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PROGRESS ON THE DEVELOPMENT OF SEISMIC RESILIENT TALL CLT BUILDINGS IN THE PACIFIC NORTHWEST

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ABSTRACT: As urban densification occurs in U.S. regions of high seismicity, there is a natural demand for seismically resilient tall buildings that are reliable, economically viable, and can be rapidly constructed. In urban regions on the west coast of the U.S., specifically the Pacific Northwest, there is significant interest in utilizing CLT in 8-20 story residential and commercial buildings due to its appeal as a potential locally sourced, sustainable and economically competitive building material. In this study, results from a multi-disciplinary discussion on the feasibility and challenges in enabling tall CLT building for the U.S. market were summarized. A three-tiered seismic performance expectations that can be implemented for tall CLT buildings was proposed to encourage the adoption of the system at a practical level. A road map for building tall CLT building in the U.S. was developed, together with three innovative conceptual CLT systems that can help reaching resiliency goals. This study is part of an on-going multi-institution research project funded by National Science Foundation.

KEYWORDS: Cross Laminated Timber, Tall building design, Seismic performance expectations, Pacific Northwest

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. A tall CLT workshop sponsored by the National Science Foundation was held recently in Seattle WA to gather insights from engineering, architectural, urban planning, and research communities on engineering and societal challenges in building tall CLT building in the U.S. The information gathered from different groups during the workshop was summarized and presented in this paper. In addition, recent development in both the practice and research related to building tall CLT structures was reviewed, the roadblocks for implementing CLT in the U.S. market were identified, the road map for building multi-story CLT building in the Pacific Northwest was laid out, and conceptual lateral CLT systems that can be implemented to achieve resiliency under earthquake loading were introduced.

2 BACKGROUND

2.1 NEW TREND FOR TALL CLT BUILDINGS

Although CLT panel has been developed for more than a decade, it is not until recently tall modern timber buildings (over 6 stories) have been erected using this material. This tall timber construction trend was originated in Europe and spreading to Australia in the past 5 years. As an example not intended to be exhaustive, Table 1 listed a few significant multi-story CLT building projects that have been finished

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recently around the world. At the same time, CLT manufacturing and utilization has been gaining traction in Canada, through adopting some of the existing approaches from Western Europe and Australia. There is also strong push for research related to CLT utilization, such as the Canadian multi-disciplinary NSERC strategic research Network for Engineered Wood-based Building Systems (NEWBuildS) initiative, which has a dedicated theme for research and engineering of CLT structures. 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. The potential is also present for the U.S. market.

Table 1: *Example Modern Tall CLT Buildings*

Project	Location	Height (story)
Murray Grove	London UK	9
Bridport House	London UK	8
Limnologen Project	Vaxjo Sweden	8
Holz8 (H8)	Bad Aibling Germany	8
Forte	Melbourne Australia	10
Cenni di Cambiamento	Milan Italy	9

