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Structural performance of hybrid SPFs-LSL cross-laminated timber panels

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HIGHLIGHTS

- Hybrid CLT with laminated strand lumber (LSL) tested under out of plane loads.
- LSL core eliminated shear failure in 3-layer panels.
- CLT panel bending strength increased by 23% through inclusion of LSL core.

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ABSTRACT

The bending and shear performance of hybrid cross-laminated timber (CLT) panels made from Spruce-Pine-Fir (South) (SPFs) and laminated strand lumber (LSL) are examined. Four configurations of three-layer CLT were fabricated: all-SPFs control specimens, all-LSL specimens, hybrid specimens with SPFs faces and an LSL core, and hybrid specimens with LSL faces and an SPFs core. Bending tests were conducted to assess flexural strength and stiffness. Additionally, three-point bending tests were performed to assess shear performance. The incorporation of LSL in the core of CLT panels increased mean panel bending stress at failure by 23% through mitigation of rolling shear failure.

1. Introduction

Originally introduced in Austria and Germany in the mid-1990s, cross-laminated timber (CLT) has become an increasingly popular alternative for multi-story timber construction in Europe [1]. CLT has recently garnered interest in North America with the establishment of several CLT and nail-laminated timber plants in Canada and the United States. CLT panels are suitable for use in walls, floors and roofs, and are typically fabricated from an odd number of flat-wise layers of solid-sawn lumber placed in alternating 90 degree directions. In the majority of cases, individual layers of boards are adhesively bonded although nail- and screw-laminated CLT is also produced. Alternative forms of CLT have been considered including placing laminations at ±45 degrees as well as hollow, box-based systems [2]. Compared to typical concrete construction, CLT structures are lightweight, sequester more carbon, possess better thermal insulation properties, and are more rapidly erected [3].

Research on the structural performance of CLT can be separated into the broad categories of seismic behavior [4–7], fire resistance [8,9], and determination of the mechanical properties of CLT. A number of studies have focused on the determination of CLT mechanical properties in flexure and shear, which are primary design properties for panels subjected to out-of-plane loading [10–15]. Sikora et al. [10] present a current and thorough review of the existing literature on this topic. Others have focused on CLT mechanical response due to in-plane loading [16–18].

As with plywood, an issue which can limit the capacity of CLT subjected to out-of-plane loading is failure in perpendicular-to-grain shear, commonly called rolling shear. Rolling shear also contributes to deflections of CLT panels. Because of its significance, several investigations have considered rolling shear properties and failure mechanisms. Zhou et al. [19] examined the effect of

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rolling shear deformations in 3-layer, black spruce CLT, measuring rolling shear modulus and conducting three-point bending tests of CLT specimens. Zhou et al. [19] also proposed a deflection adjustment factor to account for rolling shear deformations, and also concluded that bending specimen width did not significantly affect apparent elastic modulus and apparent shear modulus. Li et al. [20] implemented a torsional test for evaluating rolling shear strength in CLT, observing that thinner cross-layers tended to have higher rolling shear strengths. Hochreiner et al. [14] studied CLT plates subjected to concentrated loads and examined the evolution of rolling shear failure modes by tracking fracture development and load-deformation history using digital image correlation. Li and Lam [21] experimentally assessed rolling shear damage accumulation in CLT attributable to load cycling, and calibrated a damage accumulation model that can be used for future studies on duration-of-load behavior of CLT under rolling shear. Noting the significance of rolling shear on CLT structural performance, Aicher et al. [22] assessed the rolling shear modulus and strength of European beech, which typically has much better rolling shear properties than softwoods normally used in CLT construction, concluding that the use of beech in CLT cross-layers could be beneficial for CLT strength. Wang et al. [23] assessed the use of laminated strand lumber (LSL) in both cross-layers and face layers of hybrid CLT panels, demonstrating increased flexural capacities relative to conventional all-softwood CLT.

The literature indicates that rolling shear failure can be a limiting factor for the strength of CLT subjected to out-of-plane loading. The focus of the research reported in this paper was the structural assessment of hybrid CLT panels made from LSL and softwood lumber with the objective of increasing strength by mitigating rolling shear failures in the core layer. LSL is an engineered composite lumber that is made from approximately 300 mm long strands of fast-growing species (often aspen or poplar) that are bonded and densified during manufacture and oriented with the long axis of the structural member. LSL typically possesses good dimensional stability and very predictable strength and stiffness values compared to solid-sawn lumber. Additionally, the authors are aware of no published experimental research specifically examining the use of Northeastern U.S. Spruce-Pine-Fir (South) (SPFs) lumber in CLT. SPFs is an economically significant group of lumber species harvested in the United States that includes Eastern Spruces, Balsam Fir, Red Pine, Jack Pine, Englemann Spruce, Lodgepole Pine, Sitka Spruce and Norway Spruce. All species are subject to the same grading rules and have the same design values. CLT panel production using SPFs harvested and milled in the Northeastern US may become an important new market for lumber producers in the United States as CLT markets grow. The research reported in this paper includes characterization of the SPFs and LSL lumber used for CLT manufacturing, assessment of the bond between SPFs and LSL using a polyurethane adhesive, and testing to assess both major-axis flexural and shear strength and stiffness.

