Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation

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Introduction

Cross-laminated timber (CLT) is a relatively new heavy timber construction material (also referred to as massive timber) that originated in central Europe and quickly spread to building applications around the world over the past two decades. Using dimension lumber (typically in the range of 1× or 2× sizes) glue laminated with each lamination layer oriented at 90° to the adjacent layer, CLT panels can be manufactured into virtually any size (with one dimension limited by the width of the press), precut and pregrooved into desirable shapes, and then shipped to the construction site for quick installation. Panelized CLT buildings are robust in resisting gravity load (compared to light-frame wood buildings) because CLT walls are effectively like solid wood pieces in load bearing. The design of CLT for gravity is relatively straightforward for residential and light commercial applications where there are plenty of wall lines in the floor plan. However, the behavior of panelized CLT systems under lateral load is not well understood especially when there is high seismic demand. Compared to light-frame wood shear walls, it is relatively difficult for panelized CLT shear walls to achieve similar levels of lateral deflection without paying special attention to design details, i.e., connections. A design lacking ductility or energy dissipating mechanism will result in high acceleration amplifications and excessive global overturning demands for multistory buildings, and even more so for tall wood buildings. Although a number of studies have been conducted on CLT shear walls and building assemblies since the 1990s, the wood design community's understanding of the seismic behavior of panelized CLT systems is still in the learning phase, hence the impetus for this article and the tall CLT building workshop, which will be introduced herein. For example, there has been a recent trend in engineering to improve resiliency, which seeks to design a building system such that it can be restored to normal functionality sooner after an earthquake than previously possible, i.e., it is a resilient system. While various resilient lateral system concepts have been explored for concrete and steel construction, this concept has not yet been realized for multistory CLT systems. This forum article presents a review of past research developments on CLT as a lateral force-resisting system, the current trend toward design and construction of tall buildings with CLT worldwide, and attempts to summarize the societal needs and challenges in developing resilient CLT construction in regions of high seismicity in the United States.

CLT as Lateral Force-Resisting System: A Comprehensive Review

Although CLT has been in existence as a panelized building material for close to 20 years, construction using CLT was not truly widespread until about a decade ago. After the early 2000s, CLT construction began to see a significant increase in Europe, partially because of its ability to enable taller buildings (e.g., close to 10 stories) using a sustainable material. On the other hand, the research and understanding of panelized CLT as a lateral force-resisting system in high seismic regions was limited compared to other lateral structural systems. Early research on CLT was mainly conducted in Europe, perhaps due to the tradition of heavy timber architecture and the interest in the CLT market there. Recently, researchers in North America and other parts of the world, e.g., Asia and New Zealand, have begun to investigate the potential of using this sustainable material. A review of notable studies published through 2014 that focus on CLT as the main lateral load resisting system is summarized in the following. These studies are organized by geographical region and their significant research initiatives, providing a brief history of CLT research

related to earthquake engineering. Note that some of the research results did not get published until a later date; thus, the published reference date does not match the time of the investigation or experiments.

Table 1 summarizes the experiments conducted on CLT connections, walls, and assemblies (including buildings) that focused on seismic performance. This list was not meant to be all inclusive, as there are additional tests on CLT systems conducted by governmental and private entities that have not yet been published. Nonetheless, this list provided a snapshot of CLT seismic research primarily in the past decade, with detailed reviews of all these tests presented in this section.

Research in Slovenia and Macedonia

One of the first experimental studies on lateral resistance of CLT walls was conducted by Dujic et al. (2004) at the University of Ljubljana, Slovenia. The study was supported partially by KLH Massiveholz GmbH from Austria, one of the earliest manufacturers of CLT panels. Fifteen solid CLT walls with different anchorage details and vertical load levels were tested under monotonic and cyclic loading. Test results revealed that the load-bearing capacity of CLT shear walls is limited by anchorage strength and local failure of the wood material at the connections. Vertical load was shown to be beneficial to developing CLT wall lateral strength, especially when the anchorage was weak.

A unique experimental study on CLT panel shear walls was conducted by Dujic and Zarnic (2006) with a focus on the influence of vertical load and boundary conditions to panelized CLT wall resistance. The investigation included three different boundary conditions for shear walls with increased levels of boundary constraint, namely Case A where the top of the wall was allowed to translate and rotate, Case B where the rotation was restrained, and Case C where both vertical transition and rotation were restrained. The ultimate strength of the wall tested under the Case C boundary condition more than doubled that of Case A; thus, it was concluded that the boundary conditions have a significant impact on the lateral resistance of panelized CLT walls. With the real CLT wall boundary condition in a building clearly bounded by Cases A and C, the authors concluded that measured shear wall strength under condition Case C alone should not be used as reference for design.

Dujic et al. (2010) conducted a study on CLT shear walls with openings. Four physical specimens were tested including two walls with openings and two walls without openings. The purpose of the test was to validate a numerical model for CLT walls with openings so that more design configurations could be numerically evaluated. Mechanical characteristics of the CLT panel material and hysteretic response of the metal connectors (anchors for CLT walls) were also tested to be included in the model. A total of 36 configurations of different CLT walls were built in *SAP2000*. The parametric study concluded that openings in CLT walls of up to 30% of the wall surface will not reduce the shear capacity significantly. However, the stiffness of the walls will be affected (a reduction up to 50% of the initial stiffness was observed in some cases). This study further confirmed that panelized CLT shear wall strength is largely controlled by connectors and anchors.

Following the connection and wall tests, shake table tests were conducted on two single-story box CLT shear wall assemblies at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, Macedonia (Dujic et al. 2006; Hristovski et al. 2012). The specimens were parallel CLT walls (2.44×2.72 m) with lateral walls for stability only. Both single-panel and two-panel configurations were tested. The walls were directly seated on a concrete floor and were anchored with angle brackets. A total of 9.6 t of seismic mass was attached for each specimen. Input excitations included both recorded earthquake ground motions and harmonic excitation at relatively high frequency (5–7.5 Hz). A custom computational program developed at IZIIS was used to model the specimen responses for comparison to the shake table test results. The model utilized zero-length link element to represent friction and contact. The numerical model showed good agreement to the displacement and acceleration responses measured during the test. The shake table tests indicated that the CLT panels acted almost as rigid bodies during dynamic excitation, with the interpanel connections (in the two-panel configuration) providing a notable level of ductility.

