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FULL-SCALE SHAKE TABLE TESTING OF A TWO-STORY MASS-TIMBER ROCKING WALL BUILDING

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ABSTRACT

In order to investigate the seismic performance of open floor plan mass timber building with innovative rocking wall systems, a series of shake table tests on a full-scale two-story mass timber building was conducted at the NHERI@UCSD outdoor shake table in 2017. The test program includes two phases of testing with different rocking wall systems, namely a post-tensioned rocking wall system that was designed to sustain minimum damage during large earthquakes, and a non-post-tensioned rocking wall with replaceable components for easy repair. A total of twenty-seven seismic tests were conducted, with intensities of the input ground motions ranging from service level earthquake and maximum considered earthquake events. The results from the shake table tests indicated that the rocking wall systems tested were able to achieve the performance expectations. There was minimal damage after a series of high intensity excitations. It is feasible to achieve seismically resilient performance in open floor plan mass timber buildings with these innovative lateral systems.

Full-Scale Shake Table Testing of a Two-Story Mass-Timber Rocking Wall Building

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In order to investigate the seismic performance of an open floor plan mass timber building with innovative rocking wall systems, a series of shake table tests on a full-scale two-story mass timber building was conducted at the NHERI@UCSD outdoor shake table in 2017. The test program included two phases of testing with different rocking wall systems, namely a post-tensioned rocking wall system that was designed to sustain minimum damage during large earthquakes, and a non-post-tensioned rocking wall with replaceable components for easy repair. A total of twenty-seven seismic tests were conducted, with the intensities of the input ground motions ranging from service level earthquakes and to maximum considered earthquake events. The results from the shake table tests indicated that the rocking wall systems tested were able to achieve the performance expectations consistent with a resilient design. There was minimal damage after a series of high intensity excitations. It was concluded that it is feasible to achieve seismically resilient performance in open floor plan mass timber buildings with these innovative lateral systems.

Introduction

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 [1]. This panelized product utilizes small lumber glu-laminated in orthogonal layers 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 around the world (e.g. the 10-story Forte building in Melbourne, Australia; the 9-story Stadthaus Building in London, etc.) have highlighted the viability and benefit of tall wood construction. These benefits include a reduction in construction time, reduced demands in foundation thickness, and positive environmental impacts. 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.

The full-scale shake table test program presented in this paper is part of a recently funded National Science Foundation (NSF) project aimed at developing and validating a resilience-based seismic design (RBSD) methodology for tall wood buildings that incorporates high-performance structural

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and non-structural systems and can quantitatively account for building resilience. As shown in Figure 1, the NHERI Tall Wood project includes a series of investigative tests, development of a RBSD procedure, and ultimately a validation test of a ten-story wood building planned in 2020. The full-scale two-story building test presented here is one of the investigative tests during the first year of the project.

