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FULL-SCALE SHAKE TABLE TEST OF A TWO-STORY MASS-TIMBER BUILDING WITH RESILIENT ROCKING WALLS

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ABSTRACT

The *NHERI TallWood* project is a U.S. National Science Foundation-funded four-year research project focusing on the development of a resilient tall wood building design philosophy. One of the first major tasks within the project was to test a full-scale two-story mass timber building at the largest shake table in the U.S., the NHERI@UCSD's outdoor shake table facility, to study the dynamic behaviour of a mass timber building with a resilient rocking wall system. The specimen consisted of two coupled two-story tall post-tensioned cross laminated timber rocking walls surrounded by mass timber gravity frames simulating a realistic portion of a building floor plan at full scale. Diaphragms consisted of bare CLT at the first floor level and concrete-topped, composite CLT at the roof. The specimen was subjected to ground motions scaled to three intensity levels representing frequent, design basis, and maximum considered earthquakes. In this paper, the design and implementation of this test program is summarized. The performance of the full building system under these different levels of seismic intensity is presented.

Keywords: Cross laminated timber; NHERI TallWood project; Resilience; Rocking wall; Shake table test.

1. INTRODUCING NHERI TALLWOOD PROJECT

Tall buildings in the range of 8 to 20 stories are common for urban construction because they provided a means for developers to balance occupant density and land price. While traditional light-frame wood construction is not economically or structurally viable at this height range, a relatively new heavy timber structural material, cross laminated timber (CLT), has made tall wood building construction possible. This panelized product utilizes small lumber layers glue-laminated in an orthogonal pattern to create solid wood panels that can be used as wall and floor components in a building. Currently, a number of successful CLT building projects have been constructed around the world (e.g. the 18-story Brock

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Commons building in Vancouver, Canada; the 10-story Forte building in Melbourne, Australia; the 9-story Stadthaus Building in London, among others) and highlight the viability and potential of tall wood construction, which includes a reduction in construction time, reduced demands in foundations, and positive environmental impact. Due to its relatively light weight and reparability, there is an opportunity to develop practical mass-timber structural systems and design methods that enable resilient performance of tall wood buildings in large earthquakes.

This paper presents the results from a recently completed full-scale shake table test on a CLT building with resilient rocking wall systems. Although the building tested was only 2-stories, it should be noted that this test is part of a large National Science Foundation (NSF) project aiming at developing and validating a seismic design methodology for tall wood buildings that incorporates high-performance structural and non-structural systems. The NHERI TallWood Project is a six-university collaborative effort with industry and includes international collaboration (see Figure 1). The ultimate objective of the project is to develop a resilience-based seismic design methodology for tall wood buildings. As shown in the project schematic in Figure 1, the two-story shake table test was one of the several system level tests planned within the NHERI TallWood Project, aiming at obtaining key data on the seismic performance of CLT rocking walls and mass timber gravity frame at the system level. Beyond the collaboration team shown in Figure 1, the two-story building test included collaborations of Oregon State University, Tallwood Design Institute[11], Simpson Strong-Tie, and DR Johnson. The project will culminate with a full-scale 10-story mass timber building shake table test in 2020 back at the NHERI@UC San Diego outdoor shake table.