Table 1. Major Experimental Studies on CLT Seismic Performance

Published reference	Specimen(s)	Test procedure	Comments
Dujic et al. (2004)	15 CLT walls	Static/cyclic	One of the first cyclic tests of CLT walls
Dujic et al. (2006)	8 CLT walls showed in the results	Static/cyclic	Focused on identifying the effect of boundary conditions
Dujic et al. (2010)	4 walls with and w/o openings	Static/cyclic	Focused on identifying the effect of openings
Dujic et al. (2006), and Hristovski et al. (2012)	2 wall assemblies with seismic mass on top	Dynamic/shake table	First shake table test on CLT system
Gavric et al. (2012)	20 connections tested	Static/cyclic	Focused on finding connection overstrength
Lauriola and Sandhaas (2006)	14 CLT walls and a one-story building assembly	Static/cyclic	Wall tests indicated an equivalent damping of 14% for CLT walls; building tested under pseudo-dynamic loading
Ceccotti (2008)	A 3-story residential house	Dynamic/shake table	Identifying q factor for Eurocode 8 through system level test
Ceccotti et al. (2013)	A 7-story CLT tower	Dynamic/shake table	Largest CLT shake table test to date, concluded the SOFIE project
Tavoussi et al. (2008)	Slender CLT walls/w special anchor system	Static/cyclic	Slender wall panel with steel rod tie-down
Fragiacomo et al. (2011)	16 connector tests	Static/cyclic	Focused on finding over-strength for design
Popovski et al. (2010)	32 CLT walls of different configurations	Static/cyclic	First set of comprehensive test of CLT walls in Canada
Joyce et al. (2011)	4 interpanel connection configurations	Static/cyclic	Test focused on interpanel connection behavior
Okabe et al. (2012)	Connection, material, and walls	Static/cyclic	Using CLT made from Japanese local species
Popovski et al. (2014a)	2-story CLT house under lateral loads	Static/cyclic	Quantifying the 3D effects on the response of CLT structure under lateral loads
Amini et al. (2014)	Connector, wall, and small box structure tests	Static/cyclic	Ongoing effort to define seismic design factors for CLT panelized walls

SOFIE Project in Italy

The SOFIE project, a comprehensive research effort funded by the Trento Province of Italy in the early 2000s, was one of the most comprehensive studies on the seismic performance of CLT systems to date. The project consisted of connection tests, CLT panel shear wall tests, and multiple full-scaled building system tests. Gavric et al. (2012) summarized results of a series of panel connection tests including 20 different screwed panel configurations. Both the in-plane screwed connection and the connection between perpendicular panels were tested. These results provided information for CLT connection design where the design intent is that they remain undamaged under design seismic loads. It was concluded that the over strength factor for these connections ranges from 1.2 to 1.9, with an average value of 1.74.

Lauriola and Sandhaas (2006) reported panelized shear wall tests conducted within the SOFIE project including 14 wall tests using four different configurations (solid 2.95×2.95 m walls with and without floor/ceiling, walls with doorway opening). Two levels of vertical loads were incorporated, namely 10.2 and 18.5 kN/m. These tests confirmed that the behavior of panelized CLT walls was strongly influenced by the connections. The walls tested were able to exhibit good ductility and energy dissipation (with equivalent viscous damping of 14% on average) through localized damage at the connections. In addition to wall tests, pseudo-dynamic testing of a one-story CLT building assembly was also conducted in this study. Different from the early assembly tests conducted in 2006 by Hristovski et al. (2012), this one-story specimen was more similar to a realistic floor plan with doors and windows. Three different design variations were tested to investigate the effect of different opening sizes on the assembly performance. There was no additional vertical load applied to the building assembly. The results showed that the one-story assembly system is quite stiff but still ductile (pinched hysteresis were observed from the tests); shear deformation of the panel itself is negligible compared to the deformation of the connections.

As a part of the SOFIE project, a three-story CLT building was designed and tested at Japan's National Research Institute for Earthquake Science and Disaster Prevention (NIED) shake table facility by Ceccotti (2008) in Tsukuba, Japan. The building had approximately a 7×7 m residential floor plan and each story was about 3 m high. Tributary seismic mass for story one and two was approximately 21.4 t each and 4.6 t for the roof. The objective of this test was to experimentally determine the approximate value of the q factor for CLT shear walls should it be designed using Eurocode 8 (EN 2004). The building was subjected to 15 earthquake ground motions with PGA ranging from 0.5 to 1.2 g with only minor repairs made between tests (tightening or replacing connectors), but the building remained standing without permanent deformation after all tests. However, the connection and hold-down for the CLT walls were heavily damaged with most of the dowel connectors pulled out. A numerical model was constructed (using *DRAIN-3DX*) to simulate the dynamic response of the building through nonlinear time history analysis. CLT panels were modeled using rigid braced frames (including both wall and floor diaphragm) connected with nonlinear connector springs. The numerical model was able to achieve very good agreement with the maximum lateral deformation and uplift displacements for most of the earthquake ground motions. Based on the measured response and forces, it was suggested that a value of $q = 3.0$ was a reasonable value for design of a CLT building using Eurocode 8. This study was one of the earliest shake table tests on a CLT building specimen with realistic dimensions and configuration. The study highlighted the fact that the majority of CLT building damage during earthquakes will be concentrated at the connections, CLT wall and floor panels will mostly remain elastic, and the building exerts significant uplift demands on the lower floor anchor system. Based on these observations, Ceccotti (2008) suggested CLT would be a good candidate for converting from force-based design to a so-called no damage design (NDD) philosophy, which can be categorized as a special case of performance-based seismic design.

In 2007, Ceccotti et al. (2006, 2013) tested a seven-story CLT building at Japan's E-Defense shake table as the culmination of the SOFIE project. The building was designed using a q factor of 3 per Eurocode 8 (using an importance factor of 1.5), based on knowledge from past research. Simplified lateral force method was used to size the connections for shear walls. At a total height of 23.5 m and a floor plan of 7.5×13.5 m, the building was relatively slender in profile. The total weight of the building was 284 t. The building was subjected to a total of 10 earthquake ground motions under the program with increasing intensity levels (with maximum PGA of 0.82 g for JMA Kobe ground motion). The natural frequency of the building was measured between each test and showed moderate decrease (17–24% decrease from the initial frequency). During the tests, the building experienced some damage to the hold-down element at lower stories, indicating the importance of overturning resistance load path in multistory CLT building design. Considerable uplifts (over 10 mm) were also observed during the test at lower floor corners of the building. However, after 10 major earthquakes, the building was able to return to its original equilibrium position without residual displacement. During large earthquakes, high floor acceleration (3.8 g) at the top stories was measured. Thus, the authors suggested adding ductile elements in CLT building design to help improve building performance. The full-scaled test provided solid evidence that it is feasible to design tall CLT buildings using force-based design with an appropriate q factor but the building may experience damage to hold-down connections and high acceleration at higher floors during large ground motions.

Other Notable Efforts in Europe

Tavoussi et al. (2008) explored another alternative of using slender CLT shear wall elements as a seismic bracing system. Twelve specimens (H/b ratio equal to 2.3) were tested with different panel lamination configurations and a steel bar tie-down at the end of the wall (the tests were monotonic). Except for two premature failures due to poor lamination, the resistance of the walls turned out to be very similar because the walls simply engaged the tie-down bar as a nearly rigid block. This study also proposed an anchor system for slender CLT walls made from steel channels. The channel sections were attached to the ends of the CLT panel and connected to foundation. Three walls with different lamination configurations were tested with the channel anchor, again resulting in very similar responses.

A study to investigate appropriate design overstrength factor for CLT connections based on connector test data was conducted by Fragiacomo et al. (2011). The study indicated that the main source of ductility in CLT buildings is the ductility in the connections, which should be used as the basis for calculating overstrength for all other parts of the building if ductile failure of the system is desired. The authors suggested designing floor panel connections using overstrength, i.e., limiting diaphragm damage during earthquakes. Based on a limited number of cyclic loading tests of nail and screw connectors, a value of 1.3 was suggested for hold-downs and angle brackets for CLT walls in this study. The study also applied a nonlinear static analysis approach to design an example four-story CLT building considering system ductility. A model of the building was built using shell elements for the panels and

nonlinear springs as connections (using *SAP2000* software). The analysis revealed that ignoring ductile connections in the CLT system (by replacing nonlinear springs with rigid links) will greatly underestimate the natural period of the building and its displacement during earthquakes, and overpredict base shear. However, the authors also indicated that using only ductile springs to connect the panels may overestimate the building natural period if the effect of interpanel friction is ignored. A push-over analysis following the N2 procedure recommended by Eurocode 8 was conducted using the nonlinear model and proved the use of ductile connectors can increase the system ductility and seismic resistance.

