Journal of Physics: Conference Series **2647** (2024) 182044 | doi:10.1088/1742-6596/2647/18/182044

DYNAMIC CHARACTERIZATION OF A FULL-SCALE THREE-STORY MASS TIMBER BUILDING STRUCTURE

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Keywords: ambient vibration, dynamic testing, mass timber, output-only identification, structural dynamics, system identification.

Abstract. *A veneer-based engineered wood product known as Mass Ply Panels (MPP) was recently introduced and certified per ANSI-PRG 320. A full-scale three-story mass timber building structure was constructed and tested at Oregon State University to demonstrate the potential of MPP in the design of resilient, structural lateral force-resisting systems. The building structure comprised MPP diaphragms, laminated veneer lumber (LVL) beams and columns, and an MPP rocking wall design. Two opportunistic vibration tests were performed to characterize the dynamic properties of the structure. First, an implosion of a stadium within 600 m of the building location was used as the main excitation source, during which bi-directional horizontal acceleration data were collected for approximately 18 seconds. Second, an ambient vibration test was conducted to collect horizontal acceleration data for one hour. In both tests, sixteen accelerometers were used to measure the response of the structure. Modal features were extracted using an output-only method and compared with the estimates from a finite element model. Lessons learned can be used to inform future modeling efforts of a mass timber building to be tested on the Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at the University of California San Diego high-performance outdoor shake table.*

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1 INTRODUCTION

Mass timber buildings are a type of wooden structure that use prefabricated engineered wood products, such as cross-laminated timber (CLT) panels, mass ply panels (MPP), glued-laminated (glulam) timber beams, and/or laminated veneered lumber (LVL) beams. These buildings are gaining popularity due to their low carbon footprint and aesthetic appeal. However, as with any structure, it is essential to ensure its safety and resilience against various loads, including wind, seismic, and dynamic loads, and there is little data on the vibration characteristics of these structures.

Several experimental programs were developed to study the seismic performance of CLT wall systems in New Zealand, Europe, and North America. These programs focused primarily on the performance of panels for lateral force–resisting systems [1–15]. A few studies focused on the development of rocking wall systems, which was a concept that originated from research in precast concrete [16–20] and was successfully adapted to timber systems over the last 15 years [8, 21–32].

As CLT-wall systems become better understood due to the large number of experimental tests performed to date, there still is relatively small amount of data that exists on the dynamic, modal features, such as natural frequencies, damping, and mode shapes, of these structural systems. Operational modal analysis (OMA) is a technique that can be used to determine the modal features of structural systems by analyzing their dynamic response due to ambient or forced excitations. This technique has been widely used in various engineering fields, including characterization of the vibration properties of civil engineering structures both in-situ [33] and as part of experiments performed on shake-table tests [19, 31, 34]. In recent years, OMA has gained increased attention in the assessment of mass timber buildings due to the growing interest in using timber as a sustainable and renewable construction material. Overall, OMA is a powerful tool that can be used to improve the design and safety of mass timber buildings, enabling engineers to harness the full potential of this sustainable and innovative construction material.

The main objective of this paper is to present findings on system identification of a full-scale three-story structure that was tested at the Emmerson Laboratory at Oregon State University. The system consists of a rocking, self-centering MPP wall structural design solution summarized in this paper. Prior installation of the actuators used to test the structure to quasi-static cyclic loading, two opportunistic dynamic tests were performed to characterize the modal features of the structure. First, an implosion of a stadium within 600 m of the building location was used as the main excitation source, during which bi-directional horizontal acceleration data were collected. Second, ambient vibration testing was conducted to collect horizontal acceleration data for one hour. In both tests, data from sixteen accelerometers were used to estimate modal features. One OMA, output-only method for structural identification, is used based on lessons learned in a previous ambient vibration study [33]. The modal parameters estimated from the testing program are also compared with a linear finite-element model that is used to validate the modal identification results and study the performance of the system identification methods for this MPP rocking structures. Lastly, the modal results provide benchmark data that can be used in future designs of MPP rocking structures, including the estimation of initial and secant stiffnesses that can be used in the design of these structural systems.

