

Block Shear Bonding Performance of Laran Glued Laminated Timber under Simulated Environmental Conditions

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The block shear bonding performance was studied for glued laminated timber (glulam) manufactured from laran, a Malaysian plantation hardwood, under four treatment conditions designed to simulate service environments. Forty block shear specimens were tested to determine shear strength and wood failure percentage (WFP). The conditions comprised (a) dry (control, equilibrium laboratory climate), (b) water-soak (immersion in 20 ± 3 °C water for 24 h), (c) boiling Immersion (100 °C for 6 h followed by cooling), and (d) boil–dry–boil cycle (repeated hot–wet and drying exposure). Each specimen ($50 \times 50 \times 50$ mm³) was loaded in shear using a universal testing machine. Results revealed a progressive reduction in both shear strength and WFP with increasing treatment severity. Dry samples exhibited the highest bonding performance, while specimens subjected to the Boil–Dry–Boil Cycle showed the greatest deterioration. These findings demonstrate the sensitivity of laran glulam to moisture and thermal cycling, provide baseline data for adhesive bond durability across service classes, and offer valuable insights for improving treatment strategies, product design, and the long-term structural reliability of glulam in tropical construction contexts.

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INTRODUCTION

The Malaysian wood products industry has come a long way over the course of three decades, transitioning from being a main product exporter of timber logs to becoming an exporter of value-added wood-based products (Latib *et al.* 2022). After the exports of oil palm and rubber, timber products rank third on the list of principal export commodities of the country (Latib *et al.* 2022). Among the value-added wood-based products, engineered timber products (ETPs) are gaining increasing popularity in the architectural and construction sector as alternative green and sustainable material. The ETPs are fabricated by gluing or joining the strands, particles, fibre, veneers, or boards of timber together. They have proven to be more efficient and sustainable than heavy solid timber, in addition to being a more homogeneous composite structural component (Ding *et al.*

2023; Abed *et al.* 2022). Moreover, ETPs offer greater dimensional stability, less fluctuation in characteristics, and a wider range of uses in construction compared to typical solid timber (Han *et al.* 2023). ETPs also provide a wider use range in structural applications. According to Sotayo *et al.* (2020), ETPs have the potential to produce structural sections that are both more complicated and more robust. Furthermore, ETPs can mitigate some of the strength-reducing defects of solid timber, such as knots, thus improving durability and achieving more uniform mechanical properties. Examples of ETPs that are often used in the construction industry include cross-laminated timber (CLT), glued laminated timber (glulam), parallel strand lumber (PSL), and laminated veneer timber (LVL).

Due to the scarcity of natural forest timber supply, the increased prices of timber, as well as the small diameter logs that are harvested, commercial plantation forests were established on a significant scale by the Malaysian Ministry of Plantation Industries and Commodities (MPIC) through the Malaysian Timber Industry Board (MTIB). As part of this initiative, the Ministry has established a goal to establish 130,000 hectares of forest plantation. The plantation is anticipated to generate 26 million cubic meters of timber upon its effective implementation. To meet the growing global demand for timber products, plantation forests were established in the early 1970s (Ratnasingam *et al.* 2020). From 26,500 hectares of total harvested area in Peninsular Malaysia, Sarawak, and Sabah, only 3.8 million cubic meters of plantation timber were produced by the end of 2019 (Ratnasingam *et al.* 2020). In the implementation of the commercial plantation forest, 11 species were selected, including Rubberwood (Timber Latex Clone), *Acacia* sp. (mangium/hybrid), *Tectona grandis* (Teak), *Azadirachta excelsa* (Sentang), *Khaya* sp. (*Khaya ivorensis*/*Khaya senegalensis*), *Neolamarckia cadamba* (kelempayan/laran), *Paraserianthes falcataria* (Batai), *Octomeles sumatrana* (Binuang), bamboo, paulownia, and eucalyptus. The sector of ETPs in Malaysia is dynamic and constantly changing, with a focus on the utilisation of plantation forest species. It has the potential to make a substantial contribution to sustainable development in both the domestic and global markets. Unlocking this potential and guaranteeing the long-term sustainability of plantation-based forestry industries will necessitate ongoing investments in sustainable practices, innovation, and research. The development of ETPs using plantation timber species was demonstrated in a significant amount of previous research, development, and commercialisation conducted in Malaysia (Norshariza *et al.* 2022; Tan *et al.* 2022; Mohamad 2020; Norshariza *et al.* 2016).