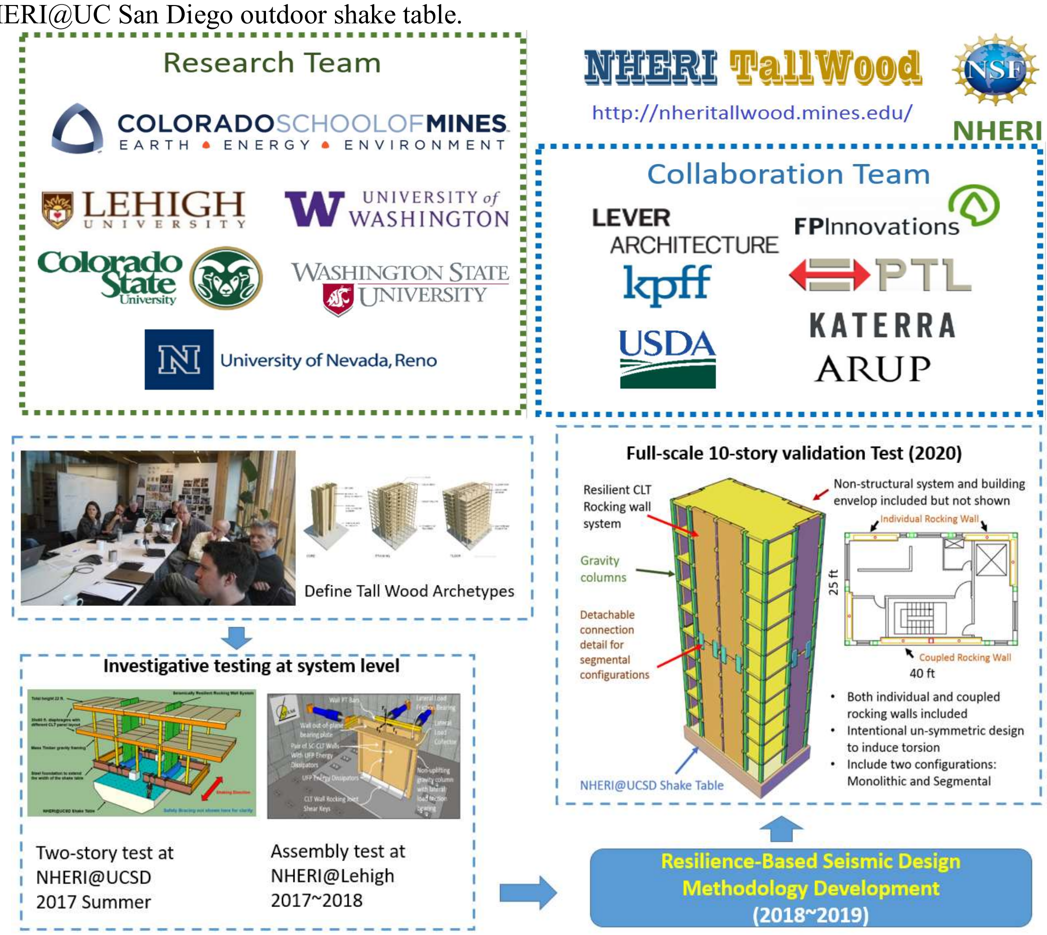

Figure 1. NHERI TallWood Project team and research plan.

[11] http://tallwoodinstitute.org/

2. SEISMIC RESEARCH ON CLT SYSTEMS

Since the invention of the CLT panel in the 1990's in Europe, construction of CLT structures has been similar to precast concrete panel construction, e.g. large CLT walls with opening pre-cut and floor diaphragm panels with mechanical connectors. This approach works well for resisting gravity loads, wind loads and small seismic loads. A number of analytical and experimental studies on CLT shear wall behaviour have been conducted by researchers around the world (e.g. Ceccotti et al. 2013, Popovski et al. 2010) and concluded that conventional CLT shear wall configurations are quite stiff under small lateral loads, and can only exhibit ductile behaviour when nonlinear deformation develops in the metal connectors. A seven-story CLT building designed to Eurocode with a low q-factor (similar to the R-factor in the United States ASCE-7 Standard) was tested at Japan's E-Defense facility in 2007 (Ceccotti et al. 2013). The roof acceleration measured during the test exceeded 4g, compared to peak ground acceleration of only about 1g (Popovski, 2010). In January 2016, a Japanese led three-story CLT building test at E-Defense that used similar conventional CLT shear wall construction. The building met life safety objectives when subjected to near-fault ground motions but experienced damage that was difficult to repair. Thus conventional platform CLT construction can likely provide collapse prevention/life safety performance, but with high acceleration amplification and significant damage during large earthquakes. Suitable building systems and corresponding seismic design methodologies for resilient CLT construction remain the major missing piece to enable resilient tall CLT buildings in regions of high seismicity (Pei et al. 2015).

