gained particular popularity with engineers and researchers due to their reliable and efficient seismic performance. As the wall rocks, there is an uplift movement at its base that is translated into vertical displacements and rotation demands at the floor level. In the current conventional approach, rigid or semi-rigid bracket plates and fasteners are used where not only the floors and connections are susceptible to damage, but also the overall seismic performance of the system is compromised.

CLT walls have been subject of numerous numerical studies and experimental tests in order to understand and study their performance in a variety of configurations (Ceccotti et al. 2013; Gavric et al. 2015a; Hashemi et al. 2018; Popovski and Gavric 2016; Yasumura et al. 2016). Furthermore, extensive research and experimental tests have been conducted to assess the performance and failure modes of the conventional wall-to-floor connections (D'Arenzo et al. 2021; Gavric et al. 2015b; Tomasi and Smith 2015). In accordance with all of these studies, it can be concluded that CLT walls exhibit a reliable behavior, remaining intact with minimal damage, while plasticization and non-linearity occurring locally at the point of connections and fasteners (Figure 1). Moreover, boundary conditions significantly affect the lateral resistance capacity of CLT walls. This includes bottom wall connections, i.e., hold-downs and shear keys, in addition to the connections between walls and floors (diaphragms). A pinching hysteresis and stiffness degradation after each cycle is observed in all experimental and numerical studies using conventional rigid and semi-rigid connections with conventional hold-downs. The pinching hysteresis indicates yield and permanent damage of the rigid or semi-rigid connections and hold-downs, resulting in considerable residual drift and leaving the structure vulnerable to aftershocks. Figure 2 presents a summary of the common failure modes for conventional connections. In experimental tests, damage was repeatedly observed to CLT floor panels due to the displacement incompatibility between the rocking motion and the floor's swaying motion. As such, this is not desirable, nor is it consistent with the objective of seismic resilience and stainability in mass timber structures. Therefore, this paper proposes an innovative wall-to-floor and wall-to-beam system that eliminates bulky rigid connections and allow safe transfer of lateral loads while dissipating seismic energy without damage as well as providing full self-centring.

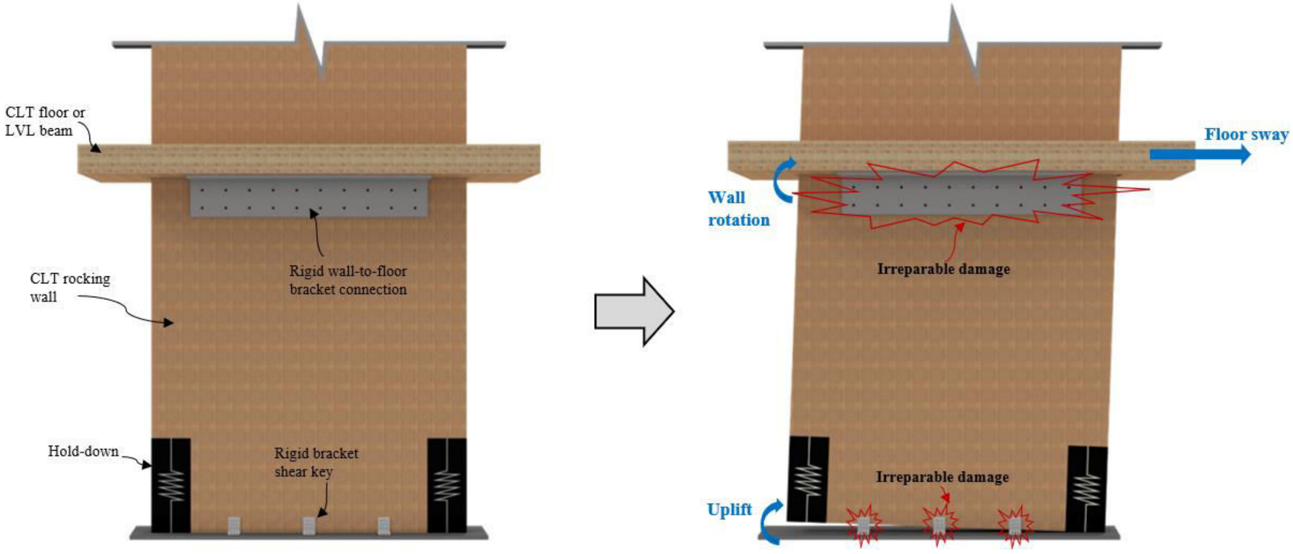


Figure 1. Rocking wall motion and its interaction with the floor and the rigid connection, leading to irreversible and irreparable damage.

