WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

Resilient Seismic Design of Tall Mass Timber Buildings: Comparison of Two Full-Scale Tri-Axial Shake Table Tests

Prashanna Mishra[1], John W. van de Lindt[2], Shiling Pei[3], Andre R. Barbosa[4], Steve Pryor[5], Jeffrey Berman[6], Barbara G. Simpson[7], Keri L. Ryan[8], Arijit Sinha[9], Patricio A. Uarac P.[10], Morgan McBain[11] Tanner Field[12], Steven Kontra[13], Ludovica Pieroni[14].

ABSTRACT: Advancements in materials, components, and building systems over the past decade have enabled the construction of taller mass timber structures, creating new opportunities for seismic design in mid- and high-rise buildings. This paper presents a systematic comparison of two full-scale shake table test programs—the 10-story NHERI TallWood and the 6-story NHERI Converging Design both conducted at the University of California, San Diego (UCSD) Large High-Performance Outdoor Shake Table (LHPOST). These projects aimed to develop and validate seismic design approaches for wood buildings in high seismic regions. Both structures employed a self-centering mass timber rocking wall system with distributed energy dissipation provided by U-shaped Flexural Plates (UFPs), enabling direct comparison of structural response and design considerations across different building heights. Despite ongoing innovations, many tall timber buildings still rely on concrete cores or steel braced frames for lateral resistance due to a limited number of code-approved timber systems and an industry preference for traditional solutions. This comparative study highlights the performance of timber-based lateral systems under seismic loading and supports their broader adoption in resilient, mid- and high-rise construction.

KEYWORDS: Mass Timber, Resilience, Shake Table Testing, Structural Dynamics.

1 – INTRODUCTION

Increasing interest in sustainable construction has led to a revolution in the use of mass timber for buildings around the world. With advancements in materials, components, and building systems over the past decade, it has become feasible to construct taller mass timber structures, thus reducing their costs to be more in-line with heavier materials [1-8,16]. However, the current reliance on concrete cores or steel braced frames for lateral force resistance systems in tall mass timber buildings reflects limited code-approved mass timber options and an industry more familiar with traditional heavier systems such as steel and concrete. The Natural Hazard Engineering Research Infrastructure (NHERI) TallWood and NHERI Converging Design research projects aimed to address limitations of mass timber lateral force resisting systems (LFRS) by developing and validating resilience-based seismic design methodologies tailored for mass timber LFRS in tall-and mid-rise buildings in high seismic regions. [3-13]

The NHERI TallWood building, as shown in Fig 1(a), was designed using a resilience-based seismic design approach validated through full-scale shake table testing. The shake-table specimen was a 10-story mass timber building and incorporated innovative structural systems including post-tensioned mass timber self centering rocking walls as its LFRS. The building was designed to withstand multiple earthquake events at Design Earthquake (DE) level and Risk-targeted Maximum Considered Earthquake (MCE_R) without suistaining major damage and to be rapidly repairable. The primary objective of that project was to demonstrate the TallWood building can perform resiliently under seismic loads while providing an environmentally sustainable and economically viable alternative to traditional construction materials. The testing program for the NHERI TallWood project conducted at the University of

[1] Mishra, Civil and Environmental Engineering, College of Engineering, Colorado State University, Fort Collins, CO, USA, Prashanna.Mishra@colostate.edu.
2 van de Lindt, Civil and Environmental Engineering, College of Engineering, Colorado State University, Fort Collins, CO, USA, jwv@colostate.edu.
3 Pei, Dept. of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO, USA, spei@mines.edu.
4 Barbosa, Civil and Construction Engineering, College of Engineering, Oregon State University, Corvallis, OR, USA, andre.barbosa@oregonstate.edu.
5 Pryor, Simpson Strong Tie, Dublin, CA, USA.
6 Berman, Civil and Environmental Engineering, University of Washington, Seattle, WA, USA, jwberman@u.washington.edu.
7 Simpson, Civil and Environmental Engineering, School of Engineering, Stanford University, Stanford, CA, USA, bsimpson@stanford.edu.
8 Ryan, Civil and Environmental Engineering, University of Navada, Reno, NV, USA. klryan@unr.edu
9 Sinha, Wood Science & Engineering, College of Forestry, Oregon State University, Corvallis, OR, USA, arijit.sinha@oregonstate.edu
10 Uarac, Civil and Construction Engineering, College of Engineering, Oregon State University, Corvallis, OR, USA, uaracpip@oregonstate.edu
11 McBain, Civil and Environmental Engineering, Stanford University, Stanford, CA, USA, mmcbain@stanford.edu
12 Field, Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA, tanner.field@oregonstate.edu
13 Kontra, Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA, steven.kontra@oregonstate.edu
14 Pieroni, Civil, Environmental, and Geomatic Engineering, University College London, London, UK, ludovica.pieroni.20@ucl.ac.uk

https://doi.org/10.52202/080513-0714

California, San Diego (UCSD) Large High-Performance Shake Table (LHPOST) allowed the comprehensive evaluation of the building performance under various seismic intensity levels.

