Development and full-scale validation of resilience-based seismic design of tall wood buildings: the NHERI Tallwood Project

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ABSTRACT: With global urbanization trends, the demands for tall residential and mixed-use buildings in the range of 8~20 stories are increasing. One new structural system in this height range are tall wood buildings which have been built in select locations around the world using a relatively new heavy timber structural material known as cross laminated timber (CLT). With its relatively light weight, there is consensus amongst the global wood seismic research and practitioner community that tall wood buildings have a substantial potential to become a key solution to building future seismically resilient cities. This paper introduces the NHERI Tallwood Project recentely funded by the U.S. National Science Fundation to develop and validate a seismic design methodology for tall wood buildings that incorporates high-performance structural and nonstructural systems and can quantitatively account for building resilience. This will be accomplished through a series of research tasks planned over a 4-year period. These tasks will include mechanistic modeling of tall wood buildings with several variants of post-tensioned rocking CLT wall systems, fragility modeling of structural and non-structural building components that affect resilience, full-scale biaxial testing of building sub-assembly systems, development of a resilience-based seismic design (RBSD) methodology, and finally a series of full-scale shaking table tests of a 10-story CLT building specimen to validate the proposed design. The project will deliver a new tall building type capable of transforming the urban building landscape by addressing urbanization demand while enhancing resilience and sustainability.

1 MOTIVATION

Tall buildings in the range of 8~20 stories are common for urban construction because they provided a means for developers to balance occupant density and land price. While traditional light-frame wood construction is not economically or structurally viable at this height range, a relatively new heavy timber structural material, cross laminated timber (CLT), has made tall wood building construction possible. This panelized product utilizes small lumber layers glu-laminated in an orthogonal pattern to create solid wood panels that can be used as wall and floor components in a building. Currently, a number of successful CLT building projects around the world (e.g. the 10-story Forte building in Melbourne, Australia; the 9-story Stadthaus Building in London, etc.) have highlighted the viability and benefit of tall wood construction, which includes a reduction in construction time, reduced demands in foundations, and positive environmental impacts. Due to its relatively light weight and reparability, there is an opportunity to develop practical mass-timber structural systems and design methods that enable resilient performance of tall wood buildings in large earthquakes.

This paper presents the research plan and vision of a recently funded National Science Foundation (NSF) project aiming at developing and validating a seismic design methodology for tall wood buildings that incorporates high-performance structural and non-structural systems and can quantitatively account for building resilience. This project involves a series of modelling and testing tasks, including a series of full-scale shaking table tests of a 10-story CLT building specimen at NHERI@UCSD outdoor shake table to validate the proposed design methodology. As it is shown in Figure 1, this project will build upon existing research and knowledge about the CLT system and performance-based seismic design (PBSD) in general to address two major knowledge gaps in resilient tall wood building design.

