Engineering Structures 168 (2018) 1–11

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Cross-laminated timber connections assembled with a combination of screws in withdrawal and screws in shear

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ARTICLE INFO

Keywords:
Cross-laminated timber
Self-tapping screws
Shear connections
Seismic design

ABSTRACT

The research presented in this paper examines the performance of 3-ply cross-laminated timber (CLT) panels connected with self-tapping screws (STS). Half-lap joints with STS loaded in either shear or withdrawal along with an innovative solution combining these two approaches were evaluated in a total of 24 quasi-static monotonic and 15 reversed cyclic tests. The CLT joint performance was evaluated in terms of load-carrying capacity, yield strength, deformation capacity, stiffness, and ductility. The results demonstrated that joints with STS loaded in shear exhibit high ductility but low stiffness, whereas joints with STS in withdrawal are very stiff but brittle. Combining STS that act in shear with STS that act in withdrawal can lead to connections with high stiffness and high ductility. The performance of STS shear connections under reversed cyclic loading is comparable to that of these connections under quasi-static loading; however, all performance values are reduced by up to 40% demonstrating the necessity to provide designers and engineers with connection performance data under cyclic loading for reliable seismic design.

1. Introduction

1.1. Tall timber structures

High strength-to-weight ratio, smaller carbon footprint, and the ease of assembly has allowed wood and engineered wood products (EWPs) to be widely used in residential applications. In non-residential construction in North America, however, these products are still underutilized. Legislation, such as the "Wood First Act" [1], passed in 2009 in British Columbia aimed to promote a culture of building with wood by requiring its use as a principal material in any provincially funded building. Subsequently, several Canadian provinces implemented code changes that allowed wood to be used in six-storey light-frame buildings. These legislative changes, along with modern connectors such as self-tapping screws (STS) [2] and technical documents for wood construction [3,4], have created new possibilities for use of wood in mid- and high-rise residential and non-residential construction. Hybrid design approaches that combine wood with other materials such as steel, are receiving much research attention [5–7]. Pushing the boundaries of wood construction, a number of landmark buildings have been completed in North America in the last five years such as the five-storey Earth Science Building in Vancouver [8] and the world's tallest timber-hybrid building, the UBC Brock Commons (18 stories, h = 53 m) [9]. Both buildings utilize Cross-laminated timber (CLT) panels for their floors.

1.2. Cross-laminated timber

CLT is a plate-type engineered wood product, made of multiple layers of wood boards with each layer oriented crosswise (90°) to the next [10]. Originally developed in Europe, Canadian and US versions of CLT handbooks [11,12] contributed to the increasing popularity of CLT in North America. The fabrication of CLT in North America is regulated by the product standard ANSI/APA PRG 320 [13]. Provisions for CLT were included in 2015 in the NDS [14] and in the 2016 supplement to the 2014 edition of CSA-O86, the Canadian Standard for Engineering Design in Wood [15].

CLT can be used in either some parts of the structure for floor and wall elements in timber or hybrid structures or as the material for the entire building [16–18]. Extensive experimental programs to quantify the seismic performance of multi-storey CLT buildings were carried out since the turn of the millennium [19–28]. Ceccotti et al. [19] performed cyclic tests focusing on CLT walls considering different connection layouts (hold-downs, anchor brackets), openings, and boundary

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https://doi.org/10.1016/j.engstruct.2018.04.052
Received 25 March 2017; Received in revised form 24 September 2017; Accepted 15 April 2018

conditions. Lauriola and Sandhaas [20] performed pseudo-dynamic tests on a full-scale one-storey building. Popovski et al. [21] conducted testing on CLT wall panels subjected to monotonic and cyclic lateral loads. They tested single panel walls with different aspect ratios, multi-panel walls with step joints and different connections (types of screws), as well as one- and two-storey wall assemblies. Gavric et al. [22,23] performed cyclic tests focusing on the behavior of coupled CLT wall panels with different types of screwed vertical joints (step and spline joints) with several different configurations of anchoring connectors and hold downs. Three-storey [24] and 7-storey buildings [25] were tested on shake tables in 2006 and 2007, respectively, demonstrating that CLT buildings can have adequate seismic performance given proper connection detailing.

Analytical models for mid-rise CLT buildings allowed for performing non-linear dynamic analyses to determine adequate seismic force reduction factors for CLT structures [26,27]. Based on this research, seismic design provisions for platform-type CLT construction were developed and implemented in CSA O86 [15]. These provisions, currently the most-comprehensive design guidance found in any design standard in the world, require that the energy-dissipative connections in a platform type CLT structure have a ductility of at least 3 to be able to claim the ductility based force modification factor R_d of 2.0.

To successfully build CLT structures, connections between individual panels and between panels and other structural components need to be designed for appropriate strength, stiffness and ductility. As CLT panels behave as rigid bodies, the desired ductility for seismic design must be obtained from the connections [15].

