RECENT PROGRESS IN NORTH AMERICAN RESEARCH ON SEISMIC RESILIENT WOOD BUILDINGS

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Abstract

Recent findings from ongoing and recently completed research projects undertaken in the United States and Canada on seismic performance and resilience of wood buildings are summarized. A significant research project aimed at determination of seismic design factors for CLT shear walls in platform type construction using the FEMA P-695 process for implementation in the US seismic design codes is in final stages. The NHERI tall wood building project is currently underway with steps to develop and validate a resilient-based seismic design methodology for tall wood buildings up to 20 stories. The design methodology will be validated through shake table testing of a 10-story full-scale building model which will be tested on world's largest wood shake table at UCSD in the summer of 2020. Investigations of CLT floor diaphragms and fire performance are also highlighted. A recently completed project entitled Seismic Risk Reduction for Soft-Story Woodframe Buildings, known as NEES-Soft, which consisted of two major full-scale test programs including a five-phase four-story shake table testing that ended in collapse testing is summarized. Hybrid simulation of a six-story building with two-story physical specimen is planned as part of a project on hybrid buildings of CLT and light-frame wood structures. Research on wood structures with post-tensioned systems is continued with testing of a single-story full-scale model building with post-tensioned CLT walls and Glulam frames designed for seismic region. The projects outline current status and future directions of the initiative towards implementation of seismic resilient wood buildings in North America.

Introduction

Wood has been gaining increasing interest as a structural material in North America over recent years. Large portions of the continent are subject to significant seismic hazard and significant research have been devoted towards improved understanding and further implementation of wood buildings in those regions. Some of the ongoing or recently completed initiatives are discussed here. The projects cover a wide variety of areas such as determination of design parameters, development of new structural systems, investigation and improvement of performance and novel application of latest testing techniques.

Development of Performance Factors for CLT Shearwall Systems

A study to investigate the seismic behavior of Cross Laminated Timber (CLT) based shear wall systems and determine seismic performance factors for the equivalent lateral force procedure (ELFP) as outlined in ASCE 7 (ASCE 7-16 2016) is nearing completion (Amini et al. 2016). That study follows the FEMA P-695 (FEMA 2009) methodology and integrates the development of a design method, experimental results, nonlinear static and dynamic analyses and incorporates uncertainties. The project includes development of archetypes such as Figure 1 required as part of the FEMA P-695 process and full-scale shear wall testing. Reversed-cyclic tests were conducted on CLT shear walls (Figure 1) to systematically investigate each potential modelling attribute that is judged within the FEMA P-695 uncertainty quantification process. Boundary constraints and gravity loading were both found to have a beneficial effect on the wall performance, i.e. higher strength and deformation capacity, so were eliminated from the remainder of the tests.

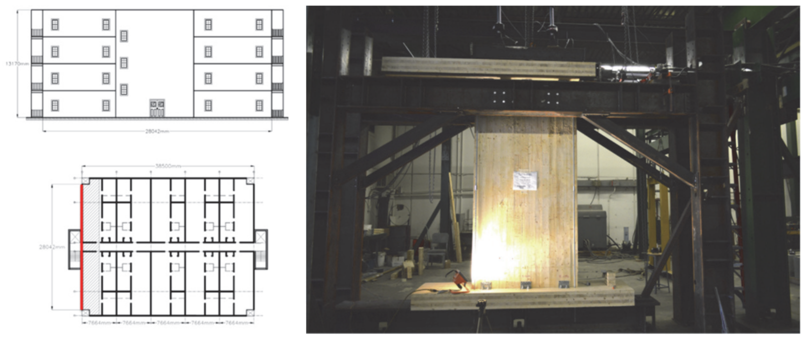

Figure 1. CLT archetype building elevation and plan (left) and shear wall test setup (right).