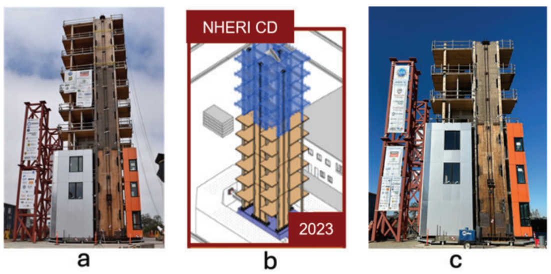

Figure 1: (a) NHERI TallWood Specimen (b) Blue representing the deconstructed floor (c) NHERI Converging Design Specimen

The results validated that mass timber buildings with properly designed LFRS can meet performance-based design objectives, such as low residual drift, limited damage, and rapid post-earthquake recovery [5,14]

Building upon the success of the TallWood project, the NHERI Converging Design project [18] sought to advance the understanding and design of mass timber structures by focusing on optimizing these structures to maximize functional recovery while incorporating sustainable building principles. A central innovation was the adoption of multi-objective optimization, a methodology that integrates various factors such as structural resilience, sustainability, cost-effectiveness, and constructability into the design process [23].

The NHERI Converging Design Project implemented three phases, each investigating distinct lateral force-resisting systems and energy dissipation mechanisms.

Phase 1 focused on integrating U-shaped flexural plates (UFPs) as energy dissipators as shown in Fig 2a with post-tensioned mass timber rocking walls. Reused shear wall panels from the NHERI TallWood Project were reduced from ten to six stories, and UFP sizes and PT forces were updated accordingly. The number and size of UFPs, as well as the post-tensioning (PT) rod forces, were determined using the Direct Displacement-Based Design (DDBD) methodology, which aims to meet performance objectives based on target drift limits and strain compatibility [17]. U-shaped flexural plates, designed to behave inelastically during intense ground shaking, ensured the energy dissipation while adhering to predefined performance criteria [18-19]

Phase 2 introduced buckling-restrained braces (BRBs) as energy dissipators. The N-S direction lateral system of the building was replaced with new Mass Ply Panel (MPP) post-tensioned rocking walls with vertically-oriented BRBs at the base, see Fig 2b. The BRBs were designed based on prototype testing at Oregon State University [16] and anchored compressive and tensile forces through gusset plates, steel side plates, and inclined, fully threaded screws. The MPP walls above the base were designed to remain essentially elastic to enforce a global tilting mode. The design aimed to lower barriers to the less well-established mass timber rocking wall LFRS by using recognized energy dissipators such as BRBs for stable energy dissipation [15,31]

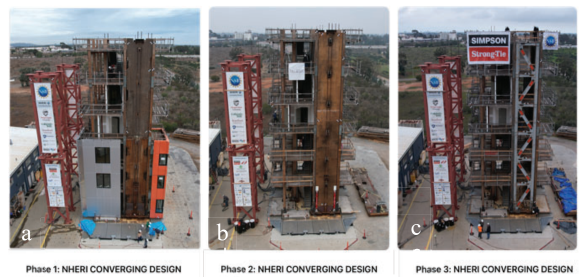

Figure 2: (a) Phase 1: Rocking walls with UFPs, (b) Phase 2: Rocking walls with BRBs, (c) Phase 3: steel Moment Frame with Yield Link Connectors.

Phase 3 replaced the mass timber SCRWs in one principal direction of shaking with a steel moment frame / concentrically braced frame (MF/CBF) with yield-link connectors for energy dissipation, shown in Fig 2c. The yield-link connections used replaceable fuse technology to absorb inelastic demands while keeping primary structural members elastic. Enhanced design procedures addressed higher mode effects for a more uniform drift profile and reduced residual drift. This phase demonstrated the potential of hybrid solutions to effectively address seismic challenges [19,21].

Phase 1 of both major projects used similar lateral force-resisting systems with designs adjusted for the different building heights and masses, thereby allowing for a systematic behavioral comparison of the tall and mid height MT buildings. This paper compares the TallWood 10-story and Phase I of Converging Design, which both had the same lateral force-resisting system type, but different heights and design approaches. The differences in design approach were primarily the number of UFP's, PT rod size, and post-tensioning force.

2 – OVERVIEW OF PROJECTS: DESIGN AND CONSTRUCTION

The NHERI TallWood Project was a groundbreaking initiative aimed at developing and validating a resilience-based seismic design methodology for tall wood buildings. As part of this effort, a full-scale, 10-story mass timber building was constructed and tested on the NHERI@UCSD outdoor shake table. The structure, standing 34.4 meters (113 feet) tall with a floor plan of 84 m² (900 ft²) per level, was designed to represent mixed-use buildings typically found in seismic regions.

https://doi.org/10.52202/080513-0714

The building featured a variety of mass timber panel products across different floors, as shown in Fig 3, with the objective of evaluating the performance of each panel type under dynamic loading.

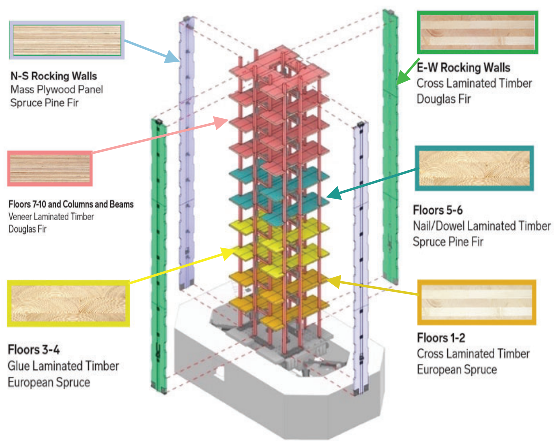

Figure 3: Mass timber structural elements (graphic courtesy of LEVER Architecture)

The first two floor diaphragms incorporated 5-ply Cross-Laminated Timber (CLT) panels, known for their high strength and stiffness in both directions. Glue-Laminated Timber (GLT) panels were used on the third floor to study their parallel behavior, while Nail-Laminated Timber (NLT) panels were installed on the fourth floor to observe their performance under large deformations. The fifth floor was built with Dowel-Laminated Timber (DLT), which is unique for its friction-fit dowels that eliminate the need for adhesives or nails. Finally, the top four floors utilized Veneer Laminated Timber (VLT) panels, which consist of cross-band laminated veneer layers, enhancing dimensional stability.

