Tall CLT Building for Seismic Regions: Opportunities and Challenges

-- Findings from The Workshop on Earthquake Resilient Tall CLT buildings

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1. Introduction

Modern urbanization necessitates the design and construction of dense and sustainable buildings. With the abundance of forest resources in North America and the existing infrastructure to manufacture and utilize wood-based structural systems, resilient wood buildings in the range of 8-20 stories has emerged as a new residential and light commercial option for North America. While light frame wood construction is typically limited to low- and mid-rise buildings (maximum 4~6 stories depending on local jurisdiction) in North America, a relatively new heavy timber system called Cross Laminated Timber (CLT) has been used in Europe and Australia to construct residential buildings up to 10 stories.

Due to the location and vicinity of natural resources, the Pacific Northwest is emerging as the first region in the U.S. that has expressed interest in incorporating CLT buildings within their urban areas as a green and sustainable option. Seattle and its surrounding communities have been actively working towards allowing tall CLT buildings to become part of the urban landscape. At the same time, CLT manufacturing and utilization has been gaining traction in Canada, through adopting some of the existing approaches from Western Europe. It is envisioned that tall CLT buildings will become a reality in North America once the economic and technical barriers related to design, construction, and performance of CLT systems is adequately addressed.

As part of an NSF funded research project that focused on seismically resilient tall CLT systems, a "Tall CLT Building Workshop" was held in Seattle WA on January 24th, 2014. More than 60 participants from research, academia, design, manufacturing and the regulatory and 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 U.S. The three focus areas were (1) economic competitiveness, (2) performance expectations, and (3) engineering challenges. This report summarizes the results from the plenary discussion and breakout sessions in each of these three areas and proposes a roadmap for developing CLT tall buildings in the U.S. with the first targeted construction in 2020.

2. Background

Cross Laminated Timber is a relatively new heavy timber construction material originally developed in Austria which has quickly spread to applications around the world over the past two decades. Using dimension lumber (typically in the range of 1x or 2x) glue laminated with each lamination layer oriented at 90 degrees to the previous layer, CLT panels can be manufactured into virtually any size (with one dimension limited by the width of the press, and the other dimension by transportation limits), precut and pre-grooved into desirable shapes, and shipped to the construction site for quick installation. Especially for multi-story building projects, there has been a significant number of construction projects globally that highlight the benefit of this new timber system in terms of high quality, rapid construction, and positive impact to the environment. To date, a number of CLT buildings close to 10 stories have been constructed in Europe and Australia, highlighting the viability of introducing tall wood construction with CLT. A significant amount of research and testing work has been performed in Europe including a full scale shake table test of a 7 story CLT tower in Japan as part of the Italian SOFIE project (Ceccotti et al. 2010). Although current building codes in North America limit the height of a wood-based building system to low-rise applications (ASCE7 limits light frame wood system to 65 ft; IBC limits for combustible wood building are 6 stories and 85 ft), a number of research projects have been initiated or completed related to CLT systems in Canada and the U.S (e.g. Popovski et al. 2010, Pei et al. 2013(a)(b), van de Lindt et al. 2013). More importantly, the interest in building tall wood buildings is evident among engineers, architects and stakeholders, and some of the background work has already been completed or is underway, from the research, engineering, and manufacturing standard communities. The first CLT panel manufacturing standard in North America was published by APA in 2011 (APA, PRG 320-2011), which is a performance based standard. Through a collaborative effort by the USDA Forest Products Lab (FPL) and FP Innovations of Canada, the first edition of U.S. CLT handbook (Karacabeyli and Douglas, 2013) was published in 2013 and addressed many manufacturing, architectural and structural design approaches and details for building using CLT. A USDA funded research project (van de Lindt et al. 2013) is currently underway to develop seismic modification factors including the response modification factor R, for CLT wall systems following FEMA P695 (FEMA, 2009) procedures, which will serve as the first step to include CLT shear wall as an option within seismic design provision of ASCE7. As the latest research effort in the U.S. on resilient CLT systems, the current NEES-CLT Planning project is funded by National Science Foundation and has the objective to design and test seismically resilient systems suitable for use in 8-20 story CLT buildings in seismic regions. This workshop served two main purposes for the NEES-CLT project and broader stakeholder community. The first objective was to gather public and industry input on the economic, technical, and regulatory challenges for adopting the CLT in the U.S.; the second objective was to initiate the open discussion process between research team and practitioners with a focus on developing the tall CLT systems.

