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Mechanical properties of laminated strand lumber and hybrid cross-laminated timber

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HIGHLIGHTS

- Hybrid CLT was fabricated using lumber and/or LSL.
- The bending properties of generic CLT were improved by using LSL as core or outer layers.
- Planar shear failure in lumber core layer was the key failure mode of CLT with a lumber cross layer.
- Tension failure in bottom layer was the key failure mode of CLT with a LSL core layer.

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ABSTRACT

Hybrid cross laminated timber (HCLT) was fabricated using lumber and/or laminated strand lumber (LSL), the mechanical performances of which were evaluated. To reach this goal, the mechanical properties of LSL and the bending properties of CLT and HCLT were measured in this study. The properties of LSL measured included the tension strength (only in the major direction), shear strength, shear modulus, and modulus of elasticity (MOE) and modulus of rupture (MOR). The failure mode of each kind of specimens was visually examined and recorded. Four types of CLT panels, one generic CLT (used as control) and three types HCLT were fabricated. The properties measured included the bending properties (in the major direction) and planar shear properties (in both major and minor directions). It was found that the HCLT had better bending and planar shear properties than that of generic CLT. The MOE and MOR of HCLT having LSL as the outer layers were 19% and 36% higher than those of generic one, respectively. The MOE and MOR of HCLT having LSL as core layer (replacing the cross lumber layer) were 13% and 24% higher than that of generic CLT, respectively. The failure modes of four types of CLT observed included the planar shear failure of cross lumber layer, tension failure of bottom LSL, and tension failure of bottom lumber, especially tension failure of lumber originated at a knot(s).

1. Introduction

Cross-laminated timber (CLT) is defined as a prefabricated solid engineered wood product made of at least three orthogonally bonded layers of solid sawn lumber or structural composite lumber (SCL) using adhesive, nails or wooden dowels. CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany [1], which has been recently gaining increased popularity in residential and non-residential construction in form of roof, floor, or wall applications in Europe and North America. Due to its cross lamination, CLT shows good dimensional stability compared to solid wood, and high in-plane stiffness and strength when used as wall element. Another advantage of CLT is that it can be prefabricated, reducing construction time and wastes. Combined with other engineered wood products, such as I-beams, laminated veneer lumber (LVL) and structural plywood, CLT demonstrates great potential of serving as crucial elements in the construction of buildings made entirely from timber. The multi-storey buildings made of CLT exhibit their excellent resistance to seismic tests [2]. Up to date, the tallest timber apartment building in the world is the Forté apartment building in Melbourne, Australia, which is 32.17 meters high. By using CLT, Forté reduces CO_2 equivalent emissions by more than 1400 tonnes when compared to concrete and steel [3].

However, generic CLT is known to be prone to the so-called planar (rolling) shear failure and excessive deflection when subjected

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to out-of-plane loading. This is particularly critical where a lumber layer doesn't have edge gluing. To address this issue, many studies have been conducted, including the measurement and prediction of the planar shear properties of CLT, evaluation of the effect of planar shear on CLT, and improvement of the planar shear properties of CLT [4–8]. Fellmoser and Blaß [4] investigated the planar shear modulus of solid Norway spruce (*Picea abies*) board using a bending vibration test and the effect of span-to-depth ratio on planar shear properties of a 3-layer CLT panel via shear analogy method. They found that the planar shear modulus of 3-layer panels ranged from 40 MPa to 80 MPa, and the planar shear strength was strongly influenced by the span-to-depth ratio being below 20. Zhou et al. [5] carried out the bending tests and two-plate shear tests for examining the influence of growth ring orientation and laminate thickness of cross layer on its planar shear properties of CLT specimens, indicating that it should be feasible to adopt the two-plate shear test for determining the planar shear modulus and strength of cross layer in CLT. Chen [6] investigated the structural performance of a box based CLT system in floor applications. She developed comprehensive three dimensional finite element models and tested the bending properties of CLT board. She found that the numerical analysis well agreed with the experimental data in terms of vertical deflection and bending stiffness. Li [7] evaluated the duration-of-load and size effects on the planar shear strength of CLT, suggesting that the planar shear duration-of-load strength adjustment factor for CLT was more severe than the general duration-of load adjustment factor for lumber. Such a difference should be considered in the introduction of CLT into the building codes for engineered wood design. Wang et al. [8] studied the feasibility of using fast-growing poplar as cross layer to fabricate cross-laminated timber (CLT). Their study showed the mechanical properties of CLT panels containing poplar were similar to those made of non-poplar wood, such as Douglas fir.