ETPs need to be tested according to approved national or international specifications or standards to ensure their durability as well as structural performance. One of the most important factors that contributes to the strength of ETPs is their bonding performance. In the context of engineered timber products, the term “bonding performance” refers to the quality and durability of the adhesive bonds that are produced between the surfaces of the wood. The high bonding capability of the wood components guarantees that they will cling firmly and keep their structural integrity despite the many stresses and environmental conditions to which they are subjected. Because these aspects inherently contribute to the total strength characteristic, it is of the utmost importance to study its bonding performance and behaviour (Adnan *et al.* 2021; Yanto *et al.* 2022; Amirul *et al.* 2023; Dong *et al.* 2023). It is necessary for the adhesive bonding to be able to endure a wide range of environmental conditions, such as differences in temperature and moisture. Durability is frequently examined using tests that mimic these conditions, such as boil tests and delamination tests. Another important criterion of bonding performance is shear

resistance of the product, especially in structural applications. To keep the structure intact together under stress, the bond must be strong enough to withstand forces that would cause the adhesion to break.

The bonding performance of ETPs is commonly assessed through a combination of shear strength and delamination tests. While delamination provides valuable insight into durability and long-term adhesive performance, the present study focuses specifically on block shear testing, evaluating shear strength and wood failure percentage (WFP) of laran glulam under four environmental conditions: dry, water soaking, boiling immersion, and boil-dry-boil cycle. These conditions were selected to simulate service environments that glulam is likely to encounter in practice (Service Class 1, Service Class 2 and Service Class 3). The omission of delamination testing does not diminish the contribution of this work, as it provides essential baseline data on the shear-related bonding behaviour of laran glulam. Future studies will extend this work by incorporating delamination testing to provide a more comprehensive evaluation of bonding performance. However, the last designed set of environmental conditions (boil-dry-boil cycle) imitates the delamination protocols.

Different environmental conditions (*e.g.*, exposure to water, temperature, and humidity fluctuations) can result in a substantial variation in the bonding efficacy of glulam (Nunes *et al.* 2014). Therefore, it is imperative to comprehend the impact of these factors on the adhesive bonds in glulam to assure their structural integrity and durability in a variety of applications. Environmental treatment conditions, including dry, water soaking, boiling immersion, and boil-dry-boil cycle representing severe outdoor conditions, have a substantial impact on the bond shear performance of glulam. In wet conditions (water soaking), the timber may swell and the adhesive bond may be compromised due to elevated moisture levels. Boiling immersion, which involves the represents extreme thermal and moisture stress, can result in the wood experiencing repeated expansion and contraction, which can lead to fatigue and the potential failing of the adhesive bond. The structural integrity of ETPs can be extremely compromised and these effects can be intensified by severe outdoor conditions, such as extended exposure to humidity or water and high temperatures.

Therefore, this study examined the block shear bonding capability of glulam made from the laran timber, a commercially significant plantation forest species, under varying environment treatment conditions circumstances. All test specimens were subjected to three distinct conditions to replicate the actual service environment. A block shear test was performed to evaluate bonding performance, in accordance with MS758 (2020). The shear strength of test samples in various conditions was evaluated, and the wood failure percentage (WFP) for each specimen was assessed and recorded. The bonding performance of laran glulam, assessed *via* shear strength, was anticipated to elucidate the bonding quality of this plantation forest species, which consequently affects the strength performance of the timber structure produced.

EXPERIMENTAL

Bonding Procedures

Laran (*Neolamarckia cadamba*) plantation logs sourced from Sabah, Malaysia, were processed into laminations, dried, and visually graded by a certified Malaysian Timber Industry Board (MTIB) grader in accordance with MS 1714:2003. The glulam

specimens were manufactured using phenol-resorcinol-formaldehyde (PRF) adhesive (AkzoNobel PRF System 1734 with Hardener System 4001), mixed in a 4:1 ratio by weight as recommended by the manufacturer. Adhesive was applied to one face of each lamella at a spread rate of 400 g/m², and the laminations were assembled into three-layer beams (135 mm × 105 mm × 1500 mm). The assemblies were pressed under a uniform hydraulic pressure of 1.1 MPa, following procedures similar to Rosli *et al.* (2023). Pressing was initiated within four hours of gluing, and the laminations were kept under pressure for at least six hours and less than 24 hours to allow sufficient curing at room temperature. After de-pressing, beams were left to continue curing under ambient laboratory conditions for several days before specimen preparation.