3. Summary of workshop program and discussion

The objective of the tall CLT workshop is to identify challenges in bringing tall CLT construction into practice for seismically active regions in North America. Expert opinions from the research, engineering, manufacture, and entire stakeholder community were collected during the workshop to develop a roadmap (discussed later) for building 8-20 story CLT buildings in Northwestern U.S. that will be resilient to major earthquakes. The one-day workshop included a

Plenary Session and three Breakout Discussion Sessions. Six informative presentations were presented during the plenary session to provide up-to-date development on CLT structural systems. For a detailed description of the plenary presentations, please visit the project website (neesclt.mines.edu). The breakout discussion include three sessions addressing different aspects of the CLT implementation issue, namely A) Societal needs and economic competitiveness; B) Performance expectations; and C) Challenges in engineering systems. Discussion from the three sessions are summarized in this document below:

A) Societal Needs and Economic Competiveness

The ability of a brand new product to meet societal needs is directly related to cost-effectiveness. If the product can provide better functionality with comparable or even lower cost, 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 to 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 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 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 which have a significant amount of repetitive architectural patterns, fast modular construction can work to the advantage of CLT very well, but will depend on careful designs to ensure its performance. The potential to save on life cycle 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 costs while sustaining or exceeding the functionality of its competitors.

During the discussion, many specific challenges for introducing CLT construction to the U.S. were brought up. Among these were:

- **Fire related code provisions:** 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 US standards (e.g. ASTM-E119), 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 US acceptance.

- **Lack of experience:** There is a lack of experience in the U.S. contactor work force to build with CLT. The construction speed benefit is directly contingent on the familiarity of the contractor with the material. Current lack of experience in the U.S. makes it more realistic to introduce CLT at 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 architects, engineers, and building officials.
- **Innovation and research funding:** the U.S. wood industry is not very accustomed to innovations and has traditionally not been as aggressive as the steel and concrete industry in providing funding for research and innovation. It is interesting to compare the progress of CLT implementation in Canada and the U.S. as two distinctly different scenarios. In Canada, forestry related products is a big economic driver with substantial governmental and political support, the regulatory system is also different from the U.S.
- **Cost and performance:** Currently in the U.S., the cost of CLT material is still expensive relative to public perception for a timber material. Although the cost of CLT will not likely to reduce 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 a certain level of confidence among workshop participants that the price of CLT will eventually evolve to a practical level that is comparable to concrete and steel options. Based on preliminary study (see Figure 1, data from Sellen Construction 2010), 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. Equivalent of higher performance than current code and existing concrete and steel structures will be expected for tall CLT buildings. It is desirable for the proposed tall CLT buildings to achieve resilience against major earthquake events, which is not possible without active seismic engineering research.

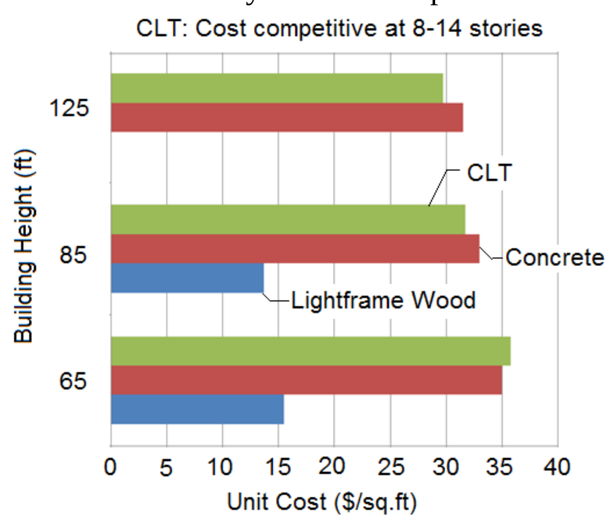

Fig. 1: CLT building unit cost compared to concrete and light frame wood systems

In summary, the workshop participants concluded it is possible to develop a CLT tall building system that will suit the societal needs of urban infill in seismic regions in the U.S. The approach is to design a resilient tall CLT building that is comparable or less expensive than concrete and steel options, can be quickly constructed, and provide equal or better seismic performance to ensure minimal interruption to business under major earthquake events. Compared to other systems, the tall CLT design will also have benefit of carbon sequestration, better energy envelope, and potential for aesthetic designs. It is expected that this prototype design will be completed and experimentally validated through the NEESCLT research effort for future implementation when market is ready.

