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FULL-SCALE 3-D SHAKE TABLE TEST OF A TEN-STORY MASS TIMBER BUILDING

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ABSTRACT: This paper provides a summary of the design, construction, and test planning of a shake table test program of a full-scale ten-story mass timber building. The shake table test program is a component of the experimental research work conducted as part of the NHERI TallWood project funded by the U.S. National Science Foundation. The goal of the NHERI TallWood project is to develop resilience-based seismic design methods for tall wood buildings through the adoption of a mass timber rocking wall lateral system and various detailing strategies for deformation-tolerant structural and non-structural connections and subassemblies. In this paper, the design configuration of the test structure is introduced, the construction process of both the structural and non-structural systems is explained, and the intended testing plan is presented. At the time of this writing, the construction of the building has been completed while the instrumentation process is ongoing. The authors intended to present initial results from the tests at the WCTE 2023 conference.

KEYWORDS: NHERI TallWood project, Shake table test, Tall wood building, Resilience, Seismic Design, Mass timber rocking wall

1 INTRODUCTION

Recently, mass timber construction materials such as cross laminated timber (CLT) have enabled taller wood construction projects including medium-to-high-rise mass timber buildings in the U.S. and around the world. Examples are the 10-story Forte building in Melbourne, Australia; the 18-story Mjøstårnet building in Norway; the 18-story Brock Commons building at the University of British Columbia, and the 27-story Ascent building in the U.S. Many of these tall wood buildings utilized non-wood lateral force-resisting systems such as reinforced concrete core walls or steel braced frames. At the same time, new mass timber-based lateral force-resisting systems have been proposed. Research on such systems continues at an impressive pace worldwide, including on post-tensioned mass timber rocking wall systems [1-3] and platform-framed CLT shear wall systems [4]. It is likely future mass timber buildings will continue to utilize a mixture of conventional and innovative lateral systems. However, amongst new mass timber lateral force-resisting systems, the post-tensioned mass timber rocking wall arguably demonstrates the greatest potential to enable a new type of tall wood building design that can achieve resilience and rapid return to functionality following an earthquake. Thus, the building can remain structurally damage free during design level earthquakes and be quickly repairable after maximum considered earthquakes.

The NHERI TallWood project was initiated in 2016 with the objective of developing a resilience-based seismic design methodology for tall wood buildings. Through funding provided by the U.S. National Science Foundation and U.S. Forest Service, the research team worked collaboratively with industry partners to develop design schematics, modelling tools, and resilience-based assessment methods in the past six years towards the goal of realizing a method to design a mass timber building based on functional recovery time. Based on past experience and assembly test data [2], the project team has completed the design of a 10-story mass timber building specimen with extracted features from realistic archetype buildings and under various physical constraints. One of the major constraints is the NHERI shake table dimensions (7.6x12.2 m) at the University of California San Diego (UCSD).

The shake table at UCSD is the world's largest outdoor shake table, thereby allowing a full-scale 10-story specimen to be constructed totalling approximately 34 meters in height. Building construction was completed in

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December 2022, and instrumentation will continue through February 2023 with over 700 channels of displacement, acceleration, and strain sensors. The tests are scheduled to be conducted between March and May of 2023. The building performance during testing will be compared to the resilience objectives intended during the design process, thus validating resilience-based seismic design approach proposed.

2 BUILDING CONFIGURATIONS

The test building utilizes a mass timber beam-column grid with mass timber floor panels as the gravity force-resisting system. Four post-tensioned rocking walls (two in each direction, constructed using CLT and mass plywood panels (MPP) respectively) serve as the lateral force-resisting system for the building. The gravity system of the building was designed using typical office live load. The beams and columns were sized considering 2 hour fire condition with exposed wood (i.e., considering a sacrificial layer of wood for wood charring). The basic design information about the building is listed in Table 1.

Table 1: *Basic design parameters for the test building*

Building Characteristics	Value
Number of stories	10
Total height	34.1m
Total floor area	840m^2
Design floor load (Dead/Live)	3.1/3.1 kN/m^2
Total building weight	295 MT
Design location	Seattle WA
Estimated period	1.8 sec

There is a large array of different mass timber materials used in the construction of the building, including CLT, Mass Plywood Panel (MPP), Glu-Laminated Timber (GLT), Veneer Laminated Timber (VLT), and Nail/Dowel Laminated Timber (NLT/DLT). The composition of different material types on various building components is shown in Figure 1. Aside from the structural system, selected floors also have non-structural partition walls and exterior envelop installed to evaluate their performance during the tests. A rendered building configuration is shown in Figure 2.