Following the seven-story test from the SOFIE project, Dujic et al. (2010) conducted a numerical study to predict the dynamic response of the building. The first trial model with *SAP2000*-nonlinear utilized shell elements for the CLT panels and multilinear spring elements for connections and hold-downs. However, numerical integration did not converge due to the use of nonlinear springs with a descending branch in the envelope. Modification was made to use the equivalent linear springs to capture the secant stiffness of the connection with a 15% artificial viscous damping. Through this simplification, the model was able to reproduce the measured interstory drifts of the structure with reasonable accuracy.

Sustersic et al. (2012) conducted a parametric study to investigate the effects of friction and vertical load on the dynamic behavior of panelized CLT system models. Similar to earlier studies, the numerical model was built with *SAP2000* using shell elements as walls, rigid plates as diaphragms, and nonlinear springs and gap elements as connections. A friction element was used between the panels when friction was considered (with a friction coefficient of 0.4, typically 0.25–0.50 for wood to wood interface). The numerical model was a four-story CLT building with a relatively simple floor plan (6.5×8.5 m) and regular story height (total height 11.2 m). A simplified model was also constructed for a single stacked wall line using braced truss instead of shell element. In this case, friction was modeled using nonlinear link element. The models were subjected to earthquake excitation with varying connector and friction parameters. The results were compared and it was discovered that both friction and vertical load have significant impact on the response of the CLT system as modeled. The study highlighted the modeling uncertainty that could be associated with CLT system when the friction mechanism within the system is not fully understood. It also indicated that neglecting vertical acceleration during nonlinear time history analysis may affect system response considerably.

Rinaldin et al. (2013) developed a numerical model to estimate the dissipative capacity of a CLT building based on component calibration approach. This study is similar to earlier efforts to model CLT connection through nonlinear springs, but focused more on detailed calibration of the nonlinear hysteretic and pinching behavior of these connectors. The model was implemented using *ABAQUS* through external subroutines for special connection elements. By comparison of the numerical simulation results to panelized wall tests and a single-story building test, the accuracy of the model to predict the energy dissipation under reverse cyclic tests was confirmed.

Research in North America

The wood industry is one of the most important economic drivers in Canada. There is strong governmental support to utilize timber as an innovative building material with a strong emphasis on its sustainability. This has helped to put Canada in a leading position for CLT research when it was first introduced in North America. In order to address moderate seismicity in the British Columbia Province of Canada, FPInnovations (FPI) initiated a series of research projects on seismic design of CLT systems. Popovski et al. (2010) conducted CLT wall tests on 32 shear walls. The wall specimens included different aspect ratio, opening, and panel combinations. There were also two-story shear walls with stacked and single-panel configurations. A wide range of connector and bracket types was also investigated. The test provided a good data set that jump-started the follow-up seismic research on CLT in North America. The main conclusions from the test were that interpanel joint and metal brackets are the main source of ductility in CLT walls, and thus should be implemented for CLT building in seismic regions.

Following the FPInnovations wall tests, Popovski and Karacabeyli (2012) made the first attempt to estimate the seismic modification factors (R-factors) for a CLT system in the National Building Code of Canada (NBCC). The study was done based on three approaches including referencing the q factor study in Europe, comparison to existing timber systems in NBCC, and following an equivalency approach recommended by AC130 (International Code Council 2013). The wall test results from Popovski et al. (2010) were used to conduct the AC130 (International Code Council 2013) equivalency approach. The final recommendation was to use $R_o = 1.5$ and $R_d = 2.0$ for the system.

A state-of-the-art summary on the seismic performance and seismic design of CLT structures at the time was presented in Popovski et al. (2011), as a part of the FPInnovations' CLT Design Handbook, Canadian edition. The information provided in the handbook on CLT as a lateral load-resisting system was instrumental in the design and construction of first CLT projects in North America.

Using the FPI set of test data on CLT walls, Schneider et al. (2012) applied an energy-based damage index to quantify the damage to CLT shear walls. Different failure modes for metal bracket connections were identified. Connection tests were analyzed using Kratzig's energy-based index (originally used for concrete members, Kratzig et al. 1989) to obtain the relationship between observed damage in the test and calculated damage index. The damage levels are quantified as None ($D < 0.2$), Minor (D: $0.2 \sim 0.35$), Moderate (D: $0.35 \sim 0.65$), Severe (D: $0.65 \sim 0.75$), and Collapse ($D > 0.75$) based on the calculation. This is one of the few studies that attempted to quantify damage to CLT connections. This type of research is needed as the design community moves towards performance-based seismic design [or NDD introduced by Ceccotti (2008)].

With the objective to investigate the three-dimensional (3D) system behavior of CLT structures subjected to lateral loads, a two-story full-scale model of a CLT house was tested under quasi-static monotonic and cyclic loading at FPInnovations (Popovski et al. 2014b). The house was 6.0×4.8 m in plan with a height of 4.9 m. A total of five (one push-over and four cyclic) quasi-static tests (one at a time) were performed in both directions. Parameters such as direction of loading, number of hold-downs, and number of screws in perpendicular wall-to-wall connections were varied in the tests. The CLT structure performed according to the design objectives, with the ultimate resistance being almost identical in both directions. Perpendicular walls had significant influence on the lateral load resistance of the house. Failure mechanisms were similar in all tests; shear failure of nails in the brackets in the first story as a result of sliding and rocking of the CLT wall panels. Half-lap joints between the CLT wall panels allowed for relative slip during their rocking as predicted in the design. Despite the rigid connection between floor panels and wall panels, rocking of the wall panels was not fully restricted by the floor panels above. Relative slip between CLT floor panels in the diaphragms was negligible, suggesting that the connections were properly designed.

The deformation in the middle of the floor and roof diaphragms was only 14% of that at the supports, suggesting that CLT slabs act as rigid diaphragms. Maximum story drift of 3.2% (inclusive of sliding) was reached during the test 05 in the N-S direction, suggesting that CLT structures can achieve relatively large story drifts when properly designed. Types of connections used, their positioning, and defining of their resistance based on the kinematic behavior of the structure is crucial for a proper design of the structure.

Joyce et al. (2011) conducted a test on interpanel connections of CLT walls. Although small in scale compared to others, these tests were unique in that they investigated the performance of angled screw connections versus traditional double spline nails. A total of four different configurations were tested, each with multiple specimens for monotonic and cyclic tests. The results from the tests were quite consistent. It was found that angled screw connections are significantly stiffer and less ductile compared to nailed connections, partially due to the combined axial and shear resistance of the screws. Thus, the study concluded that the angled screw interpanel connection was not very suitable for CLT wall connections in seismic regions.

Shen et al. (2013) used a 10-parameter SAWS hysteretic model and 16-parameter Pinch4 model in the *OpenSees* program to represent CLT bracket connections. The model parameters were calibrated based on connection test results. Then, these connections were incorporated into CLT wall models subjected under cyclic loading numerically. Comparison between the numerical model behavior and full-size CLT tests verified the accuracy of this connection-based modeling method. Since *OpenSees* is a widely adopted simulation platform for earthquake engineering research, this study highlighted the possibility of using this tool to simulate CLT system behavior with two readily available nonlinear springs.