The structural system incorporated post-tensioned rocking walls as the primary lateral force-resisting elements. These walls were flanked by boundary columns, which provided lateral stability by transferring loads through energy dissipating UFP's as shown in Fig 4. The boundary columns were fabricated using Laminated venner Lumber (LVL) and featured true pin connections at their bases, as shown in Fig 5, to allow controlled rotation during rocking events. The gravity columns were designed with rotation-tolerant beam-to-column connections capable of accommodating up to 0.05 radians of rotation without damage, allowing the structure to undergo drifts of up to 5% without causing damage to the gravity framing system. This detailing helped minimize moment transfer between columns and beams while supporting the overall rocking mechanism of the lateral system [24].

The building's non-structural elements, including prefabricated stair modules and partition walls, were designed to be drift-compatible to reduce damage during seismic events [32-33]. The testing program included ground motions of varying intensities, from DE to MCER events. The rocking wall system, combined with UFP energy dissipation devices and flexible column connections, aimed to enhance the building's seismic resilience by minimizing residual drifts and structural damage.

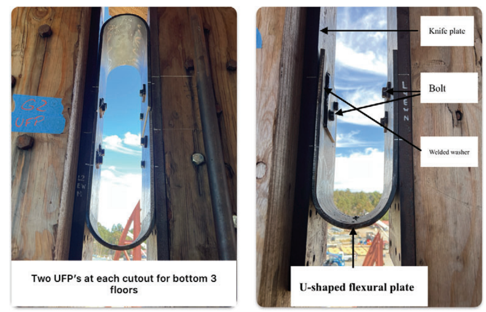

Figure 4: U-shaped Flexural Plate Detail

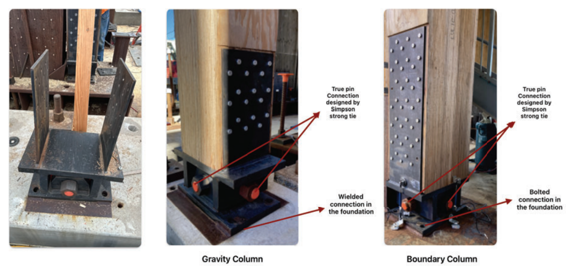

Figure 5: Column Base Connection details

The NHERI Converging Design Project extended the research from the TallWood Project by exploring new lateral force-resisting systems and mass timber configurations. The bottom six stories of the original 10-story TallWood structure were retained, while the top four stories which used VLT panels were deconstructed. The retained portion of the structure maintained key features from the TallWood Project, including the rocking wall system and column layout. The remaining six stories continued to utilize a combination of CLT, GLT, NLT, and DLT panels for the diaphragms, allowing for a comparative analysis of these mass timber systems under seismic loading. The UFPs were integrated into the rocking wall system to evaluate their effectiveness in balancing energy dissipation and re-centering capabilities.

By integrating different mass timber products, innovative lateral systems, and strategically designed column connections, the NHERI TallWood and NHERI Converging Design projects have contributed critical data to the advancement of mass timber seismic design. The research outcomes support the broader adoption of resilient and sustainable tall wood buildings in seismic regions.

2.1 Gravity System Design

The gravity system for the NHERI TallWood Project, which was then used for the NHERI Converging Design Project, was designed to transfer floor loads safely to the foundation while accommodating seismic deformations. The lower six stories of the original TallWood structure were reused for the Converging Design phase, but with modifications to the LFRS, specifically for the rocking walls as required for different phases but Phase 1 used the same rocking wall. The key components of the gravity system included gravity columns, beams, and boundary columns. Boundary columns, positioned adjacent to the rocking walls, were directly connected to the lateral system by UFPs, while gravity columns were distributed throughout the building to support vertical loads, as shown in Fig 6.

The system was designed for typical office live loads of 3.11kN/m^2, with dead loads calculated at 3.09 kN/m^2 based on material properties [22-23]. The gravity components were composed of 1.8E 2650 LVL beams and columns donated by Boise Cascade, meeting a two-hour fire rating per American Wood Council, National Design Specification (NDS) for Wood Construction, Leesburg, VA: AWC, 2018 [27]. Table 1 summarizes the flexural and compressive stress values used in the design. Columns and beams were oriented according to structural performance requirements. Gravity columns were designed for strong-axis bending along the east-west direction, while boundary columns were oriented to provide maximum lateral support. This configuration ensured compatibility with the LFRS. A detailed evaluation of the structural behavior under fire conditions was also performed, with demand-to-capacity ratios (D/C) assessed before and after fire exposure Table 2

Column bases were engineered by Simpson Strong-Tie to function as true pin connections, allowing for base rotation about the two primary orthogonal axis directions while maintaining vertical load stability. Boundary columns were bolted to the foundation beam, and gravity columns were welded to the foundation, further enhancing stability during dynamic loading events. The beam-to-column connections incorporated dowel and slotted hole mechanisms to minimize moment transfer and allow for drift-compatible behavior. Fig 7 demonstrates the beam-column connection, including strategically designed slotted holes fabricated by Simpson Strong-Tie [24,28].