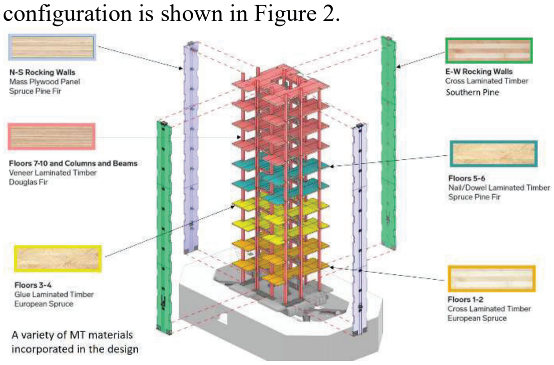

Figure 1: *Variety of mass timber material and components included in the tall wood test building*

Figure 2: *Rendering of the 10-story test building on the NHERI@UCSD outdoor shake table (Rendering courtesy of Lever Architecture)*

3 DESIGN AND CONSTRUCTION PROCESS

The objective of the NHERI TallWood Project is to develop a resilience-based seismic design methodology for tall wood buildings. The test building was designed with the objective of quantifying resilience, essentially time to functionality, as a function of building damage. In order to use resilience as a design metric, one of the first steps is to develop and validate an approach to assess and predict building damage and associated repair time following an earthquake. A fragility-based approach was utilized to link building response (i.e., floor acceleration and inter-story drift) to component and system damage, and then from damage to repair time [5]. This approach will be calibrated and validated using data obtained from the shake table tests.

As for the design of the test building, the project team took an indirect approach to address resilience. First, basic configuration parameters (e.g., rocking wall length, post-tensioning (P/T) force level, etc.) of the building and lateral force-resisting system were estimated using a prescriptive design method developed by collaborators of the project team [6]. This approach is largely force-based using demands generated with the modal response spectrum method from ASCE 7 [7] and a linearized model in ETABS [8]. Then a full nonlinear dynamic model in OpenSees [9] was used to evaluate acceleration and drift limits necessary to achieve the target resilience. Aside from the rocking wall lateral force-resisting system, which is designed to exhibit nonlinear behaviour (i.e., rocking behaviour at the base and yielding of energy dissipaters), all other structural components are designed to remain essentially elastic with negligible damage through providing sufficient overstrength or appropriate connection detailing.

Construction of the test building started in July 2022. Before construction, the outdoor shake table at UC San Diego was expanded by adding 4 cantilevered concrete foundation blocks to the long edge of the shake table. See

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Figure 3. This expansion provided a roughly 11 x 11 meter footprint for building construction. Four steel foundation beams were also installed on the shake table serving as the base of the rocking walls. All foundation components were connected to the shake table through post-tensioned steel rods. The post-tension forces were determined based on the calculated shear demands from the numerical models. Before construction started, the ground motions intended to be used during the test were replayed on the shake table to ensure clearance and to determine the tuning parameters for the shake table control.

Figure 3: *Foundation system added on the NHERI@UCSD outdoor shake table before construction started*

Construction of the NHERI TallWood test building structural system lasted for approximately 4.5 months. Swinerton Mass Timber/Timberlab was the structural contractor and planned the erection and construction engineering for the building process. The construction of the test building was especially challenging due to the limited floor plan area on the shake table, which makes temporary bracing congested. Temporary post-tensioning of the rocking walls on the lower floor had to be implemented in order to utilize the partially completed rocking wall panels as the lateral bracing system for construction loads.

The two pairs of mass timber rocking walls are a key component of the test building. Aside from the material and some minor dimensional differences, the CLT and MPP rocking walls utilized the same design. The rocking wall panels are strengthened at the base corners with steel armor plates. The post-tensioning rods were installed on the outside of the wall panels near the centre of the wall. Because of the height of the building, each rocking wall consists of 3 individual mass timber panels that had to be spliced on site. The splice connection was designed as a series of steel tension and shear rods embedded in the wall using special epoxy material. During the fabrication of the wall panels, a number of the predrilled holes at the panel splices were fabricated out of tolerance. This resulted in a change in connection design during construction to use coupler steel plates at the splices in order to bridge the mismatched hole coordinates. Between the rocking wall panel and bounding columns on each side of the wall, steel U-shaped flexural plates (UFP) were installed in order to provide energy dissipation to the lateral force-resisting system. Photos demonstrating the main details along the height of the rocking wall system can be seen in Figure 4.