2 MATERIALS AND METHODS

2.1 Building description

As part of a multi-phase research project, a full-scale three-story building specimen was designed for a site located in Seattle, WA [35] and constructed at Oregon State University A.A. "Red" Emmerson Advanced Wood Products Laboratory [36]. The specimen had a footprint of 12.2 m by 12.2 m with a total height of 9.1 m. The building structure comprised mass ply panels (MPP) diaphragms and walls, and laminated veneer lumber (LVL) beams and columns. In the East-West (EW) direction, the MPP walls of the lateral force-resisting systems (LFRS) were connected using prescribed angle connectors [37], while in the North-South (NS) direction, the LFRS consists of MPP, high-strength post-tensioned rods connecting the top of the panel to the foundation, and U-shaped flexural plates (UFPs) that provide energy dissipation capabilities attached between the MPP and boundary steel columns (Figure 1).

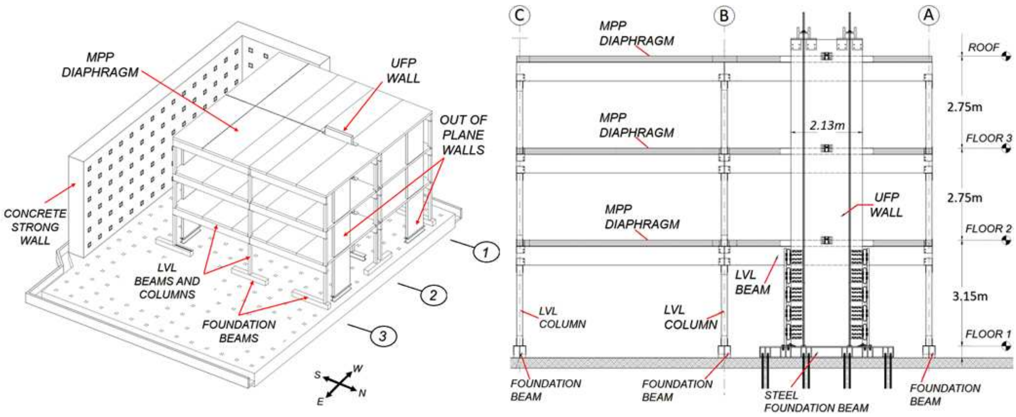


Figure 1: (a) 3D Revit model for the three-story building, (b) Elevation of axis 2.

2.2 Instrumentation setup

A set of 16 uniaxial PCB model 393B04 accelerometers was used. The uniaxial accelerometers have ~1,000 mV/g sensitivity, an acceleration measurement range of ± 5 g peak, a frequency range of 0.06 to 450 Hz, and a broadband resolution of 0.000003 g root mean square (RMS) [38]. The accelerometers were connected through coaxial cables to a portable data acquisition system (National Instruments, NI cDAQ – 9174), which transmitted the RAW data to a laptop computer with NI Labview SignalExpress 2013 software [39]. The accelerometers were attached to the underside of the MPP floors using screwed metal brackets in the locations shown in Figure 2. Six of the 16 accelerometers were attached to the roof, five to the third-floor level, and five to the second-floor level.

Two dynamic tests were performed to characterize the dynamic properties of the structure. First, on January 7th of 2022, as part of the project to complete the construction of the Oregon State University's Reser Stadium [40], the stadium's westside was imploded (Figure 3). This implosion was used as the primary excitation source over the specimen at the Emmerson Laboratory, located at approximately 600 m in a straight line (Figure 4), during which bi-directional horizontal acceleration data were collected for approximately 18 seconds. Second, an ambient vibration test was conducted to collect horizontal acceleration data for more than one hour saved in 13 subsamples of 290 seconds. For both tests, the data were collected at a sampling frequency of 1,706.67 Hz.

