

## An Overview of CLT Research and Implementation in North America

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**ABSTRACT:** Although not yet seen as common practice, building with cross laminated timber (CLT) is gaining momentum in North America. Behind the scenes of the widely publicized project initiatives such as the Wood Innovation Design Centre Building in Canada and the recent U.S. Tall Wood Building Competition, substantial research, engineering, and development has been completed or is underway to enable the adoption of this innovative building system. This paper presents a brief overview of the current status of CLT building development in North America, highlighting some recent U.S. and Canadian research efforts related to CLT system performance, and identifies future CLT research directions based on the needs of the North American market. The majority of the research summarized herein is from a recent CLT research workshop in Madison, Wisconsin, USA, organized by the USDA Forest Products Laboratory. The opportunity and need for coordination in CLT research and development among the global timber engineering community are also highlighted in the conclusions of this paper.

**KEYWORDS:** Cross Laminated Timber, Research and development, Tall wood building, Building performances, North American market.

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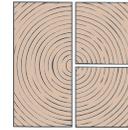
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## 1 INTRODUCTION

Only a few years ago, cross laminated timber (CLT) was still a novelty for the North American building market. But the ability of CLT to serve as a sustainable timber material for the non-residential market has attracted significant interest from the wood industry, researchers, and practitioners. CLT also has the ability to turn lower value wood stocks into a high value products and foster economic development in rural communities. Since the introduction of CLT to North America in the early 2000's, some progress has been made to enable pilot building projects in the U.S. and Canada utilizing this new construction material, despite a lack of comprehensive streamlined building code adoption. As a new product, there are practical challenges for CLT implementation in North America in terms of material supply, structural safety, serviceability and fire performance, and code acceptance. Different industry and research groups have been conducting research and development projects to address these challenges. In order to better coordinate CLT research efforts in North America as a whole, the U.S. Department of Agriculture (USDA) Forest Service, Forest Products Laboratory (FPL) partnered with the Softwood Lumber Board and organized a Mass Timber research workshop [1] in November 2015 in Madison WI. This workshop hosted representatives from major research projects related to Mass Timber, which includes CLT, in the U.S. and Canada. Together with over 125 workshop participants from industry, academia, and government, the current status of North American CLT research and future directions was discussed. Shortly after the CLT research workshop, a mass timber conference was held in Portland Oregon where additional CLT research and policy topics were discussed, together with introduction to a number of ongoing CLT building projects in the U.S. This paper presents an overview of the recent research and development from these meetings, as well as an introduction to the efforts to pursue large scale CLT building construction in the U.S. and Canada. Numerous researchers, engineers, architects, and their organizations contributed to advance North American CLT construction from non-existence to the current stage where initiatives have been taken to push the boundaries of modern timber construction, but the work is far from completed. The authors intend this paper to serve the international wood research and design community as an informative outline for the current landscape of North American CLT research and development and help support the coordination of the global CLT research in the near future.

## 2 CLT AS A NEW PRODUCT IN NORTH AMERICAN MARKET

### 2.1 Manufacture and Supply

CLT manufacturers in North America have seen a steady growth since the product was first introduced. This trend is driven by a combination of new businesses focusing on CLT manufacturing and existing engineered timber producers adding CLT manufacturing capacity to their product lines. Canada-based companies Structurlam and Nordic Structures have been producing locally sourced CLT panels since 2010 and remain the largest Canadian CLT manufacturers to date. The U.S. CLT manufacturing started later with SmartLAM in Montana being the first U.S. based CLT company (starting around 2012). As an example of the growth potential, SmartLAM has grown to produce over 1 million board feet of CLT per-month, with plans to expand and build another production facility. States in the Pacific Northwest of the U.S., especially Oregon and Washington, have shown great interest in pursuing CLT manufacturing and utilization strategically to enhance local economy. An example of this is the DR Johnson Lumber Co. In Riddle, OR began manufacturing CLT in 2015. Another U.S. CLT manufacturing facility built by Sterling Lumber Company in the Chicago suburbs will begin production in the spring of 2016. Sterling will have the ability to produce a 2.4 m by 6.1 m CLT panel every 60 seconds.

