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# EVALUATION OF LAMINATED PANELS FROM SEMANTAN BAMBOO AND OIL PALM TRUNKS FOR SUSTAINABLE COMPOSITE MANUFACTURING

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## ABSTRACT

*The increasing demand for sustainable materials in the composite industry has driven interest in alternative non-wood resources. Among them, bamboo and oil palm biomass are recognised as potential natural fibres that can be utilised to develop eco-friendly composite materials. This study aimed to evaluate the properties of laminated panels made from Semantan bamboo crush mat and oil palm trunk (OPT) veneer with different layer configurations. Three types of laminated panels are compared in the study: A bamboo mats panel, an OPT veneers panel and a hybrid panel with veneer applied as the core layer while the mats served as surface layers. The composites were fabricated using a hot-pressed technique and urea-formaldehyde (UF) resin as a binder. The panels were tested for physical and mechanical properties and the results showed that layer configuration significantly influenced these properties. The panel consisting entirely of a bamboo mat showed the best performance, while the hybrid panel was comparable in most properties tested. On the other hand, the panel with entirely OPT veneers was inferior, suggesting that the hybrid panel would be a promising alternative to wood-based products.*

**Keywords:** bamboo, laminated composite, layer configuration, oil palm trunk.

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## INTRODUCTION

Like laminated panels, engineered wood is constructed by layering thin sheets of wood veneer or lumber to enhance its strength and other properties. Compared to other wood fibre panels, laminated panels display superior performance in both physical and mechanical characteristics due to the strategic use of alternative fibres and optimised layer configurations. Plywood, cross-laminated timber (CLT), veneer, glued laminated timber (glulam) and laminated veneer lumber (LVL) are all prime examples of laminated panels. In the construction industry, laminated panels have diverse applications in roofing, flooring, partitions, furniture and entire building structures. Malaysia plays a significant part in the global timber industry. It is one of the major producers and exporters of a wide range of timber products, including sawn timber, flooring, doors and panels like plywood and medium-density fibreboard (MDF) and this sector contributes substantially to the Malaysian economy (Malaysian Timber Industry Board [MTIB], 2023). However, the focus is shifting toward sustainable alternatives due to concerns about deforestation and resource scarcity (Dieterle & Karsenty, 2020).

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Therefore, bamboo and oil palm trunks (OPT) are recognised as viable alternative materials for use in laminated panel production.

Bamboo is a renewable resource with fast growth and qualities comparable to typical wood resources. Its strength, durability and versatility make it a compelling choice for various applications, including furniture manufacturing and construction (Huang et al., 2019; Siam et al., 2019). As an abundant tropical resource, it encompasses over 80 genera and 1,600 species worldwide, with 70 species grown in Malaysia, including 50 endemics and 13 commercial species (Siam et al., 2019). Despite its many advantages, such as exceptional strength-to-weight ratios and optimum thermal, acoustic and other qualities with high tensile strength, the use of natural bamboo as a building material is limited. This limitation is primarily due to the small diameter of bamboo culms and the wide range of mechanical properties (Wang et al., 2011). To address these restrictions, bamboo composite materials have been developed (Abidin et al., 2023; Yusof et al., 2023; Zhong et al., 2017). Bamboo composite is an engineered material predominantly utilised for structural purposes in the building and construction industries. These composite materials are commonly utilised in various shapes such as beams, boards, lumber and other components. Bamboo composites have been created over the last 40 years, including bamboo scrimber (Rao et al., 2022; Yang et al., 2024), laminated bamboo (He et al., 2024; Manik et al., 2022), ply bamboo (Uyup et al., 2012) and bamboo strand-based composites (Sulastiningsih et al., 2024). Bamboo composites offer excellent dimensional stability, minimal distortion and consistent size. They also possess high wear resistance, stiffness and strength (Mili et al., 2023).

Alternatively, OPT, a biomass of palm oil plantations, offers a way to utilise by-product materials and reduce environmental impact. Oil palm plantations have seen a surge in growth across Southeast Asia, particularly in Malaysia (Parveez et al., 2020). In 2023, the total estimated production of oil palm biomass was 92.37 million tonnes based on a dry weight basis, with OPT contributing 9.83 million tonnes to this total (Malaysian Palm Oil Board [MPOB], 2024). The versatility of palm oil, with applications in food, cosmetics, pharmaceuticals, biofuels and various household products, has solidified its position as a crucial element of the Malaysian economy (Nuryawan et al., 2022; Ropandi et al., 2022; Yusof et al., 2020). In the composite industry, due to its low-grade construction, oil palm biomass has been utilised in various forms, including pellets, adsorbents, briquettes, plywood, particleboard and fibreboard (Badri & Khairul, 2006; Chong et al., 2020; Ibrahim et al., 2013, 2020; Safana et al., 2018). However, laminated panels made solely from OPT veneers exhibit inadequate physical and mechanical characteristics due to the OPT having a lower density ranging from 222–404 kg/m$^3$ (Nuryawan et al., 2022).

