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Behavior of cross-laminated timber diaphragm connections with self-tapping screws

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ABSTRACT

Monotonic and cyclic tests were carried out to determine strength and stiffness characteristics of 2.44 m (8 ft) long shear connections with 8 mm and 10 mm diameter self-tapping screws. The goal of this research is to compare test values of cross-laminated timber (CLT) diaphragm connections in seismic force-resisting systems to the design values calculated from formulas in the National Design Specification for Wood Construction (USA) and the Eurocode. Understanding and quantifying the behavior of these shear connections will provide structural engineers with increased confidence in designing these components, especially with regard to the seismic force-resisting systems. Ratios of the experimental yield strength (from the yield point on the load-deflection curve) to factored design strength were in the range of 2.1–6.1. In the ASCE 41-13 acceptance criteria analysis, the m-factors for the Life Safety performance level in cyclic tests ranged from 1.6 to 1.8 for surface spline connections and from 0.9 to 1.7 for cyclic half-lap connections. The half-lap connections with a unique combination of angled and vertical screws performed exceptionally well with both high, linear elastic initial stiffness and ductile, post-peak behavior.

1. Introduction

Cross-laminated timber (CLT) is an engineered wood product that is playing a major role in the worldwide push for wood buildings taller than the conventional limit of 5–6 stories for light-frame wood construction. As a majority of residential (and other low-rise) buildings are light-frame wood construction, the mid- and high-rise sector present new markets where wood can make a significant sustainable, cost-effective impact. The higher strength, stiffness, and solid wood volume of CLT, compared to conventional light frame construction, are the specific characteristics enabling the increased building heights of wood structures. However, the seismic behavior and analysis of a new building system like this requires additional research to accompany the existing knowledge of conventional wood construction. Floor and roof diaphragms, the horizontal components of the lateral force-resisting system of a building, are designed to resist earthquake and wind loadings. The in-plane shear forces in both light-frame wood diaphragms and CLT diaphragms are resisted by steel connections, such as nails and screws, and these provide most of the energy dissipation in the diaphragm during seismic loading.

1.1. Background

Several research programs seeking to quantify the quasi-static and cyclic performance characteristics of cross-laminated timber and their joints were carried out in Europe in the 2000s [1–3]—the infancy of the new engineered wood product—and later in North America [4]. Cyclic loading tests were conducted to investigate and quantify the ductility, energy dissipation, strength, and stiffness characteristics of the CLT components. Conventionally, the vertical elements of lateral force-resisting systems (LFRS), such as shear walls, are the primary building components designed to provide ductility in a building. Much of the initial testing that took place was on CLT shear walls and their associated connections. Performance characteristics of CLT shear walls and diaphragms (under lateral loads) are controlled by the ductile steel connections, as the CLT panels themselves are significantly more rigid. Yielding of steel nails and crushing of wood provide much of the ductility of wood systems for both shear walls and diaphragms; in addition, light-frame wood diaphragms are known to sustain much less damage compared to the similarly constructed shear walls during earthquakes [5]. To date, the authors have not encountered a building project where

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inelastic CLT diaphragm performance was assumed during design [6,7], nor has consensus been reached in design recommendations regarding this aspect [7,8].

1.2. CLT diaphragm design

Fundamental research is needed on CLT diaphragms and quantification of design parameters to make these innovative building projects cost efficient for owners. However, CLT structures are being built effectively in the U.S. and receiving local building code approval through alternate means after thorough engineering analysis; in some cases, testing programs are carried out to demonstrate performance. Diaphragm shear forces between panels, connection strengths, and diaphragm deflection can be calculated [9–15] and test data to support the calculation are available [2,3,16–20].

One option for developing the design methodologies for CLT diaphragms is to reference a research program completed for precast-concrete diaphragms [21,22]. The work contributed to the development of a new section for seismic diaphragm design in ASCE 7-16 [23] and the new diaphragm force reduction factor, R_s [24]. CLT panels in diaphragms, like pre-cast concrete slabs, effectively remain elastic during heavy loading and are substantially more rigid than the connections between the panels, which contribute to the ductility desired in a LFRS. In many structures, ductility of connections is not used for connection design directly. Instead, vertical components of lateral force-resisting systems account for the overall ductility in the R-factors in the equivalent lateral force method [32] (ASCE 7-10, Eq. 12.8-2). The new ASCE 7-16 diaphragm design force reduction factor, R_s, accounts for, among other characteristics, ductility in the diaphragm specifically. Currently, R_s factors are available only for cast-in-place concrete, precast concrete, and wood sheathed diaphragms. Ductility data compiled in these tests can be some of the data used to create R_s factors for CLT diaphragms with half-lap and spline connections.