A number of research projects related to manufacturing and supplying CLT as a product were funded in the U.S. in recent years, with some still on-going. These research efforts focused on efficient use of local wood species and market analysis. A recently concluded study investigated the use of southern pine to manufacture CLT panels for use in North American construction [2] [3]. A number of full-size 3- and 5-ply CLT panels were tested with various types of adhesives. The structural, fire, and hygrothermal characteristics of these locally produced panels were evaluated. This research provided some insights into the potential of CLT plant start-up in the southeast part of the U.S. At the same time researchers at Virginia Tech were funded by the USDA Forest Products Research Program to develop low value hardwood CLT manufacturing options [4]. A CLT supply chain study (Washington State University, on-going) was funded [5] to identify existing gaps for CLT to be successful in commercial buildings. This study proposed a "forest to market" supply chain model for major western states considering softwood availability, sawmill capacity, potential markets, and use of relatively new techniques such as high-speed mobile sawmilling. Another research effort led by researchers from Oregon State University (on-going) [5] looked at the potential of using low-value lumber from small diameter logs harvested in Pacific Northwest Forest Restoration Programs in CLT manufacturing. The researchers propose to manufacture CLT panels with core layers

made out of low-value lumber and develop corresponding product standards. It is likely that through the knowledge gained from these studies and a consistently growing local CLT market, integration of CLT manufacturing into the fabric of the existing local forest management/lumber industry will be a main direction for U.S. CLT production.

## 2.2 Code and Standards

Development of a product standard is one of the first steps needed to introduce a new product for engineering design. While CLT manufacturers in Europe adopted a proprietary approach for panel mechanical properties, the first performance-based CLT material standard for CLT in North America was developed through the collaboration of APA-The Engineered Wood Association and FPInnovations [6]. The PRG320 standard [7] was published in 2012 and recognized by American National Standards Institute (ANSI). The standard specifies a total of 7 CLT performance grades and the testing methods to quantify and determine the grades. PRG320 is referenced in the 2015 edition of the National Design Specifications (NDS) for Wood Construction in the U.S., and the 2014 edition of the Canadian National Standard for Engineering Design in Wood (CSAO86). North American CLT manufacturers have been gradually adopting this standard, with Structurlam, Nordic and the DR. Johnson Lumber Company being the first North American CLT manufacturers to obtain the APA certification to meet PRG 320. PRG320 specifies requirements for lamination and adhesive materials (referring to existing adhesive standards), as well as methods of testing and quality assurance. It does not include nail-laminated CLT or other CLT products manufactured without adhesive face bonds.

Through timely efforts of the wood engineering community and the American Wood Council, a dedicated Chapter for CLT was added to the 2015 edition of National Design Specification® (NDS®) for Wood Construction standard. Chapter 10 of the latest NDS applies to CLT manufactured according to PRG320 with reference design values provided by the manufacturer or through code evaluation reports. The description of CLT design recommendations in the NDS remains brief, but follows a similar format as other engineered wood products such as I-Joists and SCL with the application of adjustment factors for different design conditions. Chapter 12 of the NDS also indicates edge spacing requirements for dowel type connectors when applied to CLT panels. While the design provisions for CLT is expected to evolve as more information on CLT system behaviour becomes available through research and development, the timely inclusion of CLT code-referenced standards is a critical step in expanding the North American CLT market. Chapter 16 of the NDS also provides a methodology for calculating the fire performance of CLT based on a char rate approach similar to that used for other wood products.

With the 2015 International Building Code (IBC) referencing the 2015 NDS, jurisdictions adopting IBC 2015 will be able to utilize CLT building components in regular projects. In 2012, AWC sponsored an ASTM E119 fire endurance test on CLT. A 5-ply CLT specimen (6-7/8 inches thick), was covered on each side with a single layer of 5/8" Type X gypsum wallboard was loaded to the maximum load attainable by the test equipment. This test, along with a series of CLT wall and floor tests conducted by FPInnovation were used to substantiate the performance of CLT leading to the recognition of CLT as Heavy Timber and permitted uses of CLT in TYPE IV construction in the 2015 IBC. Type IV construction must be built without concealed spaces and can be used with buildings of up to 65 feet. With future (and some on-going) CLT construction routinely exceeding this limit, the International Code Council is creating a Tall Wood Ad-hoc Committee [8] to evaluate appropriate actions to take for future IBC versions to ensure safety of tall timber buildings potentially utilizing mass timber products. It is anticipated that the Committee will target submission of code changes for the 2018 Group A Cycle (IBC) in January, 2018. Adoption of CLT construction in local jurisdictions has also made progress in regions of the U.S. where interest is high, such as the recognition of CLT as a state-wide alternative method in Oregon with reference to the IBC, NDS, and ASCE 7 for seismic design methods.