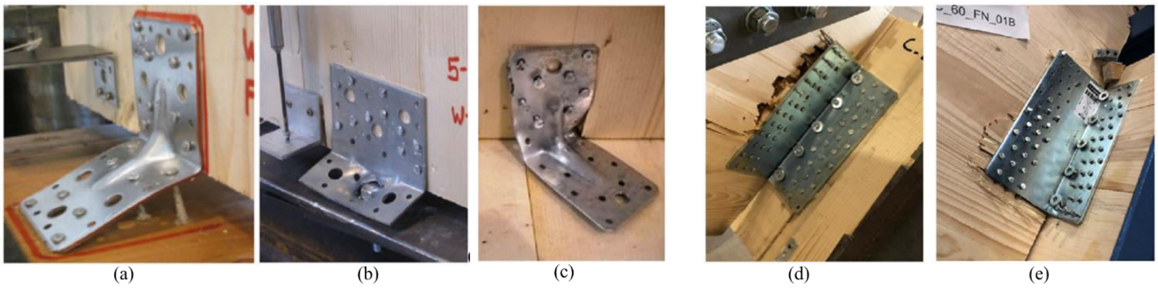


Figure 2. Connection failure modes: (a) fasteners withdrawal, (b) fasteners head pull-through, (c) metal bracket buckling, (d & e) timber panel brittle failure (tearing).

The most recent advances in wall to floor connections are described in (Moroder et al. 2017) where ten concepts for rocking walls have been presented and experimentally tested with post-tensioned LVL walls, followed by experimental testing by (Sause; et al. 2020) with post-tensioned CLT walls. These tests have also revealed that, as expected, there is a substantial influence on overall wall-beam or wall-floor stiffness and strength based on the degree of decoupling between rotational and translational deformations. It was observed that only connections (pin in slotted steel plates) which permitted vertical displacement decoupling could meet the low-damage design (damage free) criteria. According to the authors, friction forces need to be considered due to the design and nature of slotted connections, as sliding would otherwise be prevented.

2 PROPOSED SYSTEM

The proposed concept utilizes flag-shaped friction hold-downs to provide energy dissipation, self-centering, and allow safe rocking movement of the wall. Tests with rocking CLT walls and flag-shaped friction hold-downs have been conducted and demonstrated that these joints provide outstanding seismic performance along with full self-centering characteristics as well as damage-free deformation and ductility for the rocking system (Hashemi 2017; Hashemi et al. 2020). Additionally, friction dampers are employed at floor levels to take advantage of the uplift and enhance the damping capacity of the structure. Friction dampers are derivatives of symmetric slip-friction dampers introduced by (Loo et al. 2014a). This concept also incorporates the innovative shear key by (Hashemi et al. 2018) that is shown to provide adequate shear transfer while accommodating the rocking of the CLT wall. What's more, a similar shear key is proposed at the locations of wall-to-floor to subsequently transfer lateral demands from floor panel (essentially diaphragm) to wall and allow safe and damage free rocking motion. An illustration of the proposed concept is shown in Figure 3.

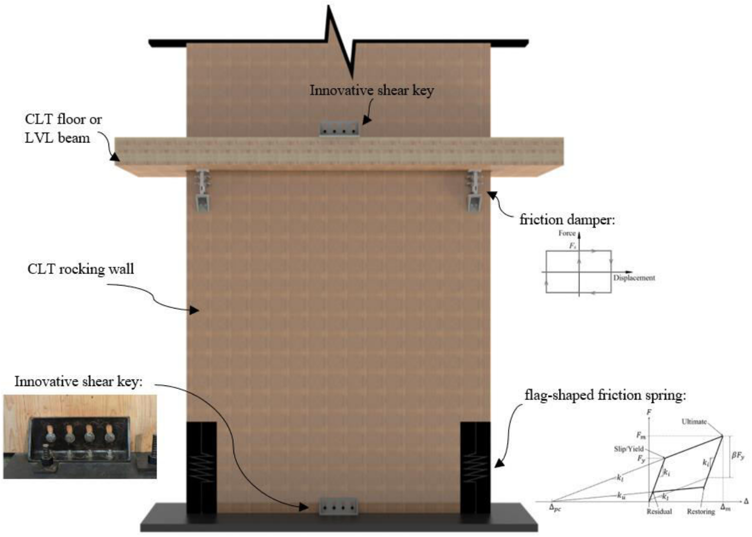
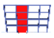


Figure 3. Proposed concept configuration.

