12th Canadian Conference on Earthquake Engineering / 12ème Conférence canadienne du génie parasismique
June 17-20, 2019 / 17-20 juin 2019
Château Frontenac, Québec, QC.
CCEE 2019

Cyclic Behavior of Self-Centering Mass Timber Wall and Floor System

S.Taban Hajimirza[1], Peter Dusicka[2], Aaron Smith[3], Corey Griffin[4]

[1] Ph.D. Candidate, Dep. of Civil and Environmental Engineering, Portland State University- Portland, OR, USA.
[2] Professor, Dep. of Civil and Building Engineering, Portland State University- Portland, OR, USA.
[3] Graduate Research Assistant, Dep. of Civil and Environmental Engineering, Portland State University- Portland, OR, USA.
[4] Associate Professor, Architecture, Penn State Altoona, PA, USA.

ABSTRACT

In an effort to contribute to the seismic resiliency of mid-rise mass-timber buildings, this paper outlines the concept of a new lateral load structural system that utilizes rocking without relying on post-tensioning for self-centering. Eliminating post-tensioning is desirable in order to limit constant compressive loads on the timber walls, which can contribute to creep, and eliminate a potentially complex aspect of the structural system through the hardware needed to accommodate large localized forces. The structural components of this structural system consist of cross laminated timber shear walls, glulam beams and glulam columns that support the floors. Under strong earthquake motion, the interaction forces between the elastic floors that are connected to the rocking shear walls result in non-linear behavior that exhibits self-centering without the need of introducing external post-tensioning as is common with other rocking low-damage systems. Ductile hold-downs were introduced at the bottom of the rocking wall to increase the hysteretic damping of the system. By focusing on a single-story response, this paper outlines the mechanics of the lateral system, summarizes the results from system-level nonlinear numerical analyses and presents preliminary results from full-scale cyclic laboratory experiments. The experimental results validate the behavior exhibited by the numerical models and demonstrate the potential for low-damage self-centering.

Keywords: Mass Timber, Rocking Walls, Self-Centering, Full-Scale Cyclic Experiments, Lateral Structural System

INTRODUCTION

Metropolitan areas have demonstrated consistent population growth within the last few decades [1]. The growing trend of urbanization over the coming years has unfolded the demand for fast and sustainable construction. To satisfy this demand, implementation of mass timber structures in mid to high-rises buildings has come under spotlight as one possible solution. To address seismic resiliency of mass-timber buildings, a new concept is introduced for low-damage self-centering structural system referred to as the **L**ow-Damage **F**loor **R**e-Centering **C**ore (LFRC). This structural system utilizes the interaction forces between the floor and the rocking shear-walls to deliver re-centering mechanism. LFRC does not rely on post-tensioning forces, which can be desirable in order to limit excessive compressive loads on the timber walls and thereby reduce creep in the walls. This can also potentially eliminate an expensive aspect of the structural system through the associated post-tensioning hardware and accommodation of large localized forces.

The proposed lateral load resisting system is aimed for mid-rise to high-rise commercial and mixed-use core buildings made from mass timber. The structural components of the LFRC building consist of cross-laminated timber (CLT) shear walls as the lateral core, glulam beams and columns that support the gravity loads via CLT floors, and ductile hold-downs, connected to the wall heel and toe, to dissipate hysteresis energy. This paper outlines the mechanics of the proposed LFRC system and demonstrate that the behavior of the structural system through results from conducted large-scale cyclic tests and nonlinear numerical analysis.

RESEARCH BACKGROUND

Despite recent research efforts, design professionals continue to encounter significant knowledge gaps to cost effectively and confidently implement a mass timber structural system for tall buildings in areas of high seismicity. With roots in Europe [2, 3, 4, 5] and Canada [6] various projects had evaluated lateral cyclic and shake table seismic performance of CLT walls and mass-timber structural systems. The investigated lateral load structural systems mainly consisted of inter-story shear walls on top of floor diaphragms, with panels connected with steel brackets and fasteners. The resulting failure modes and observed ductility relied on the deformation capacities of the fasteners and brackets, resulting in significant damage at the connections. These efforts demonstrated that despite the reported satisfactory ductility, relying on permanent-inelastic damage of the bracket connections would not be suitable for achieving an overall seismic resiliency for the associated structures.

The most promising option proposed to achieve seismic resiliency of mass timber structures has been investigated via pots-tensioned (PT) self-centering rocking shear wall systems. Basis of past research on self-centering PT rocking systems was adopted from pioneering research on precast reinforced concrete in the PRESSS program [7, 8, 9]. For use in wood structures, post-tensioning and rocking of structural components made from laminated veneer lumber, LVL was pursued in New Zealand as a seismically resilient system [10, 11, 12]. Extended research adopted similar concepts in utilizing PT and rocking to achieve self-centering for multistory PT rocking timber shear-wall configurations [13, 14]. Those studies achieved high level of seismic performance via low damage states by directing inelastic deformation to internal or external energy dissipaters and minimizing residual drifts through PT self-centering. Results from experimental and numerical analysis corroborated that lateral-load response of low-damage PT self-centering walls, as a hybrid system, exhibits energy dissipation and self-centering capability. The results verified that hybrid system could provide adequate deformation capacity to be used as a primary lateral load resisting system of multistory buildings in regions of high seismicity.

