Getting Cross-Laminated Timber into U.S. Design Codes: A Must for Affordable and Sustainable Multifamily Housing

John W. van de Lindt
Colorado State University

Maria Koliou
Texas A&M University

Pouria Bahmani
Washington State University

Abstract

Cross-laminated timber (CLT) is revolutionizing the building industry around the world by providing a sustainable, eco-friendly alternative to traditional steel and concrete in multifamily and other buildings. As a new technology, CLT must be fully studied to ensure the safety of occupants before incorporating it in U.S. building codes for routine use. U.S. design codes allow for special alternative procedures to be used for a new system, but alternative methods can be expensive and time consuming. Although CLT construction projects are underway, each is unique and somewhat expensive; therefore, to make CLT multifamily housing more affordable, seismic performance factors have to be developed for earthquake-prone regions of the United States. This article provides a brief overview of how HUD-funded researchers are working toward having the most important seismic performance factor (R-factor) adopted for use in U.S. building codes, thereby making CLT an affordable option for multifamily housing construction.

Introduction

Cross-laminated timber (CLT) is an innovative construction product that originated in Europe approximately 20 years ago and has gained considerable momentum in North America, starting with buildings in Canada and now, the United States. A team of engineers recently completed a comprehensive process to enable platform-style CLT to be proposed for inclusion in U.S. design codes (van de Lindt et al., 2020). Platform-style construction is standard when one story of walls is constructed, a floor system built on top, the next story of walls added, and so on. This is the predominant style of wood-frame building construction in the United States, particularly for single-family homes and many multifamily buildings. However, a less expensive and faster construction approach using CLT is balloon-style construction, in which three- or four-story CLT walls are tilted up and floor systems hung from them, serving as horizontal diaphragms and providing lateral stability. However, balloon-style CLT systems have not been explored enough to be able to be used effectively in multifamily housing units in the United States. The overall goal of this project is to enable construction of balloon-style CLT buildings, such as low-rise single- and multistory residential buildings, including apartment complexes. This project will remove a building code barrier to balloon CLT construction through a systematic research program, thereby enabling this new technology to be used economically and efficiently in multifamily housing projects.

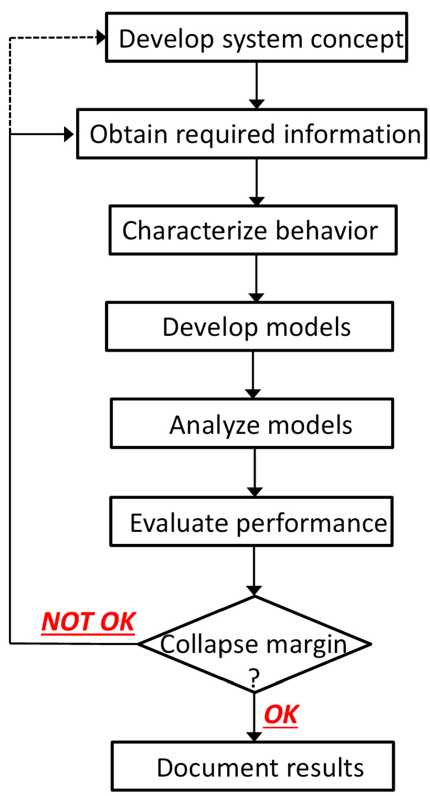
Two major barriers exist to using CLT in the United States: (1) CLT is not approved for use in seismic regions of the United States except through a direct (and time-consuming, expensive) approval by local building officials, necessitating individual building approval and, at times, certified laboratory testing of connections, which renders CLT technology less competitive; therefore, it is not used. (2) Platform-style CLT can be used for up to six stories—because such a project was completed, and the process is now in U.S. design codes (van de Lindt et al. 2020)—and uses narrow shear walls, which are not conducive to cost-effective construction in seismic regions—particularly for residential structures.