The CLT Handbook [9] developed by FPInnovations in 2011, has served as a reference for CLT related design in North America, especially when there was no design information implemented in the codes. The fire related chapter of this handbook has already been updated, while work is underway to update the chapter on seismic design.

In Canada, the implementation process in building codes and standards is also underway. With 2014 edition of CSAO86 standard been referenced in the 2015 edition of the National Building Code of Canada (NBCC) CLT can be used as a structural material. Comprehensive design provisions related to CLT were implemented in the 2016 supplement to the 2014 CSAO86. The supplement includes information on bending, shear, and combined bending and axial resistance of CLT as a structural member in floor and wall applications, deflections and vibration performance criteria for floors, shear and withdrawal resistance of connections with bolts, dowels, nails, spikes, and lag screws, CLT as a lateral load resisting system in platform type structures, and fire resistance. This design package is the most comprehensive design package for CLT structures introduced in any material standard in the world so far.

To facilitate the use of timber in tall wood-based buildings and to help the Natural Resources Canada (NRCan) tall wood demonstration projects initiative, FPInnovations has developed a technical guide for design and construction of tall wood buildings [10]. The guide was prepared to assist architects, engineers, code consultants, developers, building owners, and

Authorities Having Jurisdiction (AHJ) in understanding the unique issues to be addressed when developing and constructing tall wood buildings including CLT structures. In addition, FPInnovations has also helped Régie du Batiment du Québec in developing and publishing a technical guide for design and construction of mass timber buildings up to 12 storeys [10]. This guide provides the directives needed for designers of tall wood buildings in the province of Quebec to produce their designs, plans and specifications. Finally, the Canadian Wood Council (CWC) and its partners are currently working on code change proposal for raising the height for wood buildings from the fire prospective up to 12 storeys for the 2020 edition of NBCC.

### **2.3 Pilot Projects**

A number of landmark CLT (or mass timber) building projects that were completed or under development in North America in the past 5 years are presented briefly in this section. This list represents an innovative portfolio of the projects planned intentionally to push the boundary and challenge the existing code limitations. Most of these projects underwent special permitting by local jurisdiction, and developed customized testing and analysis programs to generate data to support their design. These experiences and data will add valuable contents to the knowledge base of CLT construction in North America.

#### ***Wood Innovation and Design Centre, Prince George BC***

Completed in 2014, this 96 feet (29.5m) eight-story building (6 storey with mezzanine, plus penthouse) remains the tallest contemporary wood building in North America as of 2016. This height record will soon be surpassed by other tall wood building projects given in this list. The building is part of the University of Northern British Columbia used mainly for education and research purposes. Designed by Michael Green Architects, the building utilized CLT as the elevator/stair core and floor diaphragm of the building. The gravity system consists of Glulam beams and columns. With significant amount of exposed wood features, the fire and smoke separation performance tests were conducted to help convince city building officials. This project has received great public attention and a number of architecture and innovation awards [11] since its opening.

#### ***Albina Yard, Portland OR***

This 4-story office building is under construction in Portland's Mississippi District. Albina Yard is the first building in the U.S. using domestically-fabricated cross-laminated timber as a structural diaphragm incorporated into a glued-laminated frame. The glulam timber frame is on a 10-foot-by-25-foot grid with concealed steel connectors.

#### ***475 West 18<sup>th</sup>, New York City***

This 120-foot-high 10-story condo building in NYC is the east coast winner of the U.S. Tall Wood Competition [12] and received the \$1.5 million prize from USDA

towards its development cost. The building will utilize a combination of heavy timber framing and CLT floor system. The architectural design (by SHoP Architects) seeks to display wood's natural beauty and will implement exposed wood components when possible, which give rise to the need to research for fire resistance of exposed wood structural members. This project team also has an ambitious target for achieving LEED Platinum certification, reducing at least 50 percent energy consumption relative to current energy codes [13]. The building construction is expected to start in 2016.

#### ***The Framework Project, Portland OR***

The west coast winner of the U.S. Tall Wood Competition is the 12-story mixed-use wood building (130 feet tall) located in Portland. Due to significant seismic loading, lateral design of this tall wood building has incorporated an innovative post-tensioned rocking wall system recently studied by a group of researchers through funding from National Science Foundation [14]. The building will utilize a rocking CLT core structure with a gravity timber glulam frame expanding out to the perimeter of the floor plan. CLT floors will be used. The primary gravity resisting system uses glulam beams and columns. The structural design by KPPF has an ambition to achieve repairable performance for moderate earthquake events on a voluntary basis. The Framework project is currently scheduled to start construction in October 2016.