1.3. Self-tapping screws

Self-tapping Screws (STS) are widely recognized as being the state-of-the-art in connector technology for timber structures [2]. STS are made of hardened steel and often produced with continuous threads to achieve a high yield moment, tensile, and torsional strength as well as high withdrawal resistance. STS are cost efficient as they usually do not require pre-drilling and are therefore faster to install than traditional lag or wood screws [2]. The thread provides a continuous mechanical connection along the embedded length, which makes STS efficient for reinforcing timber elements and connections prone to splitting [28,29]. Bending of the screws, when used as shear connectors, can be avoided and connection stiffness can be increased by installing STS at an angle (most often 45°) to the interface [2]. The influences of screw and connection parameters have been expensively investigated e.g. [30–34], including models that count for the combined shear and withdrawal action of inclined screws. Design equations for the STS withdrawal resistance are either provided by product approvals or the more generic design equations in EN 1995-1-1 [35]. However, the current CSA-O86 [15] provides no design guidance for use of STS and for the application of STS in Canada, product approvals such as [36] have to be used.

1.4. CLT panel-to-panel connections

Panel-to-panel connections within wall (or floor) assemblies have to be designed to resist the in-plane shear (and possibly out-of-plane bending) forces. As CLT panels mostly act as rigid bodies and do not dissipate energy under seismic loading, the desired energy dissipation must be achieved using ductile connections [9]. CLT wall assemblies have demonstrated adequate seismic performance when ductile dowel-type fasteners are used [37–40]. Four different types of panel-to-panel connections are most often used in CLT using STS: half-lap joints, internal spline, single surface spline, and double surface spline [10]. Sandhaas et al. [37] tested spline connections under quasi-static monotonic and reversed cyclic shear loading and estimated their load-carrying capacity with the Johansen equations defined in EN 1995-1-1 [35]. Joyce et al. [38] investigated double spline connections with STS and showed that high ductility can be achieved when STS are loaded in shear while withdrawal action resulted in a higher stiffness. Gavric et al. [39] conducted a comprehensive test program on CLT panel-to-panel connections using lap and spline joints under monotonic and cyclic loading and concluded that half-lap joints showed superior performance compared to spline joints. Hossein et al. [40] studied the feasibility of a STS assembly with double inclination of fasteners in butt-joints. Excellent structural performance in terms of strength and stiffness was obtained while the connections could be classified as highly ductile under quasi-static loading and moderately ductile under reversed cyclic loading.

2. Experimental investigation

2.1. Objective

Previous work investigated the mechanical behavior of in-plane shear CLT connections and demonstrated that the use of STS in half-lap joints can lead to stiff or ductile connections, depending on whether the STS are loaded in withdrawal or shear. The objective of the research presented herein was to investigate a novel connection assembly combining STS that act in shear with STS that act in withdrawal.

2.2. Specimen description

The test specimens consisted of assemblies of 3-ply CLT panels, each 99 mm thick. The panel laps to create the half-lap joints were 80 mm wide and 50 mm deep (half the panel thickness).

Three different specimen sizes were fabricated and subsequently tested: (1) **Small** sized specimens with two individual panels connected at one shear plane, each panel being 290 mm wide and 700 mm long (Fig. 1a). For this specimen size, depending on screw action, four, six or eight STS were installed (Table 1). Six replicates of each test series were tested under quasi-static monotonic loading. (2) **Medium** size specimens with three individual panels connected at two shear planes, each panel being 1200 mm long and 400 mm wide, as shown in Fig. 1b. For this size, 16 STS were installed in each shear plane and one respectively three replicates of each test series were tested under quasi-static monotonic and reversed cyclic loading. (3) **Large** size specimens with three individual panels connected at two shear planes, each panel being 2400 mm long and 800 mm wide, as shown in Fig. 1b. For this size, 32 STS were installed in each shear plane. One replicate of each series was tested under quasi-static monotonic loading and two replicates of each series were tested under reversed cyclic monotonic loading.

All CLT assemblies were connected with STS designed for three different actions: (1) **Shear** action with STS placed at 90° to the load, as illustrated in Figs. 2a and 3a. (2) **Withdrawal** action with STS placed at 45° to the load, shown in Figs. 2b and 3b. (3) **Combined** action with STS placed at 90° and STS placed at 45° to the load, as presented in Figs. 2c and 3c. The overview of all test series is given in Table 1. The test series labelling combined the specimen size, the STS action and the loading type, e.g. test series S-S-M stands for a test series consisting of small CLT panels, connected by STS loaded in shear under monotonic loading.

2.3. Materials

All CLT panels used for the testing were produced by Structurlam Products Ltd. meeting the requirements of ANSI/APA PRG-320 [13]. The wood species combination used was SPF (Spruce-Pine-Fir) with a mean oven dry relative density of 0.42; the adhesive used was Purbond Polyurethane. CLT grade used for the testing was V2M1 where the grade in parallel layers was SPF No. 1/No. 2 and in perpendicular layers SPF No. 3 with strength and stiffness properties according to CSA-O86 [15]. The average moisture content of the CLT at the time of connection testing was 10% (+/−2%), determined by means of a handheld