Through a collaborative effort of FPInnovations, American Wood Council, USFPL, APA, and WoodWorks U.S., the U.S. edition of the CLT handbook was developed with funding from Binational Softwood Council, USFPL, Forestry Innovation Investment (BC FII), and three CLT manufacturers (Karacabeyli and Douglas 2013). The handbook addressed many aspects related to CLT as a product and structural system such as manufacturing, architectural and structural design approaches, connections, fire performance, etc. The handbook also includes a lateral load design chapter outlining suggested design considerations for the system.

Pei et al. (2012b) proposed a concept of alternating rigid CLT shear walls (using long panels) and ductile CLT shear walls (using short panel segments) in a multistory building at different story levels. A 10-story CLT building was designed using the equivalent force procedure from ASCE7 (ASCE 2010) with an R factor of 2.0. Then, three selected stories were replaced with ductile shear walls. A numerical model was built using SAPWood (Pei and van de Lindt 2007) and subjected to a suite of earthquake ground motions. It was confirmed that lateral deformation was concentrated at the ductile layers and acceleration at higher stories was reduced significantly.

Similarly, Dolan et al. (2014) proposed adding ductile components in tall CLT buildings to improve resiliency of the system under large earthquakes. The concept of interstory isolation was applied to tall CLT construction, detailing the CLT floor diaphragms to be deformable with a slip plane with stiffness and damping elements. Through numerical simulation, it was discovered that for a 10-story building, one or two layers of deformable diaphragm at selected stories would effectively reduce floor accelerations and force demands on CLT connections.

A systematic study to identify suitable seismic design factors for CLT buildings in North America was undertaken by Pei et al. (2012c, 2013) for both the United States and Canada. The approach of the two studies was similar, but differed in the use of the corresponding codified design methods (ASCE-7 for the United States and NBCC for Canada). A set of *nominal* design capacity tables for solid CLT shear walls of different lengths and bracket configurations were developed in this study (similar tables were also included in the CLT Handbook versions for the United States and Canada). The idea is to enable an engineer to design a multistory CLT building following ASCE-7 or NBCC equivalent static force procedures. The capacity tables were developed with a simplified mechanistic model considering only the rocking behavior and connector strengths. A prototype building was designed using a range of R factors and modeled in SAPWood. Performance expectations were outlined to determine adequate R_d factor in NBCC (with R_o set to 1.5). In order to find appropriate the R factor for the U.S. code, the building backbone curves designed using different values of R were compared with those obtained if the building was designed using Direct Displacement Design (Pang et al. 2010), a performance-based design approach validated for light-frame wood buildings. Based on the comparison, it was recommended that $R = 4.5$ may be used for CLT shear walls in ASCE-7 in the United States, while $R_o = 1.5$ and $R_d = 2.0$ should be used for NBCC. The later result was consistent with the earlier estimates by Popovski and Karacabeyli (2012). However, these studies were limited by their scope in that the results were based on a single building configuration and limited shear wall component test data. Proposing seismic design parameters for building codes will require a more robust peer-reviewed approach, such as the Federal Emergency Management Agency (FEMA) P-695 methodology (FEMA 2009) for introducing new lateral force-resisting systems in ASCE-7.

Supported by the U.S. Department of Agriculture through the Forest Products Lab, a FEMA P-695 study to identify an appropriate R factor (and other seismic performance factors) for CLT shear walls is being conducted at Colorado State University by van de Lindt and colleagues (Amini et al. 2014). The project includes a three-component test program which includes (1) approximately 30 isolated wall tests; (2) box (small structure) testing; and (3) connector testing to help facilitate FEMA P-795 application for manufacturers following the project. This project is currently underway and will propose CLT as an addition to the response modification factors table within ASCE-7 as culmination to the effort.

The latest research effort in the United States on this topic deals with resilient CLT systems. An National Science Foundation–sponsored NEES-CLT Planning project (Pei et al. 2014) is currently underway to design and test seismically resilient CLT lateral force-resisting systems suitable for use in 8–20 story buildings. The objective of the project is to introduce ductility and resilience in tall CLT construction. Designs similar to that investigated by Pei et al. (2012a) and Dolan et al. (2014) will be further developed and tested. A workshop investigating societal needs and challenges to build tall CLT buildings in seismic regions of the United States was held in January 2014 at Seattle, with its major findings presented in later sections of this forum paper. The NEES-CLT project targets the development and experimental validation of innovative CLT systems by 2016, and proposed a vision to enable tall CLT buildings in the Pacific Northwest by 2020.

Research in Japan

CLT production is gaining some interest in Japan as well. Okabe et al. (2012) tested connections and panelized CLT walls made from Sugi wood, a locally available softwood species. The anchor connection was tested in tension, wall-to-diaphragm connection was tested in shear, and interpanel connection was tested in shear as well. The wall tests were conducted under different levels of vertical

load, but the difference in the observed strength for the walls was not very significant. The authors also observed that rocking deformation is the predominant behavior for CLT walls, with the interpanel connection failing in shear and each individual panel engage in rocking motion on its own. While the observation from this study was similar to that observed in tests conducted in other laboratories, valuable test data on Japanese local species CLT mechanical behavior is of good reference value for future projects in Japan.

Summary of CLT Seismic Research (2000–2014)

Experimental studies on CLT connection and wall assembly behavior over the past decade have provided valuable information for analysis and design. Panelized CLT walls develop their ductility primarily through connection deformation, while the panels remain elastic with local damage where connected. Panelized CLT walls tend to rock about their corners under lateral load when the boundary condition allows, which will engage the anchors in combined uplift and shear. On the other hand, very long wall panels (with small height-to-length ratio) will likely engage anchors primarily in shear. The boundary conditions and vertical loads all contribute to the strength and stiffness of the CLT shear walls. Numerical studies verified that component-based modeling of CLT wall assemblies using connection test data is a reasonable approach, with the panel modeled using elastic shell or block elements. However, modeling the nonlinear effects such as contact, friction, and connection hysteresis must be carefully considered as they influence the behavior of the model significantly. Test data are still critical for CLT system model validation at this point. Damage to CLT assemblies is concentrated at connections, which can be quantified through a damage index, but the work related to quantifying CLT system damage is limited.

Existing tests of the CLT systems showed that CLT buildings are very robust against collapse. Near collapse performance was used and defined using connection damage and uplift; real collapse of a CLT building has not been realized experimentally to this point. It is feasible to design a multistory CLT building using an existing force-based design methodology to protect life-safety, as long as appropriate seismic design parameters are adopted. However, the building has a tendency to generate significant uplift during earthquakes, which can induce severe damage to connections. The floor acceleration at higher levels of a multistory CLT building should be mitigated for occupants. A performance-based seismic design (or no damage design) philosophy should be adopted for tall CLT buildings in high seismic regions in order to ensure resiliency.

To date, seismic research on CLT systems is by no means complete and there remain research topics worthy of investigation. Based on the findings from past research efforts, some of the most critical studies may be suggested, which in the authors' opinion, include the understanding of panelized CLT wall behavior under realistic boundary conditions in a 3D building configuration, quantitative methods to assess CLT system damage as well as damage to nonstructural building components, a performance-based seismic design methodology for multistory CLT construction, and innovative CLT-based lateral force-resisting systems that can achieve resiliency under major earthquakes. Once these knowledge gaps are addressed through rigorous research, this new sustainable construction product will have the potential to change the urban landscape in high seismic regions.