Table 1: Design Parameters

Design Parameters	
Flexural Stress (Fb)	18.27 MPa
Compressive Stress (Fc)	20.68 MPa
True MOE (E)	12.41 GPa
Apparent MOE ($E_{apparent}$)	11.72 GPa

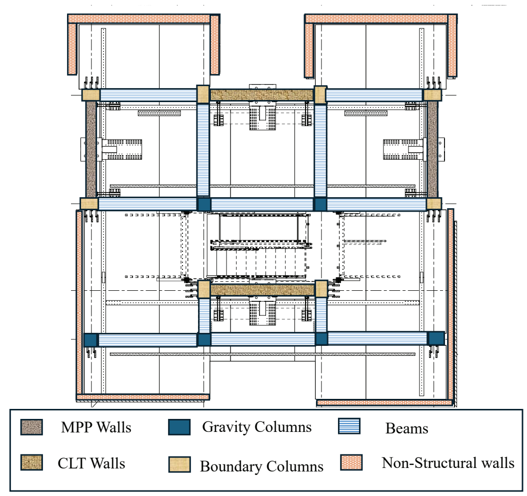

Figure 6: Typical Floor Plan with Structural elements

**Note: Non-structural components were only installed on Floors 1 through 3.*

Table 2: Member Detail

Member Sizes				
Members	**Cross section (mm)**	**Length (m)**	**D/C ratio before fire**	**D/C ratio after fire**
Columns (Floor 1-2)	311 x 381	43.89 m	0.576	1.041
Columns (Floor 3-6)	311 x 343	80.47 m	0.512	1.031
Columns (Floor 7-10)	311 x 305	80.47 m	0.288	0.677
Boundary Columns	311 x 457	273.2 m	0.480	0.752
Beams	311 x 343	294.5 m	0.459	0.732

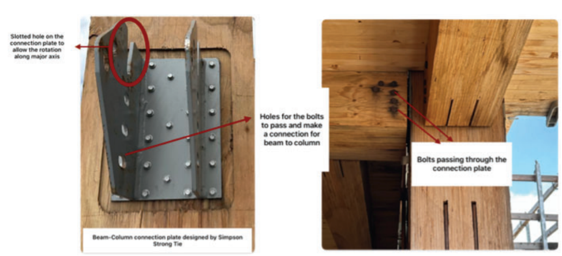

Figure 7: Beam Column Connection detail.

https://doi.org/10.52202/080513-0714

2.2 Lateral System Design

The lateral force-resisting system (LFRS) was a central feature of the design, intended to control seismic drift and minimize structural and non-structural damage during major earthquakes. Both projects utilized post-tensioned mass timber rocking walls as the primary lateral elements. These walls, extending from the base to the roof, were designed to re-center after seismic events, dissipating energy through UFPs installed at the wall boundaries.

The seismic design considered hazard levels for a site in Seattle, Washington, which experiences both crustal and subduction earthquakes. Hazard parameters, including were derived from the ATC Hazards by Location Tool and the USGS 2014 Earthquake Source Model. The short-period (S_{MS}) and one-second (S_{M1}) spectral accelerations were calculated as 1.65g and 0.72g, respectively. Uniform Hazard Spectra (UHS) were generated for return periods ranging from 43 to 975 years and are shown in Fig 8. These spectra informed the selection of ground motions used in the shake table testing[26].

Nonlinear Response History Analyses (NLRHA) were conducted during the design phase to establish drift limits, define damage states, and set performance objectives. The design aimed to balance structural resilience with drift demands, using component-specific tolerances to ensure that non-structural systems such as facades, partition walls, and stairs could maintain serviceability and reusability under high-intensity ground motions without requiring full replacement or major repairs [23]. These objectives were achieved through close collaboration with industry partners, with full-scale testing validating the effectiveness of the design approach. The hazard considered for Phase I of NHERI Converging Design Project are illustrated in Fig 9, highlighting its site-specific response spectra and performance under varying seismic intensities.

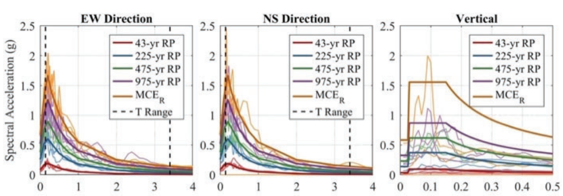

Figure 8: Response Spectra of NHERI TallWood Project[26]

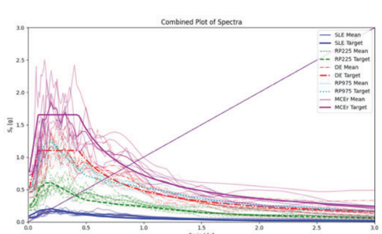

Figure 9: Response spectra of NHERI Converging Design Project[20]

3 – EXPERIMENTAL SETUP

The experimental setup for the projects involved constructing and testing full-scale mass timber buildings on the LHPOST6 at NHERI@UC San Diego. The shake table, capable of applying six degrees of freedom (three translational and three rotational components), allowed researchers to simulate realistic seismic ground motions. Both projects employed dynamic testing with uni-, bi-, and tri-axial ground motions to capture a comprehensive response under varying seismic intensities. These tests followed acceleration control protocols with input ground motions based on real earthquake records [25]

In both projects, the applied ground motions were scaled to different hazard levels representative of 43-year return period, a 225-year return period, DE, and MCE_R intensities as defined by ASCE 7-16 [29] for a seismic site in Seattle, Washington. These tests aimed to evaluate both elastic and inelastic structural performance, including energy dissipation, re-centering capabilities, and drift behavior. The NHERI TallWood Project featured a sequence of 118 tests on a 10-story mass timber structure, while the NHERI Converging Design Project involved 104 tests on a 6-story building during Phase 1.