Table 1. Environment Conditions for Block Shear Test of Laran Glulam

Condition	Simulated Environmental Exposure	Practical Relevance in Building Construction	Number of Specimens
Dry (control)	Indoor, Service Class 1 (e.g. residential or office buildings with low relative humidity).	Baseline bonding performance of laran glulam under controlled indoor conditions.	10
Water-Soak	Temporary wetting, humid indoor/semi-exposed, Service Class 2 (protected outdoor structures or humid interiors like bathrooms, kitchens).	Evaluates adhesive bond resistance against accidental wetting and temporary outdoor exposure.	10
Boiling Immersion	Severe single-cycle hot-wet exposure, analogue to Service Class 3 (accelerated durability).	Represents extreme thermal and moisture stress, e.g. prolonged water saturation or tropical outdoor exposure.	10
Boil-Dry-Boil Cycle	Extreme accelerated ageing, repeated wet-dry cycles beyond Service Class 3 (similar to delamination protocols).	Simulates repeated wet-dry cycling typical of unprotected exterior timber exposed to tropical rainfall and sun.	10
Total Number of Specimens			40

Preparation of Test Specimen

The fully cured beams were cut into block shear test specimens measuring 50 mm × 50 mm × 50 mm, following MS 758:2020 specifications, as shown in Fig. 1. Prior to testing, forty (40) specimens were conditioned at room temperature to equilibrate moisture content with the laboratory environment, ensuring stable properties before exposure to the treatment regimes (dry, water-soak, boiling immersion, and boil-dry-boil cycle) as detailed describe in Table 1. This ensured that variations observed in shear strength and wood failure percentage (WFP) reflected the influence of treatment conditions rather than differences in initial bonding or material preparation.



Fig. 1. Block shear specimens for the determination of bonding strength

Pre-treatment for Environmental Conditions

To evaluate the influence of environmental exposure on bonding behaviour, four environmental treatment conditions adapted from BS EN 314-1 (2014) applied to the glulam specimens. These conditions were selected to simulate service environments commonly encountered in building construction and were aligned, where possible, with international standards such as Eurocode 5, EN 1995-1-1: 2004. The treatment conditions groups are summarised in Table 1.

Dry conditions

For dry conditions, the samples were tested without any prior treatment.

Water-soak (Treatment 1)

All specimens were labeled prior to the pre-treatment. The water was poured into a big basin, and its temperature was regulated at 20 ± 3 °C, aligning with the ambient temperature to enable better control. The specimens were removed after 24 h of immersion and subsequently evaluated using the block shear test

Boiling immersion (Treatment 2)

In Treatment 2, the specimens were immersed in boiling water for 6 h and subsequently cooled to room temperature (20 ± 3 °C) for a minimum of 1 h. Similar to Treatment 1, all specimens were labeled in advance. The water was heated in a large pot until it attained the boiling point (100 °C), and the temperature was observed with a thermometer. Water was incrementally added as necessary to sustain the boiling temperature. After 6 h, the specimens were extracted using tongs and subsequently immersed in a large basin of room-temperature water for 1 h prior to testing.

Boil-dry-boil cycle (Treatment 3)

Treatment 3 required approximately 29 h. Initially, all specimens were labeled. The specimens were immersed in boiling water (100 °C) for 4 h, with the temperature regulated by the steady addition of water. Subsequently, the specimens were dried for 16 to 20 h in a ventilated drying oven at 60 ± 3 °C. After drying, the specimens were subjected to boiling for another 4 h, followed by cooling in water at 20 ± 3 °C for 1 h. The block shear test was conducted subsequent to wetting the samples after their removal from the cooling water.

Block Shear Test

Following the conclusion of all the treatments, a Shimadzu Universal Testing Machine (UTM) with load capacity of 50 kN and shear block apparatus were employed to determine the glueline shear performance of the glulam specimens. The specimens were firmly affixed to the shear block apparatus and subsequently positioned in the UTM to exert a load along the glueline. The force was exerted at a uniform rate of 0.06 mm/s during the test. Fig. 2 presents the block shear test apparatus. The shear strength of the test specimens was subsequently determined using Eq. 1,

$$f_v = k \frac{F_u}{A} \quad (1)$$

where f_v is shear strength in N/mm², k is a modification factor for the test specimens that has the thickness in the grain direction of the sheared area less than 50 mm, k is calculated by $k = 0.78 + 0.0044t$, t is the thickness, in mm, F_u is the ultimate load in N and A is the sheared area in mm².



Fig. 2. Shear test apparatus

Wood Failure Percentage (WFP)

The WFP is a critical metric for evaluating the bonding performance of engineered timber products, including glulam. When a bonded joint is subjected to stress to the point of failure, the WFP quantifies the extent of wood fibre failure in comparison to adhesive failure. In a wood joint, the WFP is the percentage of the failure area that occurs within the wood fibres, as opposed to at the adhesive interface. An adhesive bond that is stronger than the wood itself, as indicated by a high WFP, is indicative of a high-quality bond. Conversely, a low WFP suggests that the adhesive bond is more susceptible to failure and weaker than the wood fibres. After conducting the mechanical testing, which assessed shear strength, the WFP was determined. After the mechanical test, the surfaces of the opening in the glueline were assessed for unsuccessful bond interface. Visual evaluation was employed to estimate the wood failure area, which involves the division of the failed bond line into section surfaces and comparison with the standard BS EN 314-1 (2014), *Plywood Bonding Quality Test*. The average percentage of wood failure was calculated by estimating the percentage of wood failure in each section, as illustrated in Eq. 2.