Both bamboo and OPT emerge as promising substitutes for wood in laminated panels due to their abundance, fast growth and similar properties like wood. Thus, the utilisation of bamboo and OPT in hybrid laminated panel production enhances their inherent value proposition. These renewable resources contribute to the aesthetic appearance of the panel and exceptional mechanical properties while also mitigating environmental impact through sustainable sourcing and reduced reliance on traditional timber sources (Suhaily, 2020). The properties of bamboo, specifically Semantan bamboo and OPT are summarised in *Table 1*.

Previous studies have proven that the configuration of layers in laminated panels plays a crucial role because it directly impacts the structural integrity, strength and performance of the final product (Hua et al., 2015; Jantawee et al., 2023; Yahaya et al., 2014). Therefore, this study explores the potential of combining bamboo crush mats and OPT veneers to fabricate laminated panels with varying layer configurations, aiming to investigate their performance and suitability for diverse applications.

## MATERIALS AND METHODS

This study utilised crushed bamboo mats (*Figure 1a*) produced from flattened round Semantan bamboo (*Gigantochloa scortechini*) and oil palm (*Elaeis guineensis*) veneer (*Figure 1b*) that were supplied by local suppliers. The bamboo mats received were treated with a borax solution for one week to increase durability and protect against fungi and

**TABLE 1. PROPERTIES OF SEMANTAN BAMBOO AND OPT**

| Properties | Semantan bamboo | OPT |
|---|---|---|
| Moisture content | 48.6%–90.5% (Hamid et al., 2006) | Up to 500.0% (Bakar et al., 2008) |
| Density | 530–680 kg/m$^3$ (Hamid et al., 2006; Siam et al., 2019) | 240–530 kg/cm$^3$ (Bakar et al., 2013) |
| Modulus of rupture (MOR) | 125.00 N/mm$^2$ (Zakikhani et al., 2017) | 46.62 N/mm$^2$ (Bakar et al., 2008) |
| Modulus of elasticity (MOE) | 10,039 N/mm$^2$ (Zakikhani et al., 2017) | 2,843 N/mm$^2$ (Bakar et al., 2008) |

insect infestations. The urea formaldehyde (UF) adhesive was mixed with ammonium chloride ($NH_4Cl$) hardener in a 100:1.5 ratio to accelerate the curing process of the laminated panels. The UF adhesive was sourced from a local wood-based supplier.

Bamboo mats and OPT veneers were bonded with UF adhesive to fabricate 3-ply laminated panels (300 × 300 mm) using a 250 g/m² glue spread rate. Three panels per configuration were produced, with cores oriented perpendicularly to the outer/inner layers, mimicking plywood. The hybrid panels feature bamboo mats as outer layers and OPT veneer as the core. Additionally, panels entirely of bamboo mats or OPT veneers were fabricated, utilising each material for both outer/inner and core layers (*Figure 2b*). For the bamboo panels, the bamboo mats were placed in the middle layer to enhance shear resistance and energy absorption, which are critical for applications requiring improved toughness and durability. Conversely, in the hybrid panels, the bamboo mats were positioned on the outer layers to maximise flexural stiffness and strength, as the outermost layers primarily resist tensile and compressive stresses during bending. This strategic layering ensures that each panel design meets its targeted mechanical performance criteria. Initial cold pressing was performed at room temperature with 5 kg/cm² pressure for 15 min to enhance ply adhesion and maintain panel shape. Hot pressing was followed at 140°C and 25 kg/cm² for 12–15 min to cure the adhesive and ensure proper bonding, resulting in a final panel thickness of 10 mm. The panels were then conditioned for one week at 25 ± 2°C and 65 ± 2% relative humidity to achieve equilibrium moisture content (EMC). After conditioning, panels were trimmed and cut into test samples for physical and mechanical evaluations. The same procedure was applied to panels composed entirely of bamboo mats and OPT veneers.

### Physical and Mechanical Evaluation

Each panel was cut into dimensions of test specimens and evaluated by a series of physical and mechanical tests. A total of five samples were prepared for each test for every panel type, resulting in a total of 45 test specimens in this study.