2.2 SEISMIC PERFORMANCE ISSUE

To date, most tall CLT buildings are located in regions with no or low seismic hazard. The construction style used has been similar to precast concrete panel construction, e.g. large CLT walls and floor diaphragm panels connected together with mechanical connectors. As an example, the interior of a CLT building in a moderate seismic region of Italy is shown in Fig.1. This type of system works well for resisting gravity loads, wind loads and small seismic loads where elastic response is adequate. Suitable building systems and corresponding seismic design methodologies for resilient CLT construction remain the major missing piece to enable resilient tall CLT buildings in high seismic regions [7]. There has been some research momentum to seek CLT design and configurations that can produce satisfactory performance under large earthquakes. A shake table test of a seven-story CLT building designed to EuroCode with a low q factor (similar to the U.S. R-factor) was conducted at Japan's E-Defense facility in 2009 [2]. In that test the hold down connection details at the base were designed to ensure that the structural system remained mostly elastic during the test and thus the acceleration amplification in the upper stories was quite high [8]. While that test demonstrated sufficient structural strength and stiffness of CLT panels, it did not provide the ductile performance aligned to the seismic design philosophy adopted in the U.S. building market. A handbook was published by FP Innovations of Canada for both the U.S. and Canada markets summarizes recent development and practice in CLT design and construction [5], focusing on building style shown in Fig.1. A preliminary study by Pei et al. [6] indicated that in order to provide seismic protection similar to the level provided in current U.S. building codes, an R factor between 3 and 4 is needed to design a prototype 6-story CLT building in Los Angeles, CA, using typical panelized construction style. There is an on-going study funded by USDA to define the appropriate R factor for CLT shear walls through the FEMA P695 approach [3]. Nevertheless, CLT buildings built with this traditional construction style can experience severe damaged at the connections in large earthquakes, thus cannot provide resiliency, which is desired for future building systems in regions of high seismicity. Fully connected panelized system does not have a means to dissipate energy associated with significant lateral excitation while the structural members remain damage-free, and thus, no realistic (i.e., economically feasible) resilient approach for construction of tall CLT panelized buildings in seismic regions is available to the earthquake engineering design community. In order to address this issue, the authors are leading an ongoing research effort supported by the NSF NEES program to investigate options for seismic resilient system based on CLT material and suitable for implementing to 8-20 story buildings. This project is scheduled to be complete by 2015 and partial results from this project is presented here.

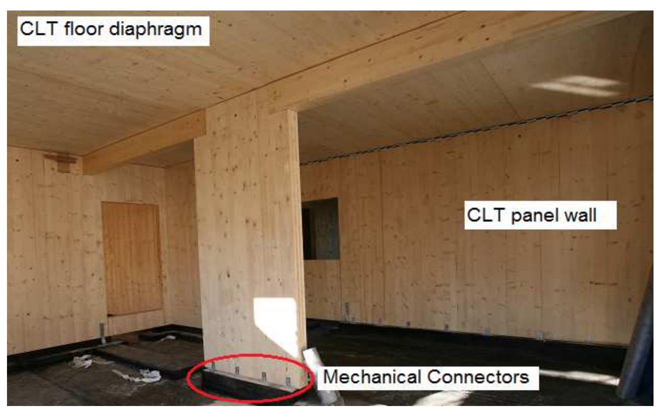

Figure 2: *Typical CLT connection style*

3 CHALLENGES OF TALL CLT BUILDING IN THE U.S.

As a new system for the U.S. market, the feasibility of tall CLT building construction should be evaluated at the societal and economical level before the development of technical details. It is also beneficial to clearly identify the needs, expectations, and potential challenges of developing such a system for seismic regions. These questions defining the scope and pathway of the development need to be answered by the engineering, architectural, and planning communities as a whole. In order to investigate the fundamental drive and challenges of tall CLT building in the U.S., a workshop was held to solicit inputs from a diverse group of experts related to tall building design and construction. The consensus of the majority participants is summarized here to form the basis of the tall CLT research.

3.1 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 first 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

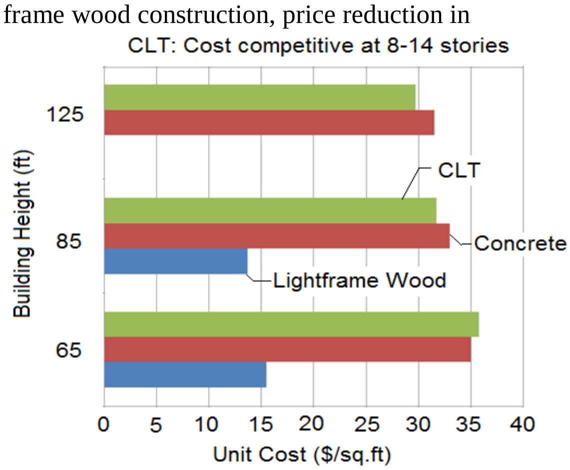

Figure 2: *Cost comparison of CLT construction (Data credit: Sellen Construction 2010)*

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 Fig.2, data from [9]), 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.

