

Overview of a Project to Quantify Seismic Performance Factors for Cross Laminated Timber Structures in the United States

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Abstract:

Cross-laminated Timber (CLT) has been extensively used in Europe and is now gaining momentum in North America; both Canada and more recently the U.S. Construction projects have shown that CLT can effectively be used as an alternative construction material in mid-rise structures and has significant potential in commercial and industrial buildings. In the United States, the CLT system is not currently recognized in seismic design codes and therefore a seismic design can only be performed through alternative methods specified in the codes. The FEMA P695 report published in 2009 presents a methodology to determine seismic performance factors namely the response modification factor, overstrength factor, and deflection amplification factor for a proposed seismic resisting system. The methodology consists of a number of steps to characterize system behavior and evaluate its performance under seismic loading. The additional benefit of the methodology is that it considers variability in ground motions and uncertainties in tests, design, and modeling. This paper presents an overview of the P695 methodology and more specifically the approach adopted to apply the methodology to Cross Laminated Timber (cross lam) systems in the United States. The type of tests and testing configurations conducted as part of this study and development of the CLT archetypes are discussed. Nonlinear models used to simulate CLT behavior at the connection, wall, and system levels are presented and the procedure to determine collapse margin ratio is explained.

Keywords: Cross-laminated timber, seismic performance factors, FEMA P695 methodology

Background:

Cross-laminated Timber (CLT) was initially introduced during the 1990s in Austria and Germany and since then has been gaining popularity in Europe and more recently in North America. The increased popularity of this innovative wood product as a viable alternative in residential and non-residential construction is due to a number of advantages such as the potential for mass production, prefabrication, rapid construction, and sustainability as an environmentally friendly renewable construction product. Very good thermal insulation, acoustic

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performance, and fire ratings are some additional benefits of this system (CLT Handbook, 2013; Ceccotti, 2008).

CLT as a lateral force resisting system

A number of studies on CLT systems undertaken in Europe and Canada (i.e. Ceccotti and Follesa, 2006; Ceccotti, 2008; Dujic and Zarnic, 2006; Dujic et al., 2008; Popovski et al., 2010) have demonstrated that a CLT system can be utilized effectively as a lateral force resisting system. The studies included tests on various types of connections; quasi-static and dynamic tests conducted on isolated CLT walls and CLT assemblies; and full scale shake table tests on a three- and seven-story building (SOFIE project). However, in the United States, CLT is not a documented lateral force resisting system and a design may only be performed through the alternative methods within the governing design code. In 2009, the Applied Technology Council (ATC) proposed a methodology published as Federal Emergency Management Agency (FEMA) report P695 which provides a rationale to evaluate seismic performance factors (SPFs) including the response modification factor (R-factor), the system overstrength factor, and the deflection amplification factor for seismic design in the U.S. The objective of the methodology is to provide an equivalent level of safety for all the structures comprised of different seismic force-resisting systems, i.e. approximately a 10% or lower probability of collapse when subjected to an earthquake having the intensity of an earthquake with a 2500 year return period (known in the U.S. at the Maximum Credible Earthquake). The FEMA P695 methodology uses nonlinear static and dynamic analyses along with statistical analysis and takes into account the variation in earthquake records and uncertainties inherent in the test data and modeling methods.

CLT prefabrication and ease of handling can facilitate production of large monolithic walls; for example, in some cases one-piece story walls. However, in this project, seismic analysis for CLT will be performed similar to light-frame wood shear panels (WSP) where analysis is conducted for certain wall aspect ratios and the result can be used to develop shear design tables similar to WSP.

Overview of FEMA P695 methodology:

As mentioned earlier, the P695 methodology will be used to evaluate seismic performance factors known as the response modification factors, R , overstrength factor, Ω_o and deflection amplification factor, C_d . R is defined as the ratio of the shear developed in the system if the system were to remain entirely linearly elastic under design ground motions V_E to the design base shear value V . Ω_o is the ratio of maximum shear strength V_{max} of the yielded system to the design base shear. C_d is defined as the ratio of the roof drift of the yielded system under design earthquake ground motions δ to the roof drift under design base shear considering the system to behave linearly elastic δ_E , multiplied by the R factor. SPFs are best described using the following equations:

$$R = \text{Response Modification Coefficient} = V_E/V$$

Ω_o = Overstrength Factor = V_{max} / V

C_d = Deflection Amplification Factor = $(\delta/\delta_E) R$

The procedure is iterative in nature and includes the following steps: (1) establish design requirements and develop specifications that is based on applicable codes and standards; (2) identification of a number of archetypes to be representative of the full design space from low-rise single family buildings to mid-rise mixed-used buildings including multi-family buildings and office buildings; The archetypes are categorized based on key design variables such as geometric variations, load intensities, and other variables that are known to have an effect on system performance; (3) a series of experimental tests on panels with varying holddown conditions and aspect ratios; the results are then used to calibrate the nonlinear numerical models; (4) the development and validation of a nonlinear computer model; the developed model takes into account degradation in stiffness and strength in the inelastic range; (5) comprehensive static (pushover) and incremental dynamic analysis (IDA) are performed to compute the median collapse that is then used to evaluate margin against collapse for the archetypes; and (6) determination of whether the seismic performance factors are acceptable based on FEMA P695 requirements. The entire procedure is overseen by a technical peer panel and their involvement is critical to each step of the process. The peer review panel will write a peer panel report for inclusion in the code adoption process. Figure 1 explains the procedure and its flow

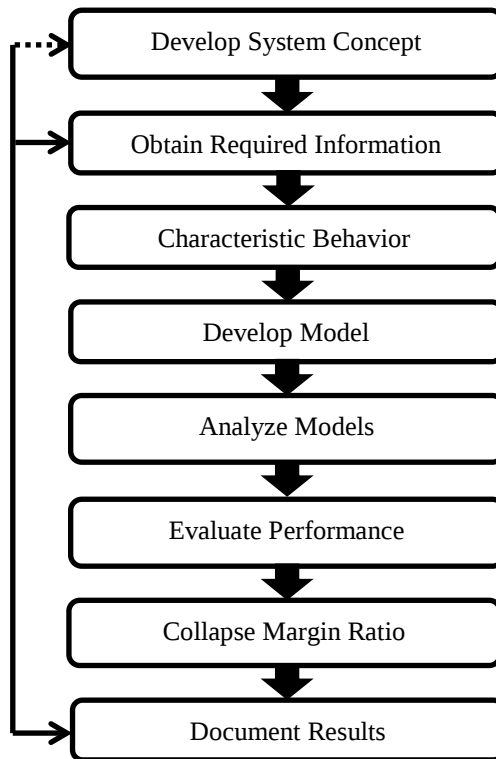


Figure 1. Overview of the process for quantifying and documenting seismic performance factors (after FEMA P695, 2009)

Required Information

Design requirements for CLT are based on ASCE/SEI 7-10, national design specification for wood construction (ANSI/AF&PA, 2012), and U.S. CLT handbook (2013). Tests will be conducted to predict strength, stiffness, and deformation characteristics of the system under consideration when subjected to simulated seismic loading. All testing will be performed in accordance with the applicable standards and specifications. Test results can also be used in developing and validating design methods for the system under consideration. According to the P695 methodology, testing is to be conducted at various levels to reliably capture and predict structural response including:

- Material test data
- Components and connections test data
- Assembly and system test data

Material testing will not be conducted as part of this study since the data can be obtained from the previous studies. Recently the American Paper Association (APA) published the ANSI/APA PRG 320 (2011) standard that provides information on performance and requirements for Rated Cross Laminated Timber. Three different types of tests that consist of connection testing on brackets, reversed cyclic loading of single isolated walls, and reversed cyclic test of two walls with a diaphragm and two walls in box type configurations will be conducted on CLT specimens. CLT wall connection testing will be performed at Forest Products Laboratory (FPL) in Wisconsin and all the other tests will be conducted in Structures Lab at Colorado State University (CSU). Simple testing configurations are shown in Figures 2-5.

Archetype Development

Archetypes or baseline structures are used to investigate seismic performance of the proposed lateral force resisting system. According to the P695 methodology, archetypes are prototypical presentation of a seismic force resisting system. Their development is an essential part of the methodology since they determine the applicable range and the design space for the lateral force resisting system. The design space is divided into various performance groups which consist of several archetype models each. Each performance group is categorized based on variables such as seismic design category, gravity load, and building height variations.

Three different categories for the archetypes are considered for the purpose of this study: single-family dwellings, multi-family dwellings, and commercial (including mixed-use) mid-rise buildings. Archetypes will be developed considering the variables shown in Table 1.