Input characteristics for CLT diaphragm computer models can be obtained from monotonic and cyclic tests of inter-panel shear connections. Connections of CLT butt joints using 8 × 180 mm, fully-threaded, self-tapping screws installed along the shear plane at a 30-degree angle-to-grain in one direction and a 45-degree angle-to-grain in the other direction, exhibited average monotonic load-based strengths (peak load) of 6.8 kN (1.5 kips) per screw and an initial stiffness of 3 kN/mm (17.1 kip/in) per screw [17]. Tests with 19 mm (3/4 in) plywood splines, 105 mm (4–1/8 in) 3-ply CLT, and vertical, 8 × 80 mm self-tapping screws in shear produced strengths (yield load) of 2.0 kN (0.45 kip) per pair of fasteners (load is transferred from one CLT panel, through one screw, across the plywood spline, to the second screw, and back into the second CLT panel) and stiffness values of 0.4 kN/mm (2.3 kips/in) per pair of fasteners [18]. Additional, U.S.-based research [20] investigated similar shear connections and compared experimental testing to the predicted design strengths in the National Design Specification for Wood Construction (NDS) [13], finding estimation indices both less than and greater than one, for different connection types.

1.3. Objectives

The goal of this research is to compare test values of cross-laminated timber (CLT) diaphragm connections in the seismic force-resisting systems to the design values calculated from formulas in the NDS (USA) [13] and the Eurocode [43]. Specific objectives are:

1. Using monotonic and cyclic tests, determine strength, stiffness, and load-deflection behavior for CLT inter-panel shear connections using SWG/Wuerth ASSY self-tapping screws.
2. Compare strength and stiffness results from specimens with varying characteristics, such as screw spacing and screw diameter.
3. Compare experimental strengths to design strengths calculated using the NDS [13] and the Eurocode [43].
4. Determine m-factors for use in acceptance criteria for the CLT connections in ASCE 41-13— Seismic Evaluation and Retrofit of Existing Buildings [25].
5. Characterize failure modes for the different connection types and loading protocols.

Table 1
Wood properties.

		V1 Grade CLT		DF-L #2	DF-L #3
		Characteristic test value[a]	Allowable design value [18]	Allowable design value [8]	Allowable design value [8]
$f_{c,0}$[b]	(MPa)	17.7	9.31	9.31	5.34
	(psi)	2565	1350	1350	775
E_0[b]	(MPa)	11,034	11,034	11,034	9655
	(psi × 10^6)	1.6	1.6	1.6	1.4
$f_{c,90}$[b]	(MPa)	10.1	5.34	4.31	4.31
	(psi)	1470	775	625	625
E_{90}[b]	(MPa)	9655	9655	–	–
	(psi × 10^6)	1.4	1.4	–	–
G[b]	(MPa)	–	–	3448	3448
	(psi × 10^6)	–	–	0.5	0.5

[a] Characteristic test values defined as population mean for stiffness properties and 5th percentile with a 75% confidence for strength properties, Table 1 in [18].

[b] $f_{c,0}$ = compressive strength parallel to grain or major direction. E_0 = modulus of elasticity parallel to grain or major direction. $f_{c,90}$ = compressive strength perpendicular to grain or major direction. E_{90} = modulus of elasticity perpendicular to grain or major direction. G = specific gravity, Tbl. 4a in [8].

2. Materials and methods

2.1. Test specimens

Six different specimen constructions were used in this research. Each specimen consisted of three separate CLT panels (each 2.44 m × 0.610 m) connected side-by-side along the long edge. CLT panels were three-ply, Douglas fir-Larch (DF-L) layups, with DF-L #3 in the core layer and DF-L #2 in the outer layers [26]. See Table 1 for properties of the wood and CLT grades. The panel producer has been given certification by the APA (Engineered Wood Association) for their V1-designated CLT product, defined as “No. 2 Douglas fir-Larch lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers” [26]. At the time of procurement, the manufacturer was certified to only produce V1-grade [26] panels with DF-L #2 in all layers; however, the panels in this study were manufactured with DF-L #3 in the core layer and DF-L #2 in the outer layers only. This layup was chosen to match the PRG-320 [26] definition.

Half-lap and surface spline connection types were tested with both 8 mm and 10 mm self-tapping screws at spacings of 152 mm (6 in) and 305 mm (12 in). Table 2 shows the details of the screws used in this project. See [27] for the Würth/SWG ASSY self-tapping screw ICC ES technical report and [28] for the European Technical Approval.

Table 2
Self-tapping screws used in specimens.[a]

Fastener Type	Brand	Model	Nominal Diameter (d_{thread})	Fastener Length (L)	Thread Type
Self-tapping Screw	Würth/ SWG	ASSY	8 mm	100 mm	Partial
		Eco	10 mm	100 mm	Partial
		ASSY	8 mm	120 mm	Full
		VG CSK	10 mm	140 mm	Full

[a] Technical data sheet in [27,28].