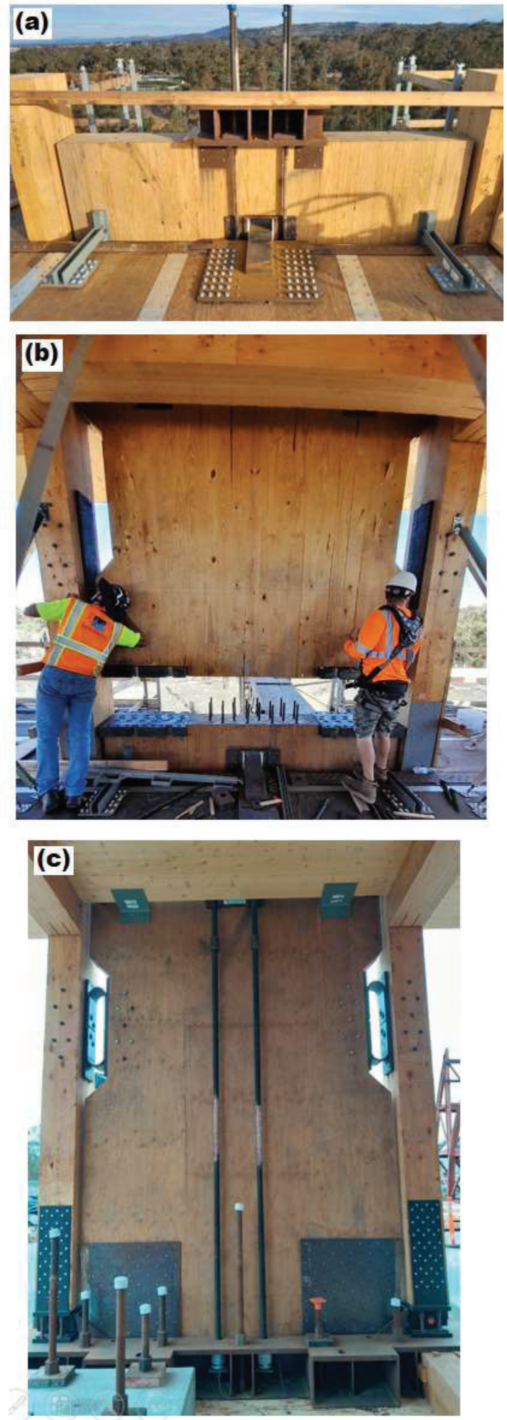

Figure 4: *Post-tensioned rocking wall system (a) PT anchor at wall top (b) Wall splice being installed (c) foundation level detail and UFP devices*

Figure 5: *Construction process of the test building*

The gravity system was erected along with the rocking wall segments. As shown in Figure 5, a modular stair and gravity columns were placed first, followed by the mass timber beam grid and floor panels. Once the gravity system reached the height of the rocking wall segment, the rocking wall panels were installed. This process was repeated 3 times during construction until the building was topped out. After that, the post-tensioning rods were extended to the top of the wall and stressed to complete the lateral force-resisting system. Once the design post-tensioning forces were applied (about 890 kN total post-tension force was applied to each wall), the construction of the structural system was complete.
In order to accurately evaluate repair time from non-structural system damage, the test specimen also included exterior façade subassemblies on the first three floors, interior partition walls, and a 10-story stair tower. Various low-damage deformation compatible details were implemented with the expectation of eliminating damage in small earthquakes and limited damage in design basis earthquakes. The details include horizontal slip joints fr walls, vertical joints at intersecting walls, and specialized joints for connecting stair stringers to mid-landings.

Figure 6: *Selected non-structural systems and components included in the test (a) Curtain wall (b) Exterior wall and windows (c) Interior partition walls.*

Figure 6 shows a few selected non-structural components, including a fire-rated curtain wall system, exterior stud wall with windows, and interior partition wall with low-damage joint details. Non-structural system construction is currently ongoing and is expected to be completed in February 2023.

