Construction and Building Materials 161 (2018) 9–15

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Effects of surface treatment and adhesives on bond performance and mechanical properties of cross-laminated timber (CLT) made from small diameter Eucalyptus timber

Zhaohua Lu [a], Haibin Zhou [b,*], Yuchao Liao [c], Chuanshuang Hu [c,*]

[a] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou 510520, PR China
[b] Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing 100091, PR China
[c] Dept. of Wood Science & Engineering, College of Materials and Energy, South China Agricultural University, Guangzhou 510642, PR China

## HIGHLIGHTS

- PUR adhesive was the best one to manufacture Eucalyptus CLT because of the better comprehensive bond performance and mechanical properties of Eucalyptus CLT.

## ARTICLE INFO

*Article history:*
Received 30 August 2017
Received in revised form 9 November 2017
Accepted 9 November 2017

*Keywords:*
Cross-laminated timber
Eucalyptus
Bond performance
Mechanical properties
Priming treatment

## ABSTRACT

The feasibility of manufacturing cross-laminated timber (CLT) using fast-grown small diameter Eucalyptus timber was explored in preliminary studies. However, eucalyptus bonded with commercial one-component polyurethane adhesive usually provides poor resistance to delamination and shear force. The effects of priming surface of eucalyptus CLT lamella intended for a bondline and different adhesives on block shear strength (BSS), wood failure percentage (WFP), and rate of delamination (RD) of Eucalyptus CLT made from small diameter lumber were studied via block shear and cyclic delamination tests at both dry and wet states. Four different types adhesives: epoxy resin (EP), emulsion polymer isocyanate (EPI), phenol resorcinol formaldehyde (PRF), and polyurethane (PUR) adhesives were used to manufacture three-layer Eucalyptus CLT panels following adhesive manufacturers' instructions. Hydroxymethylated resorcinol (HMR) and hygroscopic organic solvent N,N-dimethylformamide (DMF) primers were adopted to priming surfaces of Eucalyptus CLT lamella intended for a bondline. The results indicated that eucalyptus CLT made of small diameter lumber with the four adhesives were comparable to commercial softwood CLT. The maximum wood failure percentage (WFP) and block shear strength (BSS) values of specimens bonded with PUR adhesive at dry state were 85.2% and 3.51 MPa whereas those values of specimens bonded with EPI adhesives at wet state were 58.2% and 1.62 MPa respectively. The minimum rate of delamination (RD) value was 7.6%, which was obtained from specimens bonded with PUR adhesive. The enhancing effects of HMR and DMF priming treatment on bond performance and mechanical properties of Eucalyptus CLT bonded with the above four adhesives did not show a clear trend because their effects depended on the coupling effects of the adhesive and primer. Generally, HMR priming treatment was effective to enhance bond performance and mechanical properties of eucalyptus CLT. After HMR priming, the WFP values of eucalyptus CLT at wet state bonded with PRF and PUR adhesives increased by 27.8%, 12.4% meanwhile the BSS values increased by 31.5%, 4.9%. The RD values of specimens bonded with PRF and PUR adhesives at wet state were close to 0.0% after HMR priming.



## 1. Introduction

It is feasible to manufacture CLT using fast-grown small diameter Eucalyptus wood (Eucalyptus *urophylla* × E. *grandis*) [1]. The results indicated that the mechanical properties of Eucalyptus CLT, which was bonded with one-component polyurethane adhesive, were equivalent to those of commercial softwood CLT. However, Eucalyptus bonded with commercial one-component polyurethane adhesive usually provides poor resistance to delamination and shear [1–3]. Comparing with the softwood species commonly used for CLT production in Europe and North America,

* Corresponding authors.
*E-mail addresses:* zhouhb@caf.ac.cn (H. Zhou), cshu@scau.edu.cn (C. Hu).

https://doi.org/10.1016/j.conbuildmat.2017.11.027
0950-0618/

Eucalyptus wood is more difficult to be bonded due to its relatively high wood density, and poor adhesive penetration [4–6]. Moreover the fact that fast-grown small diameter Eucalyptus lumber has higher internal stress and proportion of juvenile wood contributes to its poor bond performance [7]. Therefore, it is of great industrial interest to explore effective techniques for enhancing the bond performance of Eucalyptus CLT.

There were several reported attempts to enhance bond properties of structural glued timber joints via use of surface primers. The hydroxymethylated resorcinol (HMR) and the novolak-based HMR (n-HMR) primers were used to enhance the bond durability of *Eucalyptus globulus* glulam for outdoor load-bearing timber structures [8]. The results indicated that glulam prepared under more stringent conditions with HMR and n-HMR primers surpassed the requirements for shear strength according to EN 391 and EN 392. Christiansen et al. [9] proved that the HMR coupling agent was feasible to enhance the exterior durability of epoxy, one-part polyurethane and phenol-resorcinol-formaldehyde (PRF) bonded southern pine specimens. Vick et al. [10–13] reported that joint specimens bonded with epoxy (EP), one-component polyurethane (1C-PUR) and PRF and surface-primed with HMR prior to binding exhibited bond of extraordinary structural durability. A substantial improvement in tensile shear strength and wood failure percentage of 1C PUR bonded wood joints was achieved by means of the hygroscopic organic solvent N,N-dimethylformamide (DMF) priming [14].

The objective of this study was to explore an efficient way via primers to enhance bond performance of Eucalyptus CLT using fast-grown small diameter lumber.

## 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 lumber with dimensions of 20 mm (Radial) by 50 mm (Tangential) by 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 moisture content around 12% before CLT manufacturing. All the lumber were first visually graded according to GB/T 29897-2013 [15]. Only those met the requirements of Grade III$_c$, which is equivalent to Grade No. 2 in North American lumber grading system, were kept for further processing. The dynamic modulus of elasticity (MOE) values of all selected lumber pieces were determined by transverse vibration technique using FFT Spectrum Analyzer (uTekL V2006) according to ASTM D6874 [16]. Only lumber pieces 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.

### 2.2. Adhesives

To study the effects of different adhesives on bond performance and mechanical properties of Eucalyptus CLT, four commercial cold curing adhesives of epoxy (EP), emulsion polymer isocyanate (EPI), phenol Resorcinol Formaldehyde (PRF), and one component polyurethane (PUR), were used for bonding tests. EP and EPI resins and their hardeners were provided by Internet Wood Glue (Guangdong, China). The EP resin (901S) with a viscosity of 28000 ± 5000 mPa.s and a solids content of 98 ± 2% was blended with polyamide resin (901B) as the hardener. The EPI adhesive (PG368) with a viscosity of 12000 ± 2000 mPa.s and a solids content of 43 ± 2% consists of a mixture of polyvinyl alcohol (PVA) water-based emulsion and an isocyanate hardener (C15). The PRF resin and hardener were purchased from Dynea (Guangdong, China). The PRF adhesive is a mixture of phenol-resorcinol emulsions (PR-1HSE) and paraformaldehyde (PFA) compound power (PRH-10A). The PUR adhesive with a viscosity of 24000 mPa.s. and a solid content of 100% was provided by Purbond AG (Switzerland).

### 2.3. Primers

N,N-dimethylformamide (DMF) and hydroxymethylated resorcinol (HMR) were used to prime the surfaces of Eucalyptus lamella with the ultimate purpose of enhancing the bond performances of Eucalyptus CLT using the four adhesives mentioned above. DMF solutions with concentrations of 5% and 50% were used. HMR was prepared on-site from accurately measured proportions of starting chemical ingredients according to [13]. The ingredients were reacted for 4 h at room temperature before applying to the lamella surfaces.

### 2.4. CLT manufacturing

To investigate the effects of adhesives on bond performance and mechanical properties of Eucalyptus CLT, four different adhesives of EP, EPI, PRF, and PUR were studied. The procedure of using graded and sorted lumber with dimensions of 20 mm by 50 mm by 800 mm to manufacture CLT was detailed in a previous publication [1]. The manufacturer's preparation instruction of each adhesive was followed in proportioning, mixing, applying, and curing the adhesive. Two replicates of CLT panels were manufactured for each adhesive.

To study the effects of surface primers on the enhanced bonding performance of eucalyptus CLT, DMF and HMR primers were studied. Eucalyptus lumber with dimensions of 300-mm long, 300-mm wide, and 18-mm thick were cut from the prefabricated CLT lamella with dimension of 2440-mm long, 1220-mm wide, and 18-mm thick. Both surfaces of eucalyptus CLT lamella intended for a bondline were spread with DMF solutions of different concentrations using a portable sprayer and with HMR by brush on each surface. Applied amount and waiting time of the two primers of DMF and HMR are shown in Table 2. After the surface was dried, it was spread by roller with an adhesive following the manufacture's instructions shown in Table 1. Then a three-layer CLT of layup of 18 mm/18 mm/18 mm with dimensions 300 mm by 300 mm was pressed under a pressure of 1.2 MPa for 120–200 min at 25 °C according to Table 1. Two CLT replicates were made for each surface priming treatment.

### 2.5. Contact angle

To study the wettability of the surface intended for a bondline after priming treatment, a photogoniometric method was adopted

**Table 1**
Manufactures' instructions of four different adhesives.

| Adhesive | Mix Ratio (Resin: Hardener) | Spread rate (g/m$^2$) | Assembly time (min) | Pressing time (min) | Pressure (MPa) | Curing temperature (°C) |
|---|---|---|---|---|---|---|
| EP | 100:80 | 180 | 30 | 160 | 1.2 | 25 |
| EPI | 100:15 | 220 | 40 | 120 | 1.2 | 25 |
| PRF | 100:15 | 180 | 50 | 180 | 1.2 | 25 |
| PUR | – | 160 | 70 | 200 | 1.2 | 25 |