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 U.S. The approach is to enable the design of 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. Compared to other systems, the tall CLT design will also have benefit of carbon sequestration, better energy envelope, and potential for aesthetic 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 steel and concrete industry to develop hybrid products that will utilize CLT in real building projects.

3.2 SEISMIC PERFORMANCE EXPECTATIONS

For the specific question of seismic performance expectations, tall CLT building performance targets should be realistically achievable with reasonable cost (be comparable or less expensive than current market holders), while comply or exceeding performance of comparable systems and building codes. There is benefit 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 be considered also. The design should be performance-based which explicitly demonstrates the advantages of the new system, while providing the owner with the option of different performance levels including current code minimum, essentially developing a tiered approach for the tall CLT expectations. A three tiered performance expectations for tall CLT buildings were proposed here as listed in Table 2.

Complying with 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. It is very helpful if the performance improvements can be communicated to the stake holders in a plain and simple to understand fashion. Using repair time needed for the building system after an earthquake can provide a good sense of relative efficiency to the general owner/public. Other more comprehensive metrics can also be used, such as REDi™ rating system [1]. Requiring overall resiliency at the system level could help public perception and willingness to implement CLT.

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 system performance will be tied to components performance, which in turn can be correlated to dynamic kinematics of the building system such as differential displacements and accelerations. These engineering parameters will eventually 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.

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 attractive enough to promote the adoption of tall CLT buildings, and would also be achievable through advanced structural system prototypes and PBSD.

3.3 ROAD MAP FOR VISION CLT2020

In order to overcome the challenges identified for building tall CLT structure in the U.S., multiple coherent research, engineering, and marketing efforts and initiatives must be implemented in the next couple of years. It is believed that a realistic goal for building a tall CLT building more than 10 stories in Pacific Northwest by 2020 (Vision CLT2020). Figure 3 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 activities to be performed, and some are outcomes from certain activities. The concept is to systematically working at each boxed item as a community in the next a couple of years to turn this into reality. 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. Then a workshop will be held near 2018 spearheaded by the

Table 2: *Tiered performance targets for 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.