4 INSTRUMENTATION PLAN

A comprehensive plan for instrumentation of the test building was developed and implemented. There are a total of over 700 instrumentation channels monitoring key aspects of the building response, namely overall building demands, rocking wall behavior, and non-structural system performances.
As shown in Figure 7, a 3D accelerometer was placed near the centre of mass of the floor diaphragm at each floor. String potentiometers will mainly be used to measure inter-story displacement, as well as absolute displacement for lower floors where they can be attached on the safety reference tower. The deformation of the rocking wall and building components are measured using LVDT sensors and tilt meters. Strain gauges were installed on key load-transferring components (e.g., tension straps and floor shear transfer keys) to monitor internal forces. Customized load cells were placed at the post-tensioning rod anchor to record rod forces. Examples of the installed sensors are shown in Figure 7.

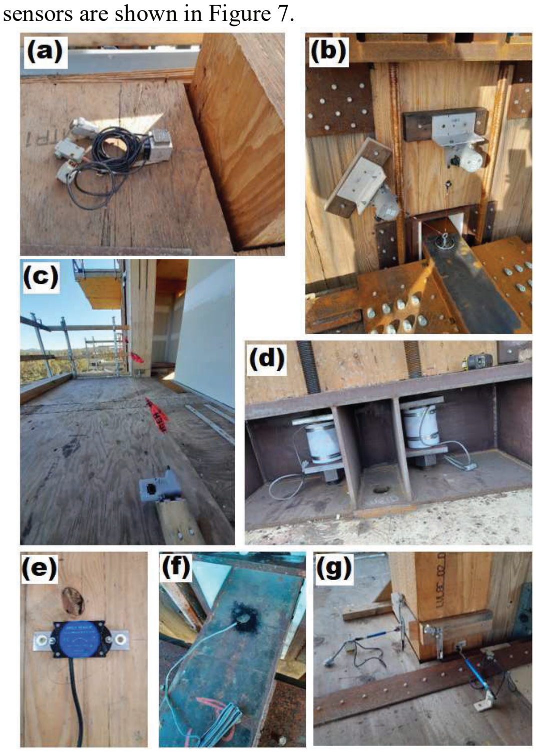

Figure 7: *A variety of sensors installed on the test building (a) Accelerometer on the floor (b) String potentiometer for small deformation (c) String potentiometer for inter-story displacements (d) Custom load cells for PT forces (e) Tilt angle sensor for rocking wall response (f) Strain gauge on key load transferring components (g) LVDT sensor for column rotation*

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A summary of all sensors implemented on the test building is listed in Table 2. Data obtained from these sensors during the test will serve multiple purposes, including providing key safety limit information during testing, calibrating and validating numerical models developed by the research team and other engineers after the test, and helping support damage fragility models of structural and non-structural components within the building. The data obtained from the tests will be archived and made public on the DesignSafe-CI database following the end of the NHERI TallWood project.

Table 2: *Summary of instrumentation channels deployed on the tallwood test building*

Building component	Sensor types*	Total number
Global Disp	SP, AC, GPS	139
Gravity system	LD, SP	79
Rocking walls	LC, AC, TL, SG, SP	196
Non-structural	AC, SP, LD	186
Stair	AC, SP, LD	109

* SP-String potentiometer, AC-Accelerometer, LC-Load cell, LD-Liner potentiometer, TL-Tilt meter, SG-Strain gauge, GPS- High precision GPS

5 TEST PROGRAM

The tests of the Tallwood building will be conducted on the newly upgraded 6-DOF high performance outdoor shake table at NHERI@UCSD in San Diego California. The research team plan to subject the building to a suite of ground motions selected and spectrally matched to represent seismic hazard at a site in Seattle WA, the location selected for the design of the building. Earthquake ground motions that will be used during testing have been selected and scaled to represent different hazard levels and sources affecting the site in Seattle, thus providing a realistic evaluation of the performance-based design for the building. The hazard levels include the 225 year, 475 year, 975 year and 2475 year return periods.