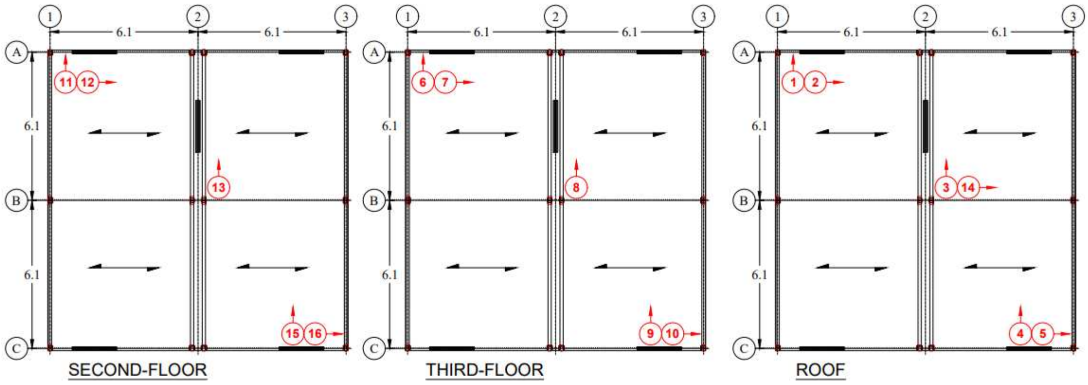
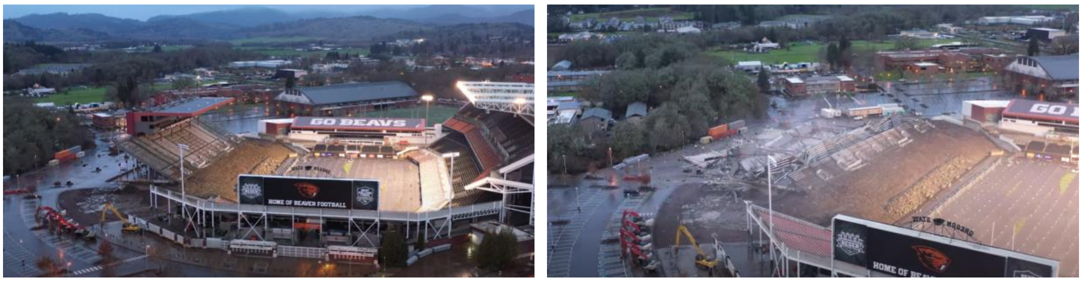


Figure 2: Floor level plans showing approximate locations of the accelerometers marked 1–16.



(a) (b)

Figure 3: Oregon State University's Reser Stadium (a) before implosion (b) after implosion. Implosion was on January 7, 2022 [41, 42].

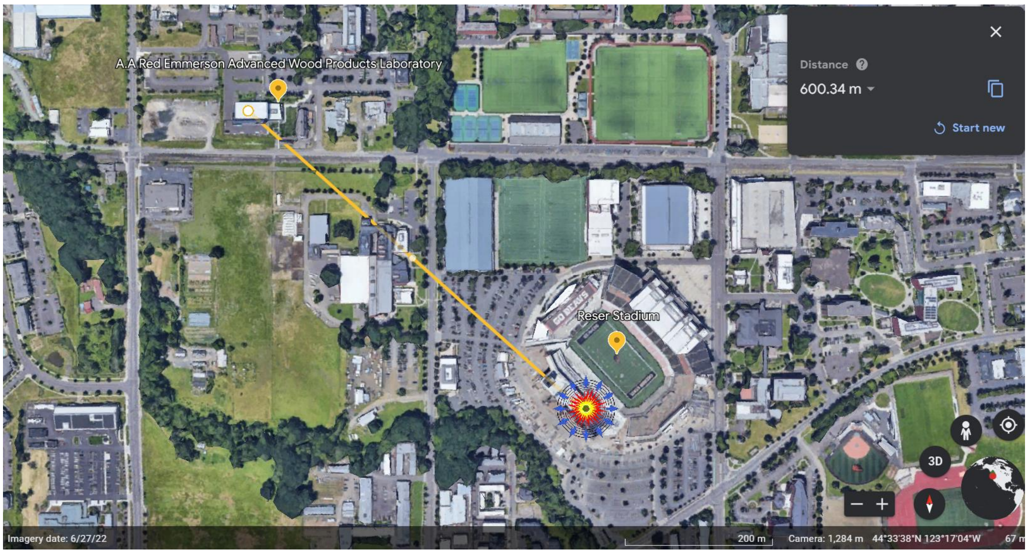


Figure 4: Satellite view of Reser Stadium and Emmerson Laboratory locations [43].

2.3 Data processing

Data were analyzed using the enhanced frequency domain decomposition (EFDD) [44] available in ARTeMIS Modal Pro [45]. For the one-hour ambient vibration, each subsample was decimated at 17.07 Hz, upper-frequency limit considered adequate for capturing the first few natural frequencies of the specimen, then a Butterworth filter [46] of order eight was employed with band-pass of 1 to 10 Hz to target the specific segments of the desired frequency spectrum. For the implosion measurement (e.g. Figure 5), the signal was decimated at 85.33 Hz [47], then a Butterworth filter of order eight was employed with a low-pass of 20 Hz [48].

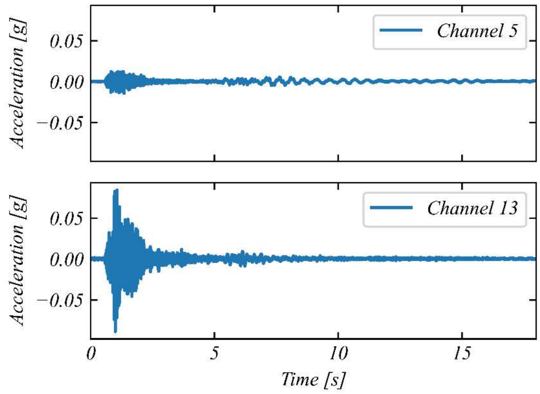


Figure 5: Implosion measurements.

2.4 Finite element model

Currently, efforts have been focused on developing a finite element model to describe the specimen's behavior in the NS direction to replicate the structure's test under quasi-static cyclic loading. A two-dimensional (2D) finite element model was developed in OpenSees [49] to characterize the building geometry shown in Figure 1b. The gravity system, along with the beam-to-column connection and the MPP wall, were modeled as elastic elements, while the post-tensioned rods and UFPs were modeled as nonlinear elements (Figure 6). A set of nonlinear springs were placed between the base of the wall and the foundation to represent the rocking behavior.

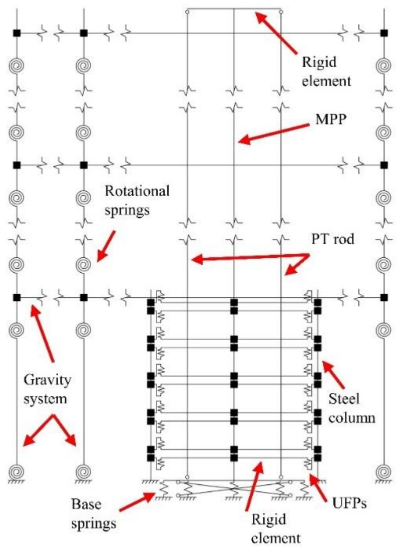


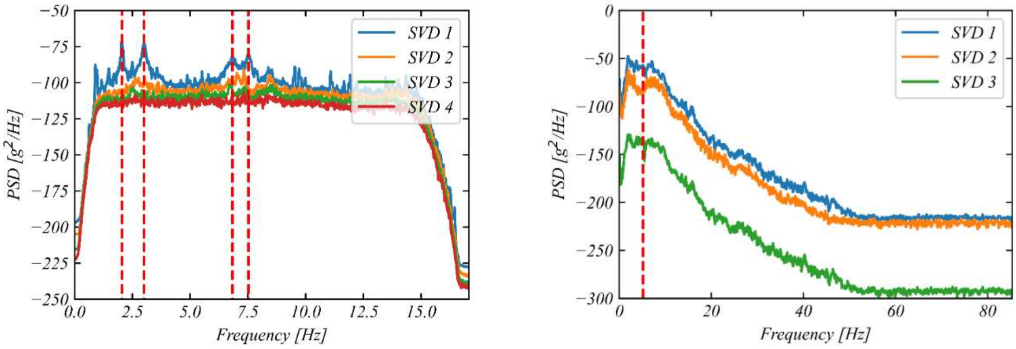
Figure 6: Finite element model.

3 RESULTS

From the 13 sets of ambient vibration measurements, the first four vibration modes were identified using EFDD, along with the mode shapes and damping associated with each mode. Figure 7a shows the singular value decomposition (SVD) obtained for one of the subsamples after using the decimation and filter previously described. Two well-defined peaks were discernable for the SVD 1 below and above 2.5 Hz. From the mode shapes, those two peaks were associated with the first translational modes in the East-West and North-South directions, respectively. Similarly, two other peaks around 7.5 Hz associated with the second mode shape were identified in the North-South and East-West directions, respectively. Table 1 summarizes the mean values of the identified natural frequencies, their respective damping ratios, and the range values in parenthesis.

The processing of the implosion measurements allowed the identification of one mode with a frequency of 5.152 Hz, damping ratio of 2.671%, and mode shape that can be described as an out-of-phase circular motion of each diaphragm. Unlike the power spectrum density (PSD) of the ambient vibration analysis, the PSD of the implosion did not have any clear peak (Figure 7b). Therefore the identification relied on the automatic mode detection [50] within ARTeMIS Modal Pro, considering a dynamic headroom of 28.396 dB and a maximum assurance criterion of 0.9.

