Institute for Working Forest Landscapes
National Center for Advanced Wood Products Manufacturing and Design
College of Forestry, Oregon State University

A. Cover Page

1. Project Title

Cross-Laminated Timber Fastener Solutions for Tall Wood Buildings

2. List of principal investigators and other key personnel names and affiliations

Role	Name (Last, First)	Affiliation
Lead PI	Sinha, Arijit	WSE, CCE, Mat. Sci., OSU
CoPI	Nairn, John	WSE, Mat. Sci., OSU
CoPI	Miller, Thomas	CCE, WSE, OSU

3. Project starting and ending date

Start Date	03/01/2016
End Date	02/28/2019
Duration (months)	36

4. Total Project Costs

Year 1	Year 2	Year 3	Total
40,554	69,537	39,885	149,976

5. Summary Abstract

A thorough understanding of connection behavior is critical for successful tall wood building design. There is a long-term research need for connection systems in Cross laminated timber (CLT). This proposal focuses on characterization of connection systems under monotonic and cyclic loading. Objectives are to (a) evaluate lateral performance of commercially available fasteners, (b) calibrate the existing 10-parameter kinematic model for available metal brackets fastened with various nails, screws, and dowel type fasteners, and (c) develop robust numerical models that predict lateral performance of CLT panel connection systems.

Single fastener and connection systems will be tested under monotonic and cyclic shear loading and withdrawal (pull), pried, and moment resistance. Full-scale wall tests will provide data on connection behavior and aid in validating models. Data from connection tests will be used to calibrate the 10-parameter hysteretic model. Finally, the Material Point Method will be used to develop high-fidelity models robust enough so untested connections types may be confidently modeled.

Results of this research will increase our understanding of connector behavior and provide a platform to model new connectors that foster markets for tall wood buildings. A key product from this project will be two graduate students who will become future industry or academic leaders in the field. A readily accessible database on connection behavior under different loading scenarios and numerical solutions for simulation of CLT connection performance under a variety of loading scenarios will be generated. This will facilitate acceptance of connection systems through alternative methods provisions in current design codes.

B. Project Description

1. Introduction and Justification

1.1 Introduction: Cross-Laminated Timber (CLT) is an innovative wood product that has been used in Europe for the last 15 years and now is gaining popularity as a viable alternative for masonry, steel, and concrete in mid-rise construction in North America. The increased popularity of this product stems from a multitude of advantages, such as mass production, prefabrication, customization, rapid construction, and reduced environmental impacts. Additionally, the material has significant structural strength in all three axis and does not rely on an underlying structural grid of beams and girders. Previous research has shown that CLT can be used as an effective lateral-force-resisting system (LFRS) to resist seismic and wind loading on the structure. However, there are no specific and established seismic design guidelines for CLT in the US, and systems must be designed based on alternative methods allowed by the codes and reviewed on a case-by-case basis. This impedes its acceptance into the construction marketplace. Most CLT-related construction has been in moderately low seismic zones in Europe and Canada. To be accepted in the US as a viable LFRS, a thorough characterization of panel performance under lateral loads including the connection systems is needed. This proposal focuses on the latter, *i.e.*, characterization of connection systems under monotonic (static, one time) and cyclic (time-varying) loading. The specific objectives of the proposal are to:

- Evaluate the performance of commercially available fastening systems for CLT loaded laterally, such as metal brackets, self-tapping screws, wood screws, etc.
- Calibrate the 10-parameter kinematic model for CLT connections (Fig. 1) involving all available metal brackets fastened together with various nails, screws, and dowel type fasteners. The 10-parameter model characterizes the hysteresis curve for the connection as it is cyclically loaded. This provides measures of the strength (ultimate failure load), stiffness (resistance to load) and ductility (beneficial effects of energy required for failure, including reduced loads allowed for design).
- Develop robust numerical models that predict lateral performance of a CLT panel connection system to be used by engineers, architects and code officials.

This proposal directly addresses the dominant themes of CLT needs and related product refinement as well as a practitioners' resource center for wood building materials, including applications and research inventory. It is also aimed at CLT and other advanced wood product applications in building design.