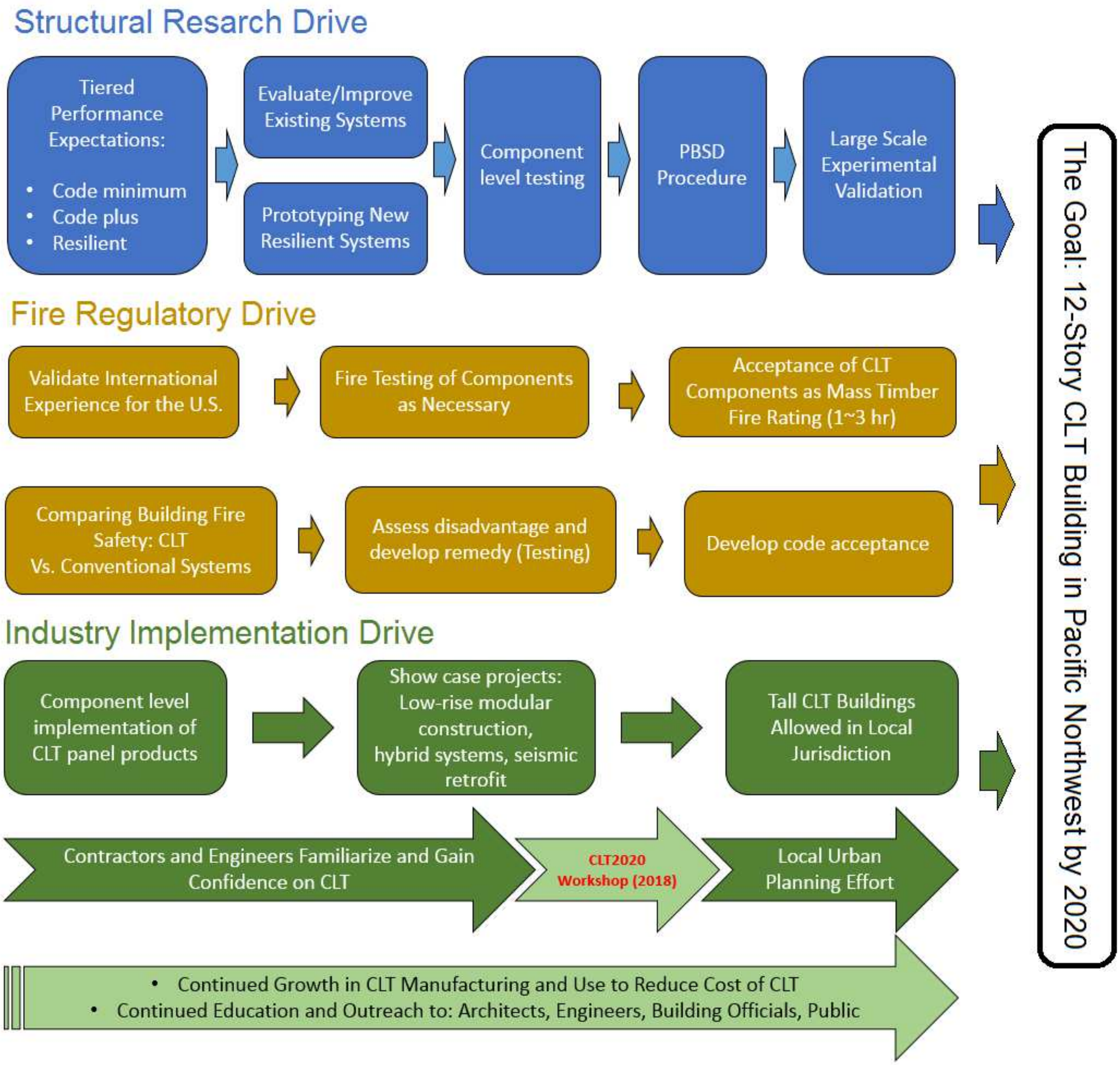

Figure 3: *Roadmap for building tall CLT buildings in the U.S.*

industry/contractor and urban planners to serve as a final push to initiate the construction of tall CLT buildings in the U.S.

While the road map shown in Figure 3 represents integrated efforts from the timber and seismic engineering community over a longer period of time. Table 3 listed the recommended actions that can be carried out in 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.

***Table 3:** 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 non-combustible 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

4 RESILIENT SYSTEM CONCEPTS

As the Tier 1 performance may be achieved through traditional panelized CLT construction with elastic design concept at locations with limited seismicity, higher performance Tiers can be very difficult to achieve on the west coast of the U.S. where large portion of the population lives near active faults. When focusing on the resilience performance target, innovative lateral systems may be integrated into a tall CLT building to generate the best cost-benefit ration in the long term.

4.1 INTRODUCING DUCTILITY

While the specific systems may differ, the fundamental concept and methodology to introduce resiliency at the system level can be shown in Fig. 4, in which multiple resilient energy dissipation layers are distributed along the height of a tall CLT building, keeping other parts of the building relatively rigid and damage free during seismic excitation. Compared to the current CLT construction that forces elastic response of the assembled panel system and high demands on connections, the added "soft" layers will elongate the system natural period and increase damping.

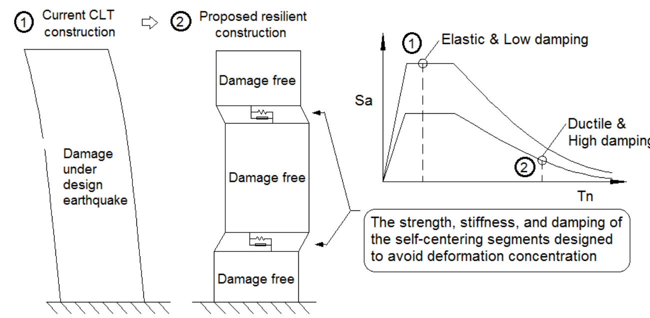

***Figure 4:** Conceptual distributed energy dissipation system*

However, the actual physical systems that can realize the desired energy dissipation and be compatible for CLT construction need to be prototypes and tested. This study is part of an integrated effort to look into three potentially viable CLT systems that may be cost effective solution to realize the concept shown in Fig. 4.

