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DEVELOPING SEISMIC PERFORMANCE FACTORS FOR CROSS LAMINATED TIMBER IN THE UNITED STATES

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ABSTRACT: This paper presents recent progress in the development of seismic performance factors for cross-laminated timber (CLT) systems in the United States. A brief overview of some of other systematic studies conducted in Europe, North America, and Japan is also provided. The FEMA P695 methodology is briefly described and selected results from connector testing and CLT wall testing are discussed. Shear and uplift tests were performed on generic angle brackets to quantify their behavior. CLT walls with these connectors were then tested investigate the influence of various parameters on wall component performance. The influential factors considered include boundary condition, gravity loading, CLT grade, panel thickness, and panel aspect ratio (height:length). Results indicate that boundary condition and gravity loading have beneficial effect on strength and stiffness of the CLT panels. CLT grade is an important parameter while CLT panel thickness only has a minimal influence on wall behavior. Higher aspect ratio (4:1) panels demonstrated less stiffness but considerably more ductility than the panels with lower aspect ratio (2:1). This paper also provides details on some on-going efforts including additional tests planned, index buildings from which P-695 archetypes will be extracted, and nonlinear modeling for this project.

1. Introduction

Cross Laminated Timber (CLT) is an innovative timber product that was developed in Europe almost two decades ago. CLT panels are constructed of at least three layers of solid-sawn or structural composite lumber boards where adjacent layers are placed orthogonally and bonded together with structural adhesive. This product offers a number of advantages such as prefabrication, rapid construction, sustainability, good thermal insulation, acoustic performance, and fire ratings (CLT Handbook, 2013; Ceccotti, 2008).

Applications for this technology varies widely and includes residential buildings, industrial and commercial buildings, and bridges. However, it is the multi-story mid-rise construction (8~12 stories) application that is of prime interest to most structural engineers and researchers. Researchers are also investigating CLT hybrid structures that can reach up to 30 stories (Green, 2012; van de Kuilen et al., 2011)

Numerous CLT buildings have been built around the world primarily in Europe, Australia, and recently in North America. Currently, a 10-story CLT building in Melbourne, Australia, is the tallest CLT building in the world (KLH). As CLT is beginning to find its way into the US construction market, many researchers and practitioners believe that it may be able to fill the mid-rise condominium, commercial, and mixed-use building market of the US urban construction. However, seismic force resisting systems based on CLT are not yet recognized in the US codes and design can only be performed using alternative methods. This provided the impetus for this project which is supported by the US Department of Agriculture. The purpose of this project is to determine seismic performance factors for CLT lateral force resisting system based on FEMA P695 methodology. This is an ongoing research at Colorado State University (CSU) and this paper presents only selected results of connector and wall tests with an overview of other aspects of the project.

2. CLT Related Research on Quantifying Seismic Performance Factors

In the early stages of its development in Europe, CLT structures were mainly constructed in low seismic regions. Although CLT was introduced over two decades ago, it was in the past decade that researchers began focusing on utilizing CLT as a lateral force resisting system which triggered an increase in the number of studies geared toward investigating CLT system behavior and performance under cyclic and dynamic loading. Most of these studies originated in Europe and more recently in North America and Japan. This section provides a brief, but by no means comprehensive, overview of some of the studies that adopted a systematic approach to investigate seismic behavior of CLT with the eventual goal of obtaining seismic performance factors or codification of some kind.

A comprehensive research program to investigate the behavior of 2D CLT wall panels was undertaken at the University of Ljubljana and partially supported by KLH Massiveholz GmbH (Dujic et al., 2005; 2006, 2006a;Dujic and Zarnic, 2006). The purpose of that project was to study performance of CLT panels subjected to constant vertical load combined with either monotonic or cyclic in-plane shear loading. The influence of various parameters such as boundary conditions, the magnitude of the vertical load, and the type of anchoring system were evaluated. Wall deformation response varied from cantilever to pure shear depending on the panel stiffness, magnitude of vertical load, and anchors.