Although the recent research efforts confirmed satisfactory performance of mass-timber PT self-centering rocking-walls, challenges remain for adopting post-tensioning through implementation of a self-centering mechanism. Factors such as creep, and thermal and relative-humidity variation causes timber to be exposed to dimensional variations which leads to post-tensioning losses [13]. CLT more so than other engineered wood products can exhibit significant creep due to the effects of orthogonal arrangements of layers and structural adhesive [15].Furthermore, careful detailing of the post-tensioning anchorage system is crucial to avoid localized plasticity, which can result in a reduction of the PT forces causing a decrease in the system capacity [16]. Therefore, PT losses, accommodation of large localized forces, and potential expensive aspect of the structural system through the associated post-tensioning makes high levels of PT in mass timber wall less desirable.

RESEARCH OBJECTIVE

The objective of the overall research was to introduce and demonstrate the possibility of a system mechanism that does not rely on post-tensioning to provide post-earthquake self-centering characteristics. The focus was to show that LFRC takes advantage of the wall-to-floor interaction for assisting with re-centering, helping to eliminate the needs for PT. Under strong earthquake motion, the interaction between the elastic floor result in non-linear behavior that exhibits self-centering. Ductile hold-down can also be connected to the bottom of the wall to increase the effective damping. This structural system aims for overall low damage and rapid return to occupancy for the design level earthquake event. This paper outlines the overall mechanics of the LFRC system under lateral earthquake loading and summarizes the system-level nonlinear numerical analyses and full-scale cyclic laboratory experiments.

MECHANICS OF SYSTEM LEVEL PERFORMANCE

The approach proposed by this research is grounded on utilization of a combination of floor dead loads and elastic forces, which are generated due to out of plane stiffness of the floors, as restoring forces to provide self-centering mechanism in rocking wall structural systems. The floor provides the elastic stiffness and the dead load at each floor contribute to re-centering. The mechanics of the structural behavior of LRFC is illustrated in Figure 1. Floors are isolated from the wall except for lateral load transfer points, referred to as Lateral Transfer Supports, LTS, and vertical load bearing brackets, referred to as Gravity Supports, GSs. LTS and GS are positioned at the center of each floor level. At each level, a continuous floor, designed as a one-way beam, spans on either side of the wall between columns separated by distance L. The floor remains isolated around the wall, minimizing floor damage that would otherwise be expected from monolithic construction.

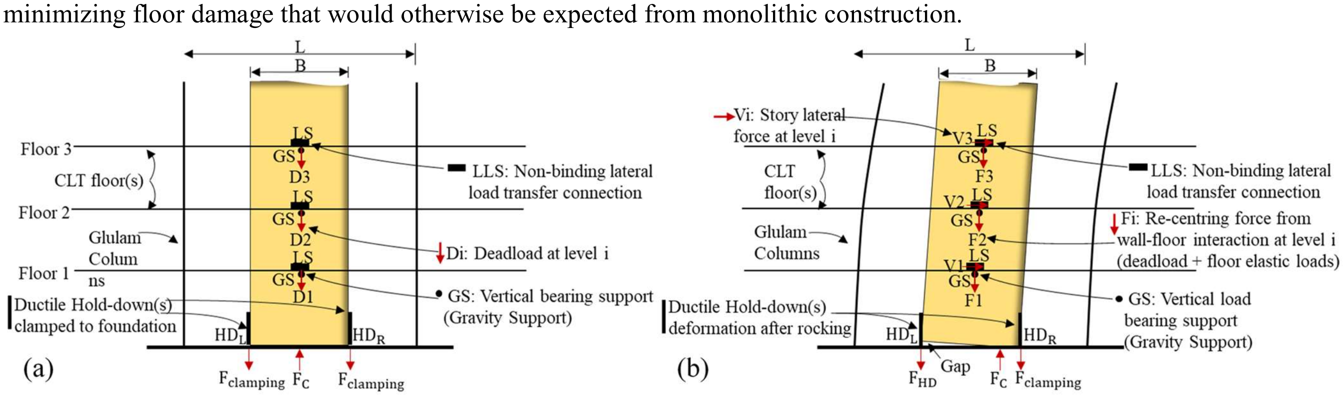


Figure 1. System Level Mechanics (a) Core loads: Dead Load Case (b) Core Loads: Re-Centering + Earthquake Case

The wall holds the GSs, which bear the vertical loads transferred form continuous floor. The GS decrease the clear span of the floor for the wall-floor interaction and, as will be explained, provide the restoring action when subjected to earthquake forces. When just gravity loads are applied, shown in Figure 1(a), the beam imposes dead load(s), D^i, onto the wall at each floor level.

The contact force, F_C, is resultant of the compressive stress between the wall and the foundation in form of the base compression force. $F_C$is the sum of all of the dead loads acting on the gravity supports and the hold-down clamping loads, F_{CHD}, applied on the wall bottom-edges at the toe and heel. The combination of the gravity and clamping loads can be used as a design condition to prevent the hold-downs from yielding under the wind load combination cases.