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 steel and concrete industry to develop hybrid products that will utilize CLT in real building projects.

B) Performance Expectations

The expected performance from tall CLT buildings should be realistically achievable with reasonable cost (be comparable or less expensive than current market holders, as outlined in discussion (A)), while comply or exceeding performance of comparable systems and building codes. Most participants of the discussion agreed that it is beneficial to target higher than current code minimum requirements when developing the performance targets of the tall CLT building systems. This will enable the development of a suite of solutions that can be selected by the stakeholders if higher level of performance is desired, essentially developing a tiered format for the tall CLT expectations. The design methodology for tall CLT buildings should be performance-based which explicitly demonstrates the advantages of the new system. In addition, the workshop participants communicated the importance of communicating the performance expectations to the stake holders in a plain and simple to understand fashion. Based on the workshop discussion, it is believed that promised higher performance does not necessarily provide significant leverage for increasing initial project cost in current business decision making process. As a result, demonstrating performance corresponding to current code requirements will be the first step (Tier 1) for the new tall CLT systems. This can be achieved through quantifying 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. These metrics can be comprehensive rating systems such as Redi (Almufti and Willford, 2013), or be more focused and specific, such as limiting damage and quick repair after moderate or larger earthquake events. Requiring overall resiliency at the system level could help public perception and willingness to implement CLT. However, the community needs to be sensitive to the additional costs for the increased level of resilience.

Specifically, building resiliency can be affected by many components including the structural system, non-structural finishes, utility lines, fire suppression system, power, telecommunication systems, and sewer. It is expected that the performance of most components can all be tied to dynamic kinematics of the building system such as differential displacements and accelerations, which can be controlled through the application of 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.

It was agreed based on discussion that connecting performance of tall CLT building to resiliency can be a viable approach for practical PBSD. The CLT planning research team is proposing following three tiers of seismic performance targets as listed in Table 1 for tall CLT buildings at 8~20 stories, with the resiliency of the building quantified using estimated repair time of the damage.

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

C) <u>Engineering System Challenges</u>

The prototyping and design of tall CLT buildings will start by defining archetypes. During the discussion, the need for building use, area, and height variation in archetypes was proposed. It is recommended that the archetypes include both residential floor plans that have a large number of interior walls, and commercial floor plans with relatively large open space. A mixed commercial and residential archetype can also be useful where the bottom stories are commercial with residential units on top. It is advantageous to incorporate a modular construction style for residential units. Although the development of the resilient system in the NEESCLT project is targeted at a wider building height range (8~20 stories), the participants believe 8~12 story range should be focused on for realistic implementation by 2020. At the same time, the zoning height regulation should be considered when developing archetypes. Certain levels of vertical irregularity should be considered in the archetypes such as off-set wall lines that do not stack directly from story to story thereby necessitating consideration of transferring overturning and diaphragm forces.

Table 1: Proposed tiered performance expectations for tall CLT buildings

Seismic Hazard Levels (POE[1])	System performance	Structural components	Non-structural components	Estimated Repair Time[4]
Tier 1: Code Minimum (Optimizing current system and detailing, force-based design)				
Service Level Earthquake (50% in 30 yrs.)	Immediate Occupancy: Minor non-structural damage	Remain Elastic	Minor damage, repairable	1~7 days
Design Basis Earthquake (10% in 50 yrs.)	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 yrs.)	Collapse prevention: Severe damage, Probability of Collapse <10%	Large residual deformation, ductility fully developed, not repairable	Major damage, not repairable	> 6 months
Near Fault Ground Motions[2]	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 yrs.)	Immediate Occupancy	Elastic	Minor damage, repairable	1~7 days
Design Basis Earthquake (10% in 50 yrs.)	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 yrs.)	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	> 6 months
Tier 3: Resilience (Resilient structural systems implemented, PBSD)				
Service Level Earthquake (50% in 30 yrs.)	Continuous Operation	Elastic/Resilient system operational	No damage	0~30 min
Design Basis Earthquake (10% in 50 yrs.)	Immediate Occupancy	Resilient system operational	Minor contents damage	1~7 days
Maximum Considered Earthquake (2% in 50 yrs.)	Planned Damage[3]	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