3 NUMERICAL MODELING

This study presents a comprehensive assessment of the proposed CLT rocking wall system with innovative low damage floor connections using case study structures with various number of storeys and configurations. Table 1 presents a summary of the case study structures and Figure 4 illustrates the assembly of the largest case study structure (seven storey K7-FD) as an example. As a means of highlighting the benefits of friction dampers, numerical analysis of each case study structure was conducted in two configurations, one with friction dampers at floor levels, the other without. It should be noted that the loading considerations are assumed to be for a commercial structure. While the first-floor measures 4.8 meters in height, all subsequent floors measure an equal 3.8 meters in height. Gravity is completely taken by the LVL gravity frame, hence the rocking CLT wall is decoupled from the gravity load resisting for the purposes of this study. CLT rocking walls are composed of Machine Stress Graded sawn timber with a modulus of elasticity of 8 GPa (MSG8) in the longitudinal direction and MSG6 in the transverse direction. ETABS software (Computers and Structures Inc) is used for the numerical analysis. Effective section properties implemented as per FPI Innovation modelling guide (Chen et al. 2022) and (Karacabeyli and Gagnon) Handbook in the ETABS models, and stress checks were performed to ensure that the stresses were within elastic limits. Hold-downs are modelled using “Damper-friction spring”, friction dampers are modelled using “Multilinear plastic-Isotropic”, and rocking toes are modelled using “Gap” link elements in ETABS. Reiterating the point that the rocking wall is decoupled from the gravity frame system and does not carry any gravitational load, what’s more the shear key (location of load transfer) is located in the center of the wall. Together, these points will contribute to reduce the stress induced to rocking toe and avoid damage to wall fibres. This was also observed in experimental tests conducted by (Hashemi et al. 2018; Loo et al. 2014b). Newmark integration algorithm method (Wilson 1998) is implemented in the models, 2% Rayleigh damping is pivoted at first mode (fundamental mode) for all models, and the mass is always lumped (CSI Analysis Reference Manual). Non-linear pushover analyses are carried out to highlight the key performance characteristics of the proposed systems, followed by dynamic time history analyses that provide a wide range of variables suitable for comprehensive analytical study. For each case study, dynamic time history analyses are conducted by scaling seven ground motion records in accordance with NZS1170.5 guidelines. Since all the case study structures are low to mid-rise buildings and below 15m height, P-delta effects were not considered in this study.

Table 1: Summary of the case study structures.

Case study wall structure:	Configuration, Ki	Number of storeys	Structure height (m)	Number of hold-downs	Number of shear keys	Number of friction dampers
K2 	K2 - FD K2 – R	2	8.6	2	2	4 -
K3 	K3 - FD K3 – R	3	12.4	2	3	6 -
K4 	K4 - FD K4 – R	4	16.2	2	4	8 -
K5 	K5 - FD K5 – R	5	20.0	2	5	10 -
K6 	K6 - FD K6 – R	6	23.8	2	6	12 -
K7 	K7 - FD K7 – R	7	27.6	2	7	14 -