CLT has now been commonly accepted as a next-generation engineered wood product that has the potential to expand the wood building market (UNECE/FAO, 2017). Although CLT was introduced more than two decades ago, only in the past decade or so have researchers started focusing on using CLT as a lateral force resisting system in buildings. The number of studies investigating CLT system behavior and performance under cyclic and dynamic loading subsequently increased. Most of those studies originated in Europe (e.g., Ceccotti, 2008; Dujic, Aicher, and Zarni, 2006; Hristovski et al., 2012) and, more recently, in North America (e.g., Pei et al., 2016; Popovski, Schneider, and Schweinsteiger, 2010; Popovski and Gavric, 2015) and Japan (e.g., Okabe et al., 2012; Tsuchimoto et al., 2014). The studies demonstrated that CLT systems can be effectively used as a lateral force resisting system, in which the structural system has shear walls that resist impacts from earthquakes; a review of some of those studies is provided in Pei et al. (2016). With the introduction of CLT to the U.S. construction market and the current modern urbanization trend (Alig, Kline, and Lichtenstein, 2004), many believe that CLT can fill a gap for certain regions of the United States, providing a mechanism for sustainable and resilient residential construction.

The process to incorporate a new seismic force resisting system (SFRS) into U.S. design codes will take years, and it requires a robust combination of experimental data and numerical analysis, both of which are explained below. Federal Emergency Management Agency (FEMA) Report P695 (2009) provides a rational procedure to calculate the margin against collapse for a portfolio of representative archetypes from the proposed lateral force resisting system. This methodology is also explained below, and exhibit 1 shows the basic components of a FEMA P695 analysis. The system concept for balloon framing of CLT wall systems is developed first, and then information is obtained on all relevant components. The behavior is then characterized, typically using an experimental program, as was done in this project. Models are developed for computer simulation (which was done in OpenSees software in this project) and then a robust analysis is conducted, with approximately 500,000 to 1,000,000 analyses to fully understand the system and evaluate its performance. The performance evaluation requires using specified methods in FEMA P695 to assess the margin against collapse to ensure that the new system is at least as safe as existing systems in the United States. The process can be iterative and require full redesign and remodeling of the archetypes, so it is time consuming. At the time of this report, the process is in redesign based on negotiations with the expert panel and code committees.

Exhibit 1

Overview of FEMA P695 Methodology



Source: Based on concepts from Federal Emergency Management Agency (FEMA)

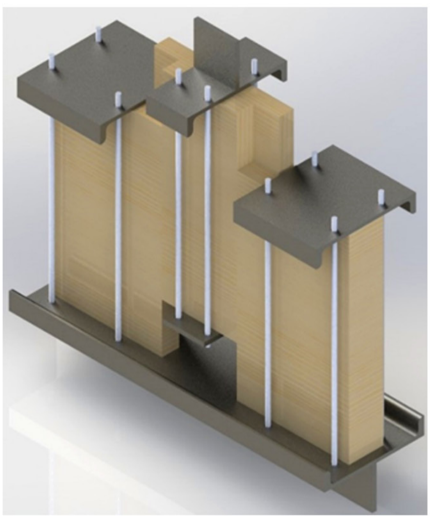
Experiments on Cross-Laminated Timber

A significant portion of the existing literature has focused on evaluating the performance of connections in CLT structures. Connections are the components that sustain damage in wood construction, and testing them is critical to evaluating their performance. Testing is needed to establish model parameters at the connection level to aid in accurately developing full-scale representations of building behavior.

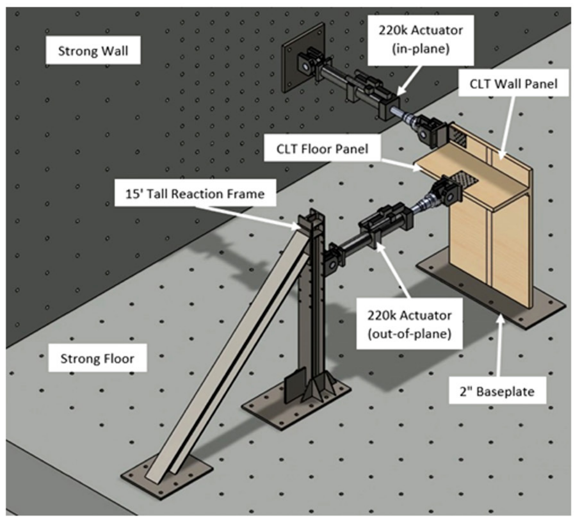
This approach is also a systematic way of minimizing uncertainties in computational modeling, given that the feasibility (in terms of availability of resources and number of tests performed) of performing many full-scale shake table tests is low compared to the cost associated with full-scale testing. In this study, detailed uniaxial[1] and biaxial[2] testing on CLT connections in two levels (connection tests and biaxial wall tests with focus on the connection response) were performed. All connection tests focused on evaluating the response of the panel-to-panel and wall-to-floor connections. Exhibits 2a and 2b show a rendering of the testing setup on a uniaxial testing machine for panel-to-panel connections and the biaxial wall test configuration with floor diaphragm, respectively. In addition, exhibits 3 and 4 show photos of the panel-to-panel test specimens and wall-to-floor specimen connections, respectively, and exhibit 5 displays photos from the full-scale wall tests.