#### ***Carbon 12, Portland OR***

Carbon 12 is an 8-story (85 feet in height) residential CLT building developed by Kaiser Group located in Portland. Similar to other tall CLT building development in the U.S., the building employed heavy timber gravity frame, CLT floor, and CLT core walls. Special features for Carbon 12 include integrated moisture and temperature monitoring and a mechanical underground parking system. The building is currently under permitting process and expected to break ground in late 2016.

#### ***The Hines T3 Project, Minneapolis MN***

Technically not a CLT building, the T3 project utilizes nail laminated timber panels as the floor system with concrete overlay for acoustics. This 7-story building is a mixed construction with one concrete bottom story, 6 wood stories on top, and a concrete elevator core. The building is intended for office use and can accommodate space programming for either open office layout or traditional private office layout. With an 11 feet story height, the total building height will be about 80 feet. The T3 building is currently at the final stage of structural construction, with expected opening of the building by fall 2016

#### ***Candlewood Suites Hotel, Huntsville AL***

The Candlewood Suites Hotel is a 4-story building with a typical hotel floor layout constructed by Lend Lease at the U.S Army Redstone facility. Although it is not a tall CLT building with challenging design features, it

highlighted the feasibility and cost-competitiveness of multi-story CLT structure even at 4 stories. The project was able to be cost-neutral when compared to typical traditional construction because of the savings in schedule and personnel. The project team concluded that CLT can be very competitive when there are schedule and labour constraints and high foundation costs. This is the first CLT hotel in the U.S. and Lend Lease's first CLT project in North America, executed with previously inexperienced workers that were trained on site. With this successful experience, Lend Lease continues to engage in additional CLT projects in the U.S.

#### ***Brock Commons at University of British Columbia (UBC), Vancouver BC***

This 18-story wood-concrete hybrid building is under construction and is planned as the first phase of the new 690-bed UBC student housing complex. The ability for UBC to permit building construction as an independent jurisdiction made this ambitious venture possible. This building that is part of the NRCan's tall wood demonstration building initiative, will be 174 feet (53m) high and take the title of the tallest wood building in North America at the time of completion (fall 2017). The structural design for gravity loads feature CLT floor panels as two-way slabs supported on a glulam column grid [15]. The columns at each story transfer the axial load directly to the column below through steel bearing connection to avoid crushing of the CLT floor panels under compression perpendicular to wood grain loads. The lateral loads are resisted by a concrete building core. The design team is targeting at LEED Gold certification for the building's energy performance.

#### ***Arbora Complex, Montreal, Québec***

Located in Montreal, Quebec, Arbora will be the largest complex in the world built from massive timber. This complex, which is in a design stage at the moment, has 597,560 square foot of usable space with a total of 273 condominiums, 30 townhouses and 130 rental units for a total of 434 residential units. With its three 8-story buildings, this development will distinguish itself on the environmental front by aiming to include 40 % of its area dedicated to green space and by striving to achieve a LEED Platinum certificate.

#### ***Origine Building, Quebec City, Quebec***

Origine, a major 13-storey residential project in Quebec City's Pointe-aux-Lièvres eco-district, will consist of a 12-floor solid wood structure on a concrete podium and measure 40.9m in height. A long time in the making, the project has drawn on input from government officials as well as research institutes, and will help pave the way for the development of a North American market for solid wood building products made in Quebec.

#### ***Other Notable Efforts***

The project list summarized in this section is not meant to be a comprehensive list of all CLT building projects in North American, but only to highlight the trend of CLT development in the region. In fact it is virtually impossible to develop an exhaustive list as new projects

of different scales continue to merge. Other notable CLT projects that are currently in progress include:

- Integrated Design Building at University of Massachusetts that combines CLT with glulam zipper trusses.
- Richard Woodcock Centre for Education at Western Oregon University is the first project to utilize Oregon-made CLT.
- Not a real construction project, but a conceptual design study of an existing 42-story concrete building in Chicago was conducted by Skidmore, Owings & Merrill (SOM) utilizing a timber/concrete hybrid system.