Trend for Tall CLT Construction

Compared to traditional light-frame wood construction, CLT systems are more suited for multistory buildings due to their robustness and the potential to achieve the required fire rating. In fact, there has been a growing trend worldwide of constructing tall CLT buildings for residential and commercial use, which is an important background that should be considered when conducting CLT seismic research. Breneman and Podesto (2013) summarized viable timber structural systems for multistory buildings, highlighting CLT as one of the main mass-timber products suitable for this purpose. In 2014, the Forestry Innovation Investment and Binational Softwood Lumber Council released a survey of international tall wood buildings, which includes 10 timber building ranging from 5 to 10 stories in height. Eight out of the 10 building projects surveyed utilized CLT as either the main lateral system or as floor panels. Although it is difficult to comment on individual designs of these systems, the successful construction of these tall CLT systems signifies the viability of the concept. A list of existing tall CLT buildings around the world is given in Table 2.

It is quite evident that urban residential and commercial applications are potential candidates for tall CLT building construction. As many densely populated regions in the world (e.g., Japan, the West Coast of the United States and Canada, etc.) have significant seismic risk, developing seismically resilient tall CLT buildings has become a logical goal for CLT research and engineering. It should be pointed out that none of the existing tall CLT constructions completed are located in high seismic regions. To date, except for some cases in Italy, midrise CLT buildings have not been adopted widely in regions of moderate to high seismicity. In addition to the development of the physical building system, a shift towards performance-based seismic design philosophy must also be made for the new tall CLT buildings in order to address the evolving needs of the future urban communities.

Opportunities and Challenges in North America

In the United States and Canada, modern urbanization necessitates the design and construction of dense and sustainable buildings. Traditional light-frame wood building height was restricted to four

Table 2. Existing Multistory Panelized CLT Buildings

Building project	Location	Height (story)	Height (m)
Murray grove	London	9 + 1	29.7
Bridport house	London	8	26.5
Limnologen buildings	Vaxjo, Sweden	8	23.8
Holz8 (H8)	Bad Aibling, Germany	8	25.0
Forte	Melbourne, Australia	10	32.1[a]
Cenni di Cambiamento buildings	Milan, Italy	9	28.0
Wood Innovation Design Centre	Prince George, Canada	6	29.3[b]

Note: Forestry Innovation Investment and Binational Softwood Lumber Council (2014).
[a]Currently the tallest contemporary timber building in the world.
[b]Currently the tallest contemporary timber building in North America.

and five stories in most current jurisdictions due to fire safety concerns. Since CLT has been successfully used around the world for taller construction, it has been attracting considerable attention in urban regions of North America. CLT manufacturing and utilization has been gaining momentum in Canada over the past 5 years, with some of the design approaches imported from Western Europe. However, there is little code and regulatory basis dedicated for CLT lateral systems in these countries at this point, and the societal needs and expectations for tall CLT buildings in seismic regions are not yet well defined.

As part of an NSF-funded research project that is focused on developing seismically resilient solutions for tall CLT systems, the Tall CLT Building Workshop was held in Seattle on January 24, 2014. More than 60 participants from research, academia, design, manufacturing, and the planning community participated in discussions related to three main topics with the charge of identifying potential opportunities and challenges for tall CLT buildings in the United States. The following section summarizes the consensus of the majority of participants during the discussion and proposes a road map for developing CLT tall buildings in the United States with the first targeted construction in 2020.

Societal Needs and Economic Competiveness

The ability of a new product to meet societal needs is directly related to cost-effectiveness. If this new product can provide better functionality with comparable or even lower costs than existing products, effective marketing will help drive public acceptance and increased use of the product. For tall CLT systems (including hybrid CLT systems with steel and concrete), the potential market is 8–20 story residential or commercial buildings in an urban environment, which is currently dominated by concrete and steel frame structural systems. Many advantages of CLT systems were identified during the workshop discussion, including construction speed, better energy performance, reduced environmental impact (through net carbon sequestration and lower embodied energy), and appearance. Despite these advantages, the collective conclusion from the discussion pointed out that the direct cost of the CLT option is still the main driving force that will determine if it can be adopted for construction projects. The environmental benefits, or the ability to rank higher in the LEED system is desirable once a project is in place, but the bottom line decision is still heavily cost-driven. Faster construction and easier handling of prefabricated wood components than concrete or steel members is an advantage for CLT that may help to drive down initial costs. For residential buildings that have a significant amount of repetitive architectural patterns, fast modular construction can help make CLT competitive, but will depend on careful designs to ensure its performance. The potential to save on lifecycle operational costs (energy efficiency due to tight envelope and timber mass) and resiliency during earthquakes should be taken into consideration when comparing long-term cost-effectiveness of design options. To capture significant market share, the CLT option has to be of comparable cost while sustaining or exceeding the functionality of its competitors.

Specific challenges for introducing CLT construction to the United States were also discussed. Among these were the following:

- Fire-related code provisions: Although not directly related to seismic performance, fire code regulation is one of the very first hurdles that must be cleared for any tall wood building. Two issues need to be addressed: (1) that of requisite fire resistance ratings for components; and (2) that a combustible mass timber building as a system, with appropriate safety provisions and design, will provide the overall level of fire safety necessary for occupant and fire fighter safety. The first can be demonstrated by testing or validation of existing testing and analysis methodology relative to U.S. standards [e.g., ASTM-E119 (ASTM 2012)], and the second by development of methods of assessment of overall building fire safety (likely a performance-based procedure). International experience has shown that this can be achieved relative to various performance-based code provisions and may provide a path to U.S. acceptance.
- Lack of experience: U.S. contractors lack experience in building with CLT. The benefit of high CLT construction speed is directly contingent on the familiarity of the contractor with the material. Current lack of experience in the United States makes it more realistic to introduce CLT at the component level to familiarize the market and contractors with this new material. Some smaller projects are already underway utilizing CLT floor diaphragms (Resident Hall Project, Colorado State University 2013). This challenge also needs to be addressed through education and outreach, especially to contractors, engineers, and building officials.
- Innovation and research funding: The U.S. wood industry can be slow to adopt innovations and has traditionally not been as aggressive as the steel and concrete industries in providing funding for research and innovation. It is interesting to compare the progress of CLT implementation in Canada and the United States as two distinctly different scenarios. In Canada, forestry-related products are a big economic driver with substantial governmental and political support, while that is not the case in the United Staes. Further, the regulatory system in Canada is different from the United States and is generally quicker to adopt innovations.
- Cost and performance: Currently in the United States, the cost of CLT material is expensive relative to common perception for a timber material. Although the cost of CLT will not decrease to a level similar to light-frame wood construction, price reduction in the U.S. market is expected as local manufacturers of CLT emerge and the market grows. There was confidence among workshop participants that the price of CLT will eventually evolve to a level that is comparable to concrete and steel options. Based on a preliminary study [Fig. 1, data from Sellen Construction (2013)], even with current cost of CLT panels, the cost of CLT design option can be as cost-effective as reinforced concrete in the Pacific Northwest. A more recent study by Mahlum Architects et al. (2014) also indicated that the CLT option at 10-story height can be slightly cheaper than the concrete alternative (4%). Equivalent or better performance than