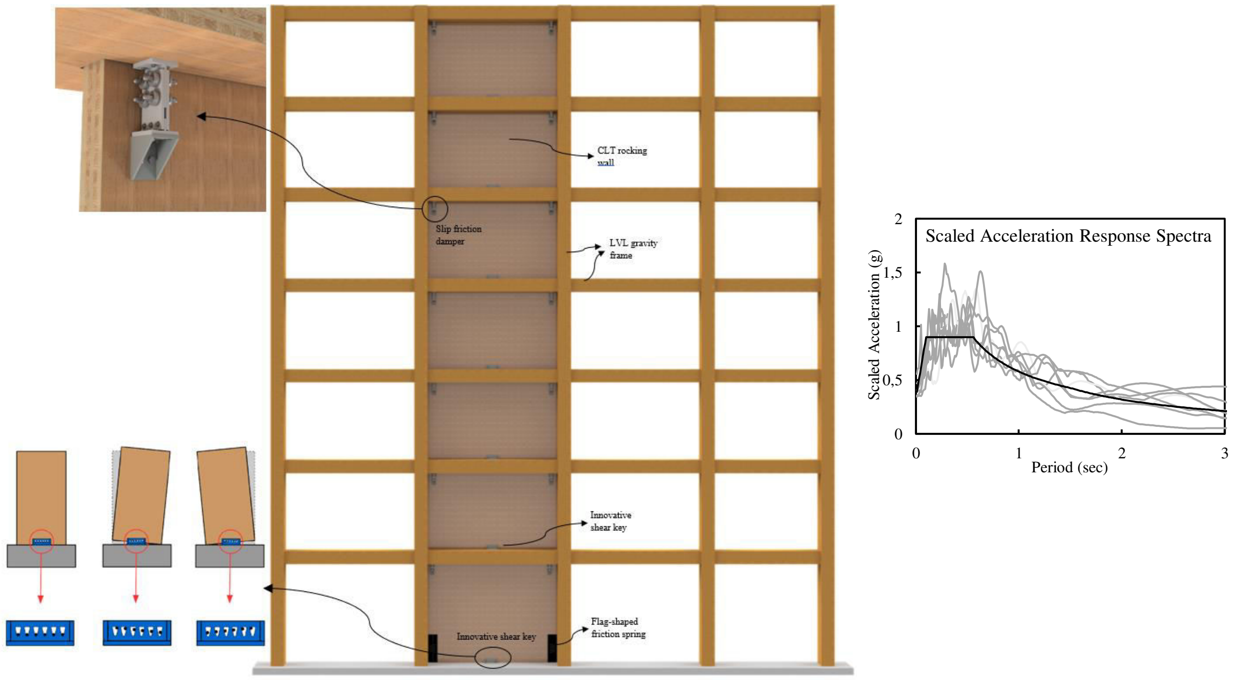


Figure 4. Assembly of the case study structure (seven story K7-FD) and scaled ground motion accelerations.

4 PROPOSED SYSTEM PERFORMANCE

It is appropriate to use non-linear pushover analysis for this study since the case study structures are regular low- to mid-rise structures and the first mode of vibration is the governing mode (fundamental mode) since more than 70% of the structures mass participates in the fundamental mode and fundamental time period does not exceed one second (MBIE 2018). Hysteretic damping ($\xi_{\text{hysteresis}}$) is calculated via Jacobsen's simplified method (hysteresis area) (Chan et al. 2021) with the provided backbone curves from cyclic pushover analyses. In Figure 5, the load-deformation curve (hysteresis) of the system is shown for cases with friction dampers (Ki-FD series) versus cases without friction dampers (Ki-R series). Non-linear pushover results show that hysteretic damping capacity ($\xi_{\text{hysteresis}}$) has increased by 7% on average with the implementation of tuned friction dampers. Increases in damping capacity is correlated with an increase in stories, or in other words, an increase in friction dampers.