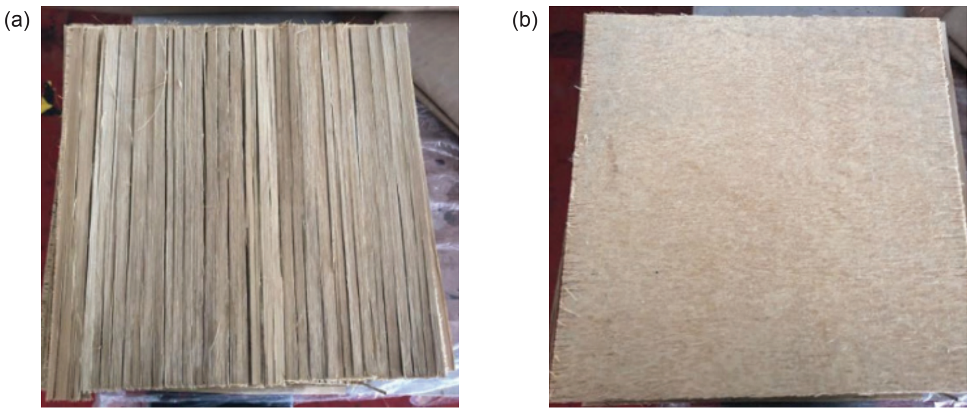


*Figure 1. (a) Crushed bamboo mats and (b) oil palm trunk (OPT) veneer.*

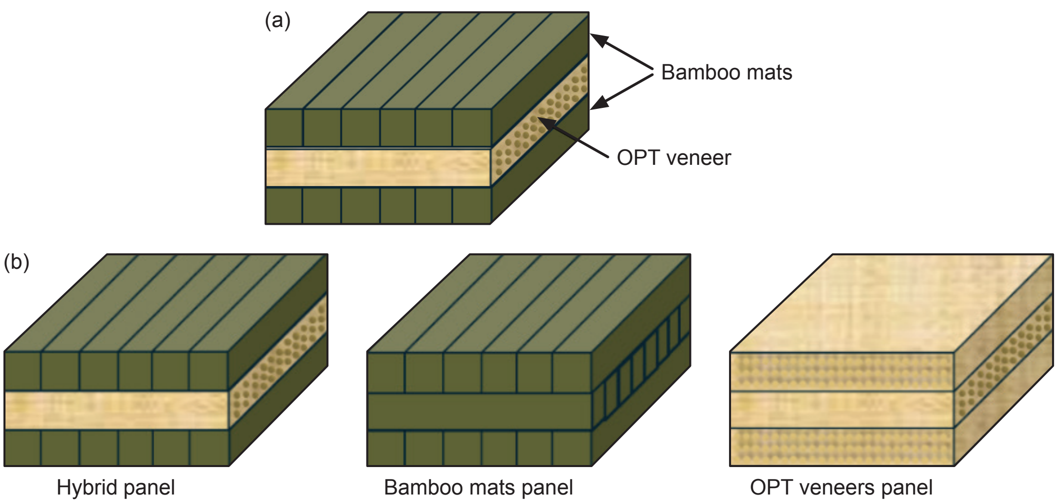


*Figure 2. (a) Configuration of the hybrid laminated panel and (b) layup of each panel.*

***Physical evaluation.*** The laminated panels were tested to evaluate their physical properties for moisture content (MC) (ASTM D4442-92), density (ASTM D2395-14), water absorption (WA) (ASTM D1037-12) and thickness swelling (TS) (ASTM D1037-12[2020]). MC is expressed in percentage (%) and was estimated by weighing the panels before and after oven drying for 24 hr as per Equation (1):

$$\text{Moisture content (\%)} = \frac{W_f - W_i}{W_i} \times 100 \qquad (1)$$

where, $W_i$ is the initial weight (g) of the test specimen before the oven-drying, and $W_f$ is the weight (g) of the test specimen after the oven-drying. Density is defined as mass per unit volume with the SI unit of g/cm$^3$ and was calculated using Equation (2):

$$\text{Density (g/cm}^3\text{)} = \frac{M}{V} \qquad (2)$$

where, $M$ is the mass (g), and $V$ is the volume (cm$^3$) of the test specimen. WA was derived by comparing the original and final weights after soaking in water for 24 hr, which is expressed in %. WA is calculated using Equation (3):

$$\text{Water absorption (\%)} = \frac{W_f - W_i}{W_i} \times 100 \qquad (3)$$

$W_i$ is the initial weight (g) of the test specimen before soaking in water, and $W_f$ is the weight (g) of the test specimen after soaking in water. TS was evaluated by measuring the change in thickness before and after water immersion for 24 hr, expressed in % and was calculated using Equation (4):

$$\text{Thickness swelling (\%)} = \frac{T_f - T_i}{T_i} \times 100 \qquad (4)$$

where, $T_i$ is the initial thickness of the test specimen before soaking in water and $T_f$ is the thickness of the test specimen after soaking in water.