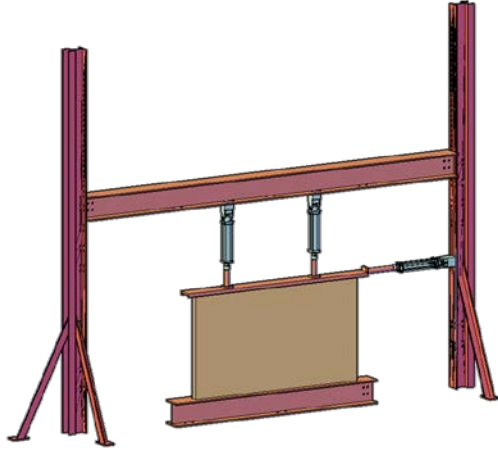


Figure 2. Isolated wall test setup (out-of-plane bracing not shown)

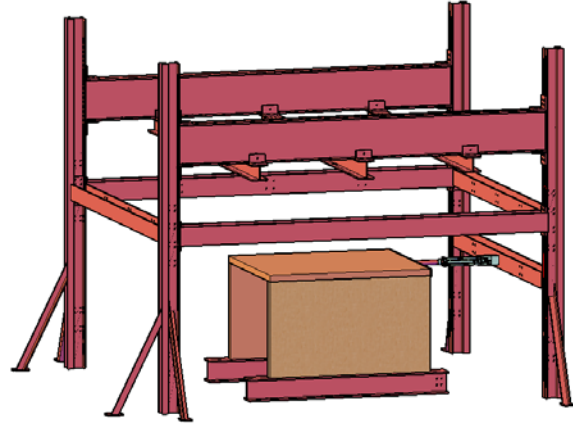


Figure 3. Two wall assemblies with a diaphragm (weight will be placed on the diaphragm in lieu of force controlled actuators)

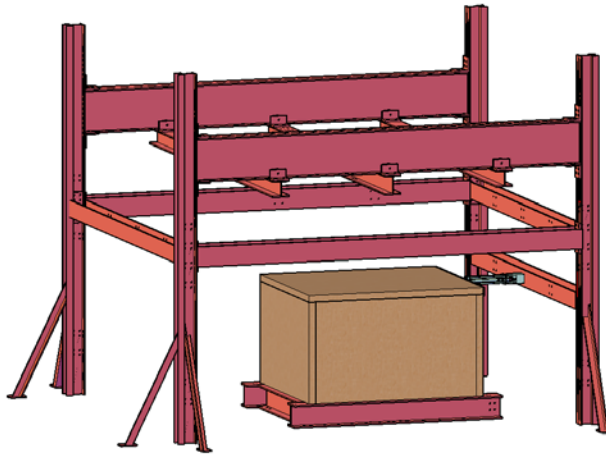


Figure 4. Box type configuration with a diaphragm

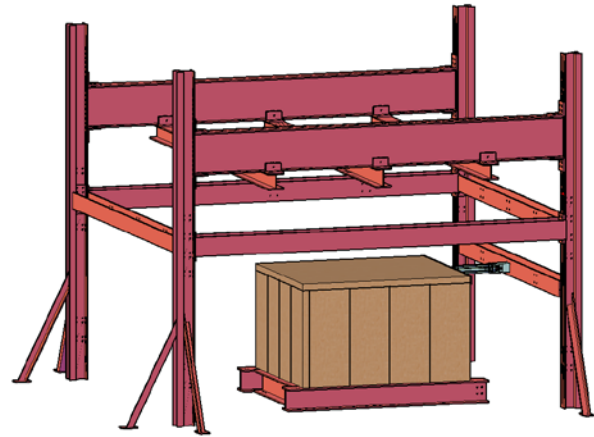


Figure 5. Box type configuration with a diaphragm using 0.6 m x 2.4 m (2' x 8') panels

Table 1. Variables considered in developing archetypes

Variable	Range
Number of stories Seismic	1 to 10
Design Categories (SDC)	D_{max} and D_{min}
Story height	2.44m to 4m
Interior and exterior nonstructural wall finishes	Not considered
CLT shear wall aspect ratios	High/Low

Nonlinear Model Development

Based on a preliminary numerical study performed for a mid-rise CLT buildings, an R-factor of 4.5 was determined reasonable for that CLT structure (Pei et al., 2012). Therefore, preliminary

analysis for CLT buildings as part of this study will be based on an R value of 4.5, Ω_o value of 3, and C_d value of 4.5. This will likely have to be revised but will serve as a reasonable starting point.

According to the P695 guidelines, the proposed nonlinear numerical models should simulate all significant deterioration mechanisms that can lead to collapse i.e. degradation in stiffness and strength, and inelastic deformation. In order to evaluate collapse of CLT structures, failure criteria should be defined in terms of story drift for simulated collapse modes. Based on previous studies, CLT systems have been shown to withstand a lateral drift of 3.5% without collapse; however, story drift leading to lateral instability is still unknown for CLT, since comprehensive collapse testing has not been performed.

If the models are unable to simulate all the collapse mechanisms, additional non-simulated collapse modes will be considered in the analysis since they are important in determining reasonable median collapse intensities. Analytical models used to simulate CLT behavior at the component and at the assembly level is explained in the following.

CLT Connections

Based on the previous studies conducted on CLT wall connections, they are determined to follow the 10-parameter CUREE model. This type of model is currently used to simulate component behavior of light-frame wood structures and adopting this model for CLT offers additional advantage of consistency with the light-frame wood components. A reverse calibration has already been performed for various connection types and presented in the US CLT handbook. Similarly typical calibration will be performed for the wall connections as part of this project. A generic 10-parameter hysteretic model is shown in Figure 6.

CLT Wall Modeling

The numerical model proposed as part of this study for simulating wall behavior is based on the recently published US CLT handbook (CLT Handbook, 2013). Previous studies and test observations indicate that CLT walls exhibit rocking behavior which forms the basis of this model. Assumptions considered in this numerical model are shown in Figure 7 and explained as follows:

- The CLT wall panel exhibits in-plane rigid body behavior
- Under lateral load, the CLT wall will rotate around the bottom corner
- Lateral slip between the wall and the floor diaphragm is neglected
- Gravity acts through center of the wall
- The wall panel hysteresis is based on panel connection deformation during rocking motion

The numerical model used as part of this study will be calibrated using the test results.

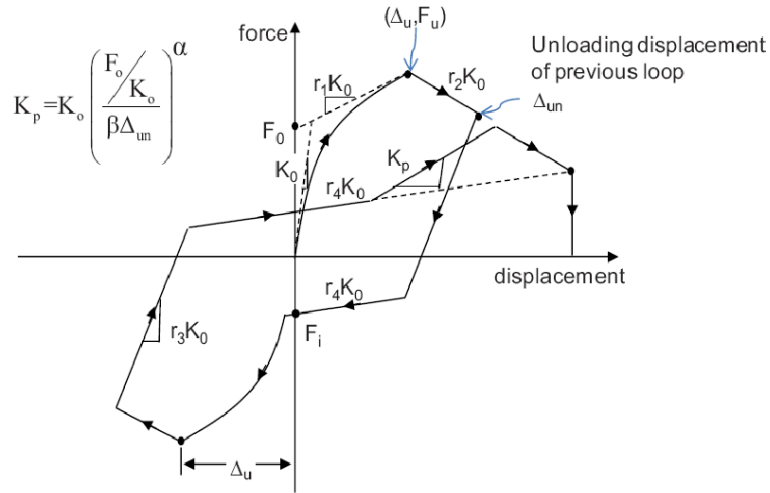


Figure 6. Loading Paths and Parameters of Modified Stewart Hysteretic Model (after Pang et al., 2010)

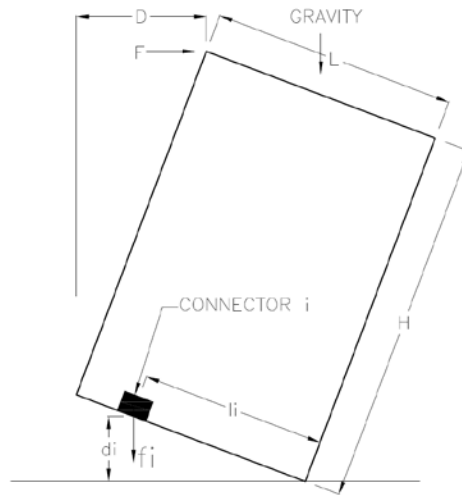


Figure 7. Kinematic model of a single CLT wall panel

Building System Modeling

Analysis will be performed using the SAPWood software (Pei and van de Lindt, 2007) that was developed as part of the NEESWood project for analysis of light-frame wood structures. The software is based on the shear-bending coupled model and the assumptions involved in this model are as follows:

- The floor diaphragm behaves as a rigid plate having 6 degrees of freedom.
- Shear resistance can be represented using hysteretic springs.

- Overturning restraint can be represented using multi-linear springs (different in tension than compression, if needed).
- The effect of finish materials ignored for now (may be added).

The accuracy and reliability of the software has been validated through a number of studies (Pei and van de Lindt, 2009; van de Lindt et al., 2010).

The basic kinematic model to be used in SAPWood is shown in Figure 8.

