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Systematic experimental investigation to support the development of seismic performance factors for cross laminated timber shear wall systems

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ABSTRACT

In the US, codified seismic design procedure requires the use of seismic performance factors which are currently not available for CLT shear wall systems. The study presented herein focuses on the determination of seismic design factors for CLT shear walls in platform type construction using the FEMA P-695 process. Results from the study will be proposed for implementation in the seismic design codes in the US. The project approach is outlined and selected results of full-scale shear wall testing are presented and discussed. Archetype development, which is required as part of the FEMA P-695 process, is briefly explained with an example. Quasi-static cyclic tests were conducted on CLT shear walls to systematically investigate the effects of various parameters. The key aspect of these tests is that they systematically investigate each potential modelling attribute that is judged within the FEMA P-695 uncertainty quantification process. Boundary constraints and gravity loading were both found to have a beneficial effect on the wall performance, i.e. higher strength and deformation capacity. Higher aspect ratio panels (4:1) demonstrated lower stiffness and substantially larger deformation capacity compared to moderate aspect ratio panels (2:1). However, based on the test results there is likely a lower bound for aspect ratio (at 2:1) where it ceases to benefit deformation capacity of the wall. This is due to the transition of the wall behaviour from rocking to sliding. Phenomenological models were used in modelling CLT shear walls. Archetype selection and analysis procedure was demonstrated and nonlinear time history analysis was conducted using different wall configurations.

1. Introduction

Since its initial introduction in Europe in the early 1990s and subsequent entry into the building market between 2000 and 2005, Cross Laminated Timber (CLT) has now been commonly accepted as a new-generation engineered wood product that has great potential to expand the wood building market [1].

This innovative mass timber product, sometimes termed X-Lam, offers a number of advantages such as the potential for mass production, prefabrication, speed of construction and sustainability as an environmentally friendly and renewable construction product. Good thermal insulation, acoustic performance, and fire ratings are some additional benefits of the system [2,3].

Despite these advantages, the lack of a current design approach is one of the challenges inhibiting widespread adoption of CLT in North America. Mohammad et al. [4] identified a multi-level strategy that includes development of a product standard, material design standard, and their subsequent adoption into the building codes. In the US, there has been recent development on all these fronts that included publication of ANSI/APA PRG320, the North American Standard for Performance-Rated Cross-Laminated Timber [5], addition of a chapter dedicated to CLT in the 2015 edition of the National Design Specification for Wood Construction® (NDS®) [6] and recognition of CLT in the 2015 International Building Code [7].

One area that requires attention is the development of seismic performance factors for CLT lateral systems so designers in the US can begin to utilize CLT shear walls in seismic regions. Recent research efforts on seismic performance of CLT buildings can be found in Europe,

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North America and Japan, with a comprehensive review done by Pei et al. [8]. These include systematic research studies in Slovenia and Macedonia [9–12], the SOFIE project in Italy [3,13–15], studies in North America [16–18], and efforts in Japan [19–21]. For additional studies focused on various aspects of CLT seismic force resisting systems, readers are referred to Gavric et al. [22,23], Tomasi and Smith [24], Izzi et al. [25,26], Pozza and Trutalli [27], and Pozza et al. [28,29].

With the introduction of CLT into the US construction market, many researchers believe that CLT can serve to fill a gap for certain building stock need in the US; specifically, the mid-rise condominium, commercial, and mixed-use building market in seismic regions. CLT based Seismic Force Resisting Systems (SFRS) are not recognized in current US design codes. CLT shear walls cannot be designed via the equivalent lateral force (ELF) design procedures [30]; therefore use of CLT for seismic force resistance can only be accomplished through alternative methods. This approach, however, is usually more costly, making CLT less competitive against other conventional structural systems. A research project at Colorado State University; funded by the USDA Forest Products Laboratory (FPL), is targeted at determining ELF seismic performance factors for CLT shear wall as a SFRS. The study follows the FEMA P-695 [31] methodology which is a systematic approach that integrates design method, experimental results, nonlinear static and dynamic analyses and incorporates uncertainties. Various phases of the project consist of development of the archetypes, design methodology, testing, modelling, and analyses. The testing phase of the project included two main phases, namely (i) connector testing (ii) and CLT shear wall testing. Test data is then used to refine the design methodology and calibrate the proposed numerical models for connectors and CLT shear walls. This paper focuses on the wall-level experimental phase and building archetype development of the project. Specifically, each test comparison presented herein leads to either inclusion or exclusion in the numerical modelling portion of the FEMA P-695 methodology; and is also included in the uncertainty quantification process.