1. Probability of exceedance. **2.** 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. **3.** 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 post-earthquake inspections. **4.** Repair time associated with the damage to structural and non-structural 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.

For the proposed resilient rocking panel system, several potential challenges and considerations for the engineering design were outlined. The tightness of the building envelope, together with details to avoid fire spreading should be considered when inter-panel movement and separation will be present in the rocking system. It is believed that the height-to-length aspect ratio of the rocking panels will affect the strength and ductility of the system. In order to achieve automatic re-centering, passive gravity load or active pre-tensioning should be added to the rocking system with carefully designed load transferring details at the wall-diaphragm interface. It is also perceived that the rocking panel system can be separated from the gravity bearing system, as long as the lateral force transfer detail between the panel and floor diaphragm is designed correctly. Majority of the participants agreed that it is desirable to limit the damage and yielding during large earthquakes to the replaceable connections instead of the CLT material itself. The non-structural component damage caused by the moving rocking interface should also be limited. Finally, when a structural system becomes complicated, durability, decay and dimensional change over time for CLT components must be considered.

For the proposed inter-story sliding system, some major concerns included clearance limits between adjacent buildings, and the deformation demand imposed on non-structural systems passing through the floors. There may exist some challenge in finding the appropriate physical system and devices to realize sliding behavior on large floor plan under significant gravity load levels. The key is to identify commercially available products which can help keep the cost of the project manageable. Overturning restraint over the sliding layers was not mentioned during the discussion, but can stand out as a challenge with archetypes with a high overall elevation aspect ratio.

For both systems, it was agreed by all participants that damage should be avoided in the diaphragm itself, which means that the diaphragm connections should be designed with substantial over-strength. This can be accomplished once the actual demands on the diaphragm connectors are understood. It is recommended to draw from the past experience in seismic failure of precast concrete diaphragms during the Northridge Earthquake, where there have already been some studies published (e.g. Fleischman et al. 2005).

Based on the suggestions from workshop participants, it is proposed to implement following steps for the development of resilient CLT system for tall buildings:

1. Develop archetypes that include both commercial and residential configurations, with various story heights in the range of 8 to 20 stories. In the commercial use configurations, large span open space should be integrated through the use of panelized rocking lateral systems and post and beam gravity systems. The residential use configurations should adopt gravity bearing wall systems with rocking shear walls or sliding diaphragm lateral system options.
2. Define resiliency performance metrics and goals for potential applications. By doing this, a clear case will be made that the tall CLT building will provide an option for achieving equivalent or better performance than current code requirements and existing buildings.

3. Through numerical simulation, identify the optimal location and configuration of the advanced lateral systems for the archetype buildings. Propose fragility of the building components and numerically check the performance of the system against desired tall CLT building resiliency targets. Design damage-free portion of the building (e.g. diaphragm) based on seismic demands on these components.
4. Design and detail the building components to ensure controlled and predictable damage patterns. Detail the connection and interfaces to address additional resiliency requirements such as fire suppression and long term durability.
5. Build and test resilient lateral systems to verify component performance and fragility. Refine the numerical model based on test data.
6. Develop a design procedure for design of tall CLT building lateral systems which can be used to achieve the target seismic performances. Design and build a full building system and verify its performance using large-scale dynamic testing, i.e. either shake table or real-time hybrid.

4. The Big Picture: Roadmap for enabling tall CLT in U.S.

The Road Map

As was discussed earlier, in order to turn the concept of tall CLT buildings into reality in seismic regions of the U.S., multiple coherent research, engineering, and marketing efforts and initiatives must be implemented in the next couple of years. Figure 2 illustrates a road map highlighting key components of the related efforts for achieving this goal by 2020 (CLT2020 vision), based on the information gathered during the tall CLT building workshop. Some of the boxed items are activities to be performed, and some are outcomes from certain activities. The idea is to systematically working at each boxed item as a community to enable building of tall CLT building by the year 2020. Additional workshops similar to this one will be needed as currently identified barriers get resolved. It is expected that the community will acquire the technical know-how for building seismic resilient CLT tall buildings by 2018 through intensive research and testing. It is expected that a workshop by 2018 spearheaded by the industry/contractor and urban planners will serve as a final push to initiate the construction of tall CLT buildings in the U.S.

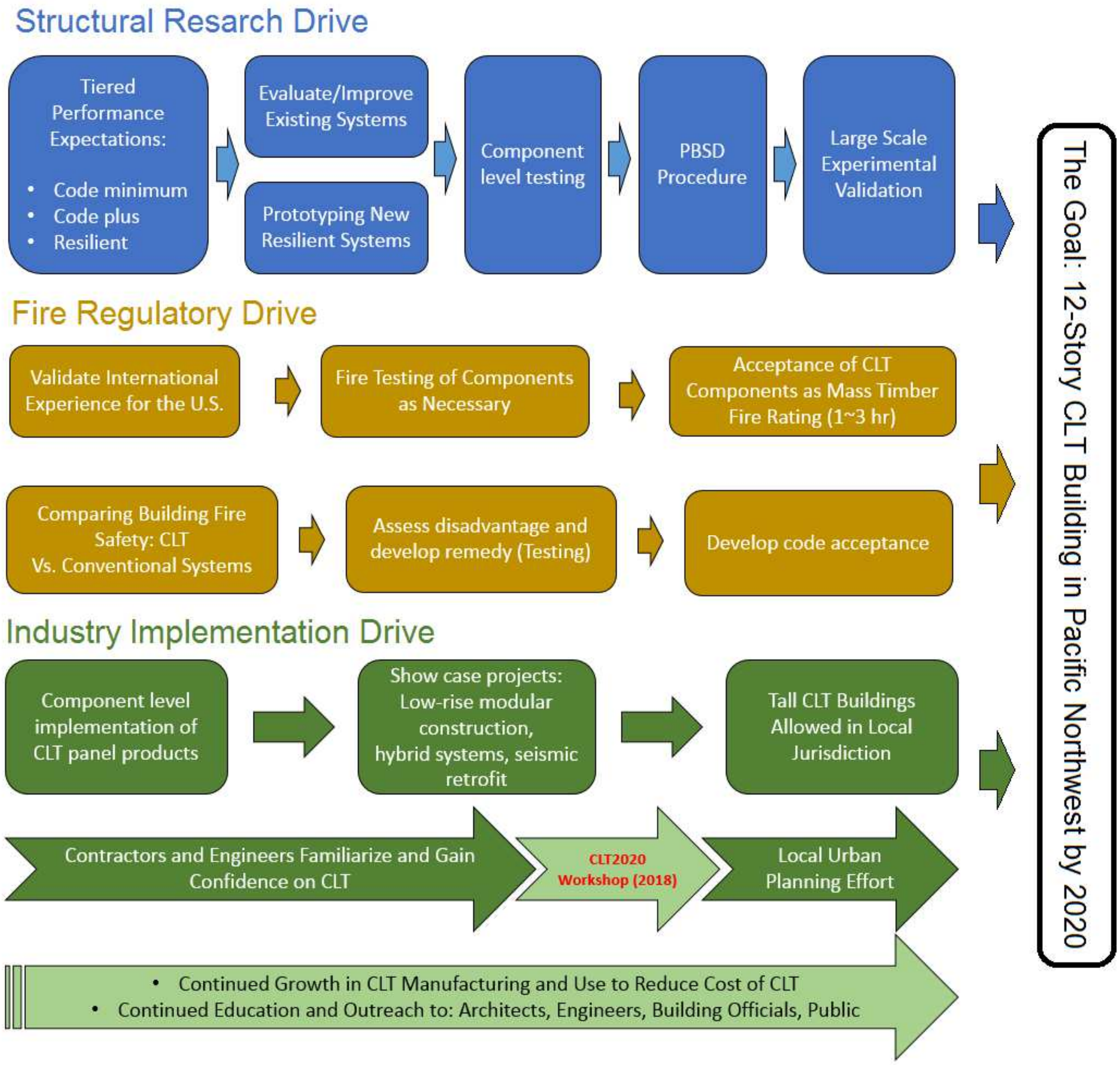

Fig. 2: Road map for enabling tall CLT building in the U.S. (CLT2020)

Plan of action

While the road map shown in Figure 2 represents integrated efforts from the timber and seismic engineering community over a longer period of time. The following list (Table 2) is the recommended actions that can be carried out in short term to move the tall CLT building initiative forward towards the goal of CLT2020. The action groups identified in the table are the suggested group to spearhead the respected activity. In order to better coordinate the interest and effort, NEESCLT research team members are assigned to each items below to serve as the contact for potential collaboration.

Table 2: Action items to pursue the CLT2020 vision

ID	Activity Description	Action group	NEESCLT contact
1	Continue growing local production of CLT	Manufacturers	Dan Dolan jddolan@wsu.edu
2	Ramp up engineering education and outreach to architects and engineers, leveraging on the Canadian experiences	Wood industry groups such as WoodWorks	Shiling Pei spei@mines.edu
3	Familiarize the public and contractors with the use of CLT through component level implementation, hybrid systems, etc.	Engineers and Architects	Hans-Erik Blomgren Hans-Erik.Blomgren@arup.com
4	Developing methods to compare CLT building system to conventional non-combustible systems to provide a basis for fire safety equivalency	Engineers, architects, and building officials, and the American Wood Council	Shiling Pei spei@mines.edu
5	Confirm and expand fire rating data and methodology	Researchers (Material and fire focus)	Shiling Pei spei@mines.edu
6	Research development of the prototype resilient CLT systems	Researchers and design professionals (Structural focus)	Jim Ricles jmr5@lehigh.edu
7	Continue working on CLT shear wall Code adoption for ASCE7 via application of FEMA P-695	Researchers and code regulatory committees	John van de Lindt jwv@engr.colostate.edu

The community should also identify a suite of potential funding mechanisms for the recommended activities, and focus on high pay-back ratio activities to support these in the short term.

5. Summary

The tall CLT building workshop held in Seattle on January 24th, 2014 synthesized valuable and practical input from all stakeholders groups on the potential technical and societal challenges for building 8-20 story CLT buildings in seismic regions in the U.S. The critical areas in which the research, engineering, construction, and regulatory communities can work on to promote the use of CLT system in urban high density building applications were identified. It is concluded that with appropriate engineering and marketing, CLT has the potential to occupy a share of the 8~20 story building market in seismic regions of the U.S. As a sustainable material, CLT can have prolonged positive impact during its life-cycle once the challenges for its implementation are systematically addressed. Ideally, the CLT tall building concept should be introduced through a number of successful, high profile, and profitable projects once the needed technical foundation is fully developed.

Following the workshop, the NEESCLT research group will continue developing seismically resilient prototype systems and archetypes for CLT construction in the 6-20 story range through the NSF funded research. A Practitioner Advisory Committee for this research project was formed to continue providing practical inputs and guidance to the research team. The final results of this research project will be made available for public reference upon the completion of the project in 2 years.

Acknowledgements

The Tall CLT Workshop is supported by National Science Foundation under George E. Brown Jr. Network for Earthquake Engineering Simulation Research (NEESR) Program. (Awards CMMI: 1344617; 1344646; 1344798; 1344590; 1344621). The financial support is greatly appreciated. The authors would also like to thank the Tall CLT Workshop participants for their comments and discussion. Special thanks to Andrew Harmsworth of GHL Consultants, Amie Sullivan of KPFF, Greg Gilda of DCI Engineers, Kris Spickler of Structlam, Leif Johnson of Magnusson Klemencic Associates, Phil Line of American Wood Council, Scott Breneman of WoodWorks, Steve Pferffer of Seattle DPD, Steve Pryor of Simpson Strong-Tie Co. for reviewing and providing valuable inputs and suggestion to the presented information in this document.

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