Due to the limitations of the 2D finite element model, only the modes in the NS direction were computed. The model results showed that the parameter that had more influence on the frequency response was the stiffness of the rotational springs. After calibrating this parameter, the frequency of the first mode was 3.015 Hz.



(a) (b)

Figure 7: SVDs plots (a) ambient vibration (b) implosion.

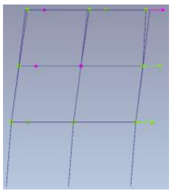
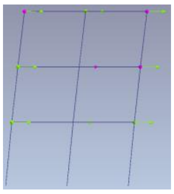
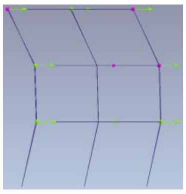
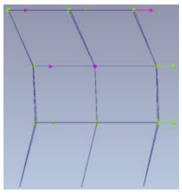
1st EW	1st NS	2nd NS	2nd EW
f=2.045 Hz (2.037 – 2.050) ξ=0.988% (0.556 – 1.731)	*f*=2.986 Hz (2.968 – 3.006) ξ=1.255% (0.843 – 1.668)	*f*=6.659 Hz (6.630 – 6.692) ξ=1.615% (1.063 – 2.050)	*f*=7.512 (7.471 – 7.536) ξ=1.093% (0.599 – 1.400)
			

Table 1: Identified natural frequencies, damping ratios and mode shapes from ambient vibration.

4 CONCLUSIONS

An ambient vibration test and the unique opportunity to measure the effects of a nearby implosion over a three-story mass timber building were conducted. One OMA method (EFDD) was used to identify the modal features of the building. The ambient vibration measurements identified four modes: the two fundamental translational modes (EW and NS directions) and two higher lateral modes (EW and NS directions). The implosion measurement identified a fifth mode associated with a different higher-order mode.

The subsampling approach of the ambient vibration into 13 sets of measurements helped reduce the uncertainty on the estimated modal features improving the confidence in the results. Additionally, the results inform of opportunities to improve the current modeling efforts to capture the system's initial stiffness better.

REFERENCES

[1] Ceccotti A, Lauriola M, Follesa M, et al. SOFIE Project - Test results on the lateral resistance of cross-laminated wooden panels. In: *1st European Conference on Earthquake Engineering and Sismicity*. Red Hook, NY: Curran Press, 2006.

[2] Dujic B, Pirmanšek K, Zarnić R, et al. Prediction of dynamic response of a 7-storey massive XLam wooden building tested on a shaking table. In: *11th WCTE World Conference on Timber Engineering*. Trentino, Italy: Trees and Timber Institute, 2010.

[3] Popovski M, Schneider J, Schweinsteiger M. Lateral load resistance of cross-laminated wood panels. In: *11th WCTE World Conference on Timber Engineering*. Trentino, Italy: Trees and Timber Institute, 2010.

[4] van de Lindt JW, Pei S, Pryor SE, et al. Experimental Seismic Response of a Full-Scale Six-Story Light-Frame Wood Building. *Journal of Structural Engineering* 2010; 136: 1262–1272.

[5] Ceccotti A, Sandhaas C, Okabe M, et al. SOFIE project – 3D shaking table test on a seven-storey full-scale cross-laminated timber building. *Earthquake Engineering & Structural Dynamics* 2013; 42: 2003–2021.

[6] Iqbal A, Pampanin S, Palermo A, et al. Performance and Design of LVL Walls Coupled with UFP Dissipaters. *Journal of Earthquake Engineering* 2015; 19: 383–409.

[7] Sustersic I, Fragiacomo M, Dujic B. Seismic Analysis of Cross-Laminated Multistory Timber Buildings Using Code-Prescribed Methods: Influence of Panel Size, Connection Ductility, and Schematization. *Journal of Structural Engineering* 2016; 142: E4015012.

[8] Ganey R, Berman J, Akbas T, et al. Experimental Investigation of Self-Centering Cross-Laminated Timber Walls. *Journal of Structural Engineering* 2017; 143: 04017135.

[9] Tannert T, Follesa M, Fragiacomo M, et al. Seismic design of cross-laminated timber buildings. *Wood and Fiber Science* 2018; 3–26.