Exhibit 2

Rendering of (a) Panel-to-Panel Connection Setup and (b) Biaxial Wall Test with Floor Diaphragm



(a)



(b)

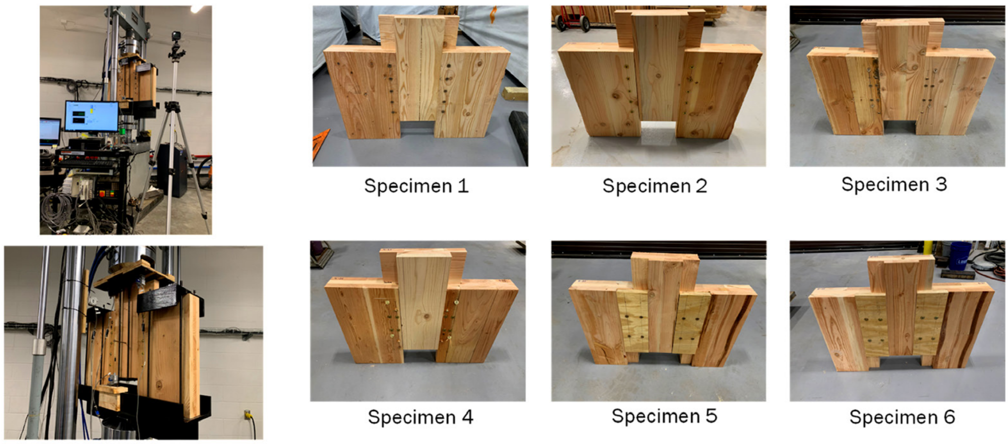
Source: Hayes (2021)

[1] In uniaxial testing, a sample is subjected to a uniaxial force until failure. The uniaxial force can be applied as either a tension or a compression.

[2] In biaxial testing, a sample is subjected to forces in both the x and y directions.

Exhibit 3

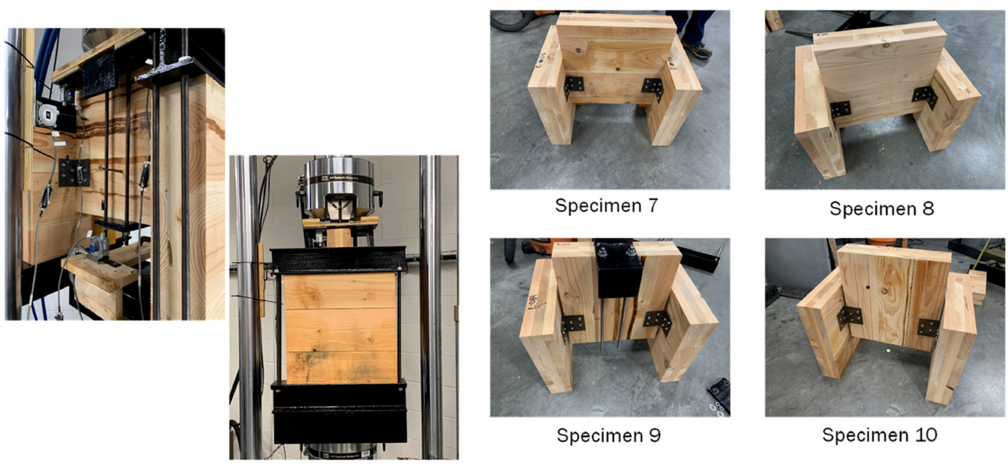
Photos of the Panel-to-Panel Test Specimens and Setup (Specimen Setups Represent Typical Panel-to-Panel Connections That Can Be Seen in CLT Buildings)



Source: Hayes (2021)