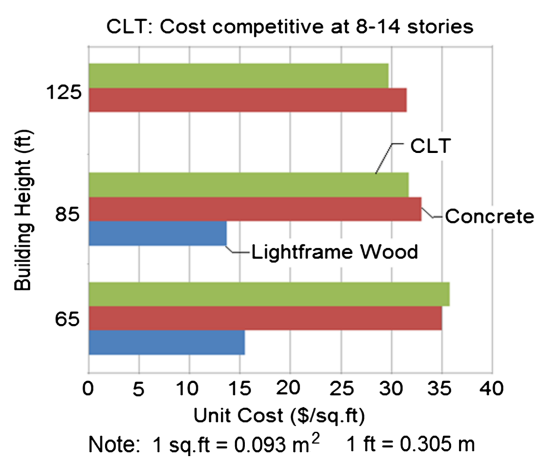

Fig. 1. Cost comparison of CLT construction (data from Sellen Construction 2013)

Table 3. Proposed Tiered Performance Expectations for Tall CLT Buildings

Seismic hazard levels (POE[a])	System performance	Structural components	Nonstructural components	Estimated repair time[b]
Tier 1: code minimum (optimizing current system and detailing, force-based design)				
Service level earthquake (50% in 30 years)	Immediate occupancy: minor nonstructural damage	Remain elastic	Minor damage, repairable	1–7 days
Design basis earthquake (10% in 50 years)	Life safety: extensive structural damage allowed but not affecting stability	Lateral system exhibit inelastic behavior, extensive repair can be done but costly	Moderate damage, repairable	1–6 months
Maximum considered earthquake (2% in 50 years)	Collapse prevention: severe damage, probability of collapse <10%	Large residual deformation, ductility fully developed, not repairable	Major damage, not repairable	Demolish/rebuild
Near fault ground motions[c]	N/A	N/A	N/A	N/A
Tier 2: code plus (innovative detailing or advanced protection systems, PBSD)				
Service level earthquake (50% in 30 years)	Immediate occupancy	Elastic	Minor damage, repairable	1–7 days
Design basis earthquake (10% in 50 years)	Limited/planned damage	Lateral system exhibit inelastic behavior, repair needed at planned locations	Moderate damage, repairable	1–2 months
Maximum considered earthquake (2% in 50 years)	Life safety: extensive structural damage allowed but not affecting stability	Lateral system exhibit inelastic behavior, repair may be costly	Moderate damage, repairable	2–6 months
Near fault ground motions	Collapse prevention: severe damage, probability of collapse <10%	Large residual deformation, ductility fully developed, not repairable	Major damage, not repairable	Demolish/rebuild
Tier 3: resilience (resilient structural systems implemented, PBSD)				
Service level earthquake (50% in 30 years)	Continuous operation	Elastic/resilient system operational	No damage	0–30 min
Design basis earthquake (10% in 50 years)	Immediate occupancy	Resilient system operational	Minor contents damage	1–7 days
Maximum considered earthquake (2% in 50 years)	Planned damage[d]	Resilient system repair needed at planned locations	Moderate damage	1–2 months
Near fault ground motions	Limited damage probability of collapse negligible	Damage extended to unplanned locations, repair may be costly	Moderate damage	2–6 months

[a]Probability of exceedance.
[b]Repair time associated with the damage to structural and nonstructural system assumes all resources needed to conduct the repair (e.g., financing, labor, material, etc.) are readily available. Thus the actual down time for the building functionality may be much longer than listed in the table due to other factors influencing the restoration efforts following an earthquake.
[c]Near fault ground motions are characterized by strong velocity and displacement pulses at relatively long period which is very likely to induce collapse. This effect is not explicitly considered in current seismic design standard.
[d]It is expected that the resilient systems will have *fuse*-like components that are designed to behave nonlinearly during strong earthquakes and easy to replace in postearthquake inspections.

current code and existing concrete and steel structures will be expected for tall CLT buildings. It is also desirable for the proposed tall CLT buildings to achieve resilience (i.e., undamaged or easily repaired) against major earthquake events, which is not possible without active seismic engineering research.

In summary, it is possible to develop a CLT tall building system that will suit the societal needs of urban infill in seismic regions in the United States. The approach is to enable the design of tall CLT buildings that are comparable or less expensive than concrete and steel options, can be quickly constructed, and provide equal or better seismic performance. Compared to other systems, the tall CLT design will also have the benefits of carbon sequestration, better energy envelope, and potential for aesthetically pleasing designs.

Currently, it is recommended that the interested parties in tall CLT buildings work on incremental implementations in manufacturing, component adoption, code compliance for fire safety, education, and outreach to prepare the society and industry for this new material. The CLT industry should not shy away from opportunities to work with the steel and concrete industries to develop hybrid products that will utilize CLT in real building projects.

Seismic Performance Expectations

During the workshop, a group discussed the likely seismic performance expectations for tall CLT buildings, which are summarized here. Tall CLT building performance targets should be realistically achievable with reasonable cost (be comparable or less expensive than current market holders), while meeting or exceeding performance of comparable systems and building codes. There are benefits to target higher than current code requirements when developing the performance targets of the tall CLT building systems, but the increased cost associated with the higher standard must also be considered. Performance-based design methods are attractive as they will explicitly demonstrate the advantages of the new system, while providing the owner with the option of different performance levels including the current code minimum. Referencing performance expectations that have been proposed for other building materials/systems, a series of tiered performance objectives for tall CLT buildings was proposed, as listed in Table 3.

Complying with current code requirements is the basic performance objective (Tier 1) for the new tall CLT systems. This can be achieved through quantifying the probability of collapse under prescribed seismic hazard levels. Moving to exceeding code performance expectations, one can demonstrate improvement of resilience of the CLT system over existing buildings through quantitative metrics. Better-than-code performance should be communicated to the stakeholders in ways that can be easily understood. Using repair time needed for the building system after an earthquake can provide a good sense of relative efficiency to the general owner/public. Requiring system-level seismic resilience could improve the public perception and willingness to implement CLT.

Of course it is acknowledged that building resilience can be affected by many components including the structural system,