Phenomenological models were fit to test hysteresis from each wall test (see Figure d) and used in modelling CLT shear walls. Nonlinear time history analysis was conducted using models for different wall configurations. A single corresponding maximum inter-story drift at each story was recorded from each analysis and multi-record IDA's developed to iteratively determine an acceptable response modification factor, R. Full results can be found in Amini (2018).

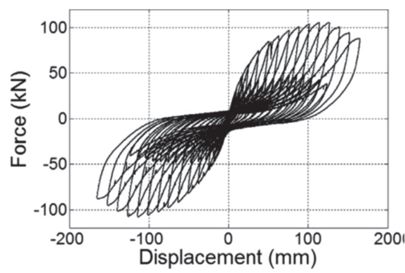

Figure 2. Test hysteresis of double panel shear wall.

Seismic Resilient Tall Wood Buildings

There has been a recent trend to construct mixed-use mass timber buildings with relatively open floor plan using a combination of beam and column components made of engineered wood products such as CLT and Glulam. In order to develop practical mass-timber lateral systems and design methods for improved performance of tall wood buildings in large earthquakes, the National Science Foundation supported a six-university research collaboration, namely the NHERI Tall Wood Project (Pei et al. 2018), that involves a series of modelling and testing tasks, including a series of full-scale dynamic tests on CLT system assemblies and buildings. In addition to pushing the envelope of wood application through CLT into the tall building arena this project uses resilience as an explicit design target, advancing PBSD of mass timber buildings towards resilience-based seismic design (RBSD).

The first series of tests was the full-scale shake table test of a two-story mass timber building with a post-tensioned resilient rocking wall lateral system, conducted in July 2017 at the world's largest outdoor shake table at UC San Diego. The test was aimed at gathering system level dynamic response of open floor plan mass timber buildings under different levels of seismic excitation. These tests are to be followed by a series of building system assembly tests to be conducted at Lehigh University, including the solutions for resilient non-structural component detailing. The ultimate outcome of the project is a set of RBSD procedures that will be validated at full scale on a 10-story building in 2020. With additional funding from other sources, the research team plans to first conduct seismic testing on the building to validate the resilient seismic performance, and then conduct system level fire tests to demonstrate the viability of fire designs implemented for tall wood buildings (the fire test is not within the NSF project scope) (Figure 3).

Figure 3. Conceptual vision for 2020 Tall Wood building test specimen (left) and two-story building test specimen in 2017 (right).

The 2-story shake table test conducted in 2017 (Figure 3) consisted of a series of 14 earthquake excitations ranging from frequent earthquake events to maximum considered earthquake events. The test result showed that the structural system was essentially damage-free after these consecutive seismic loading events. The test proved that true seismic resilience can be achieved in mass timber structural systems using post-tensioned rocking CLT walls and glulam beam and column gravity frames. In addition to the post-tensioned rocking wall system, the two-story structure was reused for testing of another two types of CLT based lateral systems, including a repairable rocking wall system (13 seismic tests) and traditional platform CLT panelized shear wall system (7 seismic tests).

NEES-Soft: Seismic Risk Reduction for Soft-Story Woodframe buildings

Recent earthquakes such as Loma Prieta and Northridge in California have highlighted the poor performance of a class of existing buildings broadly defined as soft-story wood-frame buildings. The relative stiffness and/or strength of the soft-story is significantly less than that of the upper stories. This leads to disproportionally large inter-story drifts and potential collapse of the bottom story, even before the upper stories experience significant drifts. These buildings are susceptible to severe damage and collapse during an earthquake and therefore, have been recognized as a disaster-preparedness problem. It is estimated that there are thousands of soft-story wood frame buildings in California and the United States. These buildings were generally built before 1970 and many as early as the 1920's, which means that they used construction practices not considered acceptable by today's codified standards.