Exhibit 4

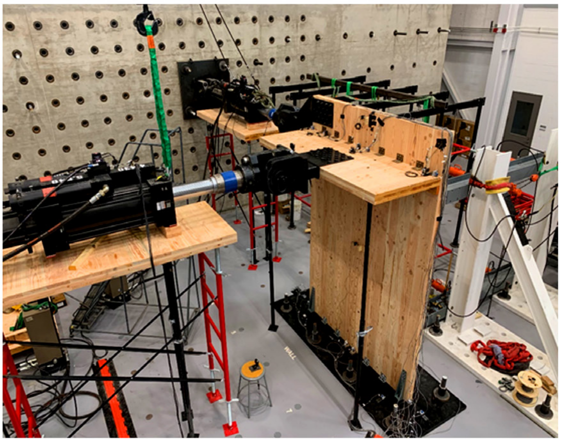
Photos of the Wall-to-Floor Test Specimens and Setup (Specimen Setups Represent Typical Panel-to-Panel Connections That Can Be Seen in CLT Buildings)



Source: Hayes (2021)

Exhibit 5

Photos of Full-Scale Specimens and Setup: (a) Tests With Floor Diaphragm, (b) Tests Without Floor Diaphragm



(a)

(b)

Source: Hayes (2021)

The connection-level and full-scale wall tests conducted as part of this study revealed that all connection configurations (including half-lap and surface spine) tested are viable methods of construction for use in balloon-style CLT construction. All configurations outperformed their design code predictions. The design code provides a significant factor of safety for designers, and nearly all test configurations had a safety factor of greater than 2, with some test configurations exhibiting a safety factor of nearly 6.

The results of this experimental program were then used to provide modeling parameters for the typical CLT balloon frame connection at the building-level modeling efforts.

Archetype Buildings and Seismic Response Modification Factors

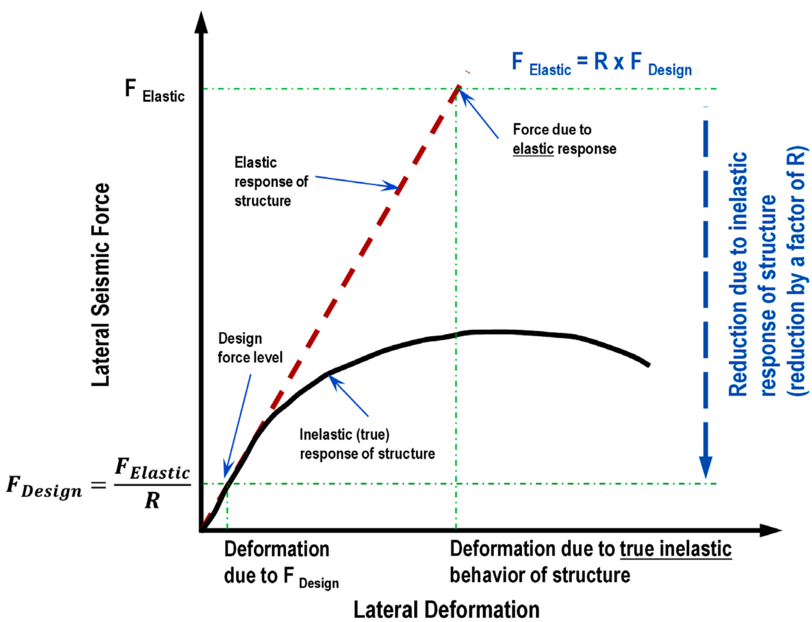
Structures can behave in two ways when subjected to lateral loads. Some structures deflect and deform under the load, but they do not experience any damage during the application of load or have any residual deformation after the load is removed. This behavior is called *linear-elastic response*. In linear-elastic structures, all the work done to deform the structure is recoverable, and no energy dissipates in the loading and unloading process. On the other hand, some structures can experience various levels of damage when subjected to load and will have residual deformation after they have been fully unloaded. In those structures, the work done to deform the structure is not fully recoverable; some part of the work permanently deforms the structure (i.e., residual deformation). Those structures are called *nonlinear-inelastic structures*. During an earthquake, many buildings behave inelastically and experience some level of damage. At first, that behavior may be seen as a disadvantage for structures to experience damage during a high-intensity earthquake, but that phenomenon can help the structure resist the seismic load better and prevent catastrophic collapse. Small and localized damage throughout can dissipate a lot of seismic energy imposed on the structure; hence, it reduces the overall deformation of the structure to a safe range. The job of structural engineers and researchers is to find a way to design connections and members to dissipate and damp the seismic energy throughout the building without compromising the safety of the structure.