Under earthquake loads, Figure 1(b), the floor imposes lateral load , V^i, at each floor level that in turn cause overturning on the wall. The load can be transferred near the center of the wall where the relative vertical movements are the lowest. The total shear force at the base is denoted as, V. For design level earthquakes, the hold-downs at the base of the wall yield upon rocking and provide hysteresis energy dissipation. Additional hold-downs between the isolated wall and the floor could be introduced to further supplement the damping at each floor level for higher mode response. The force in the hold-down , F_{HD}, will be governed by the yield strength and by the cyclic hardening characteristics. As the wall elastically deforms and rocks, vertical displacements are created along the length of the wall, B, at each floor level. Since the GSs are in bearing, after certain performance level, the supports engage the floors due to the system uplift. The floors become an elastic vertical spring. The floor stiffness can be engineered based on the cross-sectional properties and the length of the continuous spanning, L, between the columns. The elastic floor forces combined with the dead loads provides the interaction forces, F^i , on the GSs, resulting in restoring moment and self-centering mechanism. Since the GSs are in bearing only, relative wall rotation to the floor can be accommodated and the damage to the floor caused by the uplift is expected to be minimal. The floor can be designed to keep the wall deformations within the elastic range. This is in part made practical due to the long span length, L, between the columns.

The potential exists for low-damage re-centering without the use of PT is presented in Figure 2. Combination of the re-centering mechanism and the hysteresis energy dissipation, as shown in Figure 2(a) and Figure 2(b) respectively, provide the flag-shape low-damage self-centering response which is illustrated in Figure 2(c). This system can exhibit several advantages over other rocking wall implementations. These advantages include: **i)** The wall-floor interaction forces can be utilized for self-centering, which is not the case in rocking systems that isolate the floor from the wall. The interaction diminishes the need for external re-centering stiffness, which could eliminate a potentially expensive aspect of the structural system associated with post-tensioning hardware. **ii)** Unlike PT systems that provide a constant load throughout the height leading to the creep effect on the CLT panels and accommodation of large localized forces [16].The restoring forces in LFRC structures, shown in Figure 3(b), are distributed along the height of the wall by the internal axial load distribution. This shape of the internal load distribution can reduce the creep effect. **iii)** While the floor imposes uplift on the columns, the tensile internal loads offset the compressive internal dead loads in the columns as presented in Figure 3(c). Thus, the seismic response of the system does not impose additional compressive loads on the columns.

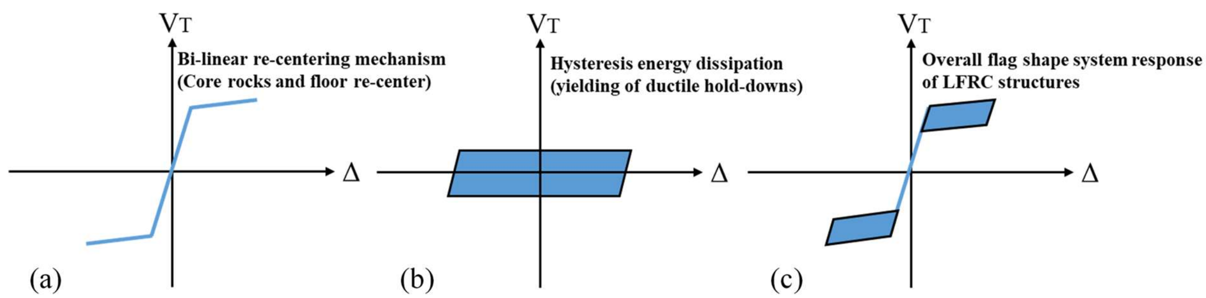


Figure 2. System Response (a) Re-centering mechanism (b) Hysteresis energy dissipation (c) Overall LFRC system response

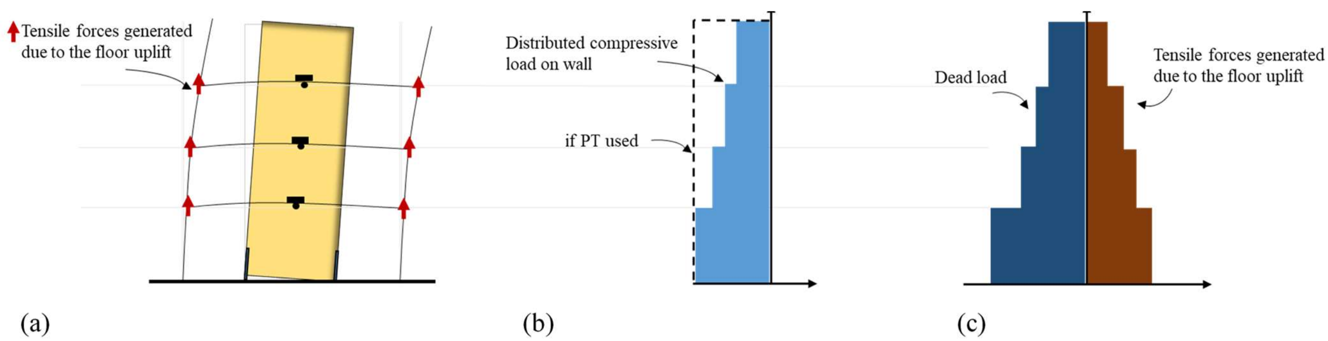


Figure 3. Internal Load Distribution (a) Schematic of the structure deformation (b) Core axial load (c) Column axial load

NONLINEAR NUMERICAL ANALYSIS

Finite-element nonlinear numerical analysis was performed for a two-dimensional (2D) single-panel one-story LFRC. The model was developed in OpenSees [17, 18].Exploratory analysis was performed to demonstrate the potential of the structural system to achieve low-damage self-centering mechanism. The geometry and schematic sketch of the numerical model, presenting the system configuration and details of the structural components, are shown in Figure 4(a) and Figure 4(b) respectively.