1.2 Justification: The integrity of all CLT structures depends critically on the performance of the connectors. Many types of dedicated CLT connections have been developed in Europe for use in structures. These include CNC-machined carpentry connections and interlocking profiles, combinations of metal brackets and nails, screws or dowels, and a variety of innovative, proprietary connection systems (Mohammad 2011; Acler 2012). Of these connection types only the combination of metal brackets with nails, screws or dowels is similar to those currently used in North America connecting light-frame shear wall assemblies. While many of the dedicated CLT connection solutions are currently subjects of testing, research and/or innovative development in some North American laboratories (notably FP Innovations in Canada), only a few manufactured in the US for the Europeans (*e.g.* Simpson HGA10) are available on the domestic market and construction sites. The APA is currently developing data and performance statistics for a reference connector that will provide a benchmark for all the developed and existing connectors.

For engineers to design CLT structures, a thorough understanding of each connector type is needed along with characteristic shear resistance values. The hysteretic 10-parameter kinematic model

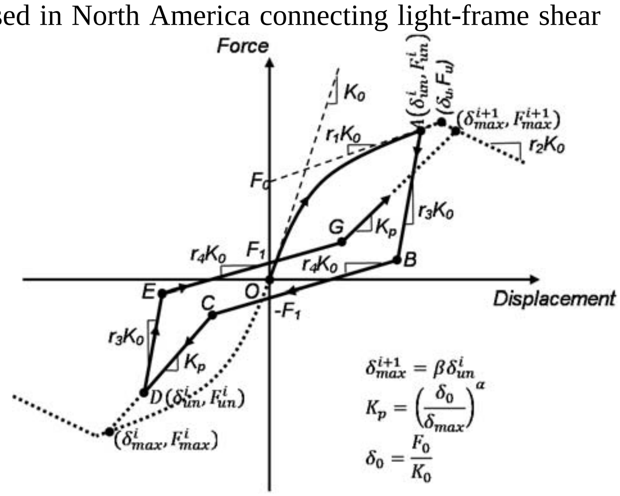

Fig. 1. 10-Parameter hysteretic kinematic model

developed by Folz and Filiatrault (2000, 2001) during the CUREE-Caltech wood frame project is widely used for fastener performance under cyclic loads for wood-frame shear walls. Based on previous studies, CLT wall connections may also be modeled using the 10-parameter model (Pei *et al.* 2013). Adopting this model for CLT offers the additional advantage of consistency with light-frame wood components. The model can be calibrated for any fastener type using cyclic test data to derive the 10 parameters that define the model. For five connections these parameters are defined in the CLT Handbook (CLT 2013). However, the metal brackets can be fastened by several different dowel type fastener. There is a need to develop calibration factors for all the widely used commercially available fasteners. Additionally, robust and validated numerical models are needed to virtually test existing and future connection systems.

2. Research Location and Methods

The research is divided into three phases: (I) Experimental characterization of fasteners; (II) Calibration of the 10-parameter kinematic model; and (III) Development and validation of numerical models. The research will be conducted under the umbrella of the National Center for Advanced Wood Products Manufacturing and Design and will have two separate physical locations on the OSU campus – Dept. of Wood Science and Engineering (WSE) and the School of Civil and Construction Engineering (CCE). The details of the three phases are:

Experimental characterization: The experimental characterization phase is divided into three sub-phases, *i.e.*, single fastener tests, component tests, and full-scale wall tests. This is designed to characterize the capacity of the three types of commonly used CLT connections: (a) wall-floor diaphragm connection, (b) wall-to-wall connection, and (c) wall-to-foundation connection. Test modes include monotonic and cyclic shear loading as well as withdrawal (pull), pried, and moment resistance. The latter set of tests will be done on individual fasteners. The research will follow the procedures in ASTM D 1761 (2010a) and those used in Acler (2012). The yield loads, ultimate loads, stiffness values and failure modes of the joints will be recorded and analyzed. The objectives of the connection tests are twofold. First, phenomenological responses of the CLT panel connections to various modes of loading will be characterized. The data are needed to design the intended structure and compare one connection type to another. Second, as the CLT connections will be numerically modeled, a robust model should include all characteristics of connections. In other words, the model should incorporate all degrees of freedom (types of deformations) of the connection to provide better predictive results. Wall tests will provide data on connection behavior of the full-scale walls under lateral loads as well as aid in validating the models. For a selected subset of connectors, two 1.2 m x 2.4 m (4 x 8 feet) walls will be tested each under monotonic (ASTM E 564), cyclic (ASTM E2126), and dynamic (Northridge Earthquake ground motions) loadings.