Designing a linear-elastic structure that does not undergo any damage is not economical and cannot be justified (except for some facilities in which avoidance of damage is essential, such as nuclear power plants). The return period for a high-intensity earthquake is 500 to 2,500 years (i.e., one such earthquake is not likely to occur for at least 500 years), depending on the seismic region where the building is being built. So, the probability of having such an earthquake during the lifetime of the structure would be very low; therefore, designing a building that can tolerate some level of damage during a high-intensity seismic event without comprising the safety of its residents is justifiable.

As mentioned previously, a *linear-elastic* structure does not dissipate energy and does not have the capability to reduce the seismic forces due to lack of damping the seismic energy, leading to uneconomical design. On the other hand, if a building can undergo some level of inelasticity (e.g., small cracks in concrete buildings or small deformations in timber buildings), the seismic energy imposed on the building will be reduced significantly and will result in far lower forces than if the building were designed to remain undamaged. Exhibit 6 presents the reduction of forces induced due to a seismic event in a structure from a linear-elastic response to a nonlinear-inelastic response. The exhibit shows that if structures are designed to undergo some level of inelasticity, the forces can be reduced by at least a factor of *R* (in some structures, that reduction is on the order of 2 to 8).

Exhibit 6

The True Inelastic (Solid Line) Versus Elastic (Dashed Line) Response of a Structure Subjected to Seismic Loading



Source: Drawing by contributing author, Pouria Bahmani

The inelastic response of members and connections is mostly due to the material properties and the nature and behavior of members and connections of the structure. To take advantage of inelasticity in material, which leads to lower internal forces in a structure and more affordable houses, the inelasticity in material must be modeled correctly using programming software. Such modeling will allow engineers to understand the "true" behavior of structures under seismic loading. The process of modeling each member and connection in a software program to represent its true inelastic behavior is very cumbersome and time-intensive and requires several days—even months—of analysis and high computational power. That process increases the design time and leads to a very expensive and time-consuming design procedure that ultimately increases the construction cost of buildings and structures, which defeats the purpose of using inelastic design of structures: more affordable buildings and structures. To address the inelasticity and nonlinear behavior of a structure during a seismic event and, at the same time, simplify the analysis and design procedure, response modification factors (i.e., R-factors) are used in building codes and standards. As shown in exhibit 6, if the R-factor for a specific lateral load resisting system is known, all members can be designed for a reduced load of $F_{Design} = F_{Elastic}/R$ by considering the inelastic behavior of the structure and without going through a time-consuming analysis and design process. In summary, the R-factors can be considered shortcuts that allow practitioners and engineers to consider the true behavior of structures and take advantage of reduced forces to establish a safe and economical design. The level of inelasticity and damage in structures that leads to the definition of R-factors must be in an acceptable range and must be investigated very carefully through a research program. In this study, the procedure described in the FEMA P695 guidelines, developed by FEMA in collaboration with Applied Technology Council (ATC) (FEMA, 2009), is used to determine the R-factor and margin against collapse of buildings.

FEMA P695 Procedure

To determine the R-factor and margin against collapse for balloon-type structures, the authors designed several building archetypes using current building code provisions in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASC/SEI 7-22 (ASCE, 2022). The archetypes were subjected to a suite of ground motions (from the FEMA P695 far-field ensemble) with increasing intensities. To determine the R-factor for balloon-type structures, the authors considered all possible configurations of traditional residential and open-floor office buildings. Doing so allows generalization of the seismic modification and gives practitioners and structural engineers flexibility in using those factors to design more affordable houses. Per FEMA P695, archetype buildings should first be grouped based on building use, aspect ratios (height-to-width ratio) of shear walls, and design parameters. Exhibit 7 presents typical three- and eight-story balloon-type buildings used in this study, and exhibit 8 presents the performance groups considered in applying the FEMA P695 collapse assessment methodology for the proposed R-factor.