In order to improve the performance of these at-risk buildings, two retrofit approaches were used: (1) Performance-Based Seismic Retrofit (PBSR) method and (2) FEMA P-807 retrofit guidelines. In the PBSR procedure the direct displacement design methodology is used to retrofit the building such that it meets the performance criteria defined within the NEES-Soft project (Bahmani et al. 2014). FEMA P-807 retrofit procedure limited retrofit only to the first story level to prevent collapse during moderate to large earthquakes. In the PBSR, retrofits were installed such that the building meets the performance criteria at the DBE and MCE level and its torsional response is reduced to an acceptable range. The two retrofit methods were validated numerically using non-linear time history analysis and then experimentally by conducting full-scale shake table tests on a four-story wood-frame building at the NEES at UC San Diego outdoor shake table facility. Cross laminated timber (CLT), steel special moment frames (SSMF), and viscous dampers combined with wood structural panels (WSP) were used as retrofit techniques in these tests. The 4-story test building had 370 m^2 of living space and was designed to be generally representative of older San Francisco buildings built between 1920 and 1970. Figure 4 presents the 4-story building constructed at the top of the shake table at UC-San Diego (Bahmani et al. 2014, van de Lindt et al. 2014).

Figure 4. 4-story wood-frame building prior to shake table test at UC-San Diego.

In the final test phase, after removal of the retrofits, the building was tested to collapse in order to investigate the soft-story collapse mechanism and quantify the collapse drift and deformation capacity for this type of buildings. Comparison is made between the behavior of the retrofitted and un-retrofitted building (Bahmani et al. 2014).

FEMA P807 – Steel Special Moment Frames. Steel special moment frames SSMF were installed at the ground level to provide adequate stiffness and strength to the soft story to meet the P807 guideline requirements. The SSMF were designed such that this retrofit technique can be applied practically to the existing buildings in a short period of time which reduces the cost of the retrofit. Perfect pined connections were used in column-to-foundation connections that eliminate retrofitting the foundation of the building with reinforced concrete. Figure 5 presents the location of the SSMF on the first story and the building profile in its maximum deformations for four seismic tests. It can be seen that the first story experienced about 2% inter-story drift under 50%MCE level earthquake which was the target performance for the retrofit design.

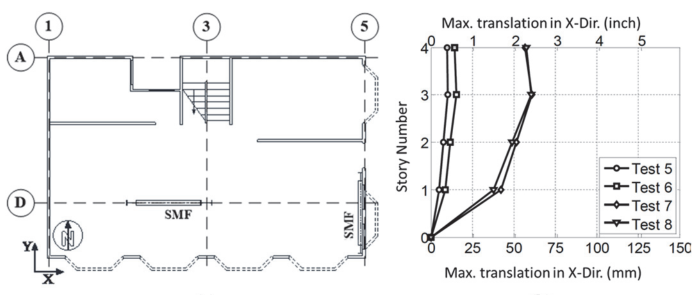

Figure 5. (a) Location of the SSMF on the first story for FEMA P-807 retrofit and (b) building maximum deformation profile.

PBSR – Steel Special Moment Frames and Wood Structural Panels. In this phase, performance-based seismic retrofit (PBSR) procedure was used to retrofit the entire building. In the PBSR procedure, the building should be designed such that almost all the stories experience the same level of inter-story drift. This leads to utilize the capacity of the upper stories to resist to the seismic loads and increases the probability of survival of the building under higher earthquake intensities. The four-story building was retrofitted using steel special moment frames and wood structural panels at the ground level and wood structural panels with different nail schedule for the upper stories. Anchor Tiedown System (ATS) rods were placed at the end posts of the wood structural panels to transfer the uplift force in the walls to the foundation and also limit the out of plane deformation of the diaphragms. Figure 6 presents the location of the SSMF on the first story and the building profile in its maximum deformations for four seismic tests. It can be seen that all stories experienced about 2% inter-story drift under MCE level earthquake which was the target performance for the retrofit design.