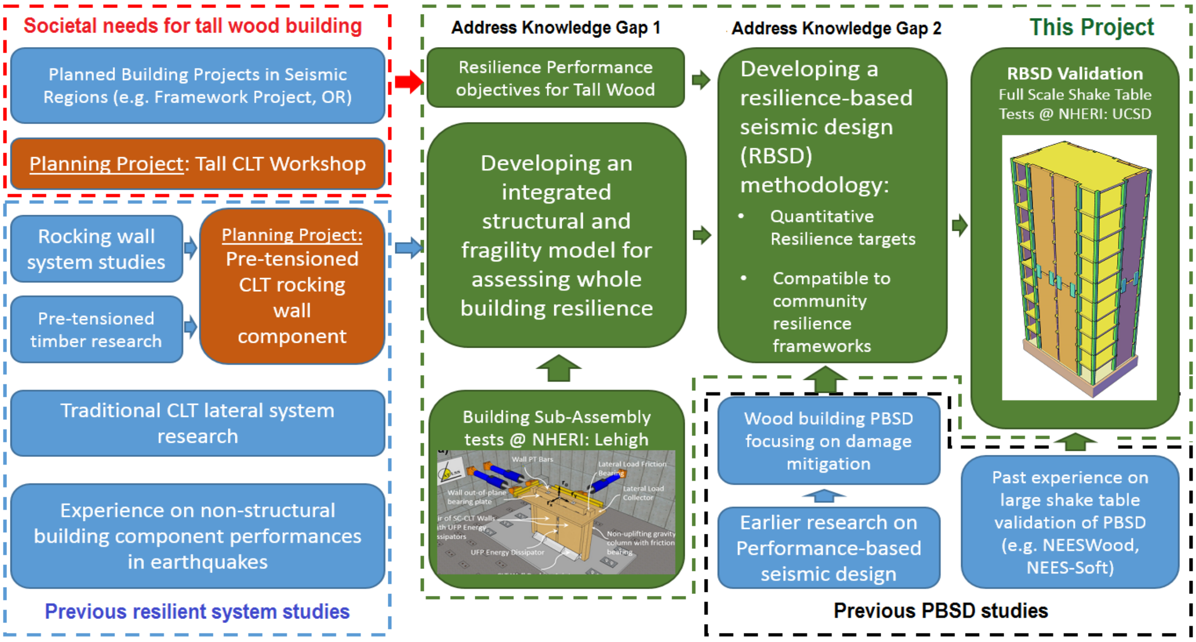

Fig.1 Societal needs, technical foundation, and scope for the proposed research

2 TECHNICAL BACKGROUND

Since the invention of the CLT panel in the 1990's, construction of CLT structures has been similar to precast concrete panel construction, e.g. large CLT walls and floor diaphragm panels with mechanical connectors. This approach works well for resisting gravity loads, wind loads and small seismic loads. A number of analytical and experimental studies on CLT shear wall behavior have been conducted by researchers around the world (e.g. Ceccotti et al. 2013, Popovski et al. 2010) and concluded that conventional CLT shear wall configurations are very stiff under small lateral loads, and can only exhibit ductile behavior when nonlinear deformation develops in the metal connectors. A seven-story

CLT building designed to EuroCode with a low q factor (similar to the R-factor in ASCE-7) was tested at Japan's E-Defense facility in 2007 (Ceccotti et al. 2013). The roof acceleration measured during the test exceeded 4g, compared to peak ground acceleration of only about 1g (Popovski, 2010). In January 2016, a Japanese led three-story CLT building test at E-Defense that used similar conventional CLT shear wall construction. The building met life safety objectives when subjected to near-fault ground motions but experienced extensive structural damage. Thus conventional platform CLT construction can deliver collapse prevention performance, but with high acceleration amplification and significant damage during large earthquakes. Suitable building systems and corresponding seismic design methodologies for resilient CLT construction remain the major missing piece to enable resilient tall CLT buildings in regions of high seismicity (Pei et al. 2015).

In recent development of seismically resilient structural systems, post-tensioned self-centering rocking walls/frames have been proven to achieve lower post-earthquake repair costs and recovery time. Of primary importance to timber buildings, post-tensioned heavy timber lateral systems have also been explored first by New Zealand researchers (e.g. Buchanan et al. 2008, Iqbal et al. 2010) and later by the authors through the Planning Project (Ganey 2015). Buildings using wood rocking wall system have been constructed in New Zealand. Experimental results indicated the CLT rocking wall system can be designed to be very ductile with negligible damage at over 5% inter-story drift. When pushed beyond 9% drift levels, the walls had only concentrated damage at the rocking toe that can be easily repaired. While rocking systems tested in isolation perform well, achieving resilience will require accommodating displacements in other building components that do not rock (gravity framing, floor diaphragms, non-structural walls). This project will be unique in that CLT rocking walls will be tested with nonstructural walls – necessitating the development of details to accommodate rocking wall displacements – and floor diaphragms. In addition, almost of prior tests on rocking wall systems and nonstructural walls have been unidirectional; thus, the proposed work will be the first to test these components bi-directionally through the assembly tests at NHERI@Lehigh facility.

