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Simple cross-laminated timber shear connections with spatially arranged screws

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ABSTRACT

This paper presents an experimental study to evaluate the use of spatially arranged self-tapping screws (STS) as shear connections for cross-laminated timber panels. Specifically, simple butt joints combined with crossed STS with different inclinations were investigated under quasi-static monotonic and reversed-cyclic loadings. The influence of the number and angle of insertion of screws, screws characteristics, friction and loading on the joint performance was explored. The yield load, load-carrying capacity and related slips, elastic stiffness, and ductility were evaluated considering two groups of tests performed on a total of 63 specimens of different size. Performance of connections with respect to the energy dissipation and loss of strength under cyclic loads was also investigated. It was shown that the spatial insertion angle of screws plays a key role in the performance of joints, not only because it relates to the shank to grain angle, but also because it affects the amount of wood involved in the bearing mechanism. Design models of STS connections are presented and discussed, and the test results are compared against analytical predictions. While good agreement for load-carrying capacity was obtained, the existing stiffness model seems less adequate with a consistent overestimation.

1. Introduction

1.1. Objective

The objective of the research presented in this paper is to investigate cross-laminated timber (CLT) assemblies made with simple butt joints and spatially arranged self-tapping screws (STS) of different orientations. Based on an extensive experimental program, considering quasi-static monotonic and reversed cyclic testing, the yield and maximum loads, connection stiffness and ductility, energy dissipation, and performance reduction under reversed cyclic loading are presented and discussed and compared to the predictions of existing design models.

1.2. Cross-laminated timber applications

Wood and its engineered derivatives are expanding into construction market segments that were traditionally dominated by steel and concrete [1,2], with tall wood buildings offering a sustainable solution to meet the growing demand for living and working spaces worldwide [3,4]. Innovative materials, systems, and connectors are contributing to the resurgence of wood as a material in sectors beyond low-rise residential construction. On the material level, the most notable development has been the introduction of CLT, which is increasingly being used in the residential and commercial mid-rise building sectors [5]. The cross-layered build-up of CLT panels makes for a dimensionally stable, stiff, strong, light and multifunctional construction material, suited for supporting in- and out-of-plane loads; it can be used for the realization of walls, floors, and cores, and can be easily connected to other members or structural materials [6,7].

Recent research that focused on the application of CLT for shear-walls [8–11] provided design guidance. Popovski and Karacabeyli [8] investigated various configurations of CLT walls and assemblies in order to establish force modification factors for the seismic design of CLT structures according to the National Building Code of Canada. Shahnewaz et al. [9] formulated equations to assess the in-plane stiffness of CLT walls with openings based on FEA. Fragiacomo et al. [10] analyzed multi-story CLT buildings with different wall assemblies under seismic loads, discussed capacity design rules for CLT structures and determined over-strength values of hold-downs and angle brackets based on non-linear static push-over analyses. Ceccotti et al. [11] presented shake table tests on a seven-story full-scale CLT building and confirmed the adoption of a seismic force reduction factor of three for the design with force-based methods, provided joint assemblies were ductile.

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On the structural system level, multiple novel hybrid solutions have been proposed for the use of wood in large-scale construction such as pre-stressed systems [12], moment resisting steel frames with CLT infill panels [13], balloon-framed mass-timber systems with steel link beams [3,14,15] and steel-CLT hybrid floor systems [16,17]. On the connection level, multiple traditional and innovative fasteners have also been tested for applications in CLT [18–21]. Gavric et al. [18] characterized typical CLT connections, providing capacity and stiffness values for seismic design. Schneider et al. [19] conceived a novel tube connection and compared preliminary experimental results to the behavior of conventional CLT connections. Loo et al. [20] proposed CLT structures with slip-friction connectors with an abrasion-resistant central plate, external mild grade steel plates, and preload bolts to reduce the damage under earthquakes. Zhang et al. [21] examined the feasibility of tall timber-based buildings with a novel steel–timber hybrid construction system with embedded steel beams in CLT panels.

The efficiency of CLT-based construction systems, including the prefabrication and assembly processes, is mainly dependent on the connections installed between CLT panels. The introduction of STS has been a game changer for wood construction in this regard. STS are commonly used to connect CLT panels (*e.g.*, walls-walls, floors-floors or walls-floors) since they allow a wide variety of different solutions, as a function of the fasteners spatial arrangements [6].

1.3. CLT panel shear connections

The connections between CLT wall (or floor) panels have to resist primarily in-plane shear forces. CLT joints can be realized in different ways to respond to functional and design requirements and can be categorized into four groups, as illustrated in Fig. 1: tendon or surface spline joints (Fig. 1a); half-lap or step joints (Fig. 1b); leaf or interior spline joints (Fig. 1c); and butt joints (Fig. 1d). For tendon joints, panels are connected at their edges using a spline placed into grooves at the CLT panel sides. For step joints, the CLT panels have a complementary step (or lap) cut. Leaf joints are made by inserting a spline in the middle. Finally, butt joints are the simplest in terms of production, as no additional hand-tool or automated machining processes are required.