Calibration of 10- parameter kinematic model: The data from the connection tests in Phase I will be used to calibrate a hysteretic connection model and withdrawal models developed by Folz and Filiatrault (2000, 2001) during the CUREE – Caltech wood frame project. This step is achieved by coding the raw data in MATLAB and OPENSEES to reverse calculate the calibration coefficients.

Numerical Modeling: At a component (single connection) scale, the main goal will be to develop high-fidelity models to verify that the approach is sufficiently accurate and robust so that untested connection types may be confidently modeled in the future. We have recently developed 3D computational mechanics methods based on the material point method (MPM) that can be applied to realistic structures in wood with actual geometries of connectors. The numerical methods can model all anisotropic properties of wood along with all needed properties of connectors. Most importantly, it can model contact and adhesion between connectors and wood that will enable modeling of dynamic and cyclic loads. The goal will be to model a single connection using complete details of wood (properties and orientation) and the connector (geometry and contact properties). The output of the models will be validated by comparison to experimental data in phase I. Additionally the model will be compared to 10-parameter kinetics models to investigate the anticipated use for designing CLT structures involving connectors.

Once modeling results are validated using experimental data, it will be interesting to use the modeling method to evaluate new connectors using virtual experiments (as opposed to manufacturing and testing those connectors). To achieve this goal, our in-house software will be enhanced to take input from

3D computer aided-design (CAD) software (*e.g.*, we have identified the OBJ file format as a suitable format and one that can be exported by most software). With integration of CAD drawing, our software will be able to draw new CLT connectors and then virtually test them in a robust and validated computer model.

3. Anticipated Outcomes

The project will be the basis for a series of publications and technology transfer activities. A key product from this project will be two graduate students trained in connection design and numerical simulations for CLT structures. As the field matures, these students will be future industry leaders in this area. The thesis projects of the supported students will be significant contributions to the current state-of-knowledge. The results of the projects will be published in peer-reviewed journals. The work will also be documented and readily available from the OSU Scholar's archive. The character of the information will be especially useful to the forest products, wood science, engineering design, and architecture communities, and therefore, the information will be published and presented in national and international forums (conferences/meetings). The PI is active in many technical organizations, including code and standard activities, where the results of this research can be disseminated and implemented. A readily accessible database on connection behavior under different loading scenarios will be an important outcome of this project. An important outlet for this information is expected to be collaborative projects with modelers who will want to incorporate these data into global structural and subassembly models. The results from this project will be included in course material for WSE 592: Advanced Wood Design and also presented via webinar through the American Society of Civil Engineers.

Numerical solutions for simulation of CLT connection performance under a variety of loading scenarios will be generated that will facilitate acceptance of connection systems through the alternative methods provisions in the current design codes. As part of this project, the Oregon Building Codes Division (OBCD) will be involved as a stakeholder group. The performance statistics of all the fasteners along with key simulation results will be available to OBCD for reference. This will help in rapid approval of plans from architects, developers, and engineers involving CLT as the primary material.

4. Timeline

Tasks	Quarters												Personnel
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	
Procure Material	■	■	■										Sinha
Press small panels		■	■	■									Sinha, GRA
Single Fastener Tests	■	■	■	■	■	■							Sinha, GRA
Component Test			■	■	■	■	■	■					Sinha, Miller, GRA
Press full-size panels						■	■						Sinha, GRA
Full-scale wall tests							■	■	■				Miller, GRA
Calibration of kinematic models					■	■	■	■	■				Miller, GRA
Numerical model development			■	■	■	■	■	■	■	■	■		Nairn, GRA
Validation of Numerical Model										■	■	■	Nairn, GRA
Reporting and Dissmeniation				■				■				■	All

5. Partner Linkages and Support

This project is a critical intersection of structural engineering, experimental mechanics, and wood material science. Consequently, the project needs expertise in these three fields and will be successful only with collaboration between WSE and CCE. The PI is a WSE faculty member with an adjunct appointment in CCE, while co-PI Miller is a CCE faculty with an adjunct appointment in WSE. Both Sinha and Nairn are also faculty within the Material Science program administered by College of Engineering. The students will pursue dual major degrees (WSE/CCE or WSE/Mat/Sci). The project will involve participation of OBCD officials and engineers from fastener producers (Simpson Strong-Tie, My-Ti-Con) in an independent technical advisory board that will make sure that the objectives of the project are completed in a timely fashion; ratify the data and analysis methods; and ensure that the results are relevant to the advancement of the industry.

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