The wall is modeled using an elastic Timoshenko beam-column element to incorporate in-plane flexural and shear deformations. To prevent slipping, the bottom node of the wall beam-column element is fixed in the lateral transitional direction of X. The base-shear is measured equal to the lateral reaction at the wall bottom node. The floor and the columns are modeled as beam-column elements and the joint-nodes between the floor and the columns are set as pin connection. The connection of the columns at the foundation level is set to pinned joint through releasing rotational directions and fixing the transitional directions of X and Y.

The top node of the wall is coupled in lateral transitional direction to the mid-span of the floor for modeling the lateral force transfer support. Thus, the story shear is transferred through equal lateral degree of freedoms from the floor level between the floor mid-span node, which is determined as a master node, and the wall top node assigned as a slave node. The floor-wall gravity-support, which is in bearing only and transfer the floor vertical loads and accommodate floor elastic bending deformation, is modeled as compression-only zero-length springs. One side of the gravity-support spring is coupled with the top node of the wall and the other side is connected to the floor center.

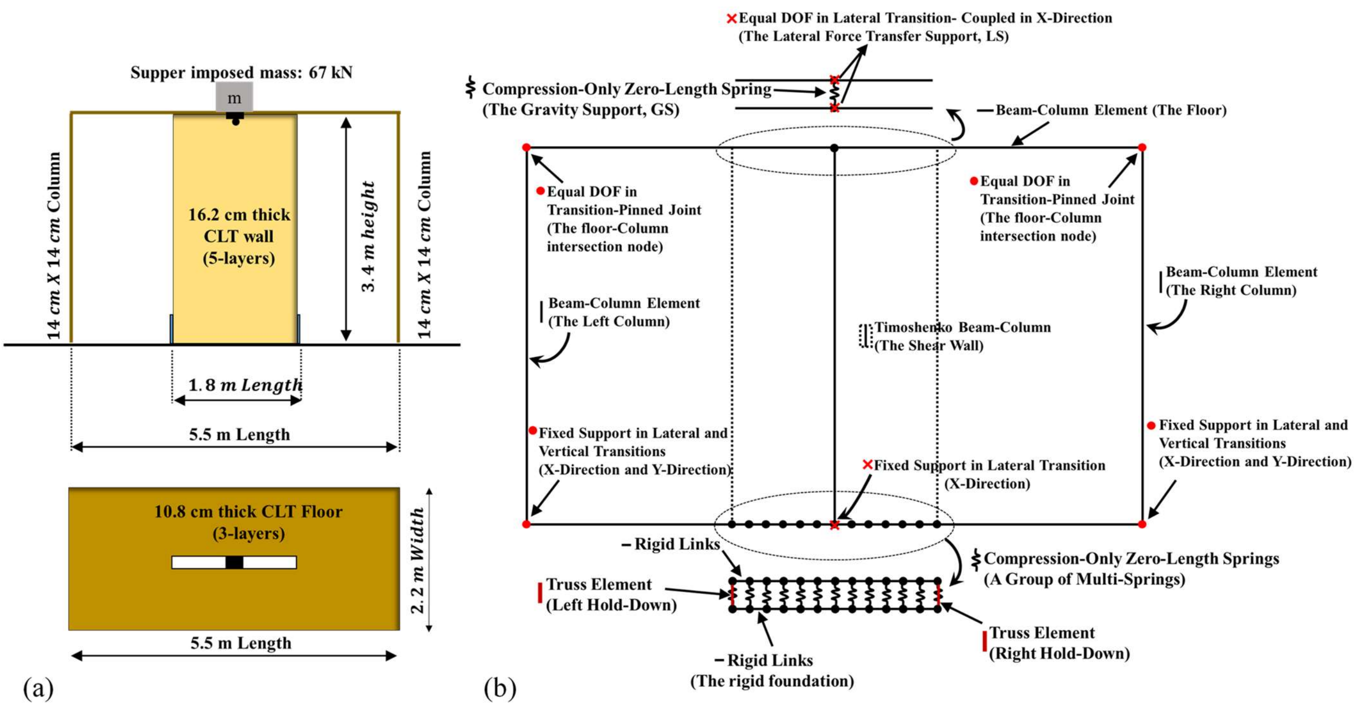


Figure 4. LFRC example for numerical analysis (a) The geometry of the model (b) Numerical model of the system