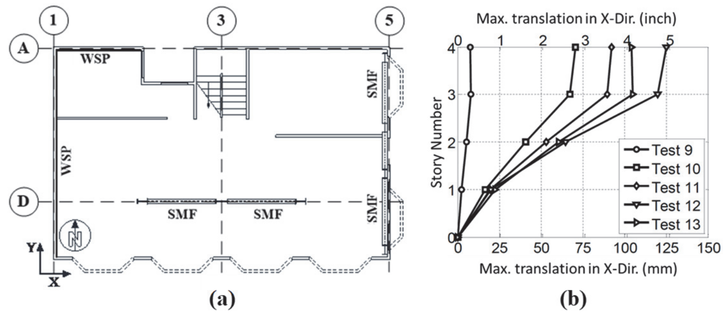

Figure 6. (a) Location of the SSMF on the first story for PBSR retrofit and (b)building maximum deformation profile.

Controlled-Collapse Test. The four-story wood frame building was subjected to eight successive seismic tests with several different ground motion records scaled to spectral accelerations ranging from 0.4g to 1.8g. Three different ground motions with different intensities were selected. The selections were such that they would provide a range of earthquake records based on differences in ground displacement. Although high ground accelerations clearly produce large inertial forces within a building it has been observed over the years that global instabilities leading to full collapse often result from large ground displacements. Figure 7 shows the photos of the collapsed building and the displacement time-history of the first story that led to the collapse of the building.

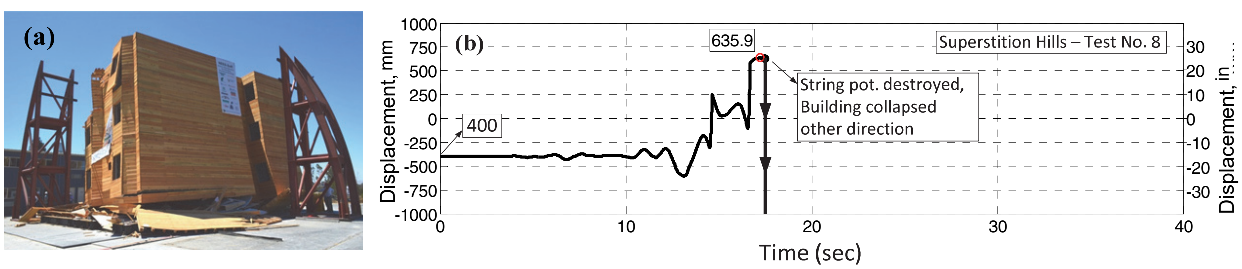

Figure 7. (a) Photos of the collapsed building and (b) displacement time-history record of the first story in the last test led to collapse.

CLT-LiFS Hybrid Buildings

Enabling Next Generation Hybridized Wood Buildings for Sustainable is a research project funded by U.S. National Science Foundation to study a combination of Cross-Laminated Timber (CLT) and traditional light-frame wood shearwall (LiFS) system. In this project, the seismic behavior and optimization of a hybridized self-centering wood system termed a CLT-LiFS that uses unbonded post-tensioning tendons, CLT rocking walls and LiFS will be investigated to enable the design of tall wood buildings that are sustainable and resilient. In this system, the CLT panel anchored with unbonded post-tensioning will be optimally combined with the light-wood frame system to exploit the beneficial features of each. While the unbonded post-tensioning in the CLT will self-center the system, the connections in the light-frame wood will provide the necessary energy dissipation. Serval fundamental research tasks at component levels have been completed include: 1) Moisture content migrations in CLT panels; 2) Modeling of creep behavior of axially loaded CLT panels; 3) Compression tests of CLT materials at different moisture contents to see the effects of moisture content in CLT to its strength and elastic modulus; 4) Estimation and reliability analysis of loss of tendon force in post-tensioned CLT panels; 5) Experimental study of connections for CLT-LiFS; 6) CLT-LiFS components tests: rocking panels and wall tests (Figure 8); 7) Optimization of CLT-LiFS walls. In addition, a hybrid simulation of six-story building will be tested at the University of Alabama and shake table test of single wall will be conducted at Colorado State University. Both tests simultaneously are under preparation at the two universities.

Results from experimental studies showed that moisture content absorption coefficients were 0.086 cm^2·day-1 (0.013 $in.^2$·day-1) and 0.208 cm^2·day-1 (0.032 $in.^2$·day-1) for SPF CLT materials with step changes in relative humidity (RH) from 50% to 70% and 70% to 90%, respectively. These coefficients are about four to five times higher than those in solid wood (Tong, 1987) of the same species due to the gaps among lumbers in CLT. From the creep test data and creep model in this study, it was found that the loss of PT cable force due to creep deformation in CLT panel was found between 2.53% and 6.37% in 3-layer CLT panels PT at 10% of compression strength, between 1.08% and 3.36% in 5-layer CLT panels PT at 10% of compression strength, and from 1.93% to 3.87% in 5-layer CLT panels with PT force at 15% of compression strength, this loss of tendon forces was calculated around nine months after post-tensioned.

The CUREE cyclic loading protocol (Krawinkler, 2001) was used for the cyclic test of a CLT LiFS. In this cyclic test, the maximum displacement of each cycle was increased for every three cycles. An increment of 0.1 in. was exerted to peak displacement less than 1 in. After the peak displacement reached to 1 in., this increment was changed to 0.2 in., as shown in Figure 9. A hydraulic actuator was attached to the top of the CLT-LiFS wall and the test protocol was applied through this actuator under displacement control. The force and displacement at the top of the CLT-LiFS wall were recorded during the test using the sensors installed inside the actuator. The relationship between force and displacement is plotted in Figure 9.

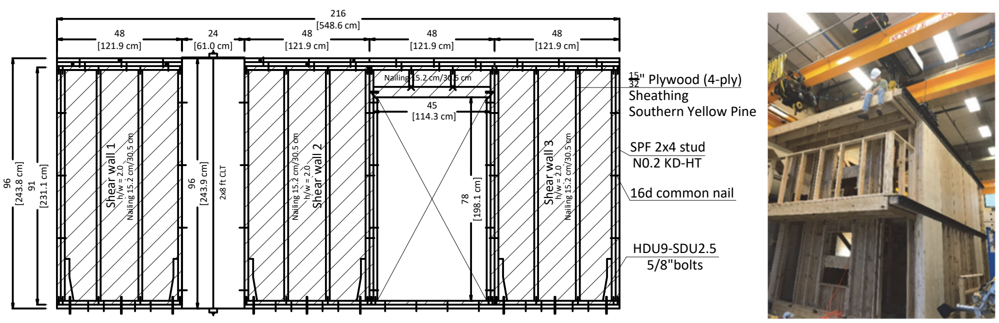

Figure 8. Configuration of CLT-LiFS wall (left) and Hybrid simulation of CLT-LiFS Building(right).

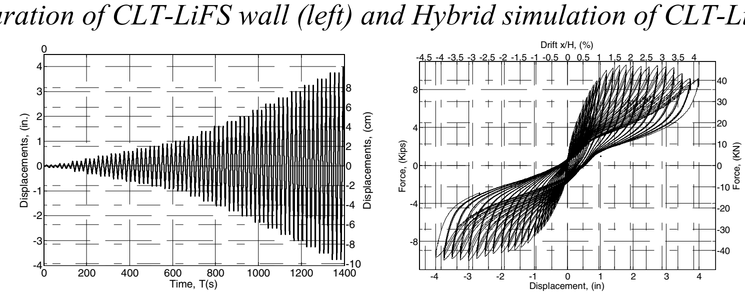

Figure 9. Cyclic loading protocol (left) and CLT-LiFS hysteresis(right).