Dujic et al. (2006b,2007,2008) also performed a series of cyclic tests to determine the influence of openings on shear strength and stiffness of the CLT panels. Two configurations of the wall with equal dimensions, one with a door and window opening and the other without openings, were considered for the testing. The study resulted in simplified formulas describing the shear strength and stiffness relationship between a wall with an opening with the wall without any openings. Two full scale shake table tests were performed at the IZIIS Laboratory, Skopje, Macedonia the purpose of which was to investigate CLT panel behavior under dynamic loading and correlating the results with the quasi-static cyclic tests (Dujic and Zarnic, 2006; Dujic et al., 2006; Hristovski et al., 2012). Dynamic results proved nonlinearity of the system and demonstrated good correlation with the quasi-static tests. The Italian SOFIE project was a multifaceted study the purpose of which was an extensive investigation of CLT behavior such as static, acoustic, thermal, and seismic performance. This collaborative effort involved the Trees and Timber Institute of the National Research Council of Italy (CRN-IVALSA), National Institute for Earth Science and Disaster Prevention in Japan (NIED), Shizouka University, and the Building Research Institute (BRI) in Japan. The study included tests on various types of connections, quasi-static tests conducted on isolated CLT walls, pseudo-dynamic tests on one-story assembly, and full scale shake table tests on a three and seven-story building (Ceccotti, 2008). The results of quasi-static tests and psuedo-dynamic tests were reported by Lauriola et al. (2006). Quasi-static monotonic and cyclic tests were performed on 2.95mx2.95m CLT panels under different vertical loading, with and without the openings. Test results showed that CLT performed as rigid panels and layout and design of connections greatly influenced the wall behavior. Full-scale shake table tests on a three-story CLT structure were conducted at the NIED Tsukuba shaking table facility (Ceccotti et al., 2006; 2006a; Ceccotti, 2008). The test specimen was 7mx7m in plan with a height of 10m. Three different configurations differing in terms of the opening layout in the external walls parallel to the shaking direction were tested in three phases. An analytical model of the three-story building was developed in DRAIN 3-DX and calibrated using the test results. The model was then subjected a number of earthquakes with holddown failure taken as the collapse mechanism. Based on the results a q factor of 3 was considered reasonable (Ceccotti, 2008). The last phase of the project was a series of 3D shake table tests performed on a seven-story building in NIED's Miki facility in Japan. The building had a plan of 7.5mx13.5m and a height of 23.5m. It was designed considering a q factor of 3 (Ceccotti, 2008) and an importance factor of 1.5 in accordance with Euro Code 8. Connections were designed such that ductility and energy dissipation occur at the holddowns, shear connectors, and the inter-panel joints. Test results showed that q factor of 3 can be taken as a reasonable value for CLT seismic design (Ceccotti et al., 2013).

FPInnovations initiated CLT related research in North America through a multi-disciplinary project the purpose of which was to investigate seismic performance of CLT structures and more specifically development of seismic modification factors (R-factors). Popovski et al. (2010) conducted a total of 32 monotonic and cyclic shear tests on 12 different wall configurations that consisted of different aspect ratio panels, openings, walls with interpanel connectors, and two-story assemblies. CLT connectors included off-the-shelf steel brackets as well as custom-made brackets. Results of these quasi-static tests verified rigid behavior of CLT panel and showed that most of the deformation occurs in the steel brackets and interpanel connectors. Popovski and Karacabeyli (2012) then used these tests results to perform an AC130 (International Code Council- Evaluation Service, 2013) equivalency approach in an attempt to quantify seismic performance factors for CLT in the National Building Code of Canada. Considering the existing timber system in NBCC and recommended q factor in European CLT research, Ro=1.5 and Rd=2.0 were proposed for the CLT system. The results obtained from these quasi-static tests were also used by Pei et al. (2013) to estimate a possible R-factor factor for an example CLT building. This was achieved by investigating CLT wall behavior using a simplified kinematic model and designing a 6-story building with performance based design procedure (PBSD). Based on the numerical analyses, an R-factor of 4.5 was considered reasonable for CLT systems. However, the study was only performed on a single building, in a specific location, and with limited test data.