It is abundantly clear that while the CLT industry and code acceptance in North America are still in their early developmental stages, there is very strong market interests in this new construction method to push the envelope of wood-based commercial construction. Some of these on-going projects face challenges that are new to CLT construction world-wide, such as building CLT over 10 stories in regions of high seismicity, and maintaining building fire performance with large portion of wood exposed. At the same time, these challenges are also being addressed through active research efforts in North America in the past several years, which will be introduced in the following section.

### **3 CLT RESEARCH IN NORTH AMERICA**

A workshop was organized in November 2015 by the Forest Products Laboratory to discuss current research efforts related to CLT in the U.S. and Canada. With more than 120 participants, the workshop reviewed findings from some recently completed projects and discussed research needs in several key areas of CLT building design and construction. The research projects discussed during the workshop are summarized in this section, followed by the identified future research needs in section 4.

#### **3.1 Structural performance**

A research project [16] funded by USDA to complete a FEMA P-695 [17] evaluation on CLT shear walls (CLT panel walls connected to floor/ceiling with metal connectors). This study is currently underway at Colorado State University and will identify seismic design parameters for CLT applicable to ASCE 7 seismic design provisions. The FEMA P-695 methodology requires a combination of research activities to justify design parameter values, including testing, nonlinear static and dynamic analyses, an extensive peer-review, and archetype and design method development. While the study is still on-going (expected to be completed by the end of 2016), researchers reported on current progresses including connector and shear wall testing results, proposed a building design space made up of 11 fully designed buildings from which the archetypes were extracted, and have developed the numerical models for those archetypes. Some examples of several performance groups within

the methodology were presented in their preliminary form with the procedure to determine the collapse margin ratio. There was very strong interest from the audience on the projected results from this research as it will fill a void in current seismic design procedure for multi-story CLT buildings.

Different from panelized CLT shear walls, a post-tensioned rocking CLT lateral system was investigated in a NSF funded research project to develop seismically resilient tall CLT buildings [14]. The focus of this study was on performance-based design using high performance lateral systems that can remain damage-free in moderate earthquakes and be repairable for larger earthquakes. A series of full-scale CLT rocking wall tests were conducted at Washington State University (WSU) and generated convincing data for the resilience potential of the proposed rocking wall systems. When designed and detailed correctly, the rocking wall system can self-center and limit damage at 5% inter-story drift. The results of this project were shared with industry and enabled the consideration of rocking CLT system in the Framework project. The project team also investigated a sliding diaphragm (as inter-story isolation) option for multi-story platform CLT construction. The prototype sliding diaphragm system was also tested with various configurations at WSU. While the current resilient CLT system project has concluded with component testing results, the research team is proposing a 2<sup>nd</sup> phase of the project to investigate system level performance and test a full scale 10-story CLT building on the shake table at UC San Diego, pending funding availability.

Buckling Restrained Brace (BRB) is a proven component to enable ductile performance in braced steel and concrete frame systems. A research effort was led by ARUP to develop a heavy timber BRB by encasing steel yielding element in glulam bracing studs. Due to the maturity level of a similar system made of steel and concrete, it is expected that a pathway towards code acceptance will be easier than CLT-based lateral systems. As a large number of tall mass timber buildings also use timber gravity frames, it is relatively straight forward to add BRB for ductile lateral resistance. In addition to conceptual design and preliminary building system analysis, ARUP is collaborating with other industry partners to conduct prototyping and testing of full scaled BRB components. The challenge in a heavy timber BRB design is to ensure compatibility between the lateral and gravity systems, and ensure gravity frame stability under large drift levels.

There is currently no design guideline for CLT diaphragms to calculate its strength and stiffness. Although it is likely the CLT diaphragm strength will be dictated by connections, PRG320 does not address in-plane panel shear strength. There have been several experimental [18] and numerical [19] research efforts on diaphragm connections. But a system level testing program is still needed to integrate connection and system performance. For design implementation, a white paper document [20] was recently released to showcase

simple CLT diaphragm design following the current CLT Handbook recommendations. A modified deflection calculation formula was also proposed to account for large panel influence.

FPIInnovations, along with UBC, and University of New Brunswick (UNB), have been on the forefront of the CLT structural performance research in Canada. Canadian researchers have received strong funding support since 2008 through several wood research initiatives such as the Network for Engineered Wood-based Building Systems (NewBuildS). The study on CLT as a lateral load resisting system (LLRS) started with reverse cyclic testing of CLT walls with different configurations at FPIInnovations [21], followed by numerical analysis to develop models for these walls and a preliminary estimation of seismic force modification factors [22]. System level lateral tests were also conducted to investigate assembly performance in a 3D house configuration [23]. In-plane shear stiffness of the CLT panels was investigated both numerically and experimentally, and analytical models were developed to predict the in-plane stiffness of CLT panels with openings [24]. At the system level, conceptual design of tall (up to 30 stories) timber-steel hybrid structural system FFFT was proposed [25]. A comprehensive study on the structural performance of a 20-storey building that includes a mass timber panel core as the prime LLRS was also conducted [26]. Finally, a comprehensive study on the use of CLT as an infill panel in steel wood hybrid construction was undertaken [27].

### 3.2 Serviceability

Serviceability issues of CLT material and building systems mainly include vibration and acoustics, hygrothermal performance, and creep. Systematic study on these topics is currently limited. The rational approaches to address these issues in current building practices have been summarized in the CLT Handbook. Experimental studies have been carried out by different groups including FPIInnovations and FPL. For example, vibration tests on 5-ply and 7-ply CLT floors were conducted by FPIInnovations with a subjective evaluation system to quantify performance. Creep tests for 5-ply and 9-ply CLT panels were also conducted. There is still a need to gather more testing data on CLT panel and assembly vibration and acoustics performances to establish a more comprehensive understanding of North American CLT material serviceability issues for different building applications.

The hygrothermal performance of CLT material and building components was investigated by FPL through laboratory testing and building monitoring. Although the existing CLT Handbook outlines recommended design for CLT building envelope, the actual performance of the CLT building regarding moisture is largely unknown. The possibility of CLT panels getting wet during construction is not negligible, and the drying performance of the panel in a realistic building configuration is not well understood. In the FPL moisture monitoring study, a number of remote moisture

sensors were installed on a CLT roof at different locations and collected about 3 years of moisture data since 2012. The results showed that the roof moisture barrier of the monitored building performed satisfactorily during the monitoring period, eventually keeping the moisture content of CLT under 10%. However, this is just one data point for satisfactory performance. Additional similar data and system level testing or actual CLT building monitoring program in the future can help fill in this knowledge gap.

### 3.3 Fire performance

Because mass timber construction will likely have exposed structural components made with wood, addressing how the exposed timber impacts a fire over its full development through to self-extinguishment becomes a fire safety issue. There are a number of research projects (primarily in Canada) focusing on CLT fire performance as a component or in a compartment setting. CLT panels with different ply configuration with and without gypsum protection were tested by FPInnovations at the NRC fire lab using standard ULC S101 fire exposure [28]. Char rates and fire resistances were determined for the panels, generating a good data set for subsequent studies. Another experimental study on CLT compartment fire performance was conducted by McGregor at Carleton University considering different level of fire load and protection levels [29]. The tests involve typical furniture fire load and a propane fire scenario. Fire in a protected room with only furniture fuel was shown to self-extinguish, with CLT remain unaffected. The unprotected CLT panel can delaminate and add to fire load. With propane fire, even protected room can fail and initiate second flashover after the gypsum board failed (due to extensive charring).

CLT floor system fire performance was investigated in another study by Aguanno at Carleton University [30]. A total of 8 floor panel configurations were tested including 3 and 5 ply panels with different level of gypsum protection. Some configurations were repeated at different scales. All specimens were loaded and tested to failure (rapidly increasing deflection or flame penetration). A numerical model was developed based on empirical temperature-dependent relationships in standard fire tests, thus may have limited portability. The results indicated that adhesive failure played a critical role in ply delamination, which starts around 200 C for the specimens tested. The deflection of CLT floor showed nonlinear trend with charring, and clearly affected more by the loss of spanning (parallel) ply than perpendicular ply.

Three partially protected CLT rooms were tested under non-standard fire load (using furniture and clothes) by Hevia at Carleton University in 2013[31]. The specimens varied mainly by where gypsum protection was applied and the ambient temperature. This study considers the impact of the architectural decision to leave one or two walls in the room exposed. The test results indicated that a certain percentage of the room interior surface area can

be left unprotected without increasing the risk of fire spread or intensity, but further research is needed.

Self-extinguishing of fire on CLT material was studied by Crielaard through small sample tests [32]. The study quantified some factors affecting self-extinguishment, including the potential of delamination, the heat flux of CLT, and the airflow. Increased thickness of the top lamination was believed to help extinguish fire because it reduced the chance of delamination.