In recent developments of seismically resilient structural systems, post-tensioned self-centring rocking walls/frames have been shown to require lower post-earthquake repair costs and recovery time. Of primary importance to timber buildings, post-tensioned heavy timber lateral systems were first explored by researchers in New Zealand (e.g. Buchanan et al. 2008, Iqbal et al. 2010) and later by the authors through a NSF-funded Planning Project (Ganey 2015). Buildings using a wood rocking wall system have been constructed in New Zealand and experimental results indicated that the CLT rocking wall system can be designed to be very ductile with negligible damage at more than 5% inter-story drift. When pushed beyond 9% drift levels, the walls had only concentrated damage at the rocking toe. While rocking systems tested in isolation perform well, achieving resilience will require other building components that do not rock (gravity framing, floor diaphragms, non-structural walls) to be able to accommodate the lateral drift without damage. This served as the impetus for conducting a full-scale shake table test for the combined mass timber building system (CLT rocking wall and gravity frame/diaphragm).

3. INVESTIGATIVE SHAKE TABLE TEST

The test building and test program were designed to answer the following key research questions:

1) Can resilient performance be achieved in an open-floor plan wood building through the use of post-tensioned CLT rocking walls?
2) How can the gravity frame system be designed so that it can tolerate large lateral drift without damage?
3) How should the lateral force transfer between the building diaphragms and rocking walls be designed?
4) How should the CLT diaphragms be designed such that they have adequate performance in large earthquakes?

These considerations led to a 6.7 m (22 ft.) tall test building (3.6 m (12 ft.) at first floor, 3.1 m (10 ft.) at the second floor) with a 17.7 x 6.1 m (58 x 20 ft.) floor plan as shown in Figure 2. The specimen had an open floor plan and relatively high diaphragm aspect ratio in the direction of the shaking. Two different diaphragm designs were implemented, including a wood-only diaphragm at the floor level and a concrete-CLT composite diaphragm design at the roof level (concrete topping not shown here). The diaphragm design was conducted by the Oregon State University collaboration team through the support of Tallwood Design Institute.

The rocking wall system was designed for seismic hazard near San Francisco, CA by the NHERI TallWood research team in collaboration with KPFF. The shear transfer detail between the rocking wall and diaphragms was adopted from an existing KPFF project (the Mass Timber Parking Garage project for the City of Springfield, Oregon, USA). The research team and KPFF engineers developed all details for the gravity frame using readily available connection products from the Simpson Strong-Tie catalog (with some minor adjustments). Several custom steel connection parts were also made as needed.

All of the CLT panels and glulam members were purchased at a discounted price from DR Johnson Lumber. All the diaphragm panels are V1 grade per APA PRG-320 (APA, 2017). The rocking wall panels are grade E2-M1. High strength Simpson ATS all-threaded rods (190 mm (5/8") diameter with yielding strength about 130 kN (30 kips)) were used as the post-tension rods.