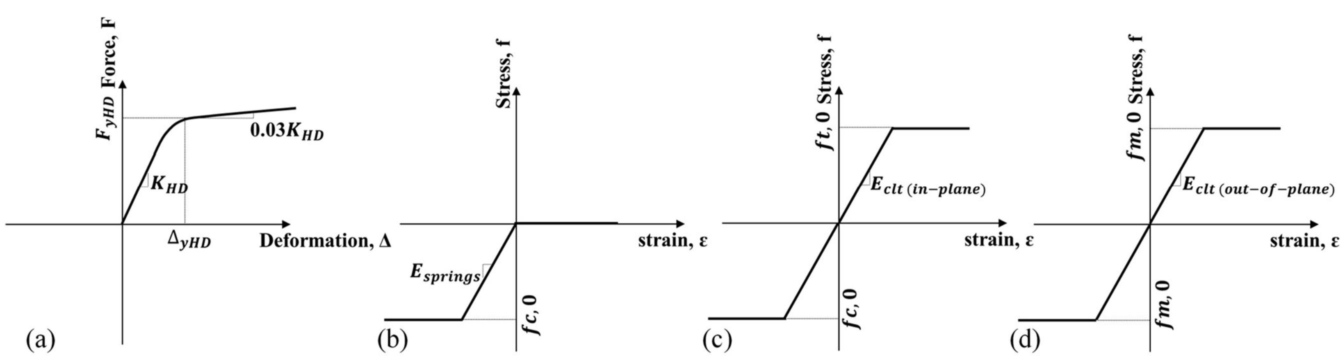


Figure 5. Material behavior of structural elements a) Hold-Downs b) Compression-only Zero Length Springs c) CLT wall in-plane loading action d) CLT floor out-of-plane loading action

Material behavior of the structural components are presented in Figure 5. The nonlinearity and crushing of the wall at base is neglected as the width of the wall at toe, with the maximum compression stresses during the rocking, will be designed to be extended by steel plate boots. The steel plate boots increase the wall-base compression area and the wall is engineered to be remained elastic. The wall is modeled as elastic perfectly plastic material.

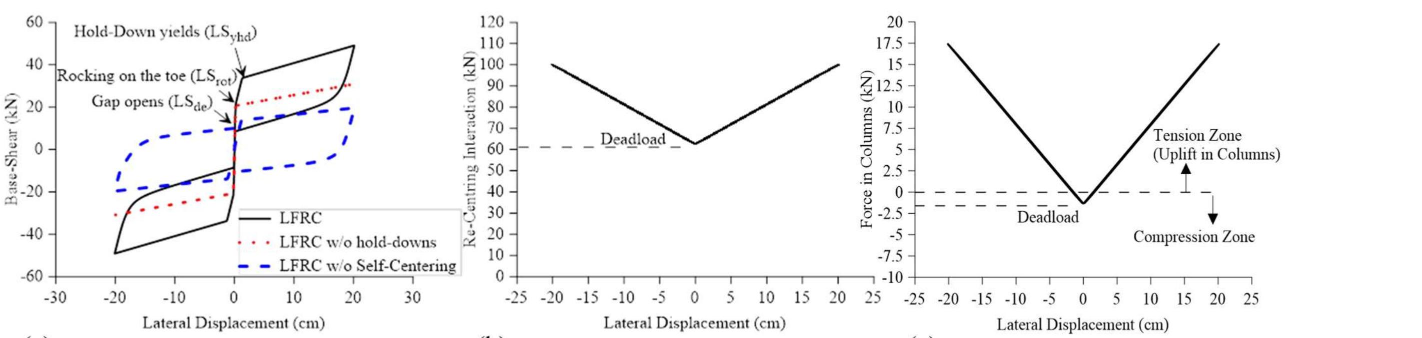
As noted in Table 1, the wall mechanical properties including compressive strength , for in-plane loading actions and parallel to the grain, f_c, 0, modulus of elasticity , $E_{Clt(in-plane)}$, and shear modulus,, $G_{Clt(in-plane)}$, were set to values recommended by the CLT manufacturer. The floor the value of bending strength, , f_m, 0, modulus of elasticity, $E_{Clt(in-plane)}$, and shear modulus, , $G_{Clt(out-of-plane)}$, were also defined based the manufacturer recommended values for out-of-plane loading action, generated due to the reaction forces via the wall uplift mechanism. The columns' material was defined as glue laminated timber with the properties recommended in NDS.

Stiffness of the group of springs are set to zero in tension simulating the gap-opening performance. The stiffness of the springs in compression was defined as the same as the CLT-wall stiffness to provide identical uniaxial compressive elastic behavior at the wall base. As the Gravity-Support, GS, spring at the floor level is in bearing only, the GS spring is defined as compression only zero-tension element with compressive stiffness as the same as the CLT-wall. The hold-downs were modeled as Steel02 material with stiffness, strength, and post-yielding stiffness equaled to K_{HD} and , F_{yHD}, and $0.03K_{HD}$ respectively. The values of material properties of the hold-downs were estimated through conducting material testing.

The numerical result for cyclic Pushover curves, including LFRC response, the system elastic response without hold-downs, and the system response with hold-downs but without re-centering, are shown in Figure 6(a). The flag shaped system behavior illustrates the viability of achieving seismic resiliency through combination of the low-damage and self-centering mechanism. Limit states are highlighted in the system response. The first limit state, LS_{de}, corresponded to decompression of the wall at heel. At this limit state, the system starts to rock, and the gap opens between the wall and the foundation. The second limit state, , LS_{rot}, occurs when the wall uplift shows nonlinear geometric behavior. The contact between the wall and foundation transfer to small length at the base and ultimately the contact surface limits to the wall toe **[14]** Finally, the third limit state, LS_{yhd}, takes place when the hold-down yields due to the tensile deformation at the heel and dissipate energy through plasticity.