$$WFP (\%) = \left(\frac{\text{Area of wood failure}}{\text{Total failure area}} \right) \times 100 \quad (2)$$

Acceptance Criteria for Shear Strength and WFP Accordance with MS 758:2020

In accordance with MS 758:2020, the acceptance criteria for the mean shear strength of the glueline are specified as follows. The minimum required shear strength is 6.0 N/mm², accompanied by a wood failure percentage (WFP) of at least 90%. For specimens with a mean shear strength ranging between 8 and 10 N/mm², a lower threshold of 72% WFP is considered acceptable. In cases where the mean shear strength reaches 11 N/mm² or higher, the WFP must exceed 45%. For timbers of lighter density, a mean shear strength of 4.0 N/mm² is deemed acceptable provided that the WFP achieves 100%.

RESULTS AND DISCUSSION

Shear Strength Analysis

Table 2 summarises the mean value of maximum shear strength and WFP for different environmental treatment conditions. The shear strength results show that dry (control) glulam had the highest mean shear (5.20 N/mm², SD 0.82, COV 15.7%), while water-soaked glulam was drastically lower (2.76 ± 1.02 N/mm², COV 37.2%). Boiling immersion (4.67 ± 0.28 N/mm², COV 6.06%) and the boil-dry-boil cycle (4.57 ± 0.25 N/mm², COV 5.52%) gave values nearly equal to control. ANOVA/Tukey grouping shows the water-soak mean (“b”) was significantly lower than the others (all “a”). In short, soaking severely reduced strength and increased variability, whereas boiling (even cyclically) had only modest effect. Fu *et al.* (2024) tested samples of timber-concrete composite and showed that increased moisture content causes a reduction in shear bond strength.

The boiling immersion and boil-dry-boil cycle glulam exhibited shear strength values comparable to those of the dry-condition. Both treatments involved a heating process through boiling followed by cooling prior to shear testing. Currently, limited research is available on the potential of heat treatment to enhance adhesive bond performance. Most previous studies have reported that timber bonding strength decreases with increasing temperature. However, this trend does not appear to apply to phenol-resorcinol-formaldehyde (PRF) adhesive. PRF is a thermosetting adhesive, which can undergo further curing if the initial bonding stage did not achieve complete polymerisation (Kim and Kim 2011). Heating may therefore promote additional curing, potentially enhancing shear strength. Rapid cooling in water is unlikely to significantly impair performance once the adhesive has formed a stable bond. Provided that the adhesive has fully cured and the applied temperature remains below its thermal resistance threshold, the heating and cooling cycle is expected to have minimal adverse effects on shear strength.

Another factor that may contribute to the increased shear strength is the reduction of thermal residual stress. The controlled heating followed by rapid cooling can reduce thermal residual stress. The reduction in stress can improve the mechanical properties of the sample including shear strength and joints (Kim and Kim 2011). The polymer structure of the adhesive can also be one of the reasons why the shear strength increases. The cooling process may cause shear bands to form in the adhesive, resulting in a restructuring of the polymer that impacts the mechanical properties. Phenol formaldehyde (PF) polymer also

provides good thermal stability, high mechanical strength, and resistance to chemicals and moisture because of its cross-linked, and three-dimensional polymer network (Beule *et al.* 2024). Therefore, in MS 758 (2020), glulam structures that are partially (Service Class 2) or fully exposed (Service Class 3) are required to use PRF adhesive due to its superior performance and post-curing ability under controlled heating and rapid cooling conditions.

In contrast, water soaking may have caused swelling and subsequent shrinkage of the low-density laran wood, inducing microcracks at the glue interface and leading to a significant decrease in shear strength (Vanya 2012). The very high COV under soak (37%) suggests uneven moisture uptake and glueline stress. The boil–dry cycling possibly introduced some adhesive micro-damage (noted by slightly lower WFP below), but overall shear did not fall significantly. These trends agree with general adhesive behavior which exterior PRF bonds maintain most strength under extreme moisture, whereas wood substrates weaken when saturated.

Generally, this shear data adds to understanding of tropical glulam performance. Laran glulam achieved reasonable shear ($\sim 5 \text{ N/mm}^2$) under dry/boil conditions. It also highlights a weakness to full immersion. This informs use in service classes, PRF adhesives (Type I) meet MS and EN bonding criteria (MS 758, 2020; FPL, 2010), but laran’s wood failure under water suggests protective measures (*e.g.* coatings or avoidance of ponding). These findings complement existing studies on fast-grown plantation timbers and reinforce that PRF adhesives provide durable bonds in humid climates, while the choice of laran must account for its moisture-induced strength loss.

Table 2. Shear Strength and WFP for Different Environmental Treatment Conditions

Condition	Dimension of Sample (mm)	Number of Test Specimen	Shear Strength (N/mm^2)			Wood Failure Percentage (%)		
			Mean (N/mm^2)	SD (N/mm^2)	COV (%)	Mean (N/mm^2)	SD (N/mm^2)	COV (%)
Dry (control)	47 x 47 x 48	10	5.20 ^a	0.82	15.67	75.50 ^a	16.19	21.45
Water-Soak (Treatment 1)	47 x 46 x 46	10	2.76 ^b	1.02	37.15	58.50 ^a	10.50	17.95
Boiling Immersion (Treatment 2)	47 x 47 x 47	10	4.67 ^a	0.28	6.06	72.50 ^a	19.78	27.28
Boil-Dry-Boil Cycle (Treatment 3)	47 x 46 x 46	10	4.57 ^a	0.25	5.52	56.00 ^a	16.85	30.09

Note: Environment treatments conditions with means followed by the same letter in the column are not significantly different (Tukey; $p > 0.05$). Values in parentheses are the standard deviation (SD) and COV is coefficient of variation

Wood Failure Percentage Analysis

The predominance of wood failure indicates that PRF adhesion exceeded or matched wood strength (Ross, 2010). In comparison to standards (MS758:2020), the WFP values for most individual glulam specimens did not meet minimum expectations as well as for the average values of the WFP for all environmental conditions. The glulam shear in this study ($\sim 2.8\text{--}5.2 \text{ N/mm}^2$) would fall into the $\leq 6 \text{ N/mm}^2$ case, implying a 90% WFP target (MS758:2020). The observed mean WFP value (56 to 75%) was below that ideal, suggesting some adhesive area participation.

In the dry and boiled cases, the glueline held well compared to the water-soak and boil-dry-boil cycle, causing the surrounding laran fibers to tear. Figure 3 presents the 90% of WFP under dry condition. The somewhat lower WFP under water-soak (~59%) suggests that the bond was relatively weaker compared to wood, perhaps due to microcracks or incomplete curing from moisture as shown in Figure 4. Similarly, after the boil–dry cycle, some adhesive-wood interface stress may have caused more adhesive failure (hence lower WFP). In general, tropical hardwoods like laran may have lower transverse strength, so even minor bond weakening can shift the failure mode.



Fig. 3. Surface failure for laran glulam sample for initial condition with failure at 90%



Fig. 4. Surface failure for laran glulam sample for water-soak (treatment 1) with failure at 50%

Figure 5 presents the frequency distribution of WFP for each environmental treatment, overlaid with a normal distribution fit representing the statistical tendency of the data. The smooth curves were generated based on the calculated mean and standard deviation of each dataset to visualize how closely the experimental results follow a normal distribution pattern. As shown, the WFP data for all treatment conditions approximated a normal trend, indicating that variation in bond performance was largely governed by random factors inherent in timber and adhesive interaction rather than systematic bias. This type of distribution is typical in glulam bond testing, where natural heterogeneity in fibre orientation, adhesive spread uniformity, and local density fluctuations influence the observed failure percentage (Frihart 2009; Frihart and Hunt 2010; Aicher *et al.* 2018).