Fire performance of CLT panel material was also investigated at the FPL. A series of CLT samples with different glue types, lamination lay-out, and protective membranes were evaluated. The goal is to find a design that maximizes the hourly fire rating so that the structural panels can be used in a larger variety of situations. Char rate is the focus of the study because it will directly translate to hourly rating of the exposed panels in buildings.

Protected compartment fire tests were conducted by AWC in 2015 for a 16x12 ft CLT room with typical fuel load from furniture and contents. Test results confirmed observations from earlier compartment fire tests that gypsum protected CLT (2 layers of 5/8" Type X gypsum wallboard used in this study) can achieve nearly damage free performance during a fire burn out event. A room with only one wall unprotected has acceptable performance under fire, while the room with two walls unprotected can experience CLT delamination.

Currently, Chapter 16 of the 2105 NDS incorporates a design methodology to calculate fire resistance for CLT using a char rate approach.

### 3.4 Other Research

Aside from research efforts directly related to lateral systems, serviceability, and fire performances, there were other interesting research topics presented during the CLT workshop, including:

- An innovative interlocked CLT panel product that does not require glue, which was developed by Euclid Timber in Utah. This product has been applied to small scale local projects including a bathhouse and cabins for girl scouts.
- An on-going project investigating blast-resistant CLT exterior walls in order to expand mass timber to civilian and military applications requiring blast protection. The study combines expertise from consulting industry (K&C) and academia (University of Maine) to develop numerical modelling capacity and test plans to quantify CLT blast resistance. Both static pressure testing and live blast testing are planned for this study
- FPL is also interested in developing tornado safe rooms using the concept of mass timber construction. The proposed prototype can be categorized as a nail-laminated mass timber system that can be easily constructed by a home owner. The prototype has been subjected to a

series of air-cannon impact tests and shown promising results.

#### 4 IDENTIFIED CHALLENGES

With different interest groups and research organizations considering CLT, the coordination of CLT research at the national and international level presents a challenge by itself. While there have been a few portal websites that promote the use of mass timber (e.g. Rethinkwood.com), the workshop participants felt there is a need for a well-maintained and easy-to-access CLT research database. This organizational support can not only help enhance the exchange of information among researchers but also help the industry to better understand the latest research advances that may be very relevant to their practices. Because of the natural lag in research and publication, it is important to organize on-going research progresses in addition to completed and published research.

Another fundamental challenge was expressed as to how the wood industry is going to train future leaders to advance new generation of mass timber construction. The current education on new trends of timber construction has been heavily relied on outreach seminars and short courses at the professional level (e.g. WoodWorks educational series). A more fundamental and systematic educational infrastructure for modern timber engineering is currently lacking in higher education in the U.S. (a large percentage of engineering schools do not even have timber design curriculum). This calls for a need to evaluate current wood education structure at trade school, university, and the practicing professional level. It might be feasible for the wood industry to collaborate with ASCE and establish a pathway to ensure access of timber design for students graduating with a Civil Engineering degree. Also, university programs with a tradition in timber engineering need to team up to strengthen the research and training infrastructure for graduate student researchers (such as the collaboration effort between University of Oregon and Oregon State University).

Aside from these two fundamental challenges, the following research topics were identified as the challenges that North American CLT community should prioritize in the next a few years:

##### ***Resistance to Lateral Loads***

The development of CLT shear wall system R factors and design guidelines and examples for seismic performance were identified as a high priority. The current FEMA P-695 project for CLT shear walls will not cover all types of CLT lateral systems due to the scope of what was able to be modelled and validated. Seismic design methodology and factors for other CLT-based systems will still be a research priority due to the demands of tall CLT buildings in seismic regions.

A design and analysis guideline for CLT diaphragms should be pursued and validated through testing as the

diaphragm is a critical structural component in lateral design. Although CLT diaphragms can be more robust than traditional wood frame diaphragms, quantitative evaluation of its strength and stiffness properties must be enabled for rational structural design. The testing of connections and full-scale experimental diaphragm testing are needed to quantify the behaviour and failure modes of CLT diaphragm. These test data will eventually lead to the standardization of CLT diaphragm design methodologies.

With new mass timber lateral systems potential to have high ductility and even resilient performance (e.g. post-tensioned rock wall and BRB frame), the deformation compatibility between gravity framing and lateral deflections needs further evaluation to ensure satisfactory building performance as a whole during large earthquake events.