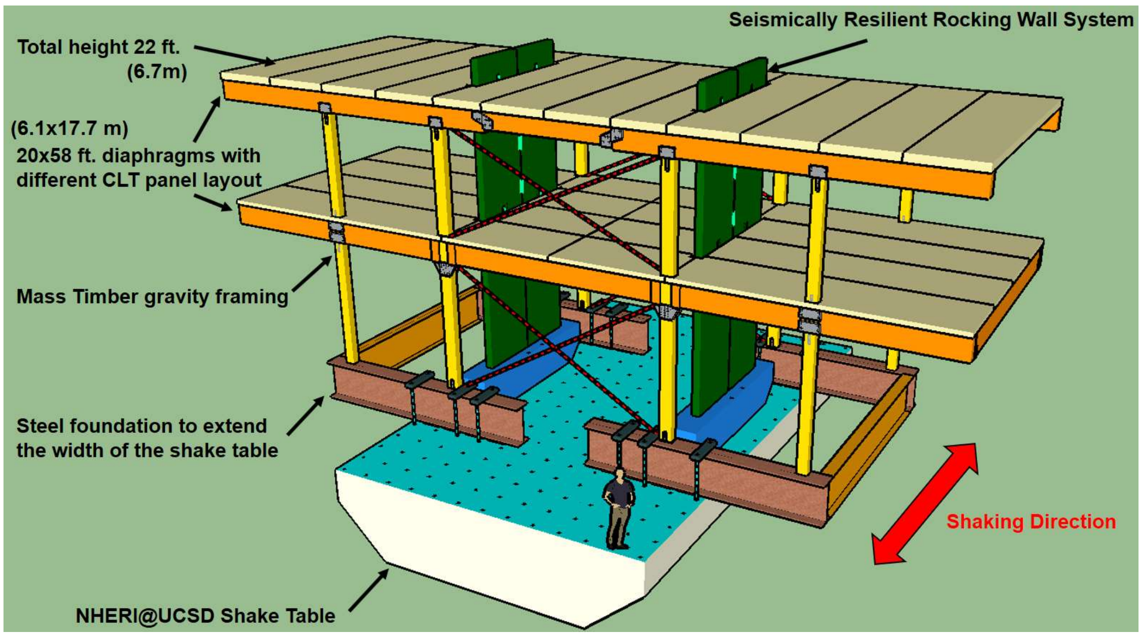

Figure 2. Concept of two-story shake table test specimen (http://nheritallwood.mines.edu/).

3.1 Test specimen construction

The construction of the test building was contracted to Seagate Structures Ltd. America with two carpenters on site during the construction process. The UCSD site crew (two persons) helped to operate the crane. Select photos that highlighted the construction process are illustrated in Figure 3. The shake table foundation was first expanded (Step 1 in Figure 3) to accommodate the building floor plan. The construction of the wood gravity frame (Steps 2 through 4) only took four days to complete. The preparation and pouring of the concrete composite layer for the roof diaphragm was done by a different contractor after the wood frame was completed (not shown in Figure 3). After the concrete had cured, the CLT rocking walls were inserted into the building (Step 5) and connected to the diaphragm and the foundation. During this process, additional steel trench plates were also placed on the floor and the roof in order to bring the total seismic mass to the design level. The last step of construction was the post-tensioning of the rocking wall. Because the needed post-tension force level was relatively low, the post-tensioning was achieved by tightening the nuts manually while monitoring the tension forces using load cells (Step 6). The completed building is shown in Figure 4.

Figure 3. Construction process (1) Foundation preparation (2) Glulam framing (3) CLT panel installation (4) Gravity system completed (5) CLT rocking wall installation (6) Post-tensioning.

Figure 4. Fully constructed test building on steel foundation connected to the shake table.

3.2 Test Program

The building was instrumented with approximately 350 sensors that included accelerometers, linear potentiometers, strain gauges, and load cells. Different components of the building, including the rocking walls, diaphragms, shear transfer connections, and gravity frames, were instrumented to help understand their behavior during dynamic loading. A brief list of the instrumentation on the test building is presented in Table 1.

Earthquake ground motions recorded from historical earthquakes were used in the test program, including ground motions from the 1994 Northridge and 1989 Loma Prieta earthquakes. These ground motions were scaled to represent different hazard levels based on the seismic design map. There were three hazard levels tested, namely the service level earthquake (SLE), design basis earthquake (DBE), and maximum considered earthquake (MCE).

Table 1. List of instrumentation installed on the two-story test building.

Building component	Instrumentation used
Global overall building	10 string potentiometers from diaphragm to fixed reference towers by the shake table
	36 accelerometers on floor and roof diaphragms
Rocking walls	16 load cells for post-tension rod forces
	30 LVDTs (20 at rocking base, 10 between walls) displacement sensors for wall uplift and panel relative slip
	16 string potentiometers to measure panel shear deformation
Diaphragms	50 strain gages on tension straps
	53 LVDTs at panel splices and concrete/wood for slip
	26 string potentiometers for out-of-plane diaphragm deformation
Gravity frame	16 string pots attached at column face to measure uplift and join rotation
Shear key	24 strain gages on the shear keys