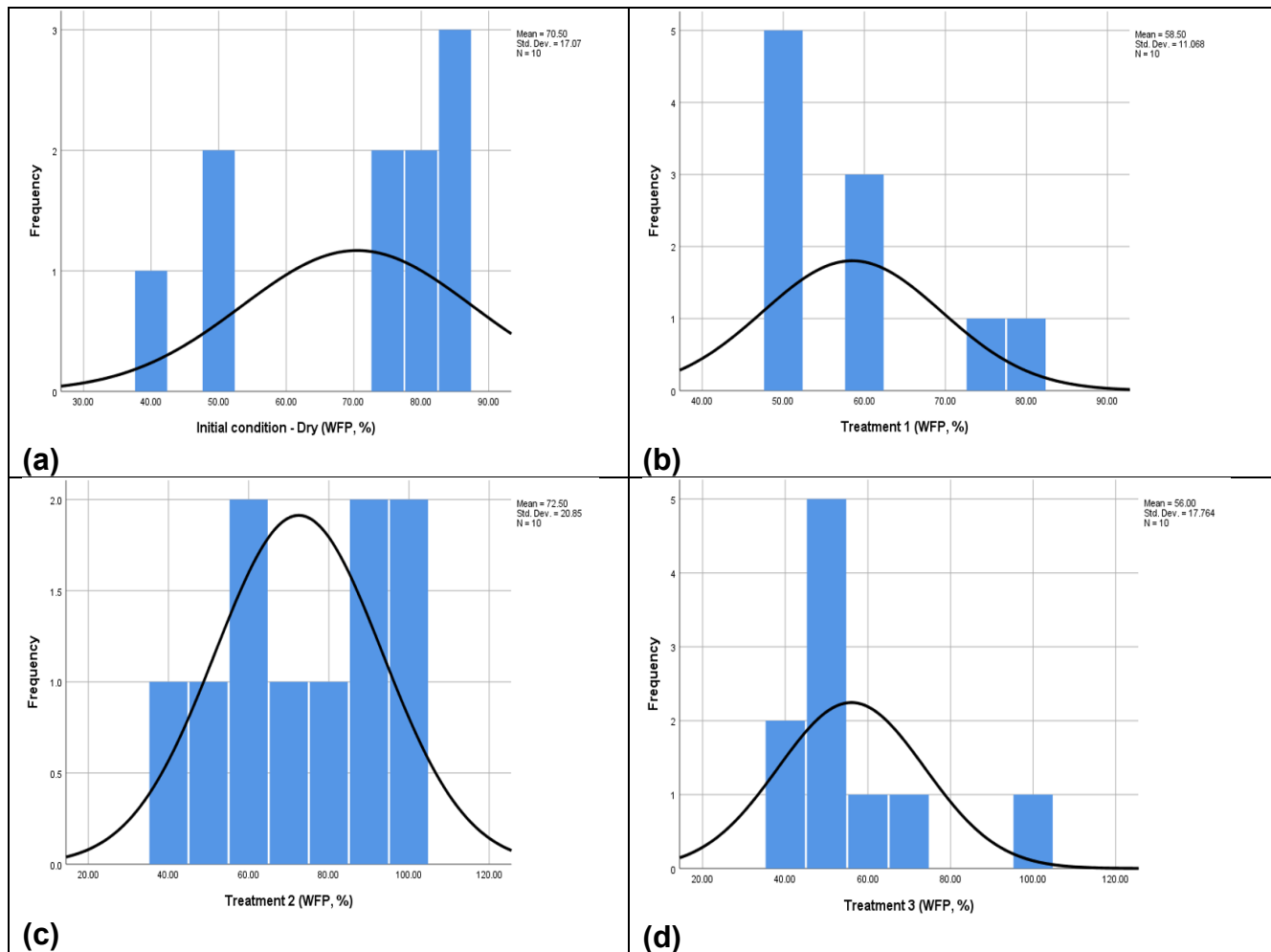


Fig. 5. Frequency distribution of wood failure percentage (WFP) for each environmental treatment condition ((a) dry, (b) water-soak, (c) boiling immersion, and (d) boil–dry–boil cycle). The smooth curves superimposed on each histogram represent the fitted normal distribution derived from the mean and standard deviation of the corresponding dataset, illustrating the statistical trend of WFP variation among specimens.

While the histograms for certain treatments, particularly the boil–dry–boil cycle (Fig. 5(d)), appear less smooth, this effect primarily reflects the limited number of replicates ($n = 10$ per treatment). Nevertheless, the sampling for each glue line was conducted in accordance with MS 758:2020, which specifies the minimum requirement for bond evaluation tests, and is considered statistically sufficient to represent the central tendency and variability of both shear strength and wood failure percentage (WFP) under each treatment condition. Given that glulam specimens involve natural wood variability, perfect symmetry or continuity in the frequency curve is rarely achieved, even with larger datasets. The observed variability thus represents the intrinsic stochastic nature of wood failure and bond-line heterogeneity, as widely reported for engineered wood composites (Aicher *et al.* 2018; Slabohm *et al.* 2022).

Furthermore, the overall shape of each distribution supports the interpretation of simulated environmental effects. The dry condition (Fig. 5(a)) exhibited a relatively narrow curve centred around higher WFP values ($\sim 76\%$), reflecting consistent bonding and minimal surface degradation. The water-soak treatment (Fig. 5(b)) showed a wider

distribution skewed toward lower WFP, indicating uneven bond degradation due to moisture penetration. In contrast, boiling immersion (Fig. 5(c)) produced a nearly symmetrical curve, confirming that the PRF adhesive maintained integrity even after exposure to boiling. The boil–dry–boil cycle displays the broadest spread, consistent with the mechanical fatigue expected from repeated thermal and moisture cycling. These observations are in line with the adhesive durability mechanisms described by Frihart (2009) and summarized in the Wood Handbook (Forest Products Laboratory, 2021), where increased environmental severity leads to reduced mean performance and greater data scatter due to interfacial degradation.