Table 1. Material properties of the model elements

Elements	**Modulus of Elasticity Compressive (E_c)**	**Modulus of Elasticity Tensile (E_t)**	**Shear Modulus (G)**	**Strength (f)**
CLT Wall In-plane action	12,000 N/mm^2	12,000 N/mm^2	250 N/mm^2	30 N/mm^2 Compressive
CLT Floor Out-of-plane action	12,000 N/mm^2	12,000 N/mm^2	690 N/mm^2	24 N/mm^2 Bending
Zero-Length Springs Compression only element	12,000 N/mm^2	-	-	30 N/mm^2 Compressive
Elements	**Effective Stiffness-K_{HD}**	**Post-Yielding Stiffness**	**Yielding Force- F_{yHD}**	
Ductile Hold-Down Truss (Unit of Area and Length)	3944 N/mm	118 N/mm	23 kN	



(a) (b) (c)

Figure 6. Results from cyclic numerical analysis a) Base-shear vs drift b) Floor Re-centering Interaction vs drift c) Force in Columns vs drift

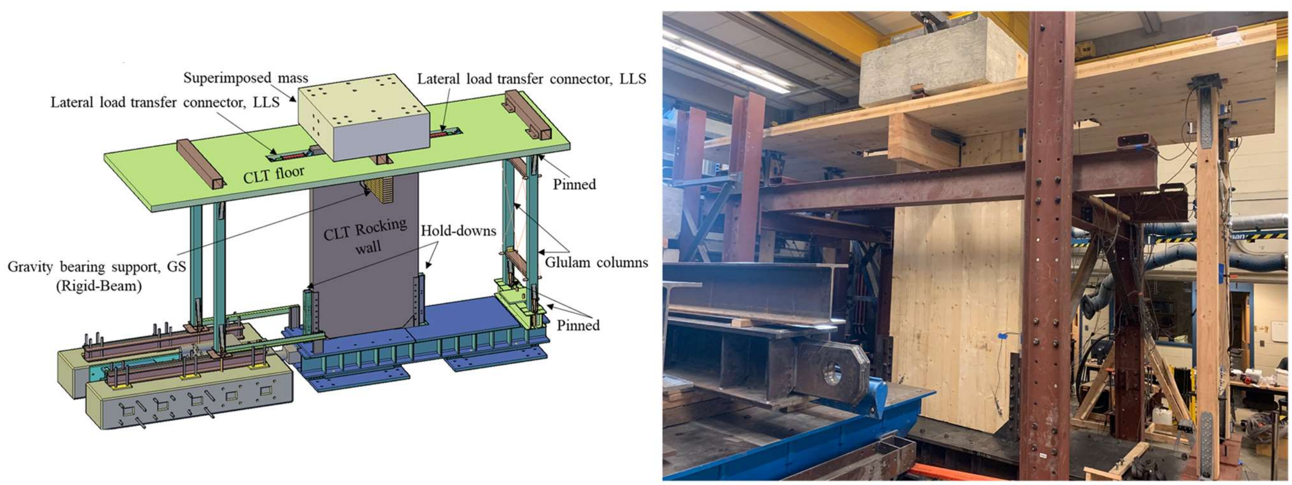
The floor-wall interaction force versus lateral displacement is presented in Figure 6(b). The value of the interaction at any particular displacement equals to combination of the dead load and the elastic force generated due to the floor deformation. When the lateral displacement is zero, the only the dead load is transferred. By increasing the lateral displacement, the interaction force increases as a result of the resistance to the system uplift. The slop of the lines in the plot is correlated to the effect of the floor stiffness on the system behavior. This effect, or the slop of the lines, can be engineered based on the cross-sectional properties and the length of the floor spanning. Theoretically, at the lowest extreme level, when the floor is extremely soft in relative to the wall, the re-centering interaction is just limited to the dead load and the floor stiffness, consequently the slop of the lines, leans toward zero. At the highest extreme level, when the floor is theoretically rigid in bending actions, the re-centering interaction and the slop of the line is infinite leading to zero uplift and lateral displacement for an elastic system.

Force in each column vs lateral displacement is plotted in Figure 6(c). At zero drift the column is in compression due to the dead load. By increasing the lateral displacement, the floor imposes uplift on the columns and after certain response level, the columns internal forces transfer from compression zone toward tension zone. As noted before, this behavior can be considered one of the advantages of the system because the tensile internal loads offset the compressive internal dead loads in the columns and the seismic response does not impose additional compressive loads on the columns.

EXPERIMENTAL SET-UP

Layout and photo of the test specimen, consisted of a single bay one story portion of the structural system, is shown in Figure 7. The specimen geometry, dimensions and component properties were designed as the same as the numerical model shown in Figure 4(a). The 5-layer and 3-layer CLT panels were used as the wall and the floor panels respectively. Four glulam columns with cross section of 14cm X 14cm were installed to support the CLT floor. The columns were connected via pinned connections at the both foundation and floor levels. A rigid beam, utilized as the gravity-support, GS, with cross-section of 46 cm X 15 cm were arranged in center of the floor to provide a load path to the wall. The beam was designed to transfer the re-centering interaction as well as to remain elastic when the system is subjected to lateral forces. Shear-support connectors, as lateral load support, LLS, were built and assembled to transfer the lateral loads from the floor to the wall. A mass block with size of 1.52 m X 1.52 m and weight of 67 kN were placed on the CLT floor slab to simulate the dead load. A lateral support frame was designed to provide out-of-plane resistance for the wall.