***Mechanical evaluation.*** The mechanical tests incorporated bending (ASTM D7264), compression (ASTM D3501-94), shear (ASTM D2718 [2011]) and wood failure percentage (WFP) (ASTM D5266 [2013]). Bending tests measured the modulus of elasticity (MOE) and modulus of rupture (MOR). MOE is the ratio within the elastic limit of stress corresponding to strain with the SI unit of MPa. The formula of MOE is stated in Equation (5) below:

$$\text{Modulus of elasticity (MPa)} = \frac{PL^3}{4bd^3\,(\Delta d)} \qquad (5)$$

where, $P$ is the load at the limit of the proportion of the force-displacement curve, $d$ is the length of the test specimen, and $\Delta d$ is the deflection at the mid-length at the limit of the proportion. MOR is the maximum load that the test specimen with the SI unit of MPa can withstand. The formula for MOR is shown in Equation (6):

$$\text{Modulus of rupture (MPa)} = \frac{3P_{max}L}{2bh^2} \qquad (6)$$

where, $L$ is the length of the test specimen, $P_{max}$ is the maximum load that the test specimen can afford, $b$ is the width of the test specimen, and $h$ is the thickness of the test specimen. Compression testing determined the maximum load that the panels could withstand. In the compression test, compressive strength with SI unit of MPa is calculated as per Equation (7):

$$\text{Compressive strength (MPa)} = \frac{P_{max}}{bd} \qquad (7)$$

where, $P_{max}$ is the maximum load that can be applied to the test specimen, $b$ is the width of the test specimen and $d$ is the length of the test specimen. A universal testing machine was used to assess shear strength, and the percentage of broken bonding surfaces was calculated to determine WFP.

### Statistical Analysis

The effects of the layer configuration were evaluated using an analysis of variance (ANOVA) at 0.05 levels of significance. Tukey HSD tests were conducted as post-hoc analysis.

## RESULTS AND DISCUSSION

### Physical Properties

***Density and moisture content.*** *Figure 3* presents the density values for the laminated panels, ranging from 0.64–0.72 g/cm$^3$. The bamboo mats panel had the highest density at 0.72 g/cm$^3$, while the OPT veneers panel had the lowest at 0.64 g/cm$^3$. This is consistent with the known higher density of bamboo compared to OPT, reflecting the material properties. Semantan bamboo densities range from 0.53–0.68 g/cm³ (Norul Hisham et al., 2006; Siam et al., 2019), whereas OPT veneer densities range from 0.15–0.4 g/cm³ (Abdul Khalil et al., 2010; Bakar et al., 2013). Thus, panels made entirely of bamboo mats exhibit higher densities than those made from OPT veneer.

These findings are consistent with previous research. Abdul Khalil et al. (2010), reported a density of 0.63 g/cm³ for OPT plywood using UF adhesive at a 300 g/m² spread rate. Similarly, Sulaiman et al. (2009) reported a density of 0.57 g/cm³ for LVL made from OPT with the same adhesive and spread rate. The density of the bamboo mat panel differed slightly from that reported by Suhaily et al. (2020), likely due to variations in bamboo species. Specifically, *Gigantochloa levis* and *Dendrocalamus asper* bamboo laminated composites were reported to have densities of 0.98 and 1.02 g/cm³, respectively, with a 200 g/m² glue spread rate.

Given that hybrid laminated panels incorporate both crushed bamboo mats and OPT veneers, their density is lower than that of bamboo mat panels but higher than OPT veneer panels. This variation is attributed to the different densities of the materials used. Additionally, the pressing processes during panel fabrication cause volume reduction through cell compression, thereby increasing the density of the laminated panels (Sulaiman et al., 2009). In summary, the density of the manufactured panels falls within Class II (0.6–0.9 g/cm³), according to SNI 03-3527 (1994).

The hybrid panel exhibited the highest MC at 5.18%, followed by the bamboo mats panel at 4.74%, and the OPT veneers panel at 4.38% (*Figure 3*). The lower MC in OPT veneer panels is attributed to more effective drying processes during manufacturing compared to bamboo crush mats (Mokhtar et al., 2011). Differences in density and porosity also affect moisture absorption rates, with OPT veneer potentially having a lower inherent MC due to its natural properties and processing methods (Chai et al., 2011). Consequently, panels with OPT veneers show lower MC than those with bamboo crush mats. The overall MC ranged from 4.38%–5.18% for all panels tested, with a mean of 4.77%, adhering to the plywood standard of a maximum 14.00% MC (JAS 003, 2014) and confirming the suitability of the panels for various applications as noted by Sumardi et al. (2020).

***Water absorption (WA) and thickness swelling (TS).*** WA and TS are critical for assessing the dimensional stability of panels, reflecting their expansion and shrinkage under various environmental conditions. *Figure 4* shows the mean WA and TS values for each laminated panel. The WA values were 39.0% for bamboo mat panels, 41.8% for hybrid panels and 77.8% for OPT veneer panels. The OPT veneers panel demonstrated significantly higher WA, attributed to its greater porosity and void content (Paridah, 2022), which enhances moisture absorption and retention compared to bamboo mat panels (Masseat et al