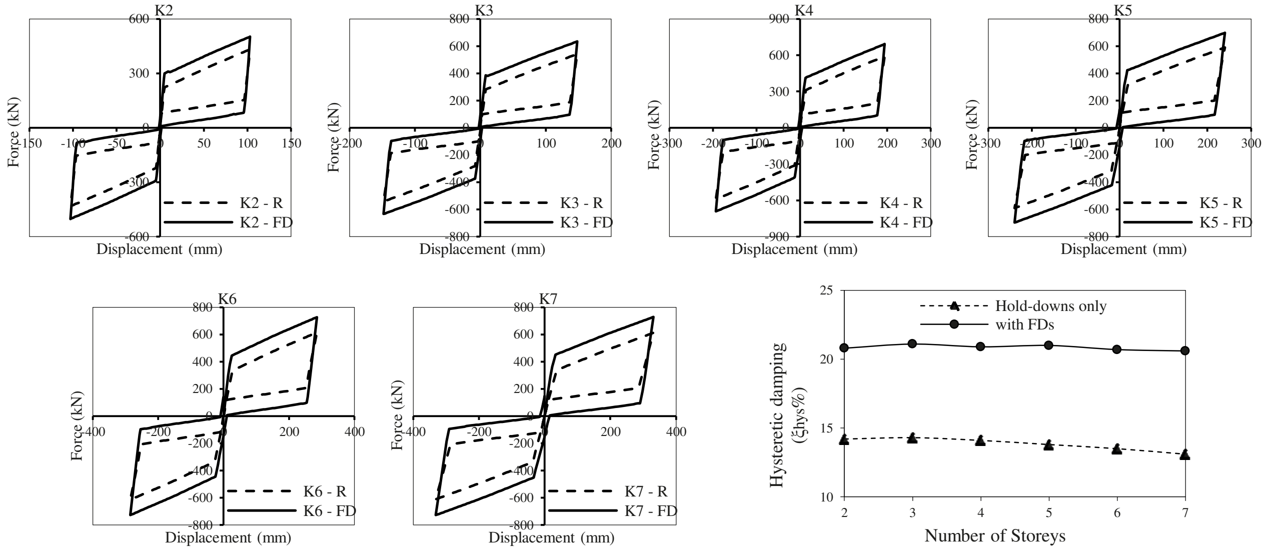
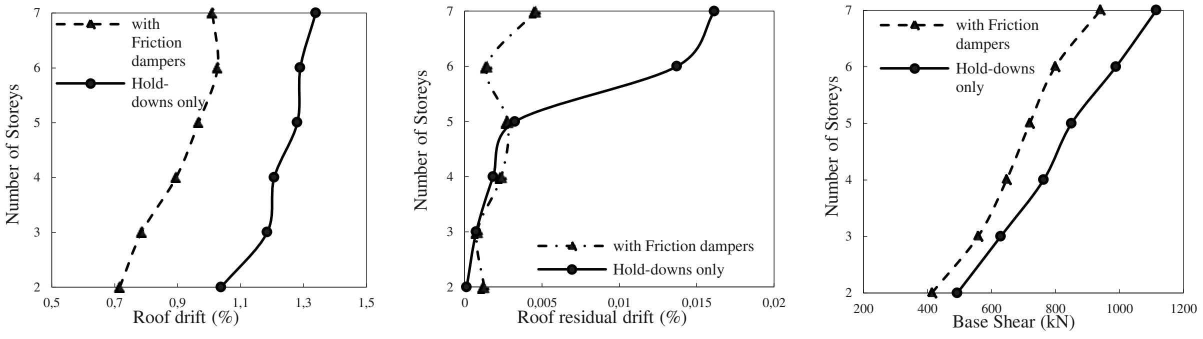


Figure 5. Comparison of system load-deformation curves of cases with and without friction dampers

Dynamic time history offers not only a wide array of variables for this study, but also incorporates all modes of vibration, thereby capturing any dynamic effects that may have been overlooked in nonlinear pushover analysis. For each case study "mean of seven" approach (Bradley 2014) is used as a means of interpreting the results. One of the most noticeable advantages of the proposed system is the reduction in displacement demands on the structure (as an important index). The roof drift of all case study structures is shown in Figure 6-a. The figure illustrates how roof drifts have been significantly reduced by an average of 35%. The greatest reduction in roof drift is about 65%, while the least reduction is about 10%. Based on these results, it is evident that the proposed system is effective in curtailing lateral displacement demands under a variety of cases.



(a) (b) (c)

Figure 6. Performance of the case study structures via dynamic time history analyses: (a) roof drift comparison (b) roof residual drift comparison (c) seismic demand (force) comparison.

Seismic force demands (base shear) have been reduced by about 15% on average. This decrease becomes more significant with taller structures, demonstrating an indication of the potential benefit of the proposed system on mitigating higher mode effects which have been of concern with tall wall structures (Priestley 2003). The residual drift graph can be used to further interpret this influence (Figure 6-b). In all cases, self-centering behavior was achieved, however, the proposed system appears to be more capable of controlling residual drifts, especially for taller walls. This provides further confidence in its likely performance during a major event in which ground motions exceed the design level, developing force and displacement demands exceeding the design levels due to dynamic amplification caused by higher mode effects. All residual drifts fall well under the permissible residual drifts levels suggested by (McCormick et al. 2008) where 0.5% residual drift is a suitable threshold, after which the structure requires repairs to ensure structural soundness.