As CLT panels mostly behave as rigid bodies, the desired energy dissipation under seismic loading must be achieved by the connections between panels. Partially-threaded (PT) or fully-threaded (FT) STS are commonly used as fasteners and considerable benefits are observed in the case of crossed inclined screws. In this configuration, the screws are subjected either to a combined shear-compression or shear-tension stress state. The resistance mechanism can be idealized as a truss system in which the screws are the truss diagonals, surrounded and stabilized in the cross-section transversal directions by the wood. CLT assemblies have been shown to provide adequate seismic performance when ductile dowel-type fasteners are used [22–26]. Sandhaas et al. [22] tested single spline joints under quasi-static monotonic and reversed cyclic shear loading and successfully described their load-carrying capacity with Johansen's model. Joyce et al. [23] tested double spline joints and achieved high ductility with STS loaded in shear and high stiffness with STS acting in withdrawal. Gavric et al. [24] investigated CLT panel-joints using lap and spline joints under monotonic and cyclic loading and concluded that half-lap joints showed superior performance compared to spline joints. Hossain et al. [25,26] studied an STS assembly with a double inclination arrangement of fasteners in butt-joints and demonstrated high strength and stiffness and moderate ductility under reversed cyclic loading.

1.4. Self-tapping screws

STS are made of hardened steel and provide high yield moment, tensile and torsional strength, and high withdrawal resistance. They usually do not require pre-drilling and are therefore fast to install [27], and FT STS can efficiently be used for reinforcing timber connections prone to splitting [28]. Screw bending, when STS are loaded in shear, can be limited and connection stiffness can be increased by installing STS at a certain angle to the interface (most often 45°) [29]. The literature on STS includes studies on parameters such as minimum fastener spacing [30,31], analyses of their axial and lateral load-carrying capacity and stiffness [32,33], and the effect of gaps and lamination angle when screws are driven in CLT panels [34,35].

Under axial loading, screws can fail in the form of tension or withdrawal. The recognized design model for screws withdrawal estimates their resistance as a function of the diameter of the fastener, wood density and the fastener penetration length. When STS are laterally loaded, their resistance is governed by the wood embedment strength and the yield bending capacity of the screw's shank as described by Johansen's model [36]. Product approvals such as [37,38] or the more generic equations in Eurocode 5 (EC5) [39] provide design guidance.

Among several types of CLT joints, butt joints with STS inserted at different angles to the side and narrow faces of the CLT panel offer cost savings and installation flexibility. Most CLT structures have been erected using joint details and STS design models provided by manufacturers. However, provisions to cost-efficient STS-based CLT joint design, most notably for connections that use spatial STS arrangements, are not very robust.

2. Design of CLT butt-joints with STS

2.1. Design models

The load-carrying capacity models for laterally loaded STS assume rigid-plastic behavior of the materials associated with yielding of screws and embedding of the wood when subjected to compression. Conversely, capacity models for axially loaded STS assume rigid-brittle behavior of materials accompanied mainly by a shear failure of the wood close to the screw thread. EC5 [39] provides models for STS subjected to lateral or axial loadings and a quadratic interaction equation in the case of screws under combined axial-lateral loading. This equation was initially developed for laterally-axially loaded nails, where strengths models do not account for the load to grain angle. Therefore, it does not properly fit to STS installed inclined and subjected to combined lateral and axial loadings.

Bejtka and Blass [40] and Jockwer et al. [41,42] proposed empirical equations to assess the load-carrying capacity of inclined screws loaded in axial and lateral directions, accounting for the loading direction angle with respect to the grain. These models, developed for an individual screw, were herein used to evaluate the resistance of CLT butt-joints with spatially inclined STS.

Fig. 2 illustrates failure modes of STS butt joints with inclined screws; Fig. 2a refers to elements connected with laterally loaded crossed STS, and Fig. 2b relates to elements connected with axially-laterally loaded crossed screws. The in-plane load-carrying capacity of laterally loaded crossed screws, R_1 (either FT or PT, Fig. 2c), is the sum of the shear resistance of fasteners and the friction between the surfaces of the timber elements. When two crossed STS with the same diameter and penetration length are installed symmetrically into equal CLT panels, the connection assembly load-carrying capacity is double that of the single screw:

$$R_1 = 2\cdot(R_v + \mu\cdot R_a\cdot\cos(\beta)) \quad (1)$$

where R_v is the screw shear resistance, μ is the coefficient of friction, R_a is the screw axial resistance, and β is the transversal angle of insertion of the screws.

In the case of connections with pairs of crossed STS loaded in a axial-lateral combination, depicted in Fig. 2b (valid only for FT screws), their in-plane resistance, R_2, is the sum of a tension-shear component and a compression-shear component: