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FEASIBILITY OF CROSS-LAMINATING HIGH-DENSITY EUCALYPTUS

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ABSTRACT: The feasibility of using *Eucalyptus bosistoana*, a high-density and naturally durable hardwood, in cross-laminated timber (CLT) was investigated. The study aimed to assess its bonding performance, a requirement for the production of high-stiffness and high-strength CLT panels. Three-layer CLT panels in single- and mixed-species layups were manufactured from *E. bosistoana* and radiata pine using a one-component polyurethane adhesive. The single-species *E. bosistoana* CLT panels exhibited poor bonding, with a 100% delamination rate (DR) and negligible wood failure percentage (WFP). Incorporating radiata pine improved bonding, reducing DR to 82% and 74% and increasing WFP to 15% and 23% when radiata pine was used as the core and surface layers, respectively. Additionally, bonding performance of hybrid CLT panels with radiata pine as the surface layers was evaluated using melamine-urea-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde resins. The melamine-urea adhesive showed the best performance among the studied adhesives, with a mean DR and WFP of 5.4% and 49.6%, respectively. This indicated that mixing high- and lower-density species to produce hybrid CLT could be a potential solution for utilizing *E. bosistoana* with its good mechanical properties in CLT manufacturing.

KEYWORDS: *Eucalyptus bosistoana*, high-density hardwood, hybrid cross-laminated timber (CLT), bonding performance, wood adhesives

1 – INTRODUCTION

Timber species with high mechanical properties are an attractive feedstock for engineered wood products (EWP) manufacturers since the stiffness and strength of timber play a crucial role in the structural performance of EWPs. Cross-laminated timber (CLT) has gained widespread attention in global construction markets as a slab or wall element over the past two decades [1]. When loaded out-of-plane, CLT floors are typically governed by serviceability limit state (SLS) rather than ultimate limit state (ULS) criteria [1]. CLT floors made from high-stiffness timber species will result in reduced out-of-plane deflection and vibration [2], allowing longer-span floors.

Eucalyptus bosistoana is a naturally durable, high-stiffness hardwood with an air-dry density of 1100 kg/m³ and a modulus of elasticity of 21 GPa [3]. Recognizing its potential as an alternative plantation species, New Zealand Dryland Forests Innovation (NZDFI) initiated a breeding program for this species and other durable eucalypts, including *E. argophloia*, *E. globoidea*, *E. tricarpa*, and *E. quadrangulata*. Among these species, *E. bosistoana* exhibited the highest strength and stiffness properties, making it ideal for EWP applications [4]. Apart from its high mechanical properties, the high extractive content including polyphenols and tannins provides this species with natural resistance to fungal decay [5].

However, the inclusion of high-density timber such as *E. bosistoana* in CLT panels presents challenges. Thick cell walls, small lumina, and high extractive content can hinder adhesive penetration and, hence, reduce bonding performance [6]. Therefore, evaluating the bonding performance is a key step toward developing high-stiffness *E. bosistoana* CLT panels.

The primary aim of this study was to evaluate the bonding performance of eucalypt CLT panels in delamination and block shear tests, following ANSI/APA PRG 320-2019 [7]. This included investigating the influence of layup configurations and adhesives on the bonding performance of *E. bosistoana* CLT panels. First, the effect of layup was examined by considering single- and mixed-species CLT layups in four configurations: EEE (Eucalyptus-Eucalyptus-Eucalyptus), EPE (Eucalyptus-Pine-

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Eucalyptus), PEP (Pine-Eucalyptus-Pine), and PPP (Pine-Pine-Pine). Second, the study evaluated the bonding performance of the hybrid CLT panels using four commercially available adhesives: one-component polyurethane (1C-PUR), melamine-urea-formaldehyde (MUF), resorcinol-formaldehyde (RF), and phenol-resorcinol-formaldehyde (PRF).

2 – BACKGROUND

The construction sector is responsible for approximately 37% of global CO_2 emissions [8]. With the global floor area expected to expand from less than 200 billion m² to approximately 240 billion m² between 2020 and 2050, selecting sustainable construction materials becomes urgent [8]. Traditionally, steel and concrete have dominated the world's building material market, collectively contributing between 80% and 90% of global CO_2 emissions of the construction sector [9].

Mass timber, an engineered wood product developed for structural use, is a sustainable alternative, enabling the construction of multi-story buildings [10]. Timber is a renewable construction material that stores carbon throughout its lifecycle [11]. Its lightweight nature offers advantages, such as smaller foundation requirements, allowing construction on weaker soils and facilitating building extensions in densely populated areas [1].

CLT, a key component of mass timber construction, consists of multiple timber layers bonded together in a crosswise configuration [1]. This structure enhances dimensional stability, load-bearing capacity, and stiffness under both, in-plane and out-of-plane loads, making CLT ideal for flooring and wall applications [1]. CLT, like other building materials, must meet performance criteria such as fire resistance, durability, and structural integrity. Critical performance factors for floors include shear and bending stiffness, strength, and vibration control, while in-plane stiffness and strength are essential for CLT shear walls. The timber species used in the laminates significantly affect these properties, necessitating careful material selection based on application, load conditions, and environmental factors.

The potential of using hardwoods in CLT manufacturing has gained interest due to their typically superior mechanical properties and potential to reduce reliance on softwood resources [10-12]. CLT panels made from white ash (670 kg/m³) and red maple (610 kg/m³) exhibited bending stiffness values up to 75% higher and bending strength values over 2.5 times greater than those made from eastern white pine (400 kg/m³) [14]. Even lower-grade *E. nitens* CLT panels, averaging 570 kg/m³, have met deflection serviceability criteria under a distributed load of 54 kPa [15]. This performance significantly exceeds the requirement for the imposed or gravitational live load stated in standards, such as AS/NZS 1170.1[16]. Additionally, hardwood CLT features reduced long-term load deflection, increasing serviceability load capacity by 17.3% and reducing the estimated 50-year creep ratio from 1.89 for C24 spruce CLT to 1.77 for *E. nitens* CLT [17]. High-density timber further enhances the fire resistance by reducing the charring rate, particularly for species with air-dry densities exceeding 700 kg/m³ [18].

However, hardwood species can face significant bonding challenges [19]. Bonding issues are particularly severe for high-density hardwoods due to their low permeability, extractive-rich surfaces, and high dimensional instability [20], [6]. Özparpucu et al. [21] found that acidic tannins and phenolic acids in hardwood species can delay curing, increase viscosity and weaken chemical bonds of glues. Removing water-soluble extractives can improve the bonding performance [22]. Bockel et al. [20] evaluated the bonding performance of beech (700 kg/m³) using 1C-PUR, 2C-PUR, MUF, and PRF adhesives. They found that wood extractives such as fatty acids, starch, and organic acids significantly impaired adhesive performance, leading to severe bond failures for all tested adhesives, with PUR adhesives experiencing complete delamination under wet conditions. Besides extractive removal and customized adhesives with lower viscosity for better flow, face milling, incising, compression rolling, surface washes, and primers have been proposed to improve the bonding performance of hardwood species [6]. Neither fine or coarse sanding could enhance the bonding performance of *Acer campestre L.* (maple) (640 kg/m³) and Turkey oak (770 kg/m³) bonded with MUF [23].

Moisture-resistant bonding is a more challenging requirement for adhesives. Although some studies on eucalypts have demonstrated that PUR with better wettability and adhesive penetration outperforms RF in dry conditions [24], it is less water resistant leading to a higher DR [25]. A similar result was also reported for ash (633 kg/m³) comparing 1C-PUR to PRF and MUF [26]. In another study, the moisture sensitive polyvinyl acetate (PVAc) adhesive showed an astonishing performance in bonding *Robinia pseudoacacia* (678 kg/m³) and *Ailanthus altissima* (602 kg/m³) achieving 100% WFP in dry conditions but it completely delaminated (100%) under wet conditions [27]. *Eucalyptus sp.* (670 kg/m³) bonded with PF and RF adhesives achieved WFP up to 64% under wet conditions, while sodium silicate and PVAc adhesives exhibited complete delamination (WFP 0%) [28].

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Mixing dense hardwood with lower-density species has been suggested to improve bonding performance. Oak with a mean density of 707 kg/m³ demonstrated severe delamination due to its high density and ring-porous structure when bonded with 1C-PUR and MUF under low-pressure conditions [29]. Mixing oak with lower-density poplar significantly improved bonding performance, reducing delamination rates to below 5% and increasing wood failure percentages to over 90% [29]. The bonding performance of seven hardwood species and two softwood species using PRF and MUF in various configurations was investigated [30]. WFP in hardwood-based CLTs was influenced by adhesive type and anatomical features, with 96% of MUF-bonded mixed hardwood combinations achieving WFP above 80%, compared to only 46% for PRF. Additionally, all MUF-bonded hardwood-softwood configurations exceeded the 80% WFP criterion, prescribed by ANSI/APA PRG 320-2019 [7]. Faircloth et al. [31] reported that mixing spotted gum species (1077 kg/m³) with southern pine (663 kg/m³) lowered DR and improved WFP. Between the configurations, hardwood as a core layer and softwood as surface layers using RF gave the best performance with a DR of 34.5% and WFP of 52%.

3 – MATERIALS AND METHODS

Delamination tests were conducted to measure bond durability under cyclic moisture exposure and drying, while block shear tests determined the extent of WFP and shear strength at the glue line. CLT panels were made of *E. bosistoana* and radiata pine. *E. bosistoana* boards with a mean air-dry density of 1094 kg/m³ and COV of 5% were milled from ~100-year-old New Zealand-grown trees. Radiata pine boards with a mean air-dry density of 497 kg/m³ and COV of 11% were provided by a local supplier. The 3-layered CLT panels were constructed in two categories: single-species and mixed-species configurations.

Single-species panels consisted of either radiata pine (PPP) or *E. bosistoana* (EEE) laminations, while mixed-species panels combined the two species, with radiata pine in the surface layers and *E. bosistoana* in the core (PEP), or *vice versa* (EPE). Each panel measured 300 mm × 300 mm × 60 mm, and three panels were prepared using 1C-PUR adhesive for each configuration. The PEP configuration was selected to compare between RF, PRF, and MUF adhesives. From each panel, six specimens were cut for delamination testing and another six for block shear testing. This resulted in a total of 18 delamination and 18 block shear specimens for each configuration.

CLT panels were manufactured from visually inspected defect-free boards with a final thickness of 20 mm after planing. The boards were conditioned for two months at 20°C and 65% relative humidity to reach the equilibrium moisture content of 12%, as specified by ANSI/APA PRG 320-2019 [7]. To ensure optimal bonding, the surfaces of the boards were activated by planing within 6 to 8 hours before gluing.

The face-gluing process was performed in accordance with the manufacturer's specifications. A 1C-PUR, Loctite HB S309 Purbond, was applied at a one-sided spread rate of 180 g/m². Prior to adhesive application, the laminate surfaces were activated by spraying with a 10% primer solution at a rate of 40 g/m² [32]. The panels were pressed with 1 MPa for 3 hours in a hydraulic cold press. PRF adhesive was prepared by mixing SYLVIC R27 RESIN and SYLVIC L4 HARDENER at a ratio of 3:1 and applied to the laminates (350 g/m²) on each side of the face jointed laminates (double-sided) [33]. A clamping pressure of 1.2 MPa was applied for 15 hours. RF adhesive was prepared by mixing SYLVIC R15 RESIN with SYLVIC RP50 HARDENER at a ratio of 4:1 and used with the same conditions as PRF [34]. MUF adhesive was made by combining Aica Aibon™ 4513 with Hardener Aica Aibon™ 5090/5090-W in a 10:1 ratio [35]. It was applied to both sides of jointed laminates (400 g/m²), and the CLT panels were pressed under the conditions described above. Panels were then stored at 20°C and 65% relative humidity for at least one week before specimens were cut into delamination and block shear samples (Fig. 1a and 1b).

The block shear test evaluated the extent of WFP at the shearing plane. Stair-step specimens with bond line areas measuring 39 mm × 51 mm were used, as per ANSI/APA PRG 320-2019 [7] and ASTM D905 [36]. Each configuration included 18 specimens, providing a total of 36 glued planes, exceeding the ASTM D905 [36] minimum requirement of 20 bond lines per joint type. To minimize damage to the core laminations, which underwent shearing twice, specimens were oriented with the grain direction of the core layer parallel to the loading direction. Shear stress was applied to the bonded areas using a shearing tool at a loading rate of 5 mm/min, following ASTM D905 [36] (Fig. 1c). Following the tests, samples were examined under a microscope to differentiate wood fibre failure from adhesive failure, specified in ASTM D5266-13 [37]. The proportion of the sheared plane attributed to wood or adhesive failure was then assessed. ImageJ was used to quantify the area of each failure mode, and the WFP was calculated as the ratio of the wood failure area to the total shear area.

WFP results were presented in box plots. Besides the mean and median, the first (Q1) and third (Q3) quartiles were shown and used to determine the interquartile range (IQR). The data points that fall outside the range of Q1-1.5×IQR to Q3+1.5×IQR were considered outliers and excluded from the data set for further statistical analysis. The resulting WFP for different configurations and adhesive types were statistically compared. The Shapiro-Wilk Test was implemented to determine the normality of the data distribution, followed by the Mann-Whitney U test for pairwise comparisons between configurations. In cases where the data distribution is non-normal, the Kruskal-Wallis test was used to determine significant differences among the configurations. A significance level of $p = 0.05$ was used for the statistical analysis, with differences considered statistically significant when $p < 0.05$.

The delamination test measured the durability of adhesive bonds under cyclic vacuum-pressure soaking and rapid drying conditions. Specimens measuring 76 mm × 76 mm × 60 mm were prepared per ANSI/APA PRG 320-2019 [7] and AITC Test T110 [38], with 18 specimens tested for each configuration. The test comprised two phases. In the vacuum-pressure soak cycle, specimens were submerged in water at 24°C and subjected to a vacuum of 77 kPa for 30 minutes, followed by a pressure of 517 kPa for two hours in a pressure vessel (Fig. 1d). During the rapid drying phase, specimens were placed in an oven at 71°C for approximately 15 hours until their weight returned to within 10–15% of the original weight (Fig. 1e).

DR was defined as the percentage of bondline length exhibiting adhesive failure to the total bondline length. Failure was visually identified through microscopic analysis at 10 times magnification (Fig. 1f). If necessary, bond line openings were examined using a chisel to distinguish wood failure from adhesive separation. A similar statistical analysis approach as for WFP was applied to DR evaluation.

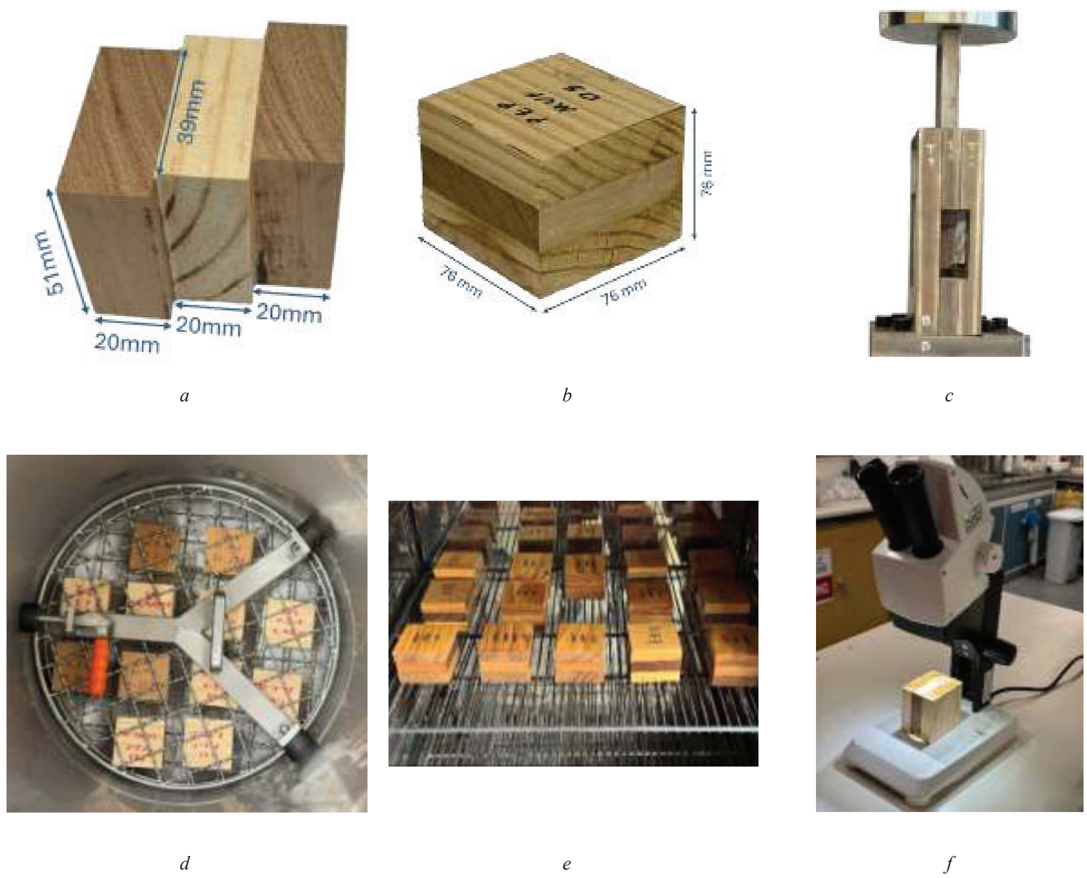

Figure 1. (a) block shear specimens, (b) delamination specimens, (c) shearing tool, (d) delamination specimens in the pressure vessel, (e) delamination specimens in the oven, (f) specimens under microscopic assessment.

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4 – RESULTS AND DISCUSSION

4.1 BLOCK SHEAR TEST RESULTS

Typical block shear failure modes of *E. bosistoana* and radiata pine 1C-PUR bonded CLT in different configurations are shown in Fig. 2. The failure surface of full *E. bosistoana* samples was covered with a thin layer of 1C-PUR adhesive (Fig. 2a). Few wood fibres representing the first one or two cell layers were present on the glue surface, but they were not considered as wood failure. Almost all EEE samples showed the same failure mode resulting in almost zero WFP (Fig. 4a). This result agreed with previous research on the bonding performance of other high-density hardwood species [6]. Further, the high extractive content of *E. bosistoana* [39] might have interfered with the adhesive reaction [40]. Conversely, Fig. 2d illustrates the failure mode of the bonding of 1C-PUR in the significantly less dense and relatively extractive-free radiata pine laminations. As can be seen in Fig. 4a, radiata pine is strongly bonded with nearly 100% WFP. Deep adhesive penetration into radiata pine has potentially contributed to good bond performance.

As anticipated based on previous studies [29], [30], mixing the dense *E. bosistoana* with the less dense radiata pine improved WFP compared to the Eucalyptus-only configuration. Based on pairwise Mann-Whitney U tests, the WFP of EEE was significantly lower compared to EPE ($p = 1.93\times10^{-7}$) and PEP ($p = 1.06\times10^{-10}$). Between the two hybrid configurations, PEP exhibited a marginally significant ($p = 0.041$) higher mean WFP than EPE (Fig. 4a). Further study is required for confirmation. It is interesting to note that although the mean WFP of EPE was only 15%, in some samples WFP can reach up to 75%, as indicated by the red dots in Fig. 4a. Single-species radiata pine CLT's WFP, with a mean value of 99.4%, was significantly higher than EEE ($p = 6.55\times10^{-14}$), EPE ($p = 6.55\times10^{-14}$) and PEP ($p = 7.30\times10^{-14}$) demonstrating the capabilities of 1C-PUR.

Fig. 4b compares WFP in PEP samples bonded with MUF, PRF, PUR, and RF adhesives. The mean WFP with MUF (50%), PRF (44%), and RF (37%) compared favourably to 1C-PUR (23%). Statistical analysis using Mann-Whitney U tests confirmed significant differences, with p-values of 2.36×10^{-5}, 1.61×10^{-4}, and 0.012, respectively. Similar to MUF, RF also exhibited a high maximum WFP of approximately 90%, albeit with a lower mean WFP of 37%. The difference between MUF and RF was marginally significant ($p = 0.038$), while no significant differences were observed between MUF and PRF ($p = 0.35$) or PRF and RF ($p = 0.20$).

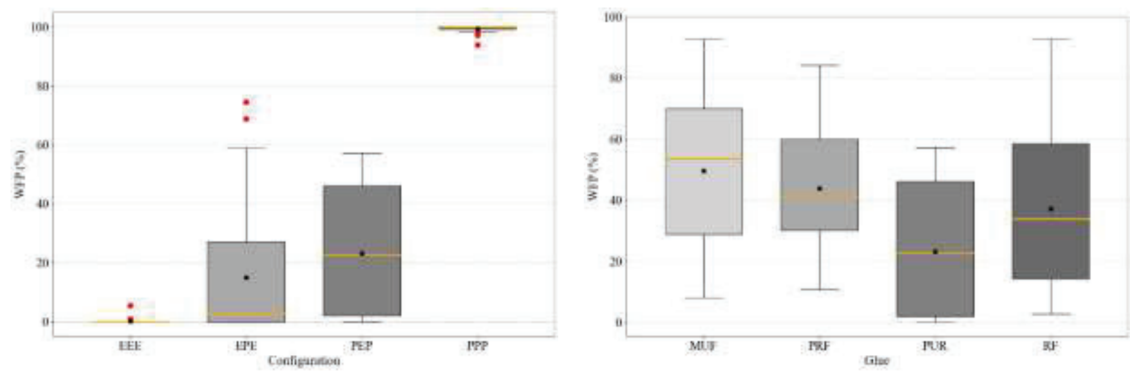
MUF, PRF, and RF enhanced WFP in a mixed-species configuration compared to 1C-PUR (Fig. 4b) since lower-density species have lower shear strength and even shallow adhesive penetration into hardwood may provide sufficient strength to cause failure in the lower-density laminate. The failure modes depicted in Fig. 5 support this, with cracks appearing in the lower-density species, resulting in an enhancement in WFP. This type of failure can be seen in most of the PEP samples bonded with MUF and PRF while only very few samples glued with RF and no sample bonded with PUR failed due to the perpendicular-to-grain shear failure of radiata pine. Evidence of radiata pine fibres detachment and adhesion to the bonded surface of *E. bosistoana* in CLT panels with different adhesives can be observed in Fig. 3.

a b c d

Figure 2. Typical failure mode of paired shear planes from 1C-PUR bonded E. bosistoana (E) and radiata pine (P) 3-layer CLT in block shear tests: a) EEE, b) EPE, c) PEP, and d) PPP.

a *b* *c* *d*

Figure 3. Typical failure modes of paired shear planes from 3-layer CLT panels made of E. bosistoana (E) and radiata pine (P) in the PEP configuration in block shear tests, using different adhesives: (a) MUF, (b) PRF, (c) PUR, and (d) RF.



a *b*

Figure 4. Comparison of WFP resulted from block shear test for the tested 3-layer CLT panels made of E. bosistoana (E) and radiata pine (P) with different configurations of EEE, EPE, PEP, and PPP (a) and in the PEP configuration with different adhesives of MUF, PRF, PUR, and RF (b).

Figure 5. The ideal failure mode of mixed species CLT with the configuration of PEP under shear test bonded with PRF, MUF, and RF: perpendicular-to-grain shear failure of radiata pine.

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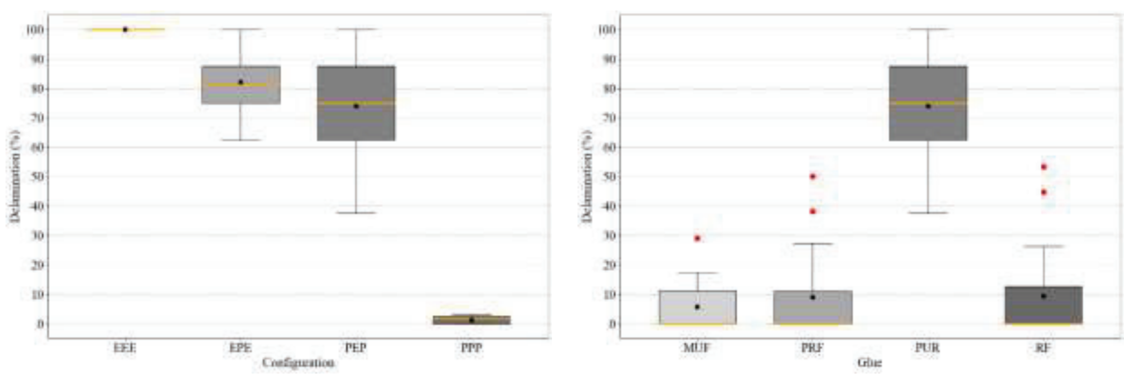
4.2 Delamination Test Results

The comparison of DR among different configurations is presented in Fig. 6a. Consistent with the block shear test results, EEE and PPP represent two extremes of bonding performance. Nearly all EEE samples exhibited complete delamination after the tests, while PPP samples demonstrated negligible delamination (Fig. 7). Mixing species improved DR performance as the mean DR reduced from 100% in EEE to 82% in EPE and 75% in PEP mixed-species CLT. However, this did not meet the 8% threshold requirement of the relevant standards, such as AITC Test T110 [38].

Statistical analysis using the Kruskal-Wallis test revealed significant differences in DR among configurations ($p = 1.16\times10^{-12}$) and adhesives ($p = 2.08\times10^{-9}$). Pairwise comparisons demonstrated that the DR of EEE was significantly higher than that of EPE ($p = 1.70\times10^{-7}$), PEP ($p = 6.04\times10^{-7}$), and PPP ($p = 3.96\times10^{-8}$). Mixed-species CLT in EPE and PEP configuration still exhibited significantly higher DR than PPP ($p = 2.75\times10^{-7}$ and $p = 2.77\times10^{-7}$, respectively). The difference between EPE and PEP was not statistically significant ($p = 0.227$).

The adhesive type significantly influenced the delamination test results. The mean DR decreased from 75% with PUR to 5%, 8.5%, and 11.1% for MUF, PRF, and RF, respectively. Representative mixed-species CLT samples subjected to the delamination test with different adhesives are shown in Fig. 8. Except for PUR, the adhesives demonstrated negligible delamination. The Mann-Whitney U tests indicated that MUF, PRF, and RF had significantly lower DR than PUR, with p-values of 1.89×10^{-7}, $3.88\times10^{-7,}$ and 5.01×10^{-7}, respectively. The difference between MUF and RF was not statistically significant ($p = 0.520$), nor was the difference between MUF and PRF ($p = 0.699$) or PRF and RF ($p = 0.857$).



a *b*

Figure 6. Comparison of DR resulted from delamination test for the tested 3-layer CLT panels made of E. bosistoana (E) and radiata pine (P) with different configurations of EEE, EPE, PEP, and PPP (a) and in the PEP configuration with different adhesives of MUF, PRF, PUR, and RF (b).

a *b* *c* *d*

Figure 7. Representative delamination of 1C-PUR bonded E. bosistoana (E) and radiata pine (P) 3-layer CLT samples with different configurations: (a) EEE, (b) EPE, (c) PEP, and (d) PPP.

a b c d

Figure 8. Representative delamination of 3-layer CLT panels made of E. bosistoana (E) and radiata pine (P) in the PEP configuration using different glues: (a) MUF, (b) PRF, (c) PUR, and (d) RF.

5- CONCLUSION

This study examined the wood failure percentage and delamination rate of *Eucalyptus bosistoana* CLT panels by conducting block shear and delamination tests. The results underscored the challenges of bonding high-density timber such as *E. bosistoana* as a single-species CLT and that mixing it with a lower-density species such as radiata pine can improve the situation.

Single-species *E. bosistoana* CLT panels exhibited poor bonding performance, with a 100% DR and negligible WFP. Incorporating radiata pine in hybrid configurations improved bonding performance, reducing the DR and increasing the WFP, yet these configurations did not meet the threshold criteria of 80% WFP and 8% DR, as specified by ANSI/APA PRG 320-2019 [7]. Specifically, the mean DR for hybrid configurations decreased from 100% in EEE to 82% in EPE and 75% in PEP, while the WFP increased to 15% and 23%, respectively. Although mixing the species could not solve the bonding problem, these findings indicate that mixing high- and low-density species can partially mitigate bonding limitations in high-density hardwoods.

Adhesive selection significantly influenced bonding performance. Among the adhesives tested, MUF exhibited the best performance by solving the delamination problem but could not meet the required WFP. It showed a mean DR of 5.4% and a WFP of 49.6% in hybrid panels with radiata pine as surface layers. PRF almost met the delamination criteria with a mean DR of 8.5% but failed the mean WFP criteria with 44%. RF also performed better than one-component PUR, with a mean WFP and DR of 37% and 11.1%, respectively, demonstrating the importance of adhesive compatibility with high-density hardwoods. Statistical analysis revealed significant differences in DR and WFP among configurations and adhesives, confirming that both factors affect the bonding performance of CLT panels.

More work is needed to realise the potential of hybrid CLT panels combining *E. bosistoana* and radiata pine for structural applications. Evaluating the effects of mechanical and chemical surface treatments along with modifying formulations of MUF, PRF, or RF on the cross-lamination of *E. bosistoana* and radiata pine are possible avenues for future work.

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