[10] Zimmerman RB, McDonnell E. Framework - A tall re-centering mass timber building in the United States. In: *11th US National Conference on Earthquake Engineering*. Oakland, CA: Earthquake Engineering Research Institute, 2018.

[11] Chen Z, Popovski M. Material-based models for post-tensioned shear wall system with energy dissipators. *Engineering Structures* 2020; 213: 110543.

[12] Chen Z, Popovski M. Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads. *Engineering Structures* 2020; 208: 109916.

[13] Chen Z, Popovski M, Iqbal A. Structural Performance of Post-Tensioned CLT Shear Walls with Energy Dissipators. *Journal of Structural Engineering* 2020; 146: 04020035.

[14] Soti R, Ho TX, Sinha A. Structural Performance Characterization of Mass Plywood Panels. *Journal of Materials in Civil Engineering*; 33. Epub ahead of print July 2021. DOI: 10.1061/(ASCE)MT.1943-5533.0003902.

[15] Ho TX, Arora A, Sinha A. In-Plane Shear Properties of Mass Ply Panels in Long-Ply Direction. *Journal of Materials in Civil Engineering*; 34. Epub ahead of print May 2022. DOI: 10.1061/(ASCE)MT.1943-5533.0004327.

[16] Priestley MJN. Overview of PRESSS Research Program. *pcij* 1991; 36: 50–57.

[17] Holden T, Restrepo J, Mander JB. Seismic Performance of Precast Reinforced and Prestressed Concrete Walls. *Journal of Structural Engineering* 2003; 129: 286–296.

[18] Restrepo JI, Rahman A. Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators. *Journal of Structural Engineering* 2007; 133: 1560–1570.

[19] Belleri A, Moaveni B, Restrepo JI. Damage assessment through structural identification of a three-story large-scale precast concrete structure. *Earthquake Engineering & Structural Dynamics* 2014; 43: 61–76.

[20] Kurama YC, Sritharan S, Fleischman RB, et al. Seismic-Resistant Precast Concrete Structures: State of the Art. *Journal of Structural Engineering* 2018; 144: 03118001.

[21] Palermo A, Pampanin S, Buchanan AH, et al. Seismic Design of multi-storey buildings using laminated veneer lumber (LVL). In: *2005 New Zealand Society for Earthquake Engineering Conference*. Wellington, New Zealand: New Zealand Society for Earthquake Engineering, 2005.

[22] Palermo A, Pampanin S, Buchanan A. Experimental investigations on LVL seismic resistant wall and frame subassemblies. In: *1st European Conference on Earthquake Engineering and Sismicity*. Red Hook, NY: Curran Press, 2006.

[23] Palermo A, Pampanin S, Fragiacomo M, et al. Innovative seismic solutions for multistorey LVLtimber buildings overview of the research program. In: *9th WCTE World Conference on Timber Engineering*. Portland, OR: Oregon State University Conference Services, 2006.

[24] Smith T, Ludwig F, Pampanin S, et al. Seismic response of hybrid-LVL coupled walls under quasi-static and pseudo-dynamic testing. In: *2007 New Zealand Society for Earthquake Engineering Conference*. Wellington, New Zealand: New Zealand Society for Earthquake Engineering, 2007.

[25] Smith T, Pampanin S, Buchanan A, et al. Feasibility and Detailing of Post-tensioned Timber Buildings for Seismic Areas. In: *2008 New Zealand Society for Earthquake Engineering Conference*. Wellington, New Zealand: New Zealand Society for Earthquake Engineering, 2008.

[26] Akbas T, Sause R, Ricles JM, et al. Analytical and Experimental Lateral-Load Response of Self-Centering Posttensioned CLT Walls. *Journal of Structural Engineering*; 143. Epub ahead of print February 2017. DOI: 10.1061/(ASCE)ST.1943-541X.0001733.

[27] Pei S, van de Lindt JW, Barbosa AR, et al. Experimental Seismic Response of a Resilient 2-Story Mass-Timber Building with Post-Tensioned Rocking Walls. *Journal of Structural Engineering* 2019; 145: 04019120.

[28] Blomgren H-E, Pei S, Jin Z, et al. Full-Scale Shake Table Testing of Cross-Laminated Timber Rocking Shear Walls with Replaceable Components. *Journal of Structural Engineering* 2019; 145: 04019115.

[29] van de Lindt JW, Furley J, Amini MO, et al. Experimental seismic behavior of a two-story CLT platform building. *Engineering Structures* 2019; 183: 408–422.

