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Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers

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HIGHLIGHTS

- Cross-laminated timber (CLT) was manufactured using fast grown small diameter eucalyptus lumber.
- The bending performances of eucalyptus CLT were equivalent to those of commercial CLTs.
- The failure modes of eucalyptus CLT highly depended on the rolling shear strength.

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ABSTRACT

Eucalyptus is one of the most important plantation species in South China. Alternate applications of plantation grown hardwood such as eucalyptus need to be developed due to decreased demands of fibers for pulp and paper industry. The feasibility of manufacturing three-layer cross-laminated timber (CLT) using fast-grown small diameter eucalyptus wood (*Eucalyptus urophylla* × *Eucalyptus grandis*) was evaluated in this study. L_9 (3^3) orthogonal tests with three factors and three levels were adopted to study the effects of adhesive spread rate, pressure, and pressing time duration on the block shear strength (BSS), wood failure percentage (WFP), and rate of delamination (RD) of CLT via block shear tests and cyclic delamination tests. The results indicated that the optimal pressing parameters were adhesive spread rate of 160 g/m^2, pressing pressure of 0.8 MPa, and pressing time duration of 200 min with one-component polyurethane adhesive used. The values of modulus of elasticity (MOE) and modulus of rupture (MOR) in the major and minor strength directions of CLT were 11,466 MPa, 24.5 MPa, 681 MPa, and 8.6 MPa, respectively. The values of transverse shear moduli and interlaminar shear strength in the major and minor strength directions of CLT were 91.8 MPa, 1.3 MPa, 241.6 MPa, and 0.5 MPa, respectively. The mechanical properties of eucalyptus CLT were equivalent to those of commercially available softwood CLT. These results indicate CLT panels manufactured from fast-grown small diameter eucalyptus lumber is promising for structural applications.

1. Introduction

Cross-laminated timber (CLT) is an engineered wood product consisting of an odd number of orthogonally oriented layers of visual and/or machine graded solid-sawn lumber. Layers are usually face-bonded via a structural adhesive [1–6]. CLT can provide uniform mechanical and physical properties due to its orthogonal layup so that it is suitable for load bearing panels (floor and roof) and shear walls [7]. Spruce-pine-fir (SPF) and Norway spruce are the common species for CLT manufacturing in North America and Europe. The North American standard of performance-rated CLT suggests softwood species with a minimum specific gravity of 0.35 for CLT manufacturing [3].

Several attempts were made to use hardwoods for structural applications due to their higher modulus and strength. Frese and Blass [8] studied the relationship between beech lumber grades and the bending strength of beam glulam beams by both numerical and experimental methods in order to derive the characteristic bending strength of beech glulam for its structural application. Castro and Paganini [9] used mechanically graded poplar (*Populus x euramericana*) and eucalyptus (*Eucalyptus grandis*) lamellas for making glulam beams. The MOE and shear modulus of such glulam beams with lamellas of higher MOE located on the tension side

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ranged from 9,283 MPa to 14,951 MPa, and 808 MPa to 819 MPa, respectively. Aicher et al. [10] reported that the rolling shear modulus and shear strength of European beech (*Fagus sylvatica*) were 370 MPa and 4.5 MPa, which were considerably higher than spruce and fir for the purpose of manufacturing CLT. Kramer et al. [11] studied the viability of a plantation grown hybrid poplar with a density of 0.3–0.35 g/cm^3 for use in performance-rated CLT. The mean MOE and 5th percentile MOR of the full-sized CLT in the major strength direction were 7,100 MPa and 18.2 MPa, respectively. It was also reported that the mechanical properties of CLT made with fast-grown poplar and SPF as a cross layer were close [12].

In China, eucalyptus has been used for solid wood and medium density fiberboard besides pulp and paper. However, the need of alternate applications of plantation grown hardwood species, such as Eucalyptus in South China, is rapidly increasing because of the decreasing demands from pulp and paper industry. CLT made with local wood species would definitely promote its applications in wood construction around the world. Comparing with typical softwoods, such as spruce (*Picea spp.*), lodgepole pine (*Pinus contorta*) and Douglas fir–larch species group, which were used mostly in Europe and North America for manufacturing CLT [2,4,13,14], eucalyptus had relative high mechanical properties and short cultivation cycles making it a good alternative for structural application. The objective of this study was to evaluate the feasibility of manufacturing CLT using fast-grown small diameter Eucalyptus wood (*Eucalyptus urophylla* × *E. grandis*). The outcomes of this study will be valuable to explore novel structural applications of eucalyptus wood.