Performance-based seismic design (PBSD) has been widely regarded as the next generation seismic design philosophy since its introduction in the 1990's. It has been applied to different building types including wood construction. In an earlier project, the authors led an effort (NEESWood project, van de Lindt et al. 2010) to develop a performance-based seismic design methodology for mid-rise light-framed wood buildings, which used inter-story drift as the design variable for targeting different performance objectives. Validation of the design methodology was done using a series of full-scale shake table test of a six-story wood frame building at Japan's E-Defense facility. While the light-framed wood system is limited in building height due to fire constraints, this project further pushes the envelope of wood application through CLT into the tall building arena. In addition, this project uses resilience (i.e., loss of and time-based recovery of functionality) as an explicit design target, advancing PBSD towards resilience-based seismic design (RBSD).

3 PROJECT PARTICIPANTS

This project is a collaborative effort between academic researchers and practitioner engineers and architects. The project team also involves researchers, engineers, manufacturers from around the world. The list of project lead investigators and senior personnel is shown in Table 1. The advisory committee members involved in decision making process of the project are listed in Table 2.

Table 1: Project team and expertise

PI and Senior Personnel	Affiliation	Expertise
	Project PI	
Shiling Pei, Assistant Professor (Lead PI)	Colorado School of Mines	Large-scale shake table test. Wood engineering education and outreach
Jeffrey W. Berman, Associate Professor	University of Washington	Numerical modeling of resilient CLT rocking wall system
Keri Ryan, Associate Professor	University of Nevada Reno	Building non-structural components seismic performance

James D. Dolan, Professor	Washington State University	Wood building design and detailing, CLT material manufacturing
John W. van de Lindt, George T. Abell Professor	Colorado State University	Performance based design, resilience of structural and other systems
James M. Ricles, Bruce G. Johnston Professor	Lehigh University	Large-scale structural testing, hybrid testing
Richard Sause, Joseph T. Stuart Professor	Lehigh University	Performance based design and evaluation of self-centering rocking wall systems
Senior Personnel		
Hans-Erik Blomgren, Structural Engineer	Katerra Inc.	Tall building design, building envelop and non-structural components
Andy Buchanan, Principal	PTL New Zealand	Pre-tensioned wood system performance and reliability
Thomas Robinson, Principal	LEVER Architectures	Tall wood building architectural design
Eric McDonnell, Structural Engineering Manager	KPFF Consulting	Structural design of tall wood building, Constructability of heavy timber systems
Douglas Rammer, Research General Engineer	Forest Products Lab	Code implementation
Marjan Popovski, Principal Scientist	FPInnovations	CLT building system lateral behavior

Table 2: Project Advisory Committees

Advisory Committee	Member	Affiliation
Design and Construction	Kelly Cobeen	WJE
	Jeff Morrow	Lend Lease
	Steve Pryor	Simpson Strong-Tie Co.
Code and Regulatory	Steve Pfeiffer	Seattle Building Official
	Ronald Hamburger	Simpson Gumpertz & Heger
	Philip Line	American Wood Council
	Borjen Yeh	APA-Engineered Wood Association
Binational Wood Industry	Kris Spickler	Structlam
	Todd Black	DR Johnson
	Williams Munoz Toro	Nordic
	Scott Breneman	WoodWorks
International Collaboration and Outreach	Asif Iqbal	University of Northern British Columbia, Canada
	Massimo Fragiacomo	University of L'Aquila, Italy
	Hiroshi Isoda	Kyoto University, Japan
	Stefano Pampanin	University of Canterbury, New Zealand

4 PLANNED TASKS

The proposed research work was planned over 4 years through distinctive research tasks that are to be completed under the supervision of the PIs. A summary of the planned tasks is presented in Figure 2.