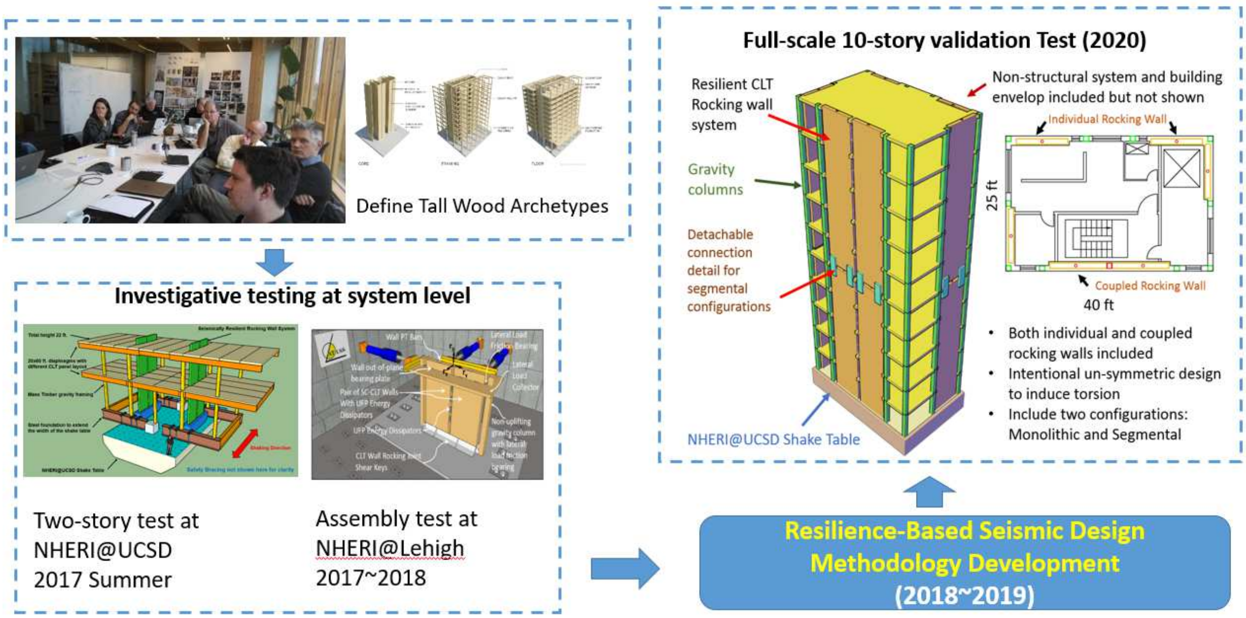

Figure 1. Plan and scope for the NHERI Tall Wood Project

Design and Construction of the Test Specimen

The design of the two-story test specimen was driven by the research questions the team seeks to answer in the investigative testing. Firstly, the CLT rocking wall concept was tested at the component level by the authors earlier [2] but has never been evaluated within a full building, i.e. at the system level. Secondly, the stability and resilience of the mass timber gravity frame system needed to be documented at large drift levels through full-scale testing. Finally, the design and performance of the CLT diaphragm under earthquake excitation needed to be evaluated. Given these objectives, the two-story wood specimen was designed to have an open floor plan supported by a heavy timber gravity frame, two types of diaphragm designs with a relatively high width-to-depth ratio in the direction of lateral loading, and two sets of resilient rocking wall systems that which could be switched out for each phase of testing. Due to the high level of prefabrication, the construction of the gravity system took only four days with the help of two carpenters and a crane operator. The design of the test specimen and selected photos from construction are presented in Figure 2.