2. Materials and methods

Materials were 38 mm × 184 mm × 3 m kiln-dried SPFs No. 2, 38 mm × 184 mm × 3 m grade 1.35E LSL boards (without wax coating on the board edges), and Henkel PURBOND HB E452 single-component polyurethane adhesive. The No. 2 grade of SPFs is a standard grading category corresponding to specific stiffness and strength design values in the US codes, and is a commonly produced grade of SPFs lumber. The SPFs lumber was procured in bulk quantities from Pleasant River Lumber in Dover-Foxcroft, Maine, USA, and as discussed later, a small percentage of the SPFs was No. 1, a higher grade with higher design values. The LSL was provided by Louisiana-Pacific Corporation's plant in Houlton, Maine, USA. The designation "1.35E LSL" refers to a specific grade of LSL that has a nominal elastic modulus of 9310 MPa. The 1.35E LSL was selected as opposed to a higher grade – 1.55E and 1.75E grades with moduli of 10,700 MPA and 12,070 MPA are also available – because its flexural strength and stiffness were expected to be similar to the SPFs. Two, three-layer CLT panels were laid up for each of four configurations as described in Table 1. The CLT panels were made from continuous boards as opposed to the finger-jointed lumber typically used in commercially fabricated CLT panels.

2.1. Lumber characterization and preparation

Each SPFs and LSL board was first E-rated using a Metriguard 340 E-Computer, its moisture content (MC) taken with a Delhorst J2000 pin moisture meter, and its dimensions measured and density calculated. In the E-rating process, the board is placed flatwise on two supports, one of which contains a small load cell. The board is struck at mid-span with a hammer, and the dynamic load cell readings are used to compute a dynamic modulus of elasticity (MOE). A total of over 900 SPFs and over 700 LSL boards were measured to permit the fabrication of additional panels beyond those discussed here. Table 2 summarizes the results of the lumber characterization study. The MOE values were adjusted to 12% MC using the procedure defined in ASTM D1990 [24] to allow direct comparison with design values.

The average SPFs MOE was significantly higher than expected. The *National Design Specification* [25] reports the mean MOE for SPFs as 7.58 GPa for No. 2 and 8.27 GPa for No. 1, and the average MOE of the all SPFs used in this study exceeded 8.27 GPa by 34%. While only 4.2% of the SPFs lumber was stamped No. 1, a visual inspection indicated that the vast majority of the SPFs lumber was red spruce (*Picea rubens*). For comparison, the *Wood Handbook* [26] gives an average MOE for clear red spruce at 12% MC of 11.45 GPa. In contrast, the LSL MOE was only 1.5% less than the tabulated value of 9.31 GPa [27]. Further, as expected the LSL MOE was much less variable than the SPFs MOE. To ensure that no excessively compliant material was used in CLT panel fabrication, the SPFs boards with MOE values in the lower 5% of the distribution, which corresponded to an MOE of less than 6.89 GPa, were removed from the lot. This shifted the mean MOE to from 11.05 GPa to 11.35 GPa and reduced the coefficient of variation (CoV) in MOE from 19.6% to 15.2%.

Following MOE testing, both the SPFs and LSL were conditioned in a dehumidification dry kiln to reduce the MC differential between the two materials and promote better adhesive bonding. The SPFs lumber was conditioned for five days after which it had reached an average MC of 10.8%. The LSL boards were conditioned for 27 days, reaching a MC of 9.4%. The resulting MC differential of 1.4% was well within the recommended moisture content differential of no more than 5% specified in *PRG 320* [28].

2.2. Assessment of bond strength

The manufacturer-recommended spread rate for the PURBOND adhesive was 100–180 g/m^2. This relatively wide range, combined with the uncertainty associated with bonding LSL to SPFs, dictated that an adhesive spread rate study be conducted. To accomplish this, adhesive compression shear block testing was performed per ASTM D905 [29] for adhesive spread rates of 98, 122, 146 and 171 g/m^2 for SPFs to SPFs and SPFs to LSL. For each adhesive spread rate and lay-up, a 127 mm × 305 mm two-layer lamination was made from which 10 shear block specimens were cut. Specimens were fabricated from conditioned boards that had been planed to a thickness of 19 mm. Laminates were pressed at 0.01 MPa for two hours per the product standard, and cured per the requirements of ASTM D905. Following each shear block test, strength and percent wood failure were recorded, and each specimen was oven-dried and weighed to determine MC. Results of the shear block tests are given in Table 3. Based on these results, an adhesive spread rate of 146 g/m^2 was chosen for CLT panel manufacturing. This adhesive spread rate gave the highest percent wood failure for the SPFs-SPFs specimens, and the highest average shear stress for the SPFs-LSL specimens. We note that the spread rates reported here will likely not be applicable to other brands and types of adhesives.

2.3. Panel fabrication and test specimen preparation

Two 2.45 m-long × 1.32 m-wide panels of each of the four CLT configurations were fabricated. Both SPFs and LSL boards with minimal warp, twist, bow or cupping were used to ensure reasonable dimensional tolerances. Within two hours of adhesive application, each board was planed to a final thickness of 35 mm, with approximately 1.6 mm removed from each face. Average MC was determined using a pin moisture meter at the time of panel lay-up. Prior to adhesive application, the lumber surface was moistened with a light water spray. A pre-measured amount of PURBOND adhesive was applied using putty knives.

Table 1
CLT Configurations.

Configuration	Face Material	Core Material
L1	SPFs (2.8%)	SPFs
L2	LSL	LSL
L3	LSL	SPFs
L4	SPFs	LSL