To expand upon their initial finding and to better understand CLT system behavior under lateral loads, Popovski et al. (2014) performed a number of quasi-static monotonic and cyclic loads on a full-scale two-story structure. The structure dimensions were 6.0mx4.8m in plan with a total height of 4.9 m. A total of five tests that included one pushover in the longer direction and two cyclic tests in each longer and shorter directions of the structure were performed. In order to investigate the effect of additional uplift stiffening and walls perpendicular to the direction of the loading, parameters such as number holddowns and number of screws in perpendicular wall-to-wall connection were varied, respectively. The CLT structure performed well exhibiting similar behavior in both directions. As a result of sliding and rocking of the panels, nail failures in the bottom brackets of the 1st story walls were observed and this failure mechanism was similar in all the test. Inter-panel connectors performed as expected and floor diaphragms exhibited rigid behavior. A maximum inter-story drift of 3.2% was observed during one of tests indicating that CLT systems can accommodate large drift. Test results confirmed that walls perpendicular to the direction of the loading have a significant influence on the behavior of the building.

Another research project was conducted at the Graz University of Technology, Austria, in collaboration with University of Kassel, Germany. The testing program was divided into three main phases, namely connector tests, wall tests, and a full-scale three-story shake table testing of a CLT structures. For connector tests, a total of 215 shear and tension tests were performed in six different configurations and for the wall tests a total of 17 tests were performed in 5 different configurations. Tests results were reported by Flatscher et al. (2014). CLT related research is also gaining momentum in Japan in an effort to include this new proposed system in the building code. Results of quasi-static tests and dynamic tests on CLT panels made of Sugi (Japanese Cedar) are reported by Okabe et al. (2012), Tsuchimoto et al. (2014), and Yasumura and Ito (2014).

3. FEMA P695 Methodology

In 2009, the Applied Technology Council (ATC) proposed a methodology published as Federal Emergency Management Agency (FEMA) report P695 which provides a methodology to evaluate seismic performance factors (SPFs) including the seismic response modification factor (R-factor), the system overstrength factor, and the deflection amplification factor for seismic design in the US. 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 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 inherit in the test data and modeling methods. The methodology introduces an iterative process that includes establishing design requirements, developing archetypes, performing a series of tests, developing and validating nonlinear models, nonlinear static and dynamic analysis, and evaluating performance.

3.1. Testing

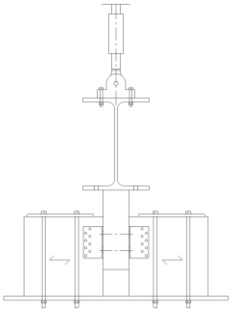
Analytical modeling alone is typically not adequate to determine the performance of new structural systems under seismic loading. FEMA P695 requires various types of tests that include material testing, components and connections, and assembly and system level tests. The purpose of these tests are to reliably capture the behavior of the proposed system, validate the proposed design methodology, and calibrate numerical models. Material testing is not conducted as part of this project since the data can be obtained from past studies and the ANSI/APA PRG 320 (2011) standard that provides information on performance and requirements for Rated Cross-Laminated Timber. For the current study, the test program has been divided into three phases that include tests on (1) connectors, (2) Isolated CLT walls, (3) and assemblies and are explained as follows.

3.1.1. Connector Testing

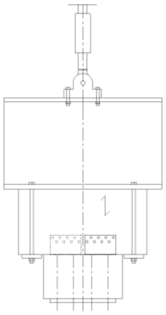
A number of studies (Lauriola et al., 2006; Dujic et al., 2006) have shown that CLT panels exhibit linear-elastic behavior and that energy dissipation and ductility in CLT systems is obtained through the connectors. Connector layout and properties greatly influence wall and eventually the system response; therefore, investigating connector behavior is of prime interest in these types of systems. The connector testing phase is divided into two parts: angle bracket connectors and inter-panel connectors. Various configurations are considered for testing; however, in this paper only the test configurations shown in Fig. 1 are discussed. Most of the connector testing performed to date has been on proprietary metal connectors. However, for the purpose of this study metal connectors were manufactured from sheet steel in the structures laboratory at CSU to keep the connector testing as generic as possible. Steel angle brackets for the attachment of wall to the supporting element is shown in Fig. 2. The angle bracket uses 16d box nails and bolts designed per National Design Specification (NDS). The metal bracket transfers all the imposed deformation to the nails that are designed to yield under lateral load and eventually pull out of the CLT panel to ensure nonlinear behavior of the fasteners.