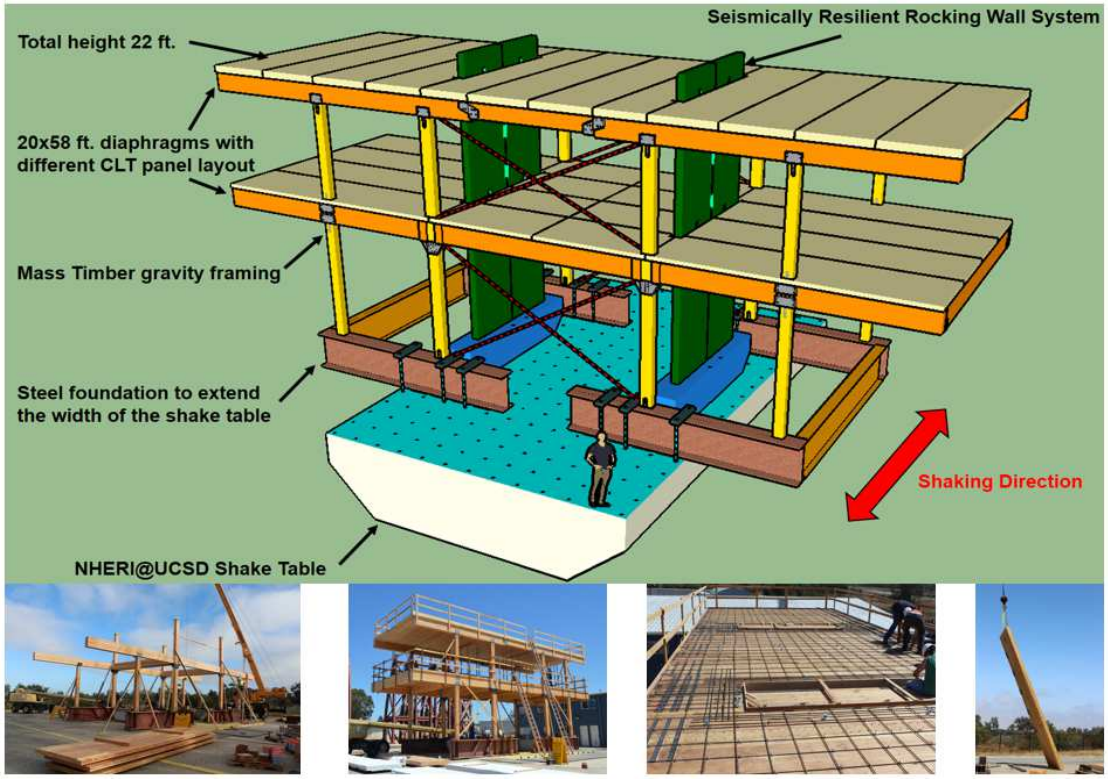

Figure 2. Specimen design and construction

Test Program

The shake table test program included two phases for two rocking wall systems. As shown in Figure 3, the first test phase on post-tensioned rocking wall included 14 shakes, ranging from frequent service level earthquake to maximum considered earthquake. The second phase which consisted of the non-post-tensioned rocking wall with replaceable components included 13 shakes. White noise excitation was implemented between each test in order to identify the natural frequency and vibration modes of the specimen. Damage inspection was conducted after large shakes because the building was essentially undamaged for service level earthquakes.

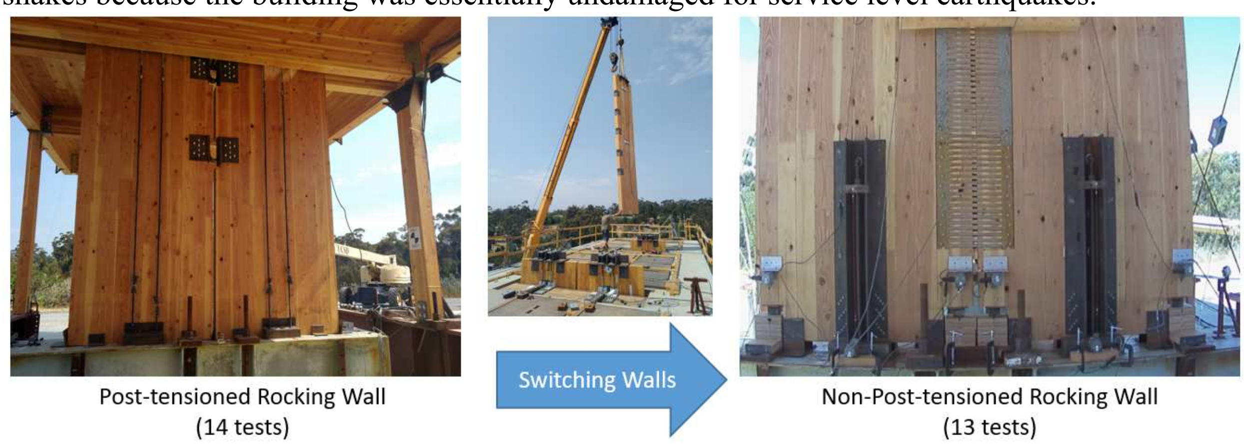

Figure 3. Testing program including two different rocking wall systems

Results and Findings

The building was instrumented heavily with approximately 350 channels. The response of the building will be discussed in the conference presentation. Overall, the damage inspection after all tests revealed very resilient performance, with essentially no visible damage (with some post-tension rod yielding at MCE level excitations) for the post-tensioned rocking wall and only repairable damage to the non-post-tensioned wall at planned locations.

Conclusions

By including a rocking wall system in a mass timber building with an open floor plan, the full-scale test of the two-story specimen answered several key research questions related to structural resilient mass-timber systems, which will facilitate the development of the RBSD procedure and subsequent tests at Lehigh University and the ten-story test program in 2020. The post-tensioned rocking wall only experienced slight post-tension losses in MCE level events and the non-post-tensioned rocking wall was only damaged at the intended replaceable locations. It was confirmed that both systems could be repaired in a relatively short time and resume building structural functionality after major earthquakes. The design of the heavy timber gravity system and the connection between the rocking wall and CLT diaphragm performed very well during all tests. The gravity frame and diaphragm were damage-free after repetitive seismic loading, tolerating large drift levels without stability issues.

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References

1. Pei, S., van de Lindt, J.W., Popovski, M., Berman, J.W., Dolan, J.D., Ricles, J., Sause, R., Blomgren, H., and D.R. Rammer, (2015) "Cross Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation," Journal of Structural Engineering, ASCE, (doi: 10.1061/(ASCE)ST.1943-

541X.0001192).
2. Ganey, R.S. (2015) "M.Sc. Thesis: Seismic Design and Testing of Rocking CLT Walls," University of Washington, Seattle, WA USA.