Overall, these results reinforce that the bonding quality of laran glulam, even under extreme environmental conditioning, remains within acceptable statistical ranges of variability for structural applications. The fitted distributions provide an effective visualization of adhesive performance consistency and further support the reliability of using PRF adhesive for tropical plantation hardwoods subjected exposed to fluctuating service conditions.

CONCLUSIONS

The shear strength and wood failure percentage (WFP) of laran glulam, a plantation hardwood, were examined in this study under various simulated environmental conditions. The findings of the study can be summarised as follows:

1. The dry condition achieved the highest shear strength (5.20 N/mm²) and wood failure percentage (~76%), whereas water-soak caused the greatest deterioration, with shear strength of 2.76 N/mm² and WFP of ~59%, indicating that prolonged moisture exposure weakens the glue-line and surrounding wood matrix.
2. In contrast, boiling immersion and boil–dry–boil cycles resulted in only minor strength reductions compared with the dry condition, suggesting that controlled heating may promote post-curing and dimensional stabilisation of the phenol resorcinol formaldehyde (PRF) bond-line
3. WFP distributions followed a normal trend, showing that bond variability is governed by natural wood heterogeneity and adhesive–substrate interaction, rather than testing inconsistency.
4. PRF adhesive exhibited durable bonding performance for laran glulam, maintaining acceptable shear strength even under extreme thermal–moisture cycles. However, the low-density nature of laran makes it susceptible to water-induced weakening, indicating that protective surface coatings or hybrid lamination with denser hardwoods would be beneficial for Service Class 2–3 applications.

While this study focused on shear strength and wood failure percentage, microscopic analysis such as Scanning Electron Microscopy (SEM) was not conducted. Incorporating such analysis in future work would provide valuable insights into bond-line morphology, surface checking, and interfacial degradation under severe environmental treatments (*e.g.*, boil–dry–boil cycles), thereby complementing the mechanical findings with microstructural evidence.

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REFERENCES CITED

- Abed, J., Rayburg, S., and Rodwell, J. (2022). "A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures," *Sustainability* 14(9), article 5570. DOI: 10.3390/su14095570
- Adnan, N. A., Md. Tahir, P., Husain, H., Lee, S. H., Uyup, M. K. A., Arip, M. N. M., and Ashaari, Z. (2021). "Effect of ACQ treatment on surface quality and bonding performance of four Malaysian hardwoods and cross laminated timber (CLT)," *European Journal of Wood and Wood Products* 79, 285-299. DOI: 10.1007/s00107-020-01609-7
- Aicher, S., Ahmad, Z., and Hirsch, M. (2018). "Bondline shear strength and wood failure of European and tropical hardwood glulams," *European Journal of Wood and Wood Products* 76(3), 861-875. <https://doi.org/10.1007/s00107-018-1305-0>
- Amirul, M., Rosli, A., Bhkari, N. M., Zuki, M. M., Chen, L. W., Azmi, A., Ahmad, Z., Purwanto, N. B., and Wong, N. (2023). "Manufacturing study on different glue spread and press pressure for glued laminated timber made from Laran," *Journal of Advanced Research in Applied Mechanics* 107(1), 20-29. DOI: 10.37934/aram.107.1.2029
- Beule, F., Teutenberg, D., Meschut, G., Teutenberg, D., and Meschut, G. (2024). "Analysis of the anisotropic mechanical properties of structural adhesive joints with curing-induced," *Journal of Adhesion Science and Technology* 39(6), 817-836. DOI: 10.1080/01694243.2024.2427799
- BS EN 314-1 (2014). "Plywood - Bonding quality - Part 1: Test methods," The British Standards Institution, United Kingdom.
- Ding, Y., Pang, Z., Lan, K., Yao, Y., Panzarasa, G., Xu, L., Lo Ricco, M., Rammer, D. R., Zhu, J. Y., Hu, M., *et al.* (2023). "Emerging engineered wood for building applications," *Chemical Reviews* 123(5), article 450. DOI: 10.1021/acs.chemrev.2c00450
- Dong, W., Wang, Z., Chen, G., Wang, Y., Huang, Q., and Gong, M. (2023). "Bonding performance of cross-laminated timber-bamboo composites," *Journal of Building Engineering* 63, article 105526. DOI: 10.1016/j.job.2022.105526
- Forest Products Laboratory. 2021. *Wood handbook— Wood as an Engineering Material*, General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 543 pp.
- Frihart, C. R. (2009). "Adhesive groups and how they relate to the durability of bonded wood," *Journal of Adhesion Science and Technology* 23(4), 601-617. <https://doi.org/10.1163/156856109X43135>
- Frihart, C. R., and Hunt, C. G. (2010). "Adhesives with wood materials: Bond formation