The NHERI TallWood test program included a greater focus on overall building performance, with multiple test phases designed to evaluate the cumulative effects of seismic events through progressive hazard levels. The NHERI Converging Design project's Phase 1 specifically focused on optimizing energy dissipation through UFPs installed at the rocking wall interfaces. This phase sought to validate the performance of UFPs in a post-tensioned system by applying a variety of ground motions with PGAs reaching up to 0.79 g.

Ground motions in both projects were bracketed by white noise excitations to monitor changes in global stiffness and damping, and visual inspections were conducted between tests to document both structural and non-structural damage. These steps enabled assessments of re-centering capabilities and connection integrity under seismic loading in both the NHERI Tallwood and Converging Design projects.

Instrumentation was integral to the test programs, with an extensive array of sensors installed throughout the structures. Accelerometers were used to measure the dynamic response of the buildings, including acceleration at different floor levels and locations. String potentiometers were installed to capture displacements in UFPs, while linear potentiometers were positioned to measure uplift at wall bases, strain in key structural components, and relative movements between diaphragms and columns. Push potentiometers monitored potential separation at splice and beam-column connections. Strain gauges were placed on post-tensioned rods, wall braces, and steel interfaces to measure axial and shear forces. Load cells at the base and roof levels of post-tensioned bars continuously tracked

https://doi.org/10.52202/080513-0714

changes in force during both construction and seismic testing. The comparison instrumentation used is shown in the Fig 10.

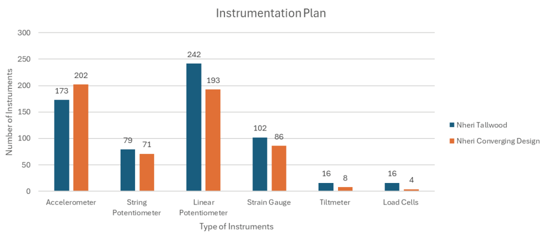

Figure 10: Instrumentation Plan Detail

Robust instrumentation enabled high-resolution data collection, allowing for a comprehensive evaluation of structural behaviour, including acceleration, displacement, strain, and inter-story drift. These data provided critical feedback for validating resilience-based design methodologies and understanding the performance of mass timber buildings in seismic regions. Despite being conducted as separate projects, both tests shared three common ground motions, enabling a comparative analysis of their performance under similar seismic conditions.

4 – RESULTS

Acceleration Response

Figure 11 presents the acceleration response histories for the NHERI TallWood (Fig. 11A, red) and NHERI Converging Design (Fig. 11B, blue) structures subjected to MCEr Ferndale ground motions (MID 90 for TallWood and MID 38 for Converging Design). For TallWood, acceleration data is shown from Level 7, which experienced the highest accelerations due to multiple modes being excited, while roof-level data is shown for Converging Design.

The peak acceleration observed in the TallWood structure was 20.28 m/s² at 10.73 seconds, whereas the Converging Design structure recorded a slightly lower peak of 18.58 m/s² at 10.55 seconds. Despite its taller and more flexible configuration, TallWood exhibited a marginally higher peak acceleration, but as mentioned above, this occurred at level 7 and not the roof during higher modal excitation.

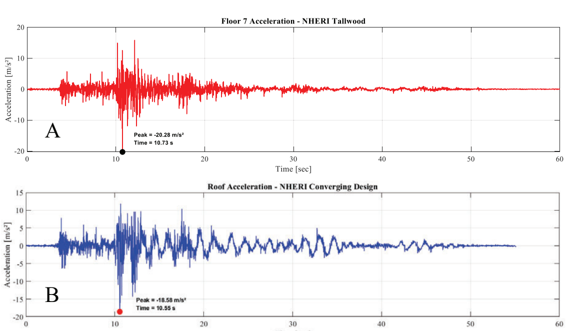

Figure 11: Comparision plot of maximum acceleration

Displacement Comparison

The roof displacement response in Fig 12 reveals that the Tallwood structure (red) also undergoes larger peak displacements, reaching ±279 mm, compared to ±203 mm in the Converging Design structure (blue). Although both structures display a similar number of oscillation cycles, Tallwood's greater amplitude and broader waveform reflect its longer fundamental period (1.95 seconds) and increased flexibility. Meanwhile, the Converging Design structure demonstrates faster decay of oscillations, indicative of higher damping efficiency and more effective energy dissipation. These comparisons underscore how system stiffness, height, and energy dissipation strategies influence both acceleration and displacement demands under strong seismic excitation.