For the steel angle brackets, shear and uplift tests are performed under monotonic and cyclic loading. All the shear tests are conducted under displacement control using the CUREE protocol with the reference displacement obtained from monotonic loading. Reference displacement is defined as the deformation at which the applied load drops below 80% of the maximum load applied to the specimen. Uplift tests are conducted in a similar manner; however, in this case specimens are subjected to non-reversed CUREE protocol due the restrained movement. Two different grades of CLT, E1 and V2, based on ANSI/APA PRG320 are considered for testing. E indicates that parallel layers are E-rated or MSR laminations and V indicates that parallel layers are visually graded laminations. In order to reliably capture statistical variability in the tests, one monotonic and ten cyclic tests were performed in each configuration. The summary of connector tests is provided in Table 1.

Both connector types, A3 and B3, performed as intended and nail withdrawal was observed, as shown in Fig. 3. No distinctive deformation of the angle brackets was noticed; thereby, indicating that nonlinear behavior is primarily limited to the fasteners.

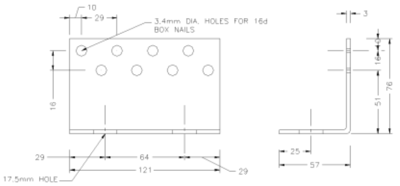


(a) Shear test configuration

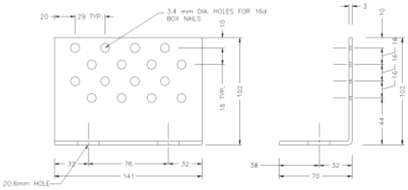


(b) Uplift test configuration

Fig. 1- Test configuratin for connector tests



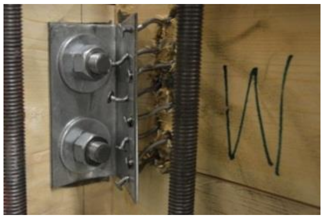
(a) A3 type connector with (8) 16d box nails



(b) B3 type connector with (16) 16d box nails

Fig. 2- Steel brackets used for connector and wall tests (dimension in mm)

(a) Before test



(b) After test

Fig. 3- Wall-to-floor angle bracket shear test

Table 1. CLT connector tests

Test Type	Connector type	CLT Grade	Tests
Shear	A3- (8)16d nails and two 15.9 mm (5/8”) rods	E1	One monotonic and 10 cyclic
		V2	
	B3- (16)16d nails with two 19mm(3/4”) rods	E1	
		V2	
Tension	A3- (8)16d nails and two 15.9 mm (5/8”) rods	E1	One monotonic and 10 non-reversed
		V2	
	B3- (16)16d nails with two 19 mm (3/4”) rods	E1	
		V2	

3.1.2. Wall tests

CLT wall tests were performed with the same connector types used in single connector tests. These tests are conducted to systematically study the effect of various parameters on wall performance that include (1) boundary condition, (2) gravity loading, (3) connector type, (4) connector thickness, (5) CLT grade, (6) CLT panel aspect ratio, (7) panel thickness, and (8) inter-panel connector (vertical joint). The purpose is to investigate their influence on overall behavior of the wall in terms of strength, stiffness, ductility, and energy dissipation. The main design assumption for these walls is that all overturning is resisted by overturning anchor (tie rod or holddowns) at wall ends and that shear is resisted by angle brackets. This assumption was also adopted in the design process of the SOFIE project as well as the wall tested by FPInnovations. Based on the results of testing by FPInnovations, this assumption resulted in a conservative design.

A photo of a 1.22mx2.44m CLT specimen tested at CSU is shown in Fig. 4. Vertical actuators under force control are used for constant vertical loading while the horizontal actuators under displacement control are used to apply the shear loading protocol. The CUREE loading protocol was used for all reversed cyclic tests. Results presented in this paper are only for the basic configuration shown in Fig.4 where connector type A3 is used in various layouts and influence of boundary condition, gravity loading, CLT grade, panel thickness, and panel aspect ratio are investigated. Other configurations including the inclusion of one or more vertical joints are currently being tested at CSU. Table 2 provides information on selected CLT wall tests. It contains CLT grade, geometry, vertical load, and the applied boundary condition.