Steel plate boots were bolted to the wall edges, at foundation level, to prevent crushing of the toe throughout rocking mechanism. The boots were not connected to the foundation and free to uplift with the system. Slip of the wall was prevented through installing steel plates at the wall edges. One side of the UFP hold-downs were bolted to the boots and the other side was connected to short steel pedestals. The pedestals were fixed to the foundation. Due to the edge uplift, the relative displacement between the boots and the fixed pedestal caused deformation of the UFPs which led to yielding of the replaceable hold-downs at the limit state of LS_{yhd}.



(a) (b)

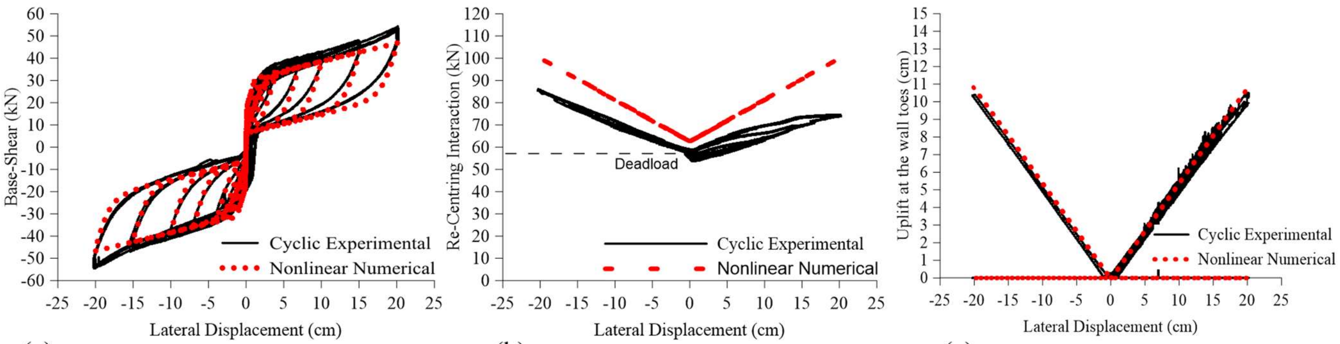
Figure 7. Full scale Laboratory test setup and layouts a) Test setup layout b) Laboratory test setup

CYCLIC EXPERIMENT OBSERVATIONS AND RESULTS

The cyclic behavior of the specimen is illustrated and compared with the numerical analysis through force-displacement curves in Figure 8(a). The specimen was sustained to self-center and minimal damages for up to 6% inter-story drift. As the magnitude of the drift increased, the test results demonstrated the progression of the LFRC performance states from linear elastic to rocking wall, shown in Figure 9 and subsequent yielding and damage of the ductile hold-downs. The overall force deformation behavior corroborated the desired flag shape cyclic response that characterizes low-damage self-centering rocking system

The re-centering interaction vs lateral displacement plots, from the cyclic experiment and numerical analysis, are shown in Figure 8(b). The results validate the effectiveness of the wall-floor connection to engage the elasticity of the floor for self-centering purposes as well as transferring the lateral force from the floor to the wall. By comparing plots, it can be observed, it can be observed the dead load force recorded by test load-cells were found to be marginally lower than predicted which was attributed to the connection slack at the CLT floor to column interface and to the CLT wall to hold-down. Slops of the plots, associated to contribution of the floor elasticity in self-centering mechanism, are approximately similar based on the results in the both cyclic test and numerical analysis. This approximation helps the engineers to numerically quantify the wall-floor interaction which was addressed in several previous research studies [15]

As illustrated in Figure 8(c), uplift of the wall toes, which is equal to elongation of the hold-downs, is plotted vs the lateral displacement. The ductile hold-downs were able to accommodate the imposed deformations, which exceeded 100 mm. As intended for a low damage system, LFRC illustrated satisfactory performance in terms of concentrating all the damages just to the hold-downs. There were no failures up to the achieved target 6% story drift in other structural components rather than hold-downs. Superficial damage was observed and was primarily localized to surface indentation on the CLT wall at the various hardware connections. Nonetheless, resulting low residual displacements demonstrated the ability of the system to self-center as the CLT floor remained elastic and was able to generate the sufficient restoring forces onto the wall. No other observable damage was recorded in the specimen, validating the seismic resiliency of the system.



(a) (b) (c)

Figure 8. Results from cyclic test and nonlinear numerical analysis a) Lateral Force vs Displacement b) Floor Re-centering Interaction vs Displacement c) Uplift at the wall toe (hold-down elongation) vs Displacement

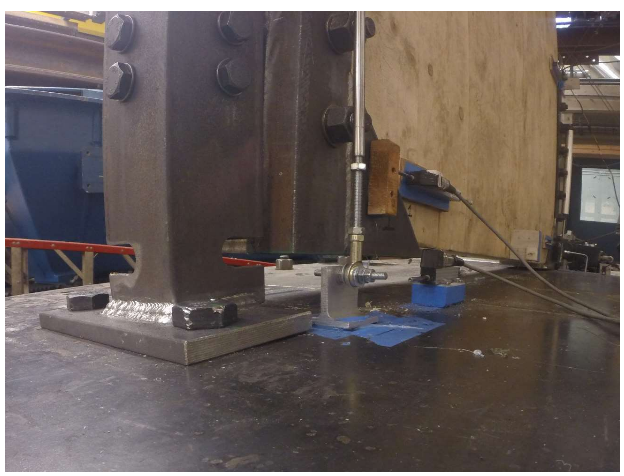


Figure 9. Rocking and gap-opening mechanism at 3% drift

CONCLUSIONS

Results from cyclic experiments as well as numerical results validate that the system has the capability to provide self-centering mechanism to CLT shear walls. The inherent interaction between the wall and the floor can be utilized to control the rocking action of the core-wall. The results verified that the floor and the wall remained elastic through load cycles and through its action limited the core wall lateral deformations. The results from the cyclic experiments along with the associated numerical analysis validated the seismic resiliency of the system and demonstrated that low-damage self-centering mass timber wall system can be achieved without relying on post-tensioning.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 1563612. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. In kind material contributions of KLH and Simpson Strong Tie for the experimental aspects are also gratefully acknowledged.