In order to achieve the desired range of hazards and sources, a total of 20 3D ground motions were selected, scaled and used to tune the shake table control before construction started. These inputs include recorded ground motions from historical earthquakes with different source types ranging from crustal earthquakes such as the Northridge Earthquake (1994) to interface subduction earthquakes such as the Tohoku, Japan Earthquake (2011). In particular, the interface subduction ground motion records contain significant amounts of excitation energy in long period ranges, which are believed to be especially detrimental to tall buildings. They also have long duration, resulting in many cycles of loading. All the ground motions at the Risk-Targeted Maximum Considered Earthquake (MCE_R) level which approximately corresponds to a 2,475 year return period, were used to tune the shake table. The test program will start at the lower hazard levels (i.e., lower levels of ground motion intensity). It will then continue with ground motions scaled to the larger and larger intensity levels. Numerical simulations will provide insight on the ground motions as the testing continues with decisions made dynamically as information is gathered following each test. The response spectra for the selected ground motions, scaled for different hazard levels, are shown in Figure 8 where the bold lines indicate averages at each hazard level. The ASCE 7 MCE_R spectrum used for design is also shown.

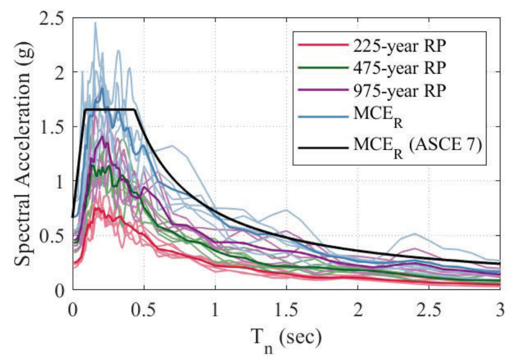

Figure 8: *Response spectra for all candidate ground motions at four representative hazard levels.*

Based on the schedule constraints, the test program will include 30 – 40 seismic tests over a period of about one month. White noise excitation will be implemented before and after each seismic test in order to gather data on the change in building dynamic characteristics. Since most of the practical design calculations currently required by the code do not consider biaxial or tri-axial excitation, the ground motion inputs were planned to first isolate the influence of multi-directional interaction. It is planned that the uniaxial ground motion components will first be applied. This will be followed by applying ground motion in the two horizontal directions and then by a full 3D motion. A typical testing sequence for one 3D seismic input at a given intensity level will include 5 tests and span over two to three days (See Table 3). This test program will help validate the design calculations/checks in a uniaxial configuration. The data from this test sequence will also be able to shed light on building response beyond code requirements in a biaxial and 3D excitation setting.

According to pre-test numerical simulation, the maximum inter-story drift during the planned test program will not exceed 3%, with the maximum drifts occurring in the MCE_R ground motions. Damage to non-structural systems at these drift levels is expected, while the structural system should experience negligible damage (except localized, expected component damage such as UFP energy dissipaters) throughout the test program. Comprehensive inspections of the test building will be conducted on both the structural and non-structural systems following significant testing events. The research team is planning for concluding the first phase of the test by April 2023.

Table 3: *As-planned typical testing sequence for a single seismic hazard level*

Test	GM record	Building direction	Comments
1	GM_H1	X	CLT wall response
2	GM_H1	Y	MPP wall response
3	GM_H2	Y	Biaxial comparison
4	GM_H1H2	XY	Biaxial test
5	GM_H1H2V	XYZ	Tri-axial test

Note: H1, H2 and V represent horizontal 1, horizontal 2 and vertical components of a ground motion.

6 KEY RESULTS

At the time of this writing, the building is still undergoing instrumentation, and no seismic tests have been conducted. The research team is expected to complete instrumentation of the structure by March 2023 and complete all testing by June 2023. It is expected that initial results from these tests will be presented in the conference presentation. It is envisioned that key testing results will include the dynamic response of the building and damage inspection outcome after large tests.

7 CONCLUSIONS

The ten-story Tallwood building test program planned in this study represents one of the most significant research efforts in recent years to experimentally validate tall wood building performance during earthquakes. Through extensive collaboration with the mass timber industry partners, the building archetype and construction details included in the test program are also readily implementable in realistic building projects for high seismic regions. While the test results are not available at the time of this paper, key details and the design methodology utilized in this project were introduced.

It is expected that the test building will have resilient performance, which corresponds to negligible damage under frequent earthquakes, negligible structural damage under design level earthquakes, and be quickly repairable under maximum considered earthquakes. The outcome from this test will help advance knowledge on mass timber structural system design and provide increased confidence to the mass timber market in regions with high seismicity around the world.

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