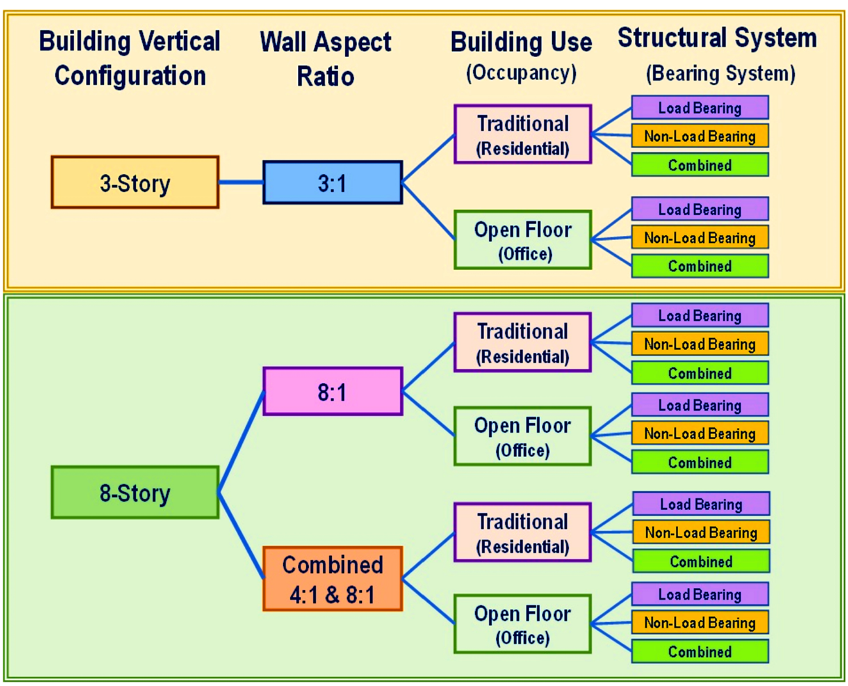
Exhibit 7

Building Archetypes: Three- and Eight-Story Buildings

Source: Drawing by contributing author, Pouria Bahmani

Exhibit 8

Building Archetypes and Performance Groups

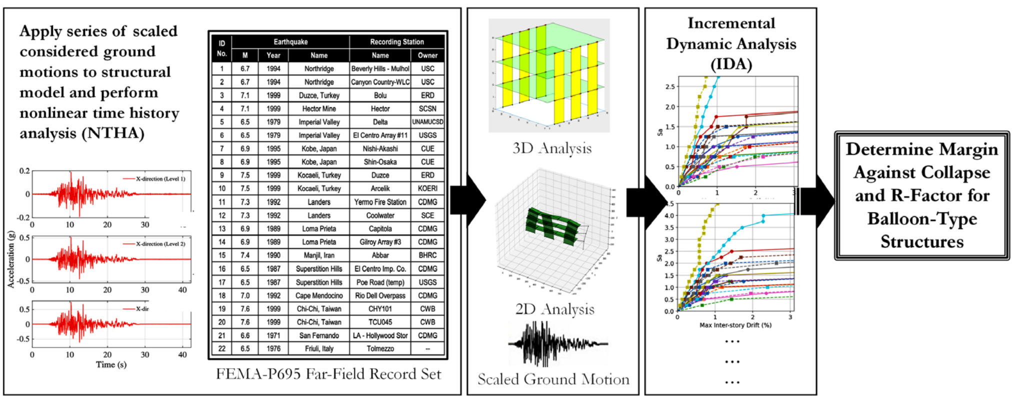


Source: Drawing by contributing author, Pouria Bahmani

In the next step, each archetype was designed in accordance with the Equivalent Lateral Force (ELF) procedure described in ASCE 7-22 for a range of response modification coefficients (i.e., R-factors) and was subjected to a suite of ground motions consisting of 22 earthquake records with increasing intensity. This task, as mentioned previously, requires thousands of nonlinear analyses to monitor the responses of all archetypes and, hence, is computationally intensive. Maximum displacements at each story and, consequently, maximum displacement for the overall structure, can then be monitored for each ground motion. This process allows one to determine the maximum displacement responses of all archetypes, and margin against collapse can be determined using statistical methods per the FEMA P695 guideline. Exhibit 9 depicts the FEMA P695 procedure to determine the R-factors.

Exhibit 9

Schematic of the FEMA P695 Process to Determine R-Factors for Balloon-Type Structures