- and performance,” in: *Wood Handbook: Wood as an Engineering Material* (Gen. Tech. Rep. FPL-GTR-190, pp. 10-1 – 10-24), U.S. Department of Agriculture, Forest Products Laboratory.
- Fu, Q., Xu, R., Kasal, B., Wei, Y., and Yan, L. (2024). “Moisture-induced stresses and damage in adhesively bonded timber-concrete composite connection,” *Construction and Building Materials* 416(4), article 135184. DOI: 10.1016/j.conbuildmat.2024.135184
- Han, L., Kutnar, A., Sandak, J., Šušteršič, I., and Sandberg, D. (2023). “Adhesive- and metal-free assembly techniques for prefabricated multi-layer engineered wood products: A review on wooden connectors,” *Forests* 14(2), article 311. DOI: 10.3390/f14020311
- Kim, D. H., and Kim, H. S. (2011). “Smart cure cycle to improve tensile load strength of the adhesively bonded joint,” in: *ICCM International Conferences on Composite Materials*, Jeju Island, Korea, pp. 1-6.
- Latib, H. A., Ratnasingam, J., Mariapan, M., Othman, K., Amir, M. A., Liat, L. C., Yi, L. Y., Ioras, F., Farrokhpayam, S. R., and Jegatheswaran, N. (2022). “Malaysian timber industry policy: Achievements, challenges, and lessons learned,” *BioResources* 17(1), 299-315. DOI: 10.15376/biores.17.1.299-315
- Mohamad, I. (2020). *Bonding Properties of Laminated Veneer Lumber (LVL) Made from Selected Malaysian Hardwood Timber*, Undergraduate Thesis, Universiti Teknologi MARA, Malaysia.
- MS758 (2020). “Glued laminated timber – Performance requirements and minimum production requirements (first revision),” Department of Standard Malaysia, Malaysia.
- Norshariza, M. B., Ahmad, Z., Abu-bakar, A., and Tahir, P. M. (2016). “Assessment in bending and shear strength of glued laminated timber using selected Malaysian tropical hardwood as alternative to timber,” *Jurnal Teknologi* 78(5-5), 111-117. DOI: 10.11113/jt.v78.8627
- Norshariza, M. B., Chen, L. W., Azmi, A., Nordin, M. S., Yam, N. W. S., Ahmad, Z., and Hua, L. S. (2022). “Bending, compression and bonding performance of cross-laminated timber (CLT) made from Malaysian fast-growing timbers,” *Journal of Renewable Materials* 10(11), 2851-2869. DOI: 10.32604/jrm.2022.022326
- Nunes, E., Cruz, H., and Palma, P. (2014). “Influence of moisture content on the shear strength of glulam joints,” *Wood Science and Technology* 48(3), 549-563. DOI: 10.1007/s00226-013-0616-2
- Ratnasingam, J., Latib, H. A., Paramjothy, N., Liat, L. C., Nadarajah, M., and Ioras, F. (2020). “Plantation forestry in Malaysia: An evaluation of its successes and failures since the 1970s,” *Forest Policy and Economics* 48, 1789-1801. DOI: 10.15835/48412167
- Ross, R. J. (2010). *Wood Handbook: Wood as an Engineering Material*, Centennial ed. General technical report FPL; GTR-190. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 2010: 1 v.
- Slabohm, C., Mai, C., and Militz, H. (2022). “Bonding acetylated veneer for engineered wood products — A review,” *Journal of Adhesion Science and Technology* 36(10), 1099-1121. <https://doi.org/10.1080/01694243.2022.2072082>
- Sotayo, A., Bradley, D., Bather, M., Sareh, P., Oudjene, M., El-Houjeiri, I., Harte, A. M., Mehra, S., O’Ceallaigh, C., Haller, P., *et al.* (2020). “Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications,” *Developments*

- in the Built Environment* 1, article 100004. DOI: 10.1016/j.dibe.2019.100004
- Tan, B. Y., Yeoh, D., and Chuan, E. (2022). "A case study on an engineered timber building in Johor Bahru," *Journal of Civil Engineering Research* 3(1), 1893-1899.
- Vanya, C. (2012). "Damage problems in glued laminated timber," *Drewno* 188, 115-128.
- Yanto, C. P. C., Pot, G., Collet, R., Chaplain, M., and Coureau, J. (2022). "Assessment of bonding durability of CLT and glulam made from oak and mixed poplar-oak according to bonding pressure and glue type," *Construction and Building Materials* 335, article 127345. DOI: 10.1016/j.conbuildmat.2022.127345

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