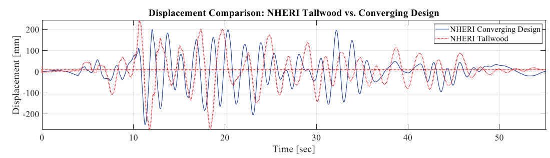

Figure 12: Comparision plot of Roof Displacement

The comparison of natural periods between the NHERI TallWood and NHERI Converging Design structures highlights fundamental differences in their dynamic behavior. The NHERI TallWood structure exhibits longer natural periods—1.95 seconds in the X direction and 2.03 seconds in the Y direction—indicating a more flexible lateral system, as expected. This flexibility results in greater dynamic amplification at higher elevations during seismic excitation. The small difference between the two periods suggests that stiffness is relatively uniform in both directions, leading to a balanced response under bidirectional ground motion.

In contrast, the NHERI Converging Design structure demonstrates significantly shorter natural periods—1.08 seconds in the X direction and 1.34 seconds in the Y direction, reflecting a stiffer structural system optimized to limit lateral deformations and reduce resonance effects. The greater disparity between the X and Y periods suggests non-uniform stiffness distribution, likely influenced by differences in lateral force-resisting system configurations. While this increased stiffness effectively reduces displacement demands, it results in greater acceleration amplification, as seismic forces are transferred more directly and with reduced deformation capacity through the structure.

Base Shear Response

The base shear response history comparison, as shown in Fig 13, provides insights into the seismic force distribution characteristics of the NHERI TallWood and NHERI Converging Design structures. The NHERI TallWood structure (red) exhibits a peak base shear of 748kN, while the NHERI Converging Design structure (blue) records a lower peak base shear of 607 kN. While

https://doi.org/10.52202/080513-0714

these absolute values indicate that TallWood sustained a greater total seismic force, the Normalized Base Shear (NBS), which accounts for total building weight, provides a more meaningful comparison of the seismic force demand per unit mass. The NHERI TallWood structure's NBS is 25.3%, whereas the NHERI Converging Design structure's NBS is 41.5%, indicating that the stiffer Converging Design structure attracted a greater seismic force relative to its weight.

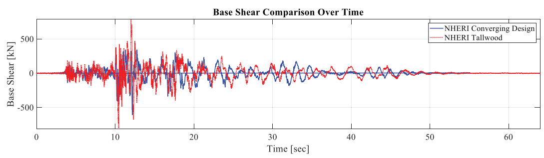

Figure 13: Base Shear Comparision Plot

The time history response further illustrates the differences in force distribution and period effects. The NHERI Tallwood structure, with its longer fundamental period (1.95s in X and 2.03s in Y), undergoes greater lateral deformations and exhibits a more gradual oscillatory response. The larger total base shear observed in Tallwood is primarily a result of its greater overall building mass, despite having a lower normalized base shear compared to the NHERI Converging Design. This behavior is reflected in the sustained base shear oscillations in the red curve, indicating prolonged energy input and dissipation over time.

Conversely, the NHERI Converging Design structure, with its shorter fundamental period (1.08s in X and 1.34s in Y), exhibits sharper, higher-frequency base shear fluctuations, as seen in the blue curve. This aligns with its stiffer lateral system, which results in higher inertial force demands per unit weight, as indicated by its higher normalized base shear.

5 – SUMMARY AND CONCLUSIONS

This study presents a comparative summary assessment of the seismic response of the NHERI TallWood and NHERI Converging Design buildings, focusing on differences in roof acceleration, displacement, base shear, and inter-story drift. The NHERI TallWood structure, with its longer fundamental period and increased flexibility, experienced higher accelerations, roof displacements, and drifts primarily due to amplified higher-mode effects. These responses highlight the need for careful drift control strategies and drift-sensitive detailing in tall mass timber systems.

In contrast, the NHERI Converging Design structure, with its shorter period, lower height, and effective energy dissipation through UFPs, demonstrated lower roof accelerations and displacements, along with faster decay of dynamic response. However, it attracted a higher seismic force relative to its weight, with NBS of 41.5% compared to 25.3% in TallWood. These findings are consistent with ASCE 7-16 Section 12.8.6, which states that longer-period structures are assigned lower design forces but tend to undergo greater deformation. Overall, the comparison underscores the importance of balancing deformation control, energy dissipation, and lateral strength in the design of resilient mass timber systems.

A key observation from this study is the inaccuracy of the ASCE 7 [29] empirical period estimation methods for mass timber rocking wall buildings. The NHERI TallWood structure exhibits a longer period than ASCE 7-16 predicts, leading to an overestimation of base shear and seismic force demands. In contrast, the NHERI Converging Design structure, with its shorter fundamental period, is better approximated by ASCE 7 empirical models, though potential underestimation of damping effects in mass timber structures may still influence the accuracy of force predictions. This discrepancy underscores the need for refined period estimation models that accurately capture the stiffness, damping, and energy dissipation characteristics of mass timber rocking wall structures. To enhance the seismic resilience of mass timber buildings, future research should focus on developing refined period estimation models, integrating supplemental damping devices, and optimizing connection detailing to control drift and acceleration amplification. Additionally, performance-based seismic design (PBSD) approaches tailored for mass timber structures should be explored to achieve an optimal balance between force reduction, deformation control, and energy dissipation. These findings contribute to the advancement of mass timber seismic design, supporting the development of more resilient and sustainable timber structures in high-seismic regions

6 – ACKNOWLEDGEMENTS

The structural system scope of this project is sponsored by NSF Grants No. 1635227, 1634628, 1634204. The nonstructural component scope of this project is sponsored by NSF Grant No. CMMI-1635363 and USFS Grant No. 19-DG-11046000-16. The use and operation of NHERI shake table facility is supported by NSF through Grant No. CMMI-2227407. The test program also received great technical, financial, and material donation support from industry leaders both with the U.S. and internationally; please see the full list of sponsors at http://nheriTallWood.mines.edu/collaboration.html. The project team is very grateful for this support.

