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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).

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