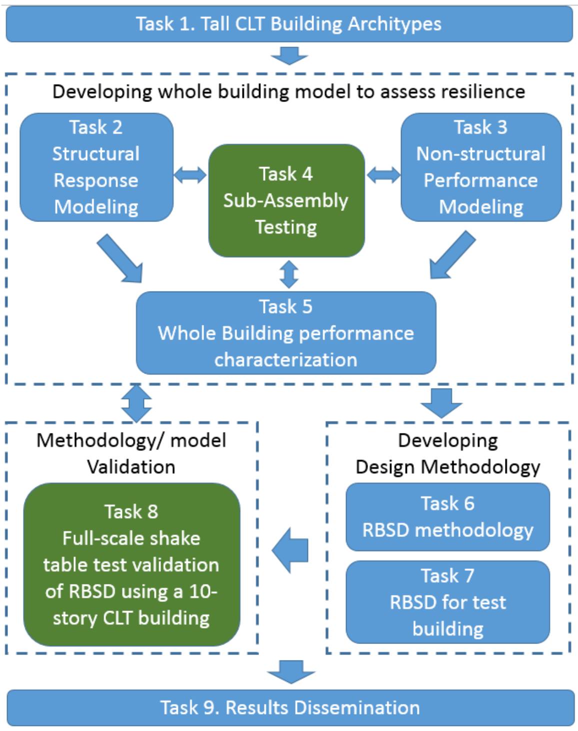

Fig.2 Proposed research tasks

- Task 1: Developing tall CLT building archetypes

At the beginning of the project, the research team will work with the Design and Construction Advisory Committee to establish a list of building types that are most likely to be adopted for tall wood construction. Several typical tall building configurations will be evaluated as candidates for implementing the resilient rocking wall system. It is envisioned that these tall building archetypes will be mixed-use applications including both residential and commercial usage, similar to the Framework Project in Portland, OR. Each of these archetypes will also include a proposed usage plan so that the non-structural components essential to building functionality can be identified.

- Task 2 - 5: Holistic modelling of tall CLT buildings with assembly level test validation

The NEESR planning grant research resulted in the development of rocking CLT wall models that compared well with the results of the experiments. Building on these models, there are two main challenges in developing structural models for tall CLT buildings: 1) existing rocking wall models and test data are limited in addressing wall behavior under biaxial loading conditions; and 2) contributions from other components of the tall CLT building system, such as the gravity load frame, diaphragms and collectors, and nonstructural elements, are not well understood.

Task 2 will develop a tall timber building system model capable of nonlinear dynamic analysis of archetype buildings subjected to ground motions, which will be combined with non-structural system functional fragility modelling in Task 3. Task 4 will involve laboratory testing of CLT rocking wall sub-assemblies (Phase 1), along with non-load bearing walls sub-assemblies that feature additional non-structural components (Phase 2). The tests on the rocking walls will enable fundamental information to be acquired related to the behavior of CLT rocking walls under bi-directional loading, as well as the performance of interface details (e.g. rocking joints, the floor diaphragm-to-rocking wall connection) under different levels of force and displacement demands. Task 4 will also serve as a means to experimentally validate the performance of selected non-structural elements identified in Task 3 as well as to calibrate the structural and resiliency prediction models developed in Tasks 2 and 3. The project team is currently design and arrange testing at Lehigh lab and the tests will be completed in 2017.

After the models are calibrated through assembly level tests, a holistic model will be developed in Task 5 and applied to analyze design variations of the archetype buildings identified in Task 1. The objective of this exercise is to investigate the impact of design choices on the seismic responses of realistic tall wood buildings. A significant amount of analysis will be conducted in this Task to provide information on the potential of archetype wood buildings identify critical components/sub-assembly systems that will impact building resilience. This information will form a knowledge base for the development of RBSD methodology in Task 6, and design/testing of the full-scale CLT specimen building in Tasks 7 and 8.

- Task 6-7: Resilience-Based Seismic Design (RBSD) of tall wood building

A Resilience-Based Seismic Design methodology will be developed in Task 6 and applied to the design of a tall wood prototype specimen building in Task 7. Although building resilience will be affected by its supporting infrastructure such as the electric power and water supply, the scope of the single building RBSD methodology in this Task will be limited to addressing time to functional conditioning on the assumption that basic services are available from the community. Thus, the RBSD methodology proposed in this task represents building resilience and the resulting functional fragility would shift based on other needs if placed into a broader community-level model. This RBSD methodology will account for the building's time to functional affected by the damage to the structural and nonstructural components within the building. The key components for the RBSD methodology include 1) selection of a building resilience performance target in terms of either a whole-building functionality fragility or a single point on the functionality fragility (e.g. a 50% probability that the building is functional in 10 days) for a given hazard level; 2) the building component design process to ensure the components perform as they are designed; and 3.) the ability to model and predict the system level functional fragility based on structural and non-structural performances. Figure 3 illustrates the proposed RBSD methodology which consists of five major steps.