2. Materials and methods

2.1. Material preparation

The Eucalyptus wood (*Eucalyptus urophylla* × *E. grandis*) used in this study was a hybrid species grown in Guangxi Province, China. The average oven-dried density was measured to be 0.58 g/cm^3 with a coefficient of variance (COV) of 5.7%. All lumbers with dimensions of 20 mm (Radius) ×50 mm (Tangential) ×800 mm (Longitudinal) were cut from logs with diameters ranging from 60 to 120 mm and then were conditioned at 25 °C and relative humidity of 65 % for at least four weeks to reach a measured average moisture content of 12.5% before CLT manufacturing. All the lumbers were first visually graded according to GB/T 29897-2013 [15]. Only those above Grade III$_c$, which is equivalent to Grade NO.2 in North America lumber grading system [16], were kept for further process. Then the dynamic MOE values of all selected lumbers were determined by transverse vibration technique using FFT Spectrum Analyzer (uTekL V2006) according to ASTM D6874 [17]. Only lumbers with dynamic MOE larger than 13,800 MPa were selected for the parallel layers of CLT and the rest were used for the perpendicular layers of CLT. The finger-jointed lumber was manufactured using automatic finger joint machine. The quality of finger-jointed lumber was controlled by adjusting the process parameters according to the tested results during in-plant inspection via control panel.

2.2. CLT manufacturing

The graded and sorted lumbers with dimensions of 800 mm by 50 mm by 20 mm were finger-jointed and edge-glued together using one component polyurethane adhesive (Purbond AG, Switzerland) to form a CLT lamella. The long wood strips were firstly finger-jointed continuously under an end pressure of 0.8 MPa for 20 min. After the adhesive in the finger-jointed connection fully cured, the finger-jointed lumbers were then cut into desired length for edge-gluing with an adhesive spread rate of 140 g/m^2. The lamella was pre-assembled and horizontally pressed under an edge clamping pressure of 0.6 MPa for 80 min. The layers were formed with a dimension of 2440-mm long, 1220-mm wide and 20-mm thick after precise edge-cutting. The two wide surfaces of layers were then sanded to reach a final thickness of 18 mm. The sanding dust was blew away from the surfaces after sanding using a pressed air spray nozzle. One component polyurethane adhesive was applied to the bonding surface of CLT lamella with a spread rate of 140–180 g/m^2. A three-layer CLT of layup 18 mm/18 mm/18 mm with a dimension of 1,220 mm by 2,440 mm was pressed under a vertical face pressure of 0.6–1.0 MPa for 160–200 min at ambient temperature. Two kinds of layups, which were prefabricated for floor and wall panels, respectively, are shown in Fig. 1. Two CLT replicates were manufactured for each individual layup with the optimized set of pressing parameters.

2.3. Optimization of pressing parameters

The three most important factors of cold pressing process are A: adhesive spread rate (A1: 140, A2: 160, A3: 180 g/m^2), B: pressing pressure (B1: 0.6, B2: 0.8, B3: 1.0 MPa) and C: pressing time (C1:160, C2: 180, C3: 200 min), which will affect the mechanical properties of CLT. L_9 (3^3) orthogonal tests with three factors and three levels were adopted to study the effects of these pressing parameters on block shear strength (BSS), wood failure percentage (WFP), and rate of delamination (RD) of CLT via block shear tests and cyclic delamination tests. One CLT panel was fabricated for each set of pressing parameters. The orthogonal experimental sets are presented in Table 1.

2.3.1. Block shear tests

Six CLT blocks with dimensions of 100 mm (length) by 100 mm (width) by 54 mm (thickness) were cut from the geometric center of CLT with initial dimensions of 600 mm (length) by 600 mm (width) by 54 mm (thickness) and further trimmed according to ASTM D 2559 [18]. Specimens with measured average moisture content of 12.5% were tested after being conditioned for seven days under a relative humidity of 65% and 25 °C. BSS and WFP were determined according to ASTM D905 [19] and D5266 [20], respectively.

2.3.2. Cyclic delamination tests

Another six CLT blocks were cut from the CLT panel following the same procedure as those for block shear tests. Cyclic delamination tests were conducted according to AITC Test T110-2007 [21] to evaluate the effects of accelerated cyclic exposure (vacuum-pressure-soak-rapid dying) on the bonds of CLT specimens. RD was determined by Eq. (1),

$$\mathrm{RD} = \frac{l}{T} \times 100\% \qquad (1)$$

where l is the length of open joints on all end-grain surfaces, mm; T is the total length of joints on all end-grain surfaces, mm.

2.4. Bending tests

Modulus of elasticity (MOE), modulus of rupture (MOR), interlaminar shear strength, and transverse shear modulus in major and minor strength directions were determined via different bending tests. The dimension of the specimens for third-point bending tests (TPB), variable-span center-point bending (VSB) tests, and short span center-point bending (SSCPB) tests were shown in Table 2. Three replicates were tested for each type of tests.