4.2 RESILIENT SYSTEM OPTIONS

Three innovative energy dissipation systems were conceptualized in this study for CLT buildings, including a deformable floor diaphragm (see Fig. 5), and single-story pre-stressed re-centering walls, multi-story segmental rocking walls (see Fig. 6). The dynamic characteristics of these systems were designed to provide displacement. Numerical models for these systems were built and subjected to different level of seismic excitation. The response of all systems were evaluated and compared to determine the optimal option for 8-20 story range.

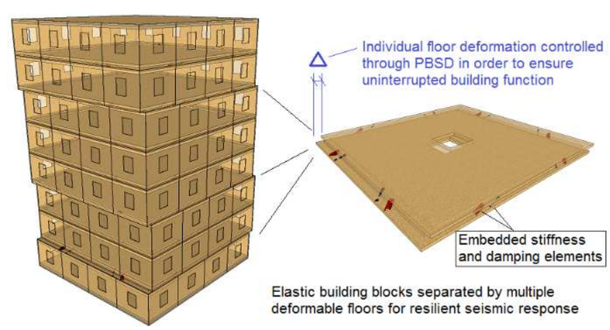

***Figure 5:** Concept of a deformable floor system*

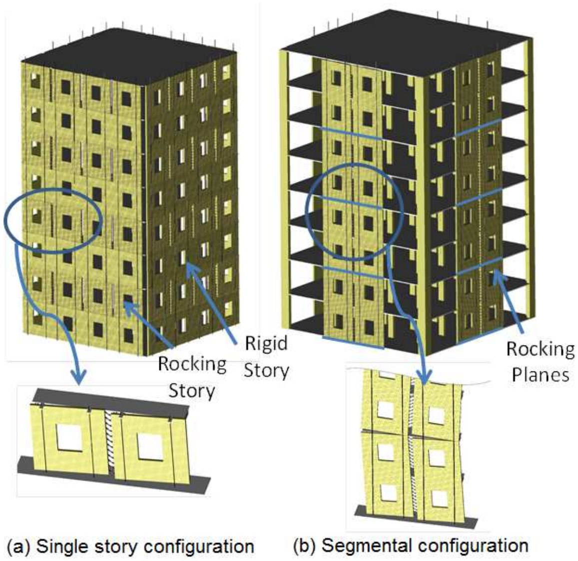

Figure 6: *Concept of single- and multiple- floor rocking system*.

Potential challenges for these resilient options were discussed during the tall CLT workshop by engineers and architects. 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).

5 CONCLUSIONS

With a consolidation of inputs on the challenges and opportunities of tall CLT construction in the Pacific Northwest from the research, engineering, and building planning community, this study highlighted a potential pathway to enable building 8-20 story CLT buildings in seismic regions in the U.S. Key areas in which the research, engineering, construction, and regulatory communities need work on to achieve the CLT 2020 vision 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.

The three-tiered performance objective for tall CLT building was proposed to serve as the basis for the PBSD development. While providing compliance to life-safety level provided by current seismic design practices, the tiered approach provided the flexibility to building owners and urban planners to opt for higher resiliency targets, enabling the implementation of advanced damage mitigation systems. Three innovative resilient structural system concepts were proposed to address the seismic resilience challenge of tall CLT buildings. Initial numerical analysis results showed promising benefit of introducing these systems. The NEESCLT planning research is currently still on-going with system prototyping and component testing scheduled in the summer of 2014.

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