[30] Barbosa AR, Soti R, Sinha A, et al. *In-plane shear and compression behavior of large scale cross-laminated timber panels*. Corvallis, OR: Oregon State University, 2019.

[31] Mugabo I, Barbosa AR, Sinha A, et al. System Identification of UCSD-NHERI Shake-Table Test of Two-Story Structure with Cross-Laminated Timber Rocking Walls. *J Struct Eng* 2021; 147: 04021018.

[32] Barbosa AR, Rodrigues LG, Sinha A, et al. Shake-Table Experimental Testing and Performance of Topped and Untopped Cross-Laminated Timber Diaphragms. *Journal of Structural Engineering* 2021; 147: 04021011.

[33] Mugabo I, Barbosa AR, Riggio M. Dynamic Characterization and Vibration Analysis of a Four-Story Mass Timber Building. *Frontiers in Built Environment*; 5. Epub ahead of print July 2019. DOI: 10.3389/fbuil.2019.00086.

[34] Moaveni B, Barbosa AR, Conte JP, et al. Uncertainty analysis of system identification results obtained for a seven-story building slice tested on the UCSD-NEES shake table. *Structural Control and Health Monitoring* 2014; 21: 466–483.

[35] Orozco O. GF, Ho TX, Araújo R. GA, et al. Innovative mass timber seismic lateral force resisting systems: Testing of a full-scale three-story building with mass ply panels (MPP) rocking walls. In: *Proceedings of the 12th National Conference on Earthquake Engineering*. 2022.

[36] Innovative Lateral Systems. *TallWood Design Institute*, https://tallwoodinstitute.org/innovative-lateral-systems/ (accessed 1 April 2023).

[37] Council AW. 2021 Special Design Provisions for Wind and Seismic with Commentary. 2021.

[38] Mugabo I, Barbosa AR, Riggio M, et al. Ambient Vibration Measurement Data of a Four-Story Mass Timber Building. *Frontiers in Built Environment*; 5. Epub ahead of print May 2019. DOI: 10.3389/fbuil.2019.00067.

[39] National Instruments. SignalExpress, https://www.ni.com/docs/en-US/bundle/373873h/resource/373873h.pdf. (2013).

[40] Completing Reser Stadium project includes implosion of stadium's west side. *Life at OSU*, https://today.oregonstate.edu/news/completing-reser-stadium-project-includes-implosion-stadium%E2%80%99s-west-side (2021, accessed 1 April 2023).

[41] Reser Stadium Implosion, https://www.youtube.com/watch?v=qrDde19TpDY (2022).

[42] Live Recording of the Reiser Stadium Implosion (Jan 7, 2022), https://media.oregonstate.edu/media/t/1_rnay5rnf (2022).

[43] Google Earth V 9.185.0.0. Google Earth distance measurement from Reser Stadium to Emmerson Laboratory, https://earth.google.com/ (2022, accessed 3 April 2023).

[44] Brincker R, Zhang L, Andersen P. Modal identification of output-only systems using frequency domain decomposition. *Smart Materials and Structures* 2001; 10: 441–445.

[45] ARTeMIS Modal Pro - Structural Vibration Solutions, https://svibs.com/applications/artemis-modal-pro/ (accessed 1 April 2023).

[46] Butterworth S. On the Theory of Filter Amplifiers. *Experimental Wireless and the Wireless Engineer* 1930; 7: 536–541.

[47] Stagg MS, Siskind DE, Stevens MG, et al. *Effects of repeated blasting on a wood-frame house*. 8896, US Department of the Interior, Bureau of Mines, 1984.

[48] Yan P, Zou Y, Zhou J, et al. Assessment of seismic impact on residences during blasting excavation of a large-scale rock slope in China. *Environ Earth Sci* 2016; 75: 949.

[49] McKenna F, Scott MH, Fenves GL. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering* 2010; 24: 95–107.

[50] Andersen P, Brincker R, Goursat M, et al. Automated Modal Parameter Estimation for Operational Modal Analysis of Large Systems. In: *2nd International Operational Modal Analysis Conference*. Copenhagen, Denmark, https://www.semanticscholar.org/paper/Automated-Modal-Parameter-Estimation-for-Modal-of-Andersen-Brincker/2b2f7cc52d0d22f0450e9fc15ddebb7d86ab8f51 (2007, accessed 4 April 2023).