REFERENCES

[1] United Nations, Department of Economic and Social Affairs, Population Division (2018). "The World's Cities in 2018—Data Booklet". (ST/ESA/ SER.A/417)"

[2] Dujic, B., Hristovski, V., Stojmanovska, M., and Zarnic, R. (2006). "Experimental investigation of massive wooden wall panel system subjected to seismic excitation". In Proceedings of the First European Conference on Earthquake Engineering and seismology, Geneva, Switzerland, 2006.

[3] Dujic B., and Zarnic, R (2006)." Study of Lateral resistance of Massive X-Lam Wooden Wall System subjected to Horizontal Loads. COST E29 International Workshop on Earthquake Engineering on Timber Structures, pages 97-104, Coimbra, Portugal, 2006

[4] Ceccotti A. and Follesa M. (2006). Seismic Behavior of Multi-Storey X-Lam Buildings. COST E29 Workshop on Earthquake Engineering on Timber Structures, Coimbra, Portugal.

[5] Ceccotti A., Follesa M., and Lauriola M.P., and Sandhaas C. (2006) "Sofie Project: Test Results on the Lateral Resistance of Cross-Laminated Wooden Panels". In Proceedings of the First European Conference on Earthquake Engineering and seismology, Geneva, Switzerland, 2006.

[6] Popovski, M., Schneider, J., and Schweinsteiger, M. (2010). "Lateral load resistance of cross laminated wood panels. In Proceedings of the 11th World Conference on Timber Engineering, Riva del Garda, Italy

[7] Priestley, N.J.M. (1996). "The PRESSS program - Current status and proposed plans for Phase III". PCI Journal. 41. 22-40. 10.15554/pcij.03011996.22.40.

[8] Priestley, N.J.M., Srutharan, S., Conley, J.R., and Pampanin, S. (1999). "Preliminary Results and Conclusions from the PRESSS Five-Story Precast Concrete Building," PCI, PCI Journal, Precast/Prestressed Concrete Institute, Vol. 44 No. 6, pp. 42-67.

[9] Conley, J., Sritharan, S., and Priestley, M.J.N. (2002). "Precast Seismic Structural Systems PRESS-3: The Five-Story Precast Test Building Vol.3-5: Wall Direction Response". Final Report Submitted to the Precast/Prestressed Concrete Institute, Report No. SSRP-99/19, Department of Structural Engineering, University of California, San Diego, La Jolla, California

[10] Palermo, A., Pampanin, S., Buchanan, A. and Newcombe, M. (2005). "Seismic Design of multi-storey buildings using laminated veneer lumber (LVL)". 2005 NZSEE Conf., New Zealand Society for Earthquake Engineering, Wellington, New Zealand; 2005. 8.

[11] Buchanan, A., Deam, B., Fragiacomo, M., Pampanin, S., and Palermo, A. (2008). "Multi-Storey Prestressed Timber Buildings in New Zealand". Structural Engineering International. 18. 166-173. 10.2749/101686608784218635.

[12] Smith, T., Pampanin, S., Fragiacomo, M., and Buchanan, A. (2008). "Design and Construction of Prestressed Timber Buildings for Seismic Areas". NZ Timber Design Journal, Volume 16 Issue 3

[13] Sarti,F., Palermo, A., and Pampanin, S. (2015). "Development and Testing of an Alternative Dissipative Posttensioned Rocking Timber Wall with Boundary Columns". Journal of Structural Engineering. 142. E4015011. 10.1061/ (ASCE) ST.1943-541X.0001390.

[14] Tugce, A., Sause, R., M.Ricles, J., Ganey, R., Berman, J., Loftus, S., Dolan, D., Pei, S. Lindt, J, and Blomgren, H. (2017). "Analytical and Experimental Lateral-Load Response of Self-Centering Posttensioned CLT Walls". Journal of Structural Engineering. 143. 04017019. 10.1061/ (ASCE) ST.1943-541X.0001733.

[15] Mohammad, M., Gagnon, S., Douglas, B.K., and Podesto, L. (2012). "Introduction to cross laminated timber". Wood Design Focus. 22. 3-12.

[16] Sarti,F. (2015)."Seismic Design of Low-Damage Post-Tensioned Timber Wall Systems". Ph.D. Thesis, Univ. of Canterbury, Christchurch, New Zealand

[17] McKenna, F. 2011. "OpenSees: A Framework for Earthquake Engineering Simulation". Computing in Science & Engineering. 13. 58 - 66. 10.1109/MCSE.2011.66.

[18] Pacific Earthquake Engineering Research Center (2016). OpenSees Software v2.5, University of California, Berkeley, CA, USA, 2007, http://opensees.berkeley.edu.