This project is being executed under the National Science Foundation CMMI award numbers 2120683, 2120684, 2120692. Support from the TallWood Design Institute/USDA Agricultural Research Service Award 58-0204-9-165 are also acknowledged. The findings, opinions, recommendations, and conclusions in this presentation do not necessarily reflect the views of others, including the sponsors. Please see the full list of sponsors at https://TallWoodinstitute.org/converging-design-partners/. The project team is very grateful for this support.

7. REFERENCES

[1] Granello, G., Palermo, A., Pampanin, S., Pei, S., & van de Lindt, J. (2020). "Pres-Lam Buildings: State-of-the-Art." Journal of Structural Engineering, 146(6), 04020085. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002603

[2] Abed, J., Rayburg, S., Rodwell, J., & Neave, M. (2022). "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures." Sustainability, 14(9), 5570. https://doi.org/10.3390/su14095570

[3] Mar, D. (2010). "Design Examples using Mode Shaping Spines for Frame and Wall Buildings." In Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering.

[4] Palermo, A., Pampanin, S., & Buchanan, A. (2006). "Experimental Investigations on LVL Seismic Resistant Wall and Frame Subassemblies." In Proceedings of First European Conference on Earthquake Engineering and Seismology

[5] Pei, S., Ryan, K. L., Berman, J. W., van de Lindt, J. W., Pryor, S., Huang, D., Wichman, S., Busch, A., Roser, W., Wynn, S. L., Ji, Y., Hutchinson, T., Sorosh, S., Zimmerman, R. B., & Dolan, J. (2024). "Shake-Table Testing of a Full-Scale 10-Story Resilient Mass Timber Building." Journal of Structural Engineering, 150(12), 04024183. https://doi.org/10.1061/JSENDH.STENG-13752

[6] Iqbal, A., Smith, T., Pampanin, S., Fragiacomo, M., Palermo, A., & Buchanan, A. H. (2016). "Experimental Performance and Structural Analysis of Plywood-Coupled LVL Walls." Journal of Structural Engineering, 142(2), 04015123. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001383

[7] Brown, J. R., Li, M., Palermo, A., Pampanin, S., & Sarti, F. (2021). "Experimental Testing of a Low-Damage Post-Tensioned C-Shaped CLT Core-Wall." Journal of Structural Engineering, 147(3), 04020357. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002926

[8] Akbas, T., Sause, R., Ricles, J. M., Ganey, R., Berman, J., Loftus, S., Dolan, J. D., Pei, S., Van De Lindt, J. W., & Blomgren, H.-E. (2017). "Analytical and Experimental Lateral-Load Response of Self-Centering Posttensioned CLT Walls." Journal of Structural Engineering, 143(6), 04017019. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001733

[10] Ganey, R., Berman, J., Akbas, T., Loftus, S., Daniel Dolan, J., Sause, R., Ricles, J., Pei, S., van de Lindt, J.W.,, & Blomgren, H.-E. (2017). "Experimental Investigation of Self-Centering Cross-Laminated Timber Walls." Journal of Structural Engineering, 143(10), 04017135. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001877

[11] Blomgren, H.-E., Pei, S., Jin, Z., Powers, J., Dolan, J. D., van de Lindt, J. W., Barbosa, A. R., & Huang, D. (2019). "Full-Scale Shake Table Testing of Cross-Laminated Timber Rocking Shear Walls with Replaceable Components." Journal of Structural Engineering, 145(10), 04019115. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002388

[12] Pei, S., van de Lindt, J. W., Barbosa, A. R., Berman, J. W., McDonnell, E., Daniel Dolan, J., Blomgren, H.-E., Zimmerman, R. B., Huang, D., & Wichman, S. (2019). "Experimental Seismic Response of a Resilient 2-Story Mass-Timber Building with Post-Tensioned Rocking Walls." Journal of Structural Engineering, 145(11), 04019120. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002382

[13] Zimmerman, R. B., Blomgren, H.-E., McCutcheon, J., & Sinha, A. (2020). "Catalyst - a Mass Timber Core Wall Building with High Ductility Hold-Downs in a Seismic Region." In Proceedings of World Conference on Timber Engineering, Santiago, Chile.

[14] Wichman, S., J. W. Berman, and S. Pei. 2022. "Experimental investigation and numerical modeling of rocking cross laminated timber walls on a flexible foundation." Earthquake Eng. Struct. Dyn. 51 (7): 1697–1717. https://doi.org/10.1002/eqe.3634.

[15] Dong, W., Li, M., Lee, C.-L., MacRae, G., & Abu, A. (2020). "Experimental testing of full-scale glulam frames with buckling restrained braces." Engineering Structures, 222, 111081. https://doi.org/10.1016/j.engstruct.2020.111081

[16] Araújo R., Gustavo A. (2022). "Design, Experimental Testing, and Numerical Analysis of a Three-Story Mass Timber Building with a Pivoting Spine and Buckling-Restrained Energy Dissipators." Master's Thesis Oregon State University.