These performance issues of planar shear can be addressed by designing new type of CLT or directly replacing one or more of the layers in a laminated strand lumber (LSL) panel(s). Researchers at the Wood Science and Technology Centre (WSTC), the University of New Brunswick, Fredericton, New Brunswick, Canada, have been developing hybrid CLT by using laminated strand lumber (LSL). LSL is a composite structural lumber consisting of oriented wood strands that are glued and compressed to form panels up to 90 mm in thickness. LSL shows greater mechanical properties than solid lumber of the same species as well as less variability [9]. LSL, a revolutionary product, is used for a broad range of applications including rim board, millwork and window, door and garage door headers, as well as for many industrial uses. New uses for this product are still evolving, including the use of LSL for vertical members in commercial applications where the framing member heights are long, and the wind loads are substantial. This study was mainly aimed at evaluating the bending properties of HCLT made of LSL and/or lumber. To reach this goal, the selected mechanical properties of LSL were measured as well.

2. Methods

2.1. Materials

2-by-4 Lodgepole pine (*Pinus contorta*) lumber used in this study was provided by Weyerhaeuser, which had a grade of #2 and better J-Grade with an average moisture content (MC) of 12% at test. The nominal dimensions of lumber were 38 mm in thickness, 89 mm in width, and 2.44 m in length. The LSL panels of a grade of 1.5E were provided by Weyerhaeuser as well, the dimensions of which were 2.44 m in length, 1220 mm in width and 38 mm in thickness. The wood species of strands used for making LSL was aspen poplar (*Populus tremuloides*). The MC of LSL at test was about 7%. One-component polyurethane adhesive (Purbond HB E452) was provided by Henkel Corporation.

2.2. Preparation of LSL specimens

The mechanical properties of LSL were directly measured in this study. The test program is given in Table 1. These properties involved the modulus of elasticity (MOE) and modulus of rupture (MOR) under static bending, shear modulus, shear strength and tension strength. The specimens of each type had their face grain direction parallel and perpendicular to the major direction of LSL, except the tension strength test due to the limitation of the panel width, which was only tested in the major direction. The groups A, C, F, I, and K had their face grain direction parallel to specimen length direction, and the groups B, G, J, and L had their face grain direction perpendicular to specimen length direction. 2 or 3 specimens of each type were cut from one LSL panel and four LSL panels were used, generating a total of 8 or 12 specimens for each group. All test specimens were stored in a conditioning chamber of a temperature of 20 °C and a relative humidity of 65% for more than 30 days before testing.

2.3. Fabrication of HCLT panels and preparation of bending and shear HCLT specimens

Three types of HCLT combining lumber with LSL were prepared in this study. The layups of 3-ply CLT and HCLT panels are given in Table 2, which were fabricated in Alberta Innovates Technology Future, Edmonton, Alberta, Canada. The HCLT had similar structure with CLT, i.e. all panels had three glued layers of boards placed in orthogonally alternating orientation, except the type LTL consisting of lumber and LSL placed in the parallel to major/longitudinal direction Table 2. Due to the dimensional limitation of LSL panel, the centre layer of TTT contained three LSL pieces leading to two gaps that were 0.6 m from two edges in the panel length direction. After preparing each layer, the surface of each layer was first air-blown to remove dust and debris and then was sprayed with 95 g of water for wetting surface. The reason of water spray was that LSL panel had relatively lower MC that the required value (larger than 8%) for curing the adhesive [1]. It should be noted that the lumber layers were not applied with edge gluing and moisting (due to its MC being higher than 8%). The adhesive was only applied at a rate of 220 g/m^2 on one surface of each layer right after two minutes of water spray. The total assembly time varied from 15 to 35 min which was well controlled under the required maximum assembly time (i.e. 45 min) of the adhesive. A 1.5 m by 2.7 m steam press was used to apply the pressure. A 0.13-mm-thick Teflon sheet was used to separate the panel and pressing plate. The one or two panels were pressed without applying side pressure under

Table 1
Types of LSL specimens.

Specimen type	Testing type	Length (mm)	Width (mm)	Face grain direction*	No. of specimens
A	Bending	848	89	//	12
B	Bending	848	89	⊥	12
C	Tension	1829	140	//	8
F	Bending	350	89	//	8
G	Bending	350	89	⊥	8
I	Bending	300	89	//	8
J	Bending	300	89	⊥	8
K	Bending	406	89	//	8
L	Bending	406	89	⊥	8

* // and ⊥ represent the parallel and perpendicular to the strength direction of LSL.