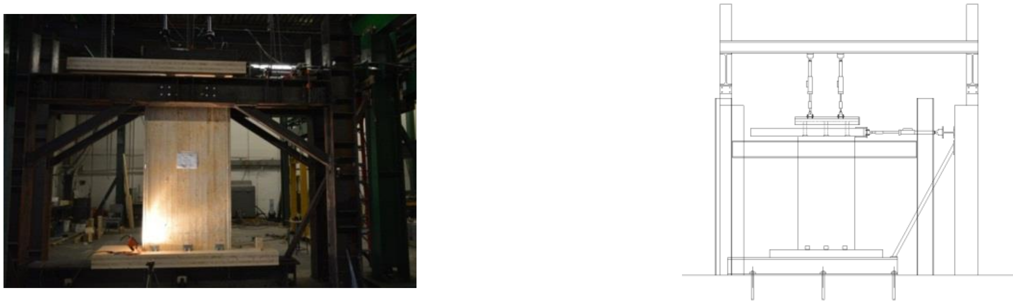


Fig. 4- Isolated wall test setup

Based on the FEMA P695 report (2009) the test boundary condition should be representative of typical construction provided it does not provide any beneficial effects. In the case of CLT walls an important boundary condition is the interface between the wall and the diaphragm. The size of the diaphragm is believed to affect the wall behavior under cyclic loading since the diaphragm in a structure may be larger compared to the walls and therefore may remain relatively horizontal throughout the loading. This in turn creates a gap between the wall panel and the diaphragm during the loading and effecting rocking of a CLT wall. In order to quantify the effect of a top boundary condition, modifications were made to the original test setup, shown in Fig. 4, to include the effect of a top diaphragm into the isolated wall test. This was done by adding supports to allow sliding of the top CLT panel while keeping it horizontal during the shear loading. The supports, shown in Fig. 5, consisted of four load cells on each end with acetal polymer plates on top. Load cells were added to determine the effect of friction and adjust the horizontal actuator values if they were significant. In order to determine the coefficient of friction of the acetal polymer plates, a total of 10 tests, each with three levels of increasing vertical load, were performed. Once the results were obtained for the friction tests, two specific tests, Tests 05 and 06, were conducted to investigate the effect of boundary condition on CLT hysteresis. Test 05 was performed without the imposed boundary condition while Test 06 included the boundary condition and thus the force values obtained from Test 06 were adjusted for friction. The hysteresis for both of these tests is provided in Fig. 6. From inspection of the hysteresis plots, it was found that the test without the boundary condition imposed produced similar load deformation response with only slight differences in strength, stiffness, and displacement capacity. As a result, additional testing utilized the less complex test set-up without boundary condition imposed.

Gravity load can also affect CLT wall component behavior and therefore, a number of tests were performed to determine its effect on the isolated CLT wall tests. A 1.22mx2.44m CLT wall under three levels of vertical loads that include no gravity, 0.922 kN/m (0.68 kip/ft), and 1.84 kN/m (1.28 kip/ft) were tested and the results of are shown in Fig. 7. These tests are Tests are 09, 03, and 04, respectively, in Table 2. From Fig. 7 one can see that an increase in gravity leads to an increase in stiffness of the panel and a slight increase in strength.

The effect of CLT grade was investigated by comparing the results of Test 09 with Test 14 and results from Test 10 with Test 17, although the thicknesses are different in the case of the latter comparison. Results are shown in Fig. 8 and Fig. 9, respectively. Based on the hysteresis, it appears that CLT grade has an influence on strength and stiffness of the CLT panels when the exact same connectors and fasteners are used. A similar trend is observed by comparing Tests 11 and 15; however, the hysteresis are not shown here. There is likely a physical property, e.g. specific gravity, that is driving this difference and this will be further investigated with the upcoming tests. Tests 19 and 20 were performed to examine the effect of panel thickness on overall wall behavior. Since CLT is a rocking system, the effect of compression perpendicular to the grain is thought to have an effect on the rocking behavior. Fig. 10 indicates that there is only a slight difference in the initial stiffness and maximum strength of different thickness panels with the thicker panel being stronger and stiffer of the two. A similar trend was observed by comparing the results of Tests 11 and 18, shown in Fig. 11; albeit in this case the difference was less significant.

In order to determine the effect of panel aspect ratio, Tests 18 and 21 were performed and the hysteresis compared in Fig.12. Preliminary results indicate that while higher aspect ratio panel exhibited less stiffness and somewhat smaller strength, it was considerably more ductile than the low aspect ratio panel. This ductility can be attributed to the rocking behavior of the panel as opposed to rocking and sliding mechanism of other tested panels. It is important to note that these tests were conducted on 2:1 and 4:1 panel aspect ratios; however, a number of 1:1 aspect ratio panels are currently being tested at CSU that will give further insight in the influence of aspect ratio on wall behavior.

Table 2- CLT wall matrix

Test #	Grade & Panel #	Height (m)	Length (m)	# Plys	Thickness (mm)	No. connectors*	Gravity Load (kN/m)
03	V2	2.44	1.22	5	168.9	3	0.92
04	V2	2.44	1.22	5	168.9	3	1.84
05	E1	2.44	1.22	5	175	3	0.92
06**	E1	2.44	1.22	5	175	3	0.92
09	V2	2.44	1.22	5	168.9	3	-
10	V2	2.44	1.22	3	99	4	-
11	V2	2.44	1.22	5	168.9	2	-
13	E1	2.44	1.22	5	175	2	-
14	E1	2.44	1.22	5	175	3	-
15	E1	2.44	1.22	5	175	2	-
17	E1	2.44	1.22	5	175	4	-
18	V2	2.44	1.22	3	99	2	-
19	V2	2.44	1.22	3	99	5	-
20	V2	2.44	1.22	7	239	5	-
21	V2	2.44	0.61	3	99	2	-

*All the connector types are A3 , **Only Test 06 was performed with the imposed boundary condition

3.1.3. Reverse cyclic testing of a wall assembly with a diaphragm

To investigate behavior of a 3D CLT system under lateral loading, tests with three different configurations are planned using a box type setup. These tests include reverse cyclic testing of walls in a box configuration using low and high aspect ratio panels, and reverse cyclic testing of 3-sided wall with a diaphragm.

3.2. Archetype Development

Development of archetypes is an essential part of the FEMA P695 methodology since they determine the applicable range and design space for the proposed lateral force resisting system. The archetypes themselves are intended to represent typical application of the seismic force resisting system and unique and irregular configurations can be handled on case by case basis. The purpose of the methodology is to verify performance of a class of building configurations and not a special case. Twelve index buildings that represent typical construction in the US were designed as an initial step of the process. These buildings range from multi-family residential building shown in Fig. 13 to a twelve-story hotel shown in Fig. 14.

Based on the FEMA P695, two dimensional archetype wall models are considered acceptable to represent wood walls. Therefore, archetypes are defined as two dimensional multi-story wall lines that are extracted from each building in the design space. 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.