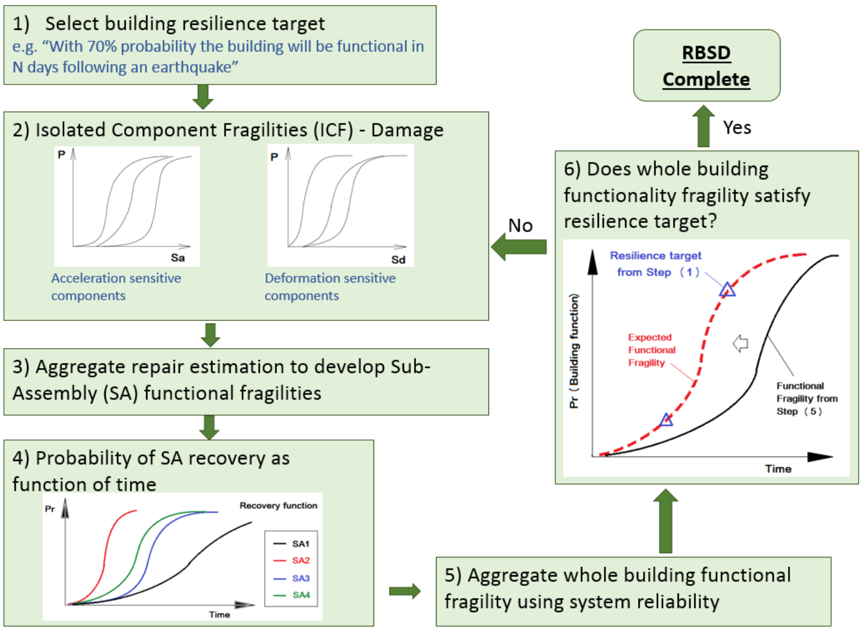

Fig.3 Framework for resilience-based seismic design

Following the RBSD methodology, a full-scale 10-story CLT prototype building will be designed for selected resilience objectives. The building will have an approximate floor plan covering the usable table surface (approximately 40x25 ft) with 9 ft story-height, as it is conceptually illustrated in Figure 10. The building will be expected to achieve continuous operation (zero-time to functional) for frequent and DBE level events, and only short term interruption for MCE and near-fault events (consistent with the resilience target established). The specimen design will be conducted in close collaboration with industry partners and the project Advisory Committees.

- Task 8: Shake table validation of the resilience design methodology

The specimen (Fig. 4) designed in Task 7 to achieve the resilience targets will be constructed and tested on the NHERI@UCSD's outdoor shake table. Collaboration with industry will ensure a feasible and economical test specimen (see Facilities and Other Resources). Based on the existing experience with the speed of CLT construction and the relatively small floor plan of the specimen, the structural frame of the building can be completed within 2 months, and 2 additional months will be needed for installation of needed non-structural components.