Consequently, there is a reduction in both the force and displacement demands of the hold-downs, resulting in smaller hold-downs required. The reduction in force and displacement demands of the hold-downs is substantial, where force demand have been significantly reduced by an average of 40%, and displacement demand have been reduced by an average of 25%. Similar to the system, the hold-down force demand reduction becomes more evident with taller structures, validating that the presence of friction dampers helps control lateral demand, enhances lateral force distribution, and mitigates higher mode effects. These reductions entail a considerable decrease in capacity, size and cost of the hold-downs. Figure 7 presents comparison of the hold-down load-deformation (hysteresis) obtained for El Centro (1940) ground motion. Furthermore, it is perceived that by utilizing smaller hold-downs, the stresses induced to critical points of CLT rocking walls can be reduced by approximately 20%. It is therefore possible to reduce the number of layers in the CLT wall or reduce the manufacturing grade of the CLT.

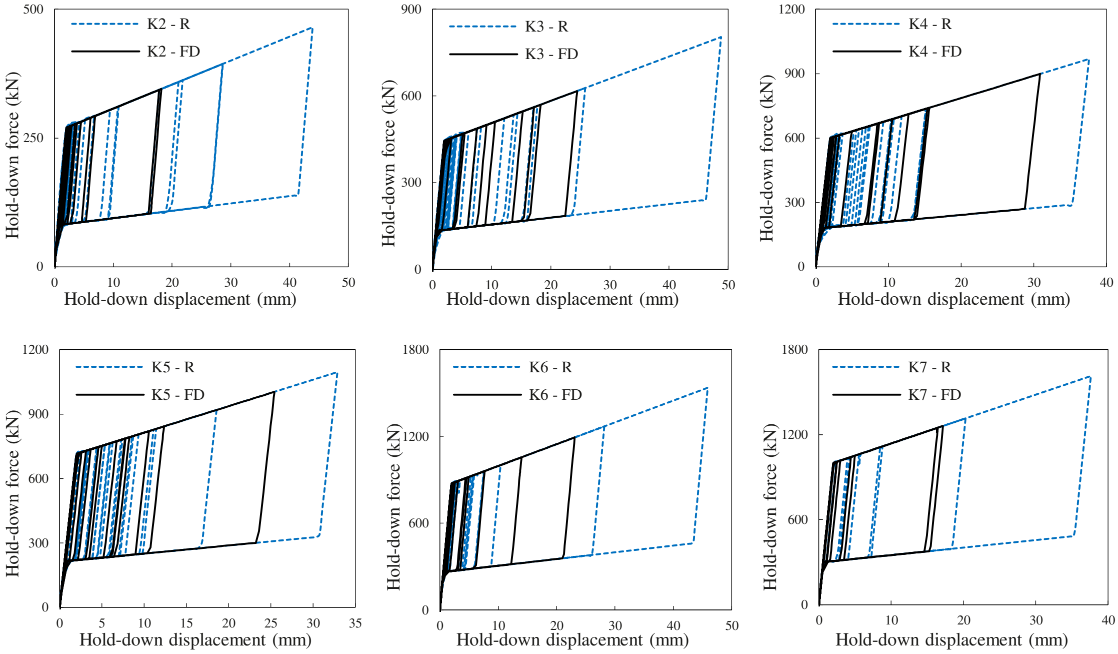


Figure 7. Comparison of critical hold-down load-deformation (hysteresis) of the case study structures for El Centro (1940) ground motion.

5 CONCLUSION

A new wall-to-floor and wall-to-beam system is presented in this paper that eliminates bulky rigid connections and addresses the shortcomings of existing conventional methods. A new shear key-like system, incorporating friction dampers, has been proposed to allow safe wall uplift, while dissipating energy at the same time. A numerical investigation of the proposed concept was conducted by selecting seven case study structures. By implementing friction dampers, the hysteretic damping capacity ($\xi_{\text{hysteresis}}$) has increased by 7% on average. According to the results of dynamic time history analyses, the most notable advantage of the proposed system is the reduction in displacement and force demand by about 35% and 15%, respectively. Furthermore, the force and displacement demand of the hold-downs has reduced noticeably by 40% and 25% respectively, leading to smaller capacity, reduced size, and more affordable hold-downs.

The result is a more economical and cost-effective design as a whole, while delivering a high-performance, competitive solution compared to conventional timber structures. The cost of friction dampers can be offset by eliminating the conventional bracket connections and reducing the number of fasteners. Potential future studies are experimental investigations and analysis of the proposed system in combination of a braced frame to highlight the potential of the proposed concept in dual structural systems.