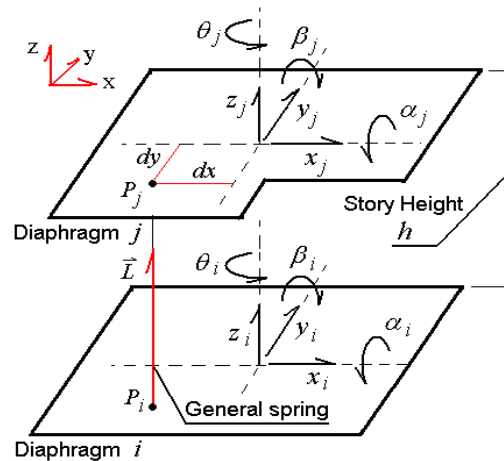


Figure 8. SAPWood kinematic model for nonlinear history analysis (after US CLT Handbook, 2013)

Nonlinear Analysis

Analyses will be performed based on the FEMA P695 methodology to determine the seismic performance factors that meet all the requirements within the methodology. This consists of nonlinear static and dynamic analysis of the archetype models that will be performed using SAPWood software.

Nonlinear static analysis is performed in accordance with Section 3.3.3 of ASCE/SEI 41-06 (2007) and the purpose is to determine period based ductility and over-strength factors for the archetypes under consideration. A generic static pushover curve is shown in Figure 11 and a pushover curve for a 2 ft x 8 ft CLT wall is illustrated in Figure 12.

Incremental Dynamic Analysis (IDA) (Vamvastikos and Cornell, 2002) will be performed on all the archetypes for a set of 22 predefined large-magnitude ground motion records termed “Far-Field” earthquakes available in P695. All the archetypes are analyzed for the Maximum Credible Earthquake (MCE) and the results of the IDA are used to plot the cumulative distribution function (CDF) which then leads to the determination of collapse spectral acceleration (Ibarra et

al., 2002). Median collapse intensity, S_{CT} , is defined as the intensity corresponding to 50% probability of collapse.

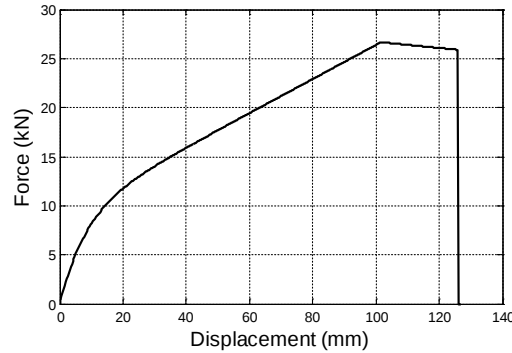


Figure 9. Pushover curve for 0.61 m x 2.44 m (2ft x 8ft) CLT wall

Performance Evaluation

The seismic performance factors will be evaluated and the adjusted collapse margin ratio (ACMR) determined (FEMA, 2009). The collapse margin ratio is defined as the ratio of median collapse intensity, S_{CT} , to the MCE intensity, S_{MT} , and can be calculated as

$$CMR = S_{CT} / S_{MT} \quad (1)$$

A study conducted by Baker and Cornell (2006) showed that spectral shape of the ground motion record had a profound influence on the collapse margin ratio (CMR) which is incorporated in the methodology by applying a spectral shape factor. This factor is determined based on the fundamental period of the archetype, T , and the period based ductility, μ_T . The adjusted collapse margin ratio (ACMR) is then computed as

$$ACMR = SSF_i * CMR_i \quad (2)$$

It's important to note that regardless of the type of analysis conducted, there are always uncertainties and variability involved in the analysis. Four major sources of uncertainty that significantly influence CMR calculations are identified in P695 namely record-to-record variability, design requirements, test data, and modeling. Their values are based on completeness and accuracy of the pertinent information. Detailed discussion on each of the uncertainties and calculation of the total uncertainty is provided in FEMA P695 report and are omitted here for brevity.

Acceptable ACMR values are based on the calculated total uncertainty and accepted collapse probability and are obtained from Table 7.3 of P695. The collapse probability for MCE ground motions considered in the P695 is 10% and 20% for an average across each performance group

(described earlier) and each index archetype, respectively. If the ACMR meets the collapse criteria, the trial R value and other calculated seismic performance factors are considered acceptable per the methodology. However, if not, the archetypes are re-designed and entire process repeated until an acceptable ACMR is obtained.

Closure

CLT is an innovative wood product that is gaining popularity as a viable alternative for masonry, concrete, and steel in mid-rise construction. Research has shown that CLT can be used as an effective lateral force resisting system. However, there are no specific seismic design guidelines in the U.S. pertaining to this new product and the system must be designed based on alternative methods allowed by the codes, which will limit its use. This paper provides an overview of the FEMA P695 methodology which will be applied to CLT in the United States in order to make it a viable alternative in high seismic regions. At the time of this paper the project is in the first Phase and is anticipated to be completed in 2015.

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