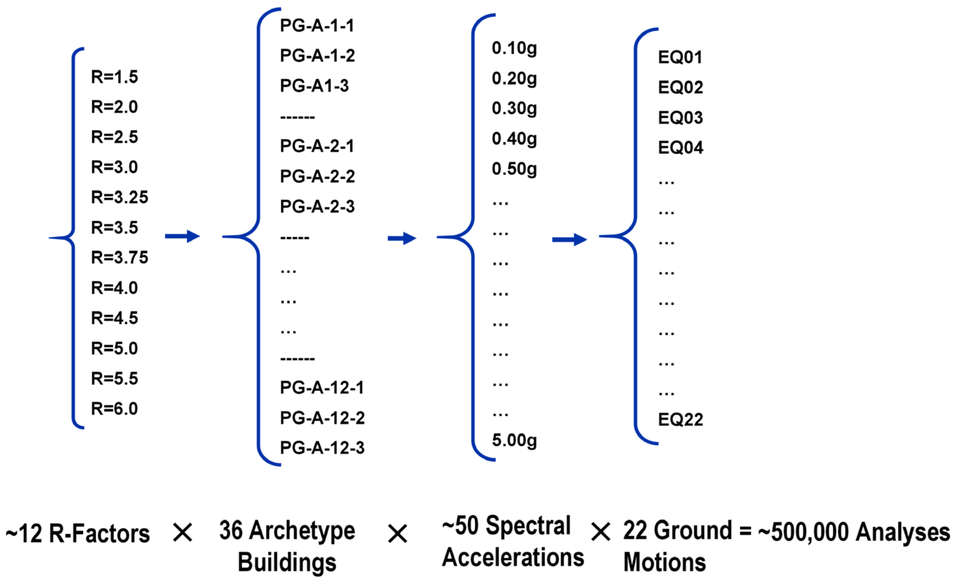


Source: This exhibit developed by the authors

Exhibit 10 shows the number of possible nonlinear analyses that must be completed to determine the R-factor for balloon-type structures. The first column in the exhibit shows a range of R-factors that are considered in this study. Each R-factor can be considered a "trial" R-factor that can be used to design a balloon-type building if the margin against collapse is in an acceptable range based on the FEMA P695 guideline. The second column presents a list of archetype buildings (total of 36) that are used in this study. The third column presents the increase in intensity of ground motions. Ground motion records can be scaled to spectral acceleration to have higher or lower intensities. Therefore, if a wide range of spectral acceleration is used, all possible ground motion intensities can be studied, and the response of the archetype building to each ground motion can be investigated. The last column shows the 22 far-field ground motions from the FEMA P695 guideline. These ground motions were selected such that they include all possible types of ground motions, with different durations and maximum ground acceleration. Therefore, by going through column 1 to column 4 of exhibit 10, all possible balloon-type structures and possible ground motions with different intensities were investigated. An estimated half a million nonlinear analyses must be conducted as part of this study, which require high computational power to complete. Supercomputers are used to reduce the analysis time. The analyses will be conducted in this study to determine the R-factor so that practicing engineers do not need to run nonlinear analysis to design balloon-type structures, which will save a lot of time and effort during the design of multifamily residential or office buildings. This process ultimately reduces the cost of designing and constructing mass timber balloon-type structures and leads to more affordable housing in the United States.

Exhibit 10

Estimated Number of Nonlinear Analyses Required to Determine R-Factor



Source: This exhibit developed by the authors

U.S. Design Code Adoption Process

Based on the work of the authors, a best practices document for balloon-type CLT construction will be developed and will serve directly as the design code proposal to the Provisions Update Committee (PUC) of the Building Seismic Safety Council (BSSC) and eventually be used to add the design procedure to ASCE 7 in 2028. Before full adoption, the process document will be available to local engineers and architects to adopt, with the approval of their local building officials. The adoption process is time-consuming and relies on a proposal and then a balloting process and finally a public comment period to ensure the safety of all housing and buildings in the United States. However, mass timber—in this case, cross-laminated timber—will ultimately provide a cost-effective, sustainable alternative for multifamily housing far into the future. After all, wood is the most sustainable construction material on Earth.

Conclusions

Cross-laminated timber balloon-style multifamily construction is on the cusp of becoming a mainstream reality, provided it can be made more cost effective. This HUD-supported project is providing the technical support, evidence, and guidance to make that reality possible through a rigorous testing and analysis program, which will work its way through the U.S. design code process. This process is, at times, cumbersome but nonetheless ensures that U.S. building codes are some of the safest and regulated standards in the world.

Acknowledgments

This project is funded by the U.S. Department of Housing and Urban Development (HUD)—Project Award No. H-21682 CA, and the authors gratefully acknowledge that funding. The content in this article reflects the views of the authors and does not necessarily reflect the views of HUD. The authors also acknowledge contributions from Benjamin Hayes and Milad Roohi and thank Jagruti Rekhi for managing and coordinating this work on HUD's behalf. Finally, the authors thank the editors and two referees for their helpful comments.