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7 REFRENCES

Bradley, Brendon A. (2014), 'Seismic performance criteria based on response history analysis: Alternative metrics for practical application in NZ', *Bulletin of the New Zealand Society for Earthquake Engineering*, 47 (3), 224-28.

Ceccotti, Ario, et al. (2013), 'SOFIE project - 3D shaking table test on a seven-storey full-scale cross-laminated timber building: 3d shaking table test on a seven-storey full-scale x-lam building', *Earthquake engineering & structural dynamics,* 42 (13), 2003-21.

Chan, Nicholas, et al. (2021), 'Damping-Ductility Relationships for Flag-Shaped Hysteresis', *Journal of structural engineering (New York, N.Y.),* 147 (7).

Chen, Zhiyong, Tung, Dorian, and Karacabeyli, Erol (2022), *Modelling Guide for Timber Structures* (First Edition edn., Special Publication SP-544; Canada: FPInnovations).

Computers and Structures Inc 'ETABS', (20; Berkeley, California: Computers and Structures, Inc ;).

D'Arenzo, Giuseppe, Seim, Werner, and Fossetti, Marinella (2021), 'Experimental characterization of a biaxial behaviour connector for CLT wall-to-floor connections under different load directions', *Construction & building materials,* 295, 123666.

Gavric, Igor, Fragiacomo, Massimo, and Ceccotti, Ario (2015a), 'Cyclic Behavior of CLT Wall Systems: Experimental Tests and Analytical Prediction Models', *Journal of structural engineering (New York, N.Y.),* 141 (11).

--- (2015b), 'Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures', *Materials and structures,* 48 (6), 1841-57.

Hashemi, Ashkan (2017), 'Seismic resilient multi-story timber structures with passive damping', (University of Auckland).

Hashemi, Ashkan, et al. (2018), 'Experimental Testing of Rocking Cross-Laminated Timber Walls with Resilient Slip Friction Joints', *Journal of structural engineering (New York, N.Y.),* 144 (1).

Hashemi, Ashkan, et al. (2020), 'Enhanced Seismic Performance of Timber Structures Using Resilient Connections: Full-Scale Testing and Design Procedure', *Journal of structural engineering (New York, N.Y.),* 146 (9).

Karacabeyli, Erol and Gagnon, Sylvain *Canadian CLT handbook* (2019 edition. edn., Special publication, SP-532E; Pointe-Claire, QC: FPInnovations).

Loo, Wei Y., Quenneville, Pierre, and Chouw, Nawawi (2014a), 'A new type of symmetric slip-friction connector', *Journal of constructional steel research,* 94, 11-22.

Loo, Wei Y., et al. (2014b), 'Experimental testing of a rocking timber shear wall with slip-friction connectors', *Earthquake engineering & structural dynamics,* 43 (11), 1621-39.

MBIE (2018), 'Engineering Assessment Guidelines, Part C: Seismic assessment of existing buildings, Section C2: Assessment procedures and analysis techniques', in Ministry of Business Innovation and Employment (ed.).

McCormick, Jason, et al. (2008), 'Permissible residual deformation levels for building structures considering both safety and human elements'.

Moroder, Daniel, et al. (2017), 'Diaphragm Connections in Structures with Rocking Timber Walls', *Structural engineering international : journal of the International Association for Bridge and Structural Engineering (IABSE),* 27 (2), 165-74.

Popovski, Marjan and Gavric, Igor (2016), 'Performance of a 2-Story CLT House Subjected to Lateral Loads', *Journal of structural engineering (New York, N.Y.),* 142 (4).

Priestley, M. J. N. (2003), 'Does capacity design do the job? : An examination of higher mode effects in cantilever walls', *Bulletin of the New Zealand Society for Earthquake Engineering,* 36 (4), 276-92.

Sause;, Richard, et al. (2020), ' Multi-directional cyclic testing of cross-laminated timber rocking wall-floor diaphragm sub-assemblies', *17th World Conference on Earthquake Engineering (17WCEE)* (Sendai, Japan).

Tomasi, Roberto and Smith, Ian (2015), 'Experimental Characterization of Monotonic and Cyclic Loading Responses of CLT Panel-To-Foundation Angle Bracket Connections', *Journal of materials in civil engineering,* 27 (6).

Wilson, Edward L. (1998), *Three dimensional static and dynamic analysis of structures : a physical approach with emphasis on earthquake engineering* (2nd edn.; Berkeley, Calif: Computers and Structures Inc.).

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