[17] van de Lindt, J. W., J. Furley, M. O. Amini, S. Pei, G. Tamagnone, A. R. Barbosa, D. Rammer, P. Line, M. Fragiacomo, and M. Popovski. 2019. "Experimental seismic behavior of a two-story CLT platform building." Eng. Struct. 183 (Mar): 408–422. https://doi.org/10.1016/j.engstruct .2018.12.079.

[18] Seyed Hossein Zargar, S.; Patricio Uarac,;Andre R. Barbosa, A.; Arijit Sinha; Barbara Simpson;John W. van de Lindt and Nathan C. Brown "Comparing Optimization Approaches in the Direct Displacement-Based Design of Tall Mass Timber Lateral Systems" (https://ascelibrary.org/doi/epdf/10.1061/9780784485248.085)

[19] Barbosa, A., B. Simpson, J. van de Lindt, A. Sinha, T. Field, M. McBain, P. Uarac, S. Kontra, P. Mishra, L. Gioiella, L. Pieroni, S. Pryor, B. Saxey (2025). "Shake table testing program for mass timber and hybrid resilient structures datasets for the NHERI Converging Design

 https://doi.org/10.52202/080513-0714

project", in Shake table testing program of 6-story mass timber and hybrid resilient structures (NHERI Converging Design project). DesignSafe-CI. https://doi.org/10.17603/ds2-rh8q-rn95

[20] Uarac P. P. A., Barbosa, A. R., Sinha, A., van de Lindt, J. W., Simpson, B. G. (202X). “Full-Scale Shake Table Testing of a Resilient Six-Story Mass Timber Building with Self-Centering Rocking Walls.” Journal of Structural Engineering.

[21] Field, T., Barbosa, A.R., Pryor, S., Simpson, B., Uarac, P.P.A, Sinha, A., van de Lindt, J.W. (2025). Shake-Table Testing of a Full-Scale Six-story Resilient Mass Timber-Steel Hybrid Building. Submitted to Journal of Structural Engineering

[22] Busch, A. (2023). “Design and Construction of Tall Mass Timber Buildings With Resilient Post-Tensioned Mass Timber Rocking Walls” Ph.D. Thesis, Colorado School of Mines.

[23] Huang, D. (2023). Optimized Seismic Design and Dynamic Response Analysis of Mass Timber Rocking Wall Lateral System. Ph.D. Thesis, Colorado School of Mines.

[24] Pryor, S., Pei, S., van de Lindt, J., and Huang, D. (2024). “Seismically Resilient Connections for Mass Timber Buildings.” In Proceedings of 18th World Conference on Earthquake Engineering, Milan, Italy.

[25] Pei, S., J. W. van de Lindt, A. R. Barbosa, J. W. Berman, E. McDonnel, J. D. Dolan, H. E. Blomgren, R. B. Zimmerman, D. Huang, and S. Wichman. 2019. “Experimental seismic response of a resilient 2-story mass-timber with post-tensioned rocking walls.” J. Struct. Eng. 145 (11): 04019120. https://doi.org/10.1061/(ASCE)ST.1943-541X .0002382.

[26] Wichman, S. 2023. “Seismic behavior of tall rocking mass timber walls.” Ph.D. thesis, Dept. of Civil and Environmental Engineering, Univ. of Washington.

[27] American Wood Council, *National Design Specification (NDS) for Wood Construction*, Leesburg, VA: AWC, 2018.

[28] Pryor, S., Pei, S., van de Lindt, J. W., and Huang, D. (2024). “Seismically resilient connections for mass timber buildings.” *Proc., World Conf. on Earthquake Engineering*, Tokyo, International Association of Earthquake Engineering.

[29] American Society of Civil Engineers (ASCE). (2017). Minimum design loads and associated criteria for buildings and other structures (ASCE/SEI 7-16). Reston, VA: American Society of Civil Engineers.

[30]Araújo R., G. A., Simpson, B. G., Barbosa, A. R., Pieroni, L., Ho, T. X, Orozco O., G. F., Miyamoto, B., and Sinha, A. Experimental and Numerical Simulation of a Three-Story Mass Timber Building with a Pivoting Wall and Buckling-Restrained Boundary Elements. 2025 (submitted to the Journal of Structural Engineering).

[31] McBain, M., Simpson, B., Araújo, R. G. A., Pieroni, L., Barbosa, A. R., van de Lindt, J. W., Sinha, A., Brown, N., Kontra, S., Mishra, P., Gioiella, L., Sorosh, S., Hutchinson, T., Pryor, S., Field, T., & Uarac, P. (2024, September). Shake table testing of a six-story, full-scale, mass timber rocking wall using buckling-restrained boundary elements as energy dissipators [Conference presentation]. World Conference on Earthquake Engineering, Milan, Italy

[32] Roser, W., Wichman, S., Ji, Y.-E., Wynn, S. L., Ryan, K., Berman, J. W., Hutchinson, T. C., & Pei, S. (2023). *Evaluation of Non-structural Walls with Drift-Compatible Details in a 10-Story Mass Timber Building Shake Table Test*. In *Fifth International Workshop on the Seismic Performance of Non-Structural Elements (SPONSE)*.

[33] Sorosh, S., Zhang, J., Hutchinson, T. C., Ryan, K. L., Smith, K. W., Kovac, A., Pei, S., Barbosa, A. R., & Simpson, B. (2024, December). Detailing for seismically resilient steel stair systems: Validation in the mass timber (10 and 6-story) programs (Paper No. 7-2). 18th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience (ATC 15-17 Workshop), San Diego, CA