During the test program, the research team hosted two public testing events, in which the original Northridge ground motion record was applied to test building twice in a row. These tests were planned in order to demonstrate the ability of the building to withstand two large earthquakes consecutively without the need for repair. At the final day of testing, after imposing multiple MCE ground motions without observing damage in the building, the researchers increased the scale factor of the ground motion to 120% of the original MCE level (reaching an approximate return period of 3900 years) in order to induce yielding behavior of post-tension rods. The list of ground motions and the intensities used in the test program was presented in Table 2. The spectral acceleration plots of the ground motion inputs (obtained using the measured shake table feedback acceleration) were presented in Figure 5.

Table 2. Ground motions and intensities for the 14 shake table tests.

ID	Ground Motion	Hazard level	PGA (g)	S_a @ T = 0.9 sec (g)
1	Loma Prieta	SLE	0.17	0.16
2	Loma Prieta	SLE	0.19	0.16
3	Northridge	SLE	0.19	0.18
4	Superstition Hill	SLE	0.13	0.12
5	Northridge	DBE	0.54	0.70
6	Northridge Repeated	Original	0.56	0.76
7	Imperial Valley	SLE	0.14	0.22
8	Northridge Repeated	Original	0.55	0.76
9	Loma Prieta	DBE	0.54	0.50
10	Superstition Hill	DBE	0.48	0.43
11	Loma Prieta	MCE	0.66	0.58
12	Northridge	MCE	0.76	0.92
13	Superstition Hill	MCE	0.68	0.63
14	Northridge	MCE x 1.2	0.89	1.12

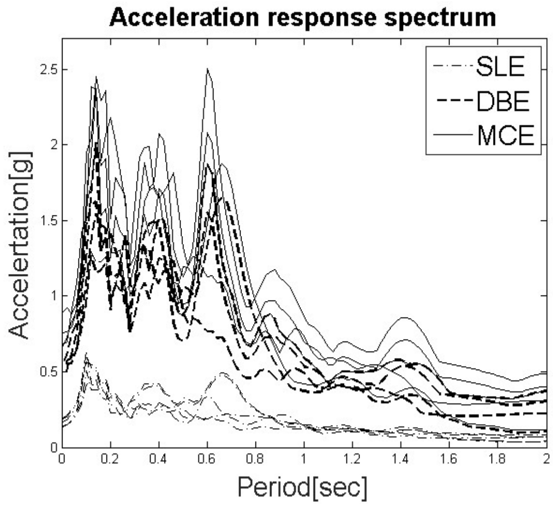

Figure 5. Spectral acceleration of the ground motions used in the test program.

4. PRELIMINARY RESULTS

The test program generated a rich set of data that will take a significant amount of time to verify, organize, process, and analyze. At the time of the development of this paper, the research team is still in the process of conducting comprehensive analysis on the data obtained. However, some preliminary but important results and conclusions that have already been verified are presented herein. Additional data will be presented at the conference.

4.1 Lateral responses

The lateral deformation of a building has been shown to be closely correlated to damage during an earthquake. It is important to assess the test building's ability to tolerate lateral deformation without damage. The building experienced a maximum roof response of about 350 mm, which corresponds to 5% total drift over the building height. The ratio of measured displacements at the roof and floor levels revealed that the building lateral response was dominated by a linear first mode forced by rocking walls that were relatively rigid.

White noise tests were conducted on the building before and after seismic excitation. The building responses under white noise were used to estimate the natural period of the building. Although there were variations among different tests, the overall building first period was approximately between 0.8 and 0.9 seconds, which is quite long for a two-story building. This observation highlighted the challenge of ensuring stiffness when using rocking wall systems in tall buildings.

The acceleration amplification on the floor and roof level relative to the ground motion acceleration was mitigated for large earthquakes. Especially for MCE level ground motions, the average acceleration recorded on the building was not significantly larger than the PGA. This is a benefit of the rocking wall system in that the conclusion is that there would likely be less content damage.