Authors

John W. van de Lindt is the Harold H. Short Endowed Chair Professor at the Department of Civil and Environmental Engineering at Colorado State University. Maria Koliou is an assistant professor at the Zachry Department of Civil and Environmental Engineering at Texas A&M University. Pouria Bahmani is an assistant professor at the Department of Civil and Environmental Engineering at Washington State University.

References

Alig, Ralph J., Jeffrey D. Kline, and Mark Lichtenstein. 2004. "Urbanization on the US Landscape: Looking Ahead in the 21st Century," *Landscape and Urban Planning* 69 (2): 219–234.

American Society of Civil Engineers (ASCE). 2022. *Minimum Design Loads for Buildings and Other Structures (ASCE Standard ASC/SEI 7-22)*. Reston, VA: ASCE.

Ceccotti, Ario. 2008. "New Technologies for Construction of Medium-Rise Buildings in Seismic Regions: The XLAM Case," *Structural Engineering International* 18 (2): 156–165.

Dujic, Bruno, Simon Aicher, and Roko Zarni. 2006. "Racking Behavior of Light Prefabricated Cross-Laminated Massive Timber Wall Diaphragms Subjected to Horizontal Actions," *Otto Graf Journal* 17: 125–142.

Federal Emergency Management Agency (FEMA). 2009. *Quantification of Building Seismic Performance Factors (FEMA P695)*. Washington, DC: FEMA.

Hayes, B. N. 2021. *Experimental and Analytical Assessment of Internal and Panel-to-Floor Connectors for Cross Laminated Timber (CLT) Balloon-Style Construction*, Master of Science Thesis, Texas A&M University, College Station, TX.

Hristovski, Viktor, Bruno Dujic, Marta Stojmanovska, and Violeta Mircevska. 2012. “Full-Scale Shaking-Table Tests of XLam Panel Systems and Numerical Verification: Specimen 1,” *Journal of Structural Engineering* 198 (11): 2010–2018.

Okabe, Minoru, Motoi Yasumura, Kenji Kobayashi, Takeshi Haramiishi, Yo Nakashima, and Kazuhiko Fujita. 2012. “Effect of Vertical Load Under Cyclic Lateral Load Test for Evaluating Sugi CLT Wall Panel.” Paper presented at World Conference on Timber Engineering, New Zealand Timber Design Society, Auckland, New Zealand, July 16–19.

Pei, Shiling, John W. van De Lindt, Marjan Popovski, Jeffrey W. Berman, J. Daniel Dolan, James Ricles, R. Sause, Hans-Erik Blomgren, and Douglas R. Rammer. 2016. “Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation,” *Journal of Structural Engineering* 142 (4): E2514001.

Popovski, Marjan, and Igor Gavric. 2015. “Performance of a 2-Story CLT House Subjected to Lateral Loads,” *Journal of Structural Engineering* 142 (4): E4015006.

Popovski, Marjan, Johannes Schneider, and Matthias Schweinsteiger. 2010. “Lateral Load Resistance of Cross-Laminated Wood Panels.” Paper presented at World Conference on Timber Engineering, Auckland, New Zealand, July 16–19.

Tsuchimoto, Takahiro, Naohito Kawai, Motoi Yasumura, Tatsuya Miyake, Hiroshi Isoda, Chihiro Tsuda, Sota Miura, Satoshi Murakami, and Takafumi Nakagawa. 2014. “Dynamic and Static Lateral Load Tests on Full-Sized 3-Story CLT Construction for Seismic Design.” In *World Conference on Timber Engineering (WCTE 2014)*, edited by A. Salenikovich. Red Hook, NY: Curran Associates.

United Nations Economic Commission for Europe/Food and Agriculture Organization of the United Nations (UNECE/FAO). 2017. “Forest Products Annual Market Review 2009–2010.” Geneva Timber and Forest Study Paper 25. Geneva: UNECE/FAO Forestry and Timber Section.

van de Lindt, John W., M. Omar Amini, Douglas Rammer, Philip Line, Shiling Pei, and Marjan Popovski. 2020. “Seismic Performance Factors for Cross-Laminated Timber Shear Wall Systems in the United States,” *Journal of Structural Engineering* 146 (9): 04020172. doi.org/10.1061/(ASCE) ST.1943541X.0002718.