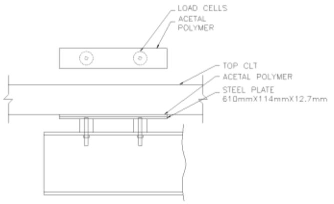


Fig. 5- Floor diaphragm supports

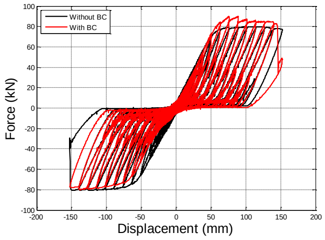


Fig. 6- Hysteresis for tests with and without floor diaphragms

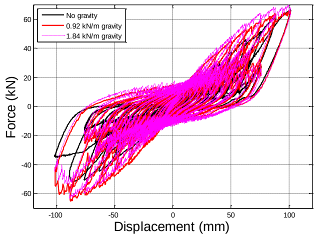


Fig. 7- 1.22mx2.44mx168.9mm specimen tested under different vertical loading

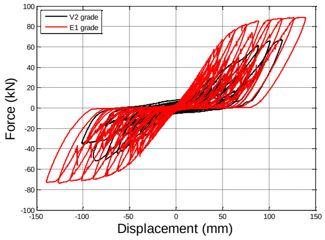


Fig. 8- Hysteresis for tests on two different grades of CLT

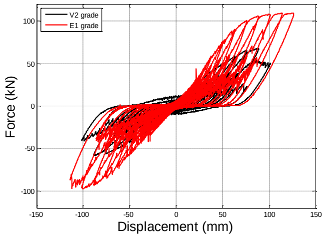


Fig. 9- Hysteresis for tests on two different grades of CLT

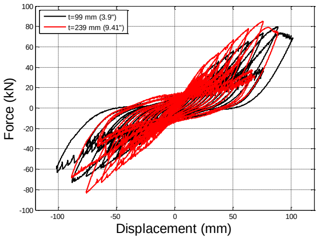


Fig. 10- Hysteresis for different panel thicknesses

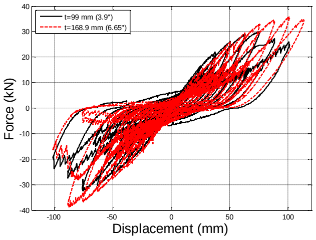


Fig. 11- Hysteresis for different panel thicknesses

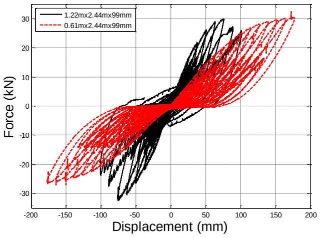


Fig. 12- Hysteresis for 4:1 and 2:1 aspect ratio panels

3.3. Numerical Modeling and nonlinear analysis

According to the FEMA P695 guidelines the proposed numerical model should be able to simulate nonlinear behavior and all significant deterioration mechanisms that can lead to collapse i.e. degradation in stiffness and strength, and inelastic deformation. Nonlinear static and dynamic analysis is performed on the archetype models. Nonlinear static analysis is performed in accordance with Section 3.3.3 of ASCE/SEI 41-06 (2007) and its purpose is to determine period based ductility and over-strength factors for the archetypes.

Incremental Dynamic Analysis (IDA) (Vamvastikos and Cornell, 2002) will be performed on all the archetype for a set of 22 predefined far-field ground motion records. All the archetypes are analyzed for Maximum Credible Earthquakes (MCE) and IDA results are used to plot cumulative distribution function (CDF) that leads to determination of collapse spectral acceleration (Ibarra et al., 2002). This part of the work is currently in planning and will be carried out when the wall testing is finished.

4. Closure

CLT is an innovative technology that is gaining popularity for use in mid-rise construction. Various studies have been conducted in Europe and Canada in an effort to quantify seismic performance factors for CLT and the purpose of this U.S.-based project is to apply the FEMA P695 methodology to CLT with the eventual goal of including this new system in ASCE 7. Testing is one of the major steps identified in the P695 methodology and this paper presents the results of selected number of tests conducted at CSU. Generic brackets for shear transfer designed per NDS requirement performed as intended and the nonlinear behavior was primarily limited to the yielding and withdrawal of the fasteners. Following the box-style test phase, extensive numerical analyses will be conducted to identify seismic performance factors in line with the methodology described by FEMA P695. The project will be completed by the end of the 2015 calendar year with the final phase of peer review occurring shortly thereafter.

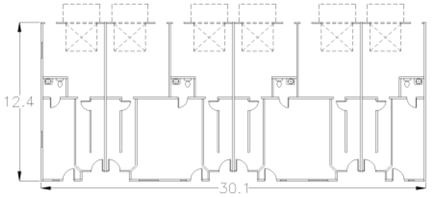


Fig. 13- Index building 1st floor plan for a 3-story multi-family residential building (dimensions in meters)

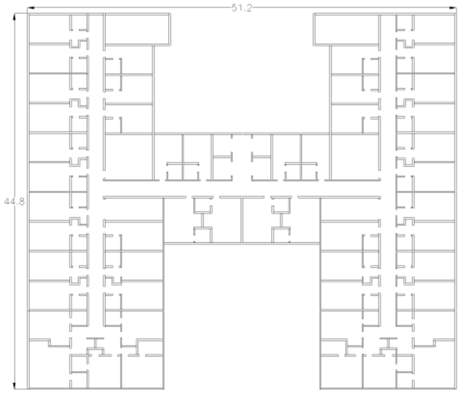


Fig. 14-Index building floor plan for a 12-story CLT hotel (dimensions in meters)

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