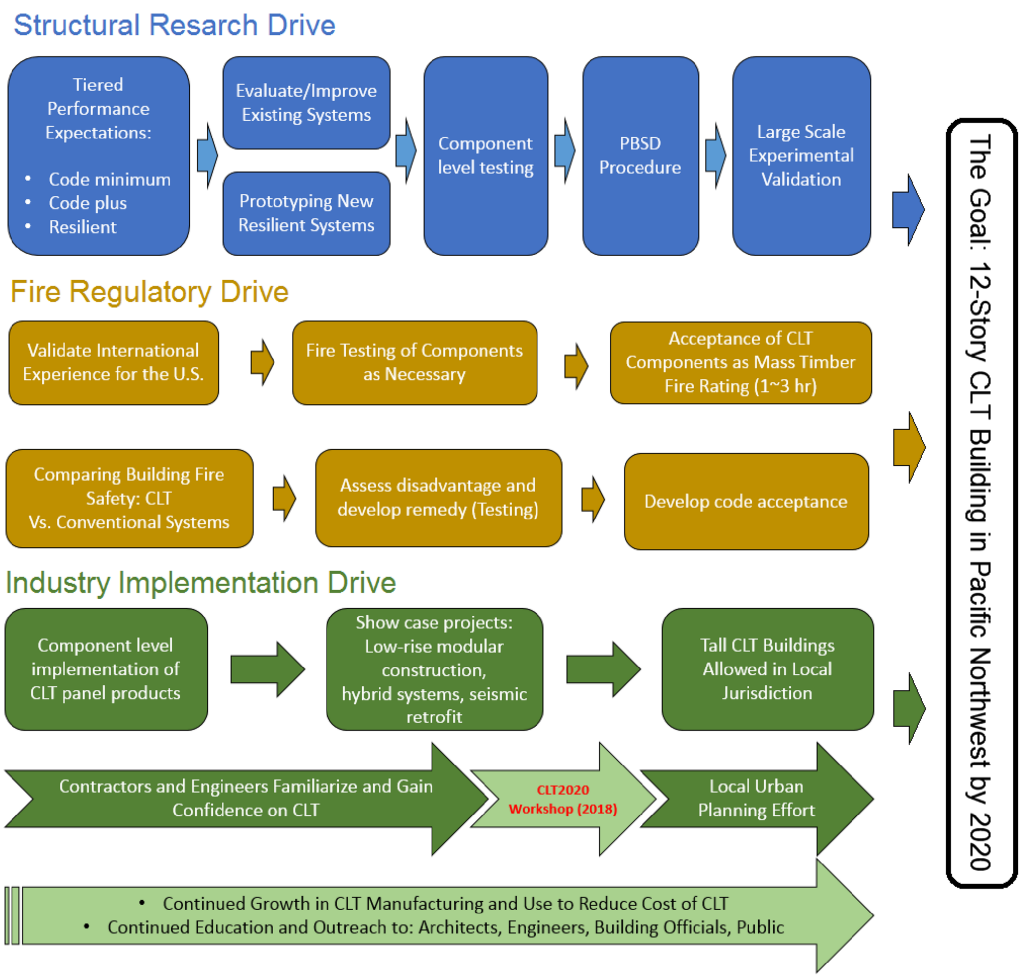

Fig. 2. Road map for building tall CLT buildings in the United States by 2020

Table 4. Action Items to Pursue the CLT2020 Vision

Activity description	Action group
Continue growing local production of CLT	Manufacturers
Ramp up engineering education and outreach to architects and engineers, leveraging on the Canadian experiences	Wood industry groups such as WoodWorks
Familiarize the public and contractors with the use of CLT through component level implementation, hybrid systems, etc.	Engineers and architects
Developing methods to compare CLT building system to conventional noncombustible systems to provide a basis for fire safety equivalency	Engineers, architects, and building officials, and the American wood council
Confirm and expand fire rating data and methodology	Researchers (material and fire focus)
Research development of the prototype resilient CLT systems	Researchers and design professionals (structural focus)
Continue working on CLT shear wall code adoption for ASCE7 via application of FEMA P-695	Researchers and code regulatory committees

nonstructural finishes, utility lines, fire suppression system, power, telecommunication systems, and sewer. It is expected that the system performance will be tied to component performance, which in turn can be correlated to the dynamic response of the building system such as differential displacements and accelerations. These engineering parameters will eventually be controlled through the application of performance-based seismic design (PBSD). While it is expected that there will be acceleration-sensitive components in the building, the discussion indicated that the focus of tall CLT PBSD should be on deformation-related performance issues. Due to the potential acceleration amplification effects at the height range proposed, special requirements for limiting acceleration should also be considered.

Although the details of the performance metrics will need to be developed through further research, the proposed performance levels were believed to be flexible and attractive enough to promote the adoption of tall CLT buildings, and would also be achievable through advanced structural system prototypes and PBSD.

Road Map for Vision CLT2020

In order to overcome the challenges identified for building tall CLT structures in the United States, multiple coherent research, engineering, and marketing efforts must be implemented in the coming years. Considering the desire and engineering preparation for tall CLT buildings, it is believed that construction of a CLT building more than 10 stories high in the Pacific Northwest by 2020 (Vision CLT2020) is achievable. Fig. 2 illustrates a road map highlighting key components of the related efforts for achieving this goal, based on the information gathered during the tall CLT building workshop. Some of the boxed items are necessary activities, and some are outcomes from activities. The proposed road map provides needed steps to realize Vision CLT2020 in a systematic fashion. It is expected that the community will acquire the technical knowledge for building seismic resilient CLT tall buildings by 2018 through intensive research and testing. Then, a workshop will be held near 2018 spearheaded by the industry/contractor and urban planners to serve as a final push to initiate the construction of tall CLT buildings in the United States.

The road map shown in Fig. 2 represents integrated efforts from the timber and seismic engineering communities over a longer period of time. Table 4 lists the recommended actions that can be carried out in the short term to move the tall CLT building initiative forward. The action groups identified in the table are the suggested group to spearhead the respected activity.

Summary and Conclusions

As a result of nearly 20 years of development and research, a fundamental understanding of panelized CLT as a lateral force-resisting system has been established. CLT is a robust heavy-timber system that depends primarily on connection deformation to develop ductility and hysteretic damping under seismic loading. Multistory CLT buildings can be designed using traditional force-based design approaches, but will experience damage to their connections during strong earthquakes, high accelerations, and correspondingly large base shear and uplift demands. In order to address the needs for resilient tall CLT buildings in high seismic regions, innovative CLT lateral force-resisting systems and corresponding performance-based seismic design procedures need to be developed. This is one of the key future directions for CLT seismic research. A three-tiered performance objective for tall CLT buildings was proposed in this study to serve as the basis for the PBSD development.

Specifically, the opportunities and challenges for building tall CLT structures in the Pacific Northwest of the United States were summarized. With appropriate engineering and marketing, CLT has the potential to occupy a share of the 6–10 story building market in this region. A road map and suggested activities in the next 4–6 years were proposed to achieve CLT Vision 2020, which is to construct the first of many tall CLT buildings in the Pacific Northwest by 2020. As a sustainable material, CLT can have prolonged positive impact during its lifecycle once the challenges for its implementation are systematically addressed.

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References

ABAQUS 3DS [Computer software]. Waltham, MA, Ansys.

Amini, M. O., van de Lindt, J. W., Pei, S., Rammer, D., Line, P., and Popovski, M. (2014). "Overview of a project to quantify seismic performance factors for cross laminated timber structures in the United States." *Materials and joints in timber structures*, Springer, Netherlands, 531–541.

ASCE. (2010). "Minimum design loads for buildings and other structures." *ASCE7*, Washington, DC.

ASTM. (2012). "Standard Test Methods for Fire Tests of Building Construction and Materials." *E119-12a*, West Conshohocken, PA.

Breneman, S., and Podesto, L. (2013). "Timber skyline: A review of structural systems for high-rise wood structures." *Proc., SEAOC 2013 Convention*, Structural Engineers Association of California, Sacramento, CA.

Ceccotti, A. (2008). "New technologies for construction of medium-rise buildings in seismic regions: The XLAM case." *Struct. Eng. Int.*, 18(2), 156–165.

Ceccotti, A., Lauriola, M. P., Pinna, M., and Sandhaas, C. (2006). "SOFIE project—Cyclic tests on cross-laminated wooden panels." *Proc., 9th World Conf. on Timber Engineering*, Oregon State Univ., Corvallis, OR.

Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C., and Kawai, N. (2013). "SOFIE project—3D shaking table test on a seven-storey full-scale cross-laminated timber building." *Earthquake Eng. Struct. Dyn.*, 42(13), 2003–2021.

Dolan, J. D., Bordry, V., Pei, S., and van de Lindt, J. (2014). "Tall cross-laminated timber building: Design and performance session WW300 experimental and modeling studies on wood frame buildings." *Structures Congress 2014*, ASCE, Washington, DC, 2886–2893.

DRAIN-3DX [Computer software]. Berkeley, CA, Univ. of California.

Dujic, B., Aicher, S., and Zarnic, R. (2006). "Testing of wooden wall panels applying realistic boundary conditions." *Proc., 9th World Conf. on Timber Engineering*, Oregon State Univ., Corvallis, OR.

Dujic, B., Pucelj, J., and Zarnic, R. (2004). "Testing of racking behavior of massive wooden wall panels." *Proc., 37th CIB-W18 Meeting*, International Council for Building Research and Innovation, Rotterdam, Netherlands.

Dujic, B., Strus, K., Zarnic, R., and Ceccotti, A. (2010). "Prediction of dynamic response of a 7-storey massive XLam wooden building tested on a shaking table." *World Conf. on Timber Engineering*, Italian National Research Council, Roma, Italia, 20–24.

Dujic, B., and Zarnic, R. (2006). "Study of lateral resistance of massive X-Lam wooden wall system subjected to horizontal loads." *COST E29 Int. Workshop on Earthquake Engineering on Timber Structures*, Coimbra, Portugal, European Cooperation in Science and Technology, Brussels, Belgium, 97–104.

European Committee for Standardization (CEN). (2004). "Eurocode 8: Design of structures for earthquake resistance—Part 1: General rules, seismic actions and rules for buildings." *EN 1998-1*, Brussels, Belgium.

Federal Emergency Management Agency (FEMA). (2009). "Quantification of building seismic performance factors." Washington, DC.

Forestry Innovation Investment and Binational Softwood Lumber Council. (2014). "Summary rep.: Survey of international tall wood buildings." ⟨http://www.rethinkwood.com/sites/default/files/wood-resourse-pdf/Survey%20Tall%20Wood_REPORT%20WITHOUT%20APPENDICIES_web.pdf⟩ (Oct. 16, 2014).

Fragiacomo, M., Dujic, B., and Sustersic, I. (2011). "Elastic and ductile design of multi-storey crosslam massive wooden buildings under seismic actions." *Eng. Struct.*, 33(11), 3043–3053.

Gavric, I., Fragiacomo, M., and Ceccotti, A. (2012). "Strength and deformation characteristics of typical XLam connections." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

Hristovski, V., Dujic, B., Stojmanovska, M., and Mircevska, V. (2012). "Full-scale shaking-table tests of XLam panel systems and numerical verification: Specimen 1." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0000754, 2010–2018.

International Code Council. (2013). "Prefabricated wood shear panels." *AC 130*, Washington, DC.

Joyce, T., Ballerini, M., and Smith, I. (2011). "Mechanical behaviour of in-plane shear connections between CLT wall panels." *Proc., 44th CIB-W18 Meeting*, International Council for Building Research and Innovation, Rotterdam, Netherlands.

Karacabeyli, E., and Douglas, B. (2013). *CLT handbook*, FPInnovations, Pointe-Claire, QC, Canada.

Lauriola, M. P., and Sandhaas, C. (2006). "Quasi-static and pseudo-dynamic tests on XLAM walls and buildings." *COST E29 Int. Workshop on Earthquake Engineering on Timber Structures*, European Cooperation in Science and Technology, Brussels, Belgium.

Okabe, M., Yasumura, M., Kobayashi, K., Haramiishi, T., Nakashima, Y., and Fujita, K. (2012). "Effect of vertical load under cyclic lateral load test for evaluating Sugi CLT wall panel." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

OpenSees [Computer software]. Berkeley, CA, Univ. of California.

Pang, W., Rosowsky, D. V., Pei, S., and van de Lindt, J. W. (2010). "Simplified direct displacement design of six-story woodframe building and pretest seismic performance assessment." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0000181, 813–825.

Pei, S., et al. (2014). "Progress on the development of seismic resilient tall buildings in the Pacific Northwest." *World Conf. on Timber Engineering 2014*, FPInnovations Pointe-Claire, QC, Canada.

Pei, S., Popovski, M., and van de Lindt, J. W. (2012a). "Seismic design of a multi-story cross laminated timber building based on component level testing." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

Pei, S., Popovski, M., and van de Lindt, J. W. (2013). "Analytical study on seismic force modification factors for cross-laminated timber buildings." *Can. J. Civ. Eng.*, 40(9), 887–896.

Pei, S., and van de Lindt, J. W. (2007). *User's manual for SAPWood for windows, version 1.0*, Colorado State Univ., Fort Collins, CO.

Pei, S., van de Lindt, J. W., and Popovski, M. (2012b). "Approximate R-factor for cross-laminated timber walls in multistory buildings." *J. Archit. Eng.*, 10.1061/(ASCE)AE.1943-5568.0000117, 245–255.

Popovski, M., Gavric, I., and Schneider, J. (2014a). "Performance of two-storey CLT house subjected to lateral loads." *FP Innovations Research Rep., FPIPRODUCT-1-6896*, Vancouver, BC, Canada.

Popovski, M., and Karacabeyli, E. (2012). "Seismic behaviour of cross-laminated timber structures." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

Popovski, M., Karacabeyli, E., and Ceccotti, A. (2011). "Seismic performance of cross-laminated timber buildings." Chapter 4, *Canadian design handbook on cross-laminated timber*, *FP Innovations Special Publication SP-528E*.

Popovski, M., Pei, S., van de Lindt, J. W., and Karacabeyli, E. (2014b). "Force modification factors for CLT structures for NBCC." *Mater. Joints Timber Struct.*, 543–553.

Popovski, M., Schneider, J., and Schweinsteiger, M. (2010). "Lateral load resistance of cross-laminated wood panels." *World Conf. on Timber Engineering*, Italian National Research Council, Roma, Italia, 20–24.

Rinaldin, G., Amadio, C., and Fragiacomo, M. (2013). "A component approach for the hysteretic behaviour of connections in cross-laminated wooden structures." *Earthquake Eng. Struct. Dyn.*, 42(13), 2023–2042.

SAP2000 [Computer software]. Walnut Creek, CA, Computers & Structures.

Schneider, J., Stiemer, S. F., Tesfamariam, S., Karacabeyli, E., and Popovski, M. (2012). "Damage assessment of cross laminated timber connections subjected to simulated earthquake loads." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

Sellen Construction. (2013). *CLT modular construction: Residential opportunities*, Presentation to Lake Union Partners, Seattle.

Shen, Y. L., Schneider, J., Tesfamariam, S., Stiemer, S. F., and Mu, Z. G. (2013). "Hysteresis behavior of bracket connection in cross-laminated-timber shear walls." *Constr. Build. Mater.*, 48, 980–991.

Sustersic, I., Fragiacomo, M., and Dujic, B. (2012). "Influence of the connection behaviour on the seismic resistance of multi-storey crosslam buildings." *World Conf. on Timber Engineering 2012*, New Zealand Timber Design Society, Auckland, New Zealand.

Tavoussi, K., Winter, W., and Pixner, T. (2008). "Development of earthquake bracing systems for multi-storey buildings using slender shear wall elements in cross-laminated timber (CLT)." *Research Rep.*, Vienna Univ. of Technology, Austria.