4.2 Post-tensioned wall performance

The rocking wall responses remained elastic for all SLE and DBE level tests. Even for some MCE level tests, the post-tensioned rods remained elastic and there was little damage to the wall panels themselves. Some prestressing losses were observed during large MCE level tests but were adjusted/repaired easily by re-tightening the anchor bolts. The final test was scaled beyond MCE level in order to cause yielding of the prestressing bars. After that test, a few bars saw a significant tension force reduction (approximately 50%), which indicated yielding of the bar.

The rocking wall was able to re-center the building perfectly in all SLE and DBE tests, and most of the MCE tests. Even when the post-tension bar yielded, the building was re-centered by the walls with a residual drift of less than 0.5%.

4.5 Damage inspection

Damage inspection was conducted initially after each test. But when it was discovered that SLE level test did not result in any damage, the inspection was done only for DBE and MCE level tests. There was no visible damage on the gravity frame system and the rocking walls except some cosmetic local chipping and crushing (e.g. rocking wall corner chipping as shown in Figure 6 and marked with black ink). This type of damage did not affect structural performance or stability of the system. There was no damage observed for the CLT diaphragm. There was no damage to the connections between the rocking wall and diaphragm either because the vertical slot detail in the rocking wall (see Figure 7) efficiently transferred the lateral force without limiting the movement of the wall and diaphragm during the movement. Test results validated the resilience design objectives intended for the system.

Figure 6. Observed damage to rocking wall corner after MCE level test.

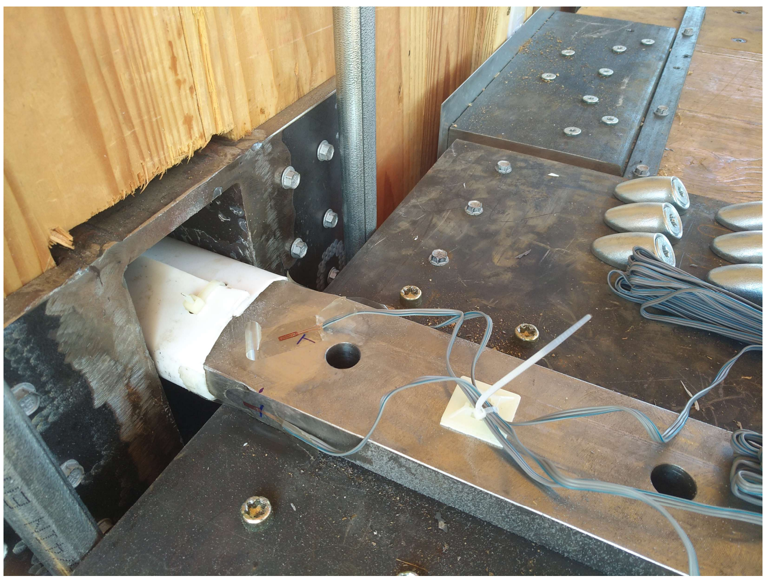

Figure 7. No damage at the wall-diaphragm shear transfer connections.

5. CONCLUSIONS

A two-story mass timber building was tested at full-scale on the NHERI@UCSD outdoor shake table in July 2017. As part of a multi-year collaborative NHERI TallWood Project, the test demonstrated resilient behaviour for a two-story mass timber structural system with post-tensioned rocking walls and glulam gravity frames. Based on the preliminary results of this two-story test, the following conclusions can be drawn:

1) CLT rocking walls can be designed to be compatible with heavy timber gravity frames to provide an open floor plan building that will survive repeated earthquakes at DBE and MCE intensity levels without visible damage.
2) CLT diaphragms are significantly more rigid than traditional wood diaphragms made of joists and floor sheathing panels. They can be constructed rapidly and perform well in large earthquakes when used in combination with resilient rocking wall systems.
3) One viable way to design the connection detail between diaphragm and rocking wall is to use a slotted shear key detail not restricting the rocking movement of the wall. Due to installation tolerances, the shear demands in these keys can be non-uniform, which warrants significant over-strength in design if no detailed analysis was conducted.
4) The gravity connection details for this test building can maintain stability and damage-free performance at 5% inter-story drift.

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