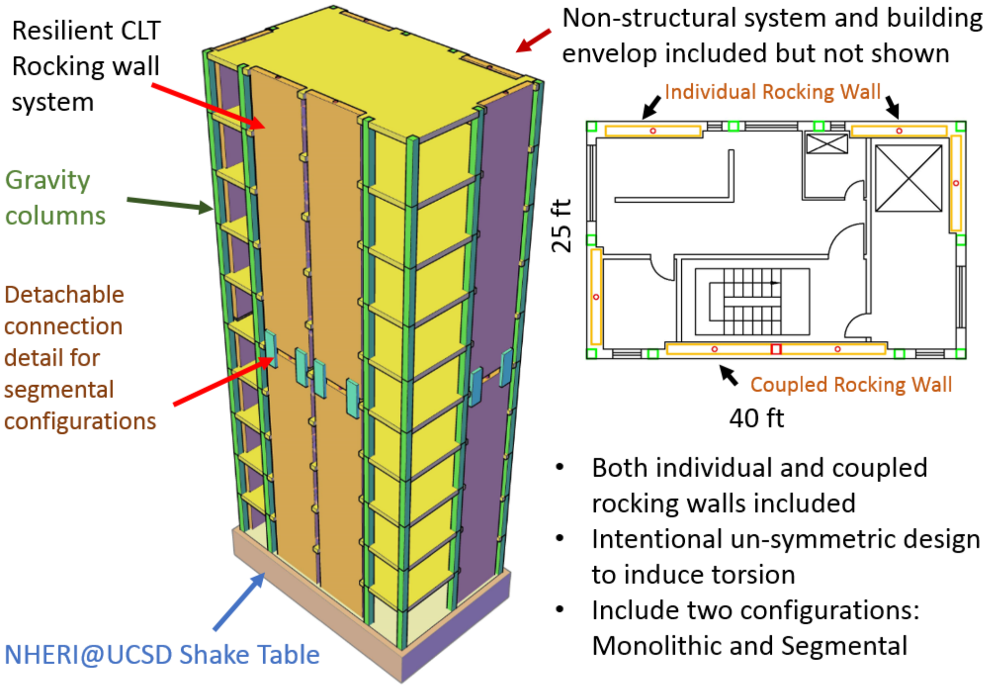

Fig.4 Concept of the 10-story full scale test at NHERI@UCSD facility

As shown in Figure 4, the building will consist of a heavy timber gravity framing system, a post-tensioned CLT rocking wall lateral system, and a CLT floor diaphragm system. The aforementioned monolithic and segmental rocking wall concepts will be tested in different phases of the testing program. The monolithic configuration will be tested first, then the detachable connection at CLT rocking panel joints will be released to enable segmental rocking behavior. The post-tension force within the walls will be adjusted accordingly based on design results. Nonstructural systems to be installed (after thorough evaluation of existing similar system level test data) include pressurized piping system, egress system (stair and functioning elevator), main electric line for testing, façade and interior finishing, and selected acceleration sensitive contents. While keeping the testing scope manageable, the project team will take the advantage of the available space in the specimen to test the performance of several potentially viable configuration options for these systems. For example, different stories in the specimen will be assigned with different functionalities (office, residential, etc.), with some stories having the same functionality but different non-structural details. Between shaking table tests, damage inspection and needed repair will be conducted. The preliminary numerical simulations will be conducted in parallel with the testing. We will use model simulation with testing data validation as a tool to make necessary adjustment to ensure the efficiency and safety of the testing program.

The test program will also serve as an ideal vehicle for payload opportunities. Being the first tall CLT structure striving to achieve a resilient design and tested at full scale, there are many innovations and new products that can be generated outside the project scope by industry and international researchers. The project team will coordinate with these interests and evaluate the pay-load plans so that they do not interfere with project objective.

- Task 9: Education and Outreach

The Education and Outreach activities of this research project will be planned throughout the duration of the project to achieve three major goals: 1) Effective transfer of tall wood building RBSD knowledge to the research and design community; 2) Educate the public on tall wood construction in seismic regions; and 3) Inspire the next generation engineers and researchers through graduate and undergraduate student involvement in the research. Key activities technical presentations, public and media events for testing, and an international blind prediction contest.

5 CONCLUSIONS

While the research project was just funded and is currently underway, it is expected that the results from this project will enable resilient tall wood building construction in high seismic regions in the U.S. and around the world, transforming the way tall buildings are designed and constructed in the future. The proposed RBSD methodology will improve the resilience of the individual tall buildings and have a positive impact on the seismic resilience of cities located in seismic regions. This project will enable a brand new sustainable construction practice that is also cost-competitive, thus increasing demands for the wood production and provide added value for forest resources. The experimental programs proposed in this project will serve as a unique educational opportunity for the general public on seismic hazard mitigation, structural engineering, and resilience building concept. It is the intention of introducing this project through this conference to the international wood research and engineering community so that meaningful collaborations can be established between the project team and potential future industry and academic collaborators.

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