2. Overview of the FEMA P-695 methodology

FEMA P695 is a methodology to evaluate ELF seismic performance factors (SPF), which include the response modification factor (R-factor), the system overstrength factor (Ω), and the deflection amplification factor (C_d) for seismic design in the United States. 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 and illustrated in Fig. 1.

R = Response Modification Coefficient = V_E/V.
Ω_o = Overstrength Factor = V_{max}/V.
C_d = Deflection Amplification Factor = $(\delta/\delta_E)\,R$.

The methodology is an iterative process that consists of nonlinear static and dynamic analyses on a number of archetypes that are prototypical representations of the seismic force resisting system. Critical to the P695 process is that the archetypes used within the analyses must comprehensively represent the anticipated design space for the SFRS proposed for inclusion in the US design codes. These analyses result in computing the so-called "margin against collapse" of each archetype and hence the proposed system with specific requirements dictated by FEMA P695. It takes into account uncertainties inherent in the test data and modelling methods as well as inherent variability in the suite of ground motion records. This iterative process is illustrated in Fig. 2.

A key aspect of the methodology is that it is overseen by a technical peer panel and their involvement is critical throughout. It culminates in a project report along with the peer panel review that is then used to support modification of relevant US design codes.

3. Experimental procedures

The FEMA P-695 methodology requires testing to reliably capture behaviour of the proposed system. Tests include material testing, components and connections, and assembly and system level tests. Material testing is not conducted as part of this project because material design strength is in accordance with the ANSI/APA PRG 320 [5] product performance standard. One critical aspect of this project is the use of non-proprietary components and connectors already addressed by US design codes to facilitate building code recognition but also to provide a test-based performance baseline to allow for proprietary (and other) systems to demonstrate equivalence.

3.1. Connector testing

Investigating connector behaviour is important since the CLT wall and lateral system responses are greatly influenced by the connector layout and properties [9,14]. CLT panels exhibit linear elastic behaviour and the energy dissipation and ductility is primarily achieved through the connectors. A generic connector is used throughout the P-695 process for CLT described herein is to ensure applicability of the US design codes and to provide a test-based performance baseline to allow for proprietary (and other) systems to demonstrate equivalence. Most of the connector tests from other studies to date have been performed using proprietary metal connectors and fasteners. The connector testing includes two types: the angle bracket connectors and the inter-panel connectors. Angle brackets were tested under shear and uplift, while inter-panel connectors were tested in shear only. However, in this study, metal connectors (i.e. angle brackets and inter-panel connectors) were manufactured from sheet steel in the machine shop at CSU and commodity nails were used in metal connectors to enable the connector testing to be generic. Steel angle brackets used for attachment of the wall to the supporting element is shown in Fig. 3. These generic connectors are designed per steel design standards and the National Design Specification® (NDS®) for Wood Construction [6] such that the nails yield under loading and pull out of the CLT panel. The CLT shear wall design method requires adequate embedment of the fasteners to ensure Mode III or Mode IV yielding per NDS.

Shear and uplift tests for angle brackets were performed under monotonic and cyclic loading. All shear tests were conducted under displacement control using the CUREE protocol [32], shown in Fig. 4, with the reference displacement obtained from a monotonic test. The reference displacement is defined as the deformation at which the load drops below 80% of the maximum load applied to the specimen. In the case of uplift tests, the specimen was subjected to a single-sided CUREE loading protocol. In order to reliably capture statistical variability in the tests, one monotonic and ten cyclic tests were performed for each connection configuration. Two different grades of CLT, E1 and V2, based on ANSI/APA PRG320 [5] were also considered in the testing. For E1 grade the parallel layers are Spruce-pine-fir and perpendicular layers are No.3 SPF while for V2 grade the laminations are No. 1/No. 2 SPF and No. 3 SPF in parallel and perpendicular directions, respectively. The testing matrix is provided in Table 1 and the testing configuration is shown in the schematic in Fig. 5. Connectors performed as intended and nail yielding and withdrawal was observed during the testing. Fig. 6 shows an A3 type connector before and after the tests.

3.2. CLT shear wall tests

CLT shear wall tests were performed with the same generic connectors used in the connector testing. The purpose of these tests was to systematically investigate the influence of various factors on the