As can be seen in the hysteresis plot in Figure 9, the CLT-LiFS wall reached the peak force of 10.5 kips (46.7 KN) with the top wall drift at 1.75 in. (4.45 cm). Due to the large displacement on the top of the CLT-LiFS wall during the cyclic test, the wall exhibited some damage. The nails that connected the post-tensioned CLT panel with LiFS wall were fractured and large gaps between these two components were observed by the end of the tests. Some edge nails at the bottom perimeter of the LiFS wall were completely pulled out. In the other parts, the nails were partially pulled out around 1 in. (2.54 cm), but no sheared off nails were observed. From the hysteresis shown in Figure 9, a residual displacement is calculated at which the lateral force measured by sensor in actuator is zero. It can be observed that the residual displacement of the CLT-LiFS wall was very small, about 0.45 in. (1.143 cm) compared with 6 in. for light-frame wood structure alone (Shao et al. 2014). This indicates the excellent self-centering capability of the post-tensioned CLT panel in this new hybrid structural system.

Developments in Post-tensioned Timber Systems

Structural systems with members made of Engineered Wood Products (EWPs) bound together with standard post-tensioning arrangements have been developed over the last decade. Having the ability of almost complete self-centering and using additional energy dissipating elements these systems commonly known under the name of Pres-lam, are particularly suitable for seismic applications.

To facilitate further applications of Pres-lam systems in Canada and in the US, FPInnovations has acquired the Intellectual Property (IP) rights for the use of these post-tensioning systems in North America in 2015. As a part of FPInnovations' implementation strategy, a number of research programs have been launched recently in British Columbia, Canada to facilitate use of CLT and other North American made EWPs in post-tensioned buildings. FPInnovations in collaboration with the University of Northern British Columbia has tested a number of single and coupled CLT Pres-lam walls (Chen and Popovski 2018, Iqbal and Popovski 2017). An example of a coupled post-tensioned CLT wall been tested is shown in Figure 10. The projects also focused on new developments and testing of connection details for seismic applications leading towards development of guidelines for practical applications, by FPInnovations as the IP owner, in conjunction with collaborative research by other research institutions.

In addition, full scale model of a single-story building with post-tensioned CLT walls and Glulam frames (Figure 10) designed for seismic region will be studied at FPInnovations. The assembly will also serve to work out practical details of the arrangements and connections. The structural systems are tested individually and performances of the systems are critically analyzed for in-depth understanding of the behavior. Numerical models have been developed and the results match well when compared again experimental data.

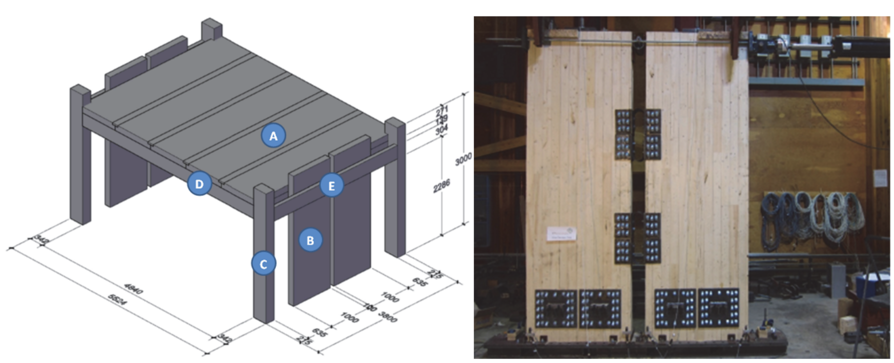

Figure 10. Single-story post-tensioned timber building model (left) and coupled wall specimen (right).

Conclusion

The projects described here illustrate the initiatives and their contributions in latest advances in design methodologies, development of structural systems, improvements in performance of existing structures and leading-edge investigation approaches. They are expected to have tangible effects in promotion of wood buildings construction, particularly in seismic regions.

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