Increase in wood building height and scale calls for higher capacity connections and construction details. There is always a need for innovation in connections and the subsequent testing and research to validate their performance and development of design guidelines. However, this part of research can likely be conducted by the industry via a proprietary product model, as it has been done for some existing special connections for mass timber framing.

##### ***Building Performance***

Durability of mass timber construction is often questioned by the general public as wood is traditionally viewed to be less resistant to environmental deterioration compared to steel and concrete. Currently, little is known about the effect of exposure of CLT to bulk water and the appropriate level of protection in current CLT construction practice. There is a lack of data on how large scale CLT buildings perform in the long run. Building moisture research is needed to demonstrate hygrothermal performance of CLT and tall wood buildings during transport, construction, and operation cycles. Data collection may take a relatively long period.

Due to the lightness of the material (relative to concrete), there exist needs for performance-based vibration design guidelines for mass-timber floors, as the design sometime is controlled by stiffness rather than strength. Wind-induced vibration in tall wood buildings is another design consideration that needs evaluation from both occupant comfort and structural performance perspectives. Coupling vibration research with acoustics research could also be beneficial.

The design considerations for different aspects of building performance also overlap. Research on how these different requirements interact with each other and the guiding principle to achieve optimal design is needed for new CLT archetypes. This research is likely to be conducted first for specific projects, and later a common guideline could potentially emerge after enough experience was accumulated.

It will be extremely beneficial to the wood industry if the CLT building developers can be incentivised to invest in in-service building performance monitoring systems to generate needed performance data that can later be used to educate and convince the building officials and the public.

### ***Fire Safety***

Communication and education regarding fire performance of mass timber structures is a barrier for these building systems. Research needed for best practice to share what we already know about mass timber fire performance with fire service, code officials, and the insurance industry. In the short term, there is a pressing need to develop documented fire performance data to convince the ICC and increase heights and area limitations for Heavy Timber/mass timber construction (Type IV) to an appropriate level.

Standardized fire performance testing and data presentation should be developed and agreed to within the industry. The testing and rating should be done for connections with different level of concealment. Impact of different adhesives on fire performance is needed in order to establish equivalency in different adhesive types.

Numerical modelling for mass timber building fire performance and subsequent risk analysis are needed. A relatively achievable target in short term will be to prove that CLT/mass timber performs in a superior way from other wood framing systems when exposed to fire. Some testing data already exists and more can be generated if a risk-based framework for evaluating wood building fire performance can be established and widely adopted.

### ***Material Resources and Other Research Topics***

Additional quantitative data-driven research on the costing aspects of CLT projects is needed. Research that can be of immediate value includes development of case studies with detailed cost information, complete economic impact studies, and general market research associated with costs.

Better understanding of sourcing for mass timber products is needed. There is a knowledge gap between the potential sources such as beetle-killed and forest fire thinning materials, and what is accessible/economical to use. This research should have both a structural component to address the quality of these materials, and an economic component to address viability.

## **5 CONCLUSIONS**

In the past several years, the wood engineering community in North America has made significant progress toward adoption and advancing CLT construction as a new sustainable option for large scale commercial applications. Currently, the North American CLT industry is experiencing an initial surge of milestone projects that will define the future landscape

of mass timber construction in the decades to come. In a 2014 tall CLT workshop organized by the authors [15], a vision of CLT2020 is proposed to enable 12-story CLT building in the Pacific Northwest by 2020. It turned out that the industry is aggressively taking a lead in this effort and will complete this vision ahead of time (the Framework Project will be completed before 2020). This is a time of great opportunity and challenges, the engineers and researchers have to be vigilant about the potential risks associated with these brand new building types. It is expected that the North American CLT market will continue to grow with successfully executed projects adding to public confidence on this new building type. Enhancement of mass timber education at different levels is critical since human capital is the key to grow any industry, including mass timber and CLT.

Research to support code acceptance and standardized design methods is still the pressing need for research on CLT in North America. Sustained growth of the CLT industry needs more than a number of high-profile projects that need special permitting. For CLT to become a viable option for urban development, tall CLT buildings at 8~20 stories needs to become a standardized building type recognized in the IBC and NBCC. This calls for significant research and data collection on building performance related to structural, serviceability, and fire. A comprehensive database for CLT research and performance data will greatly facilitate this effort. Eventually, developing economically viable CLT buildings with better seismic performance than what is required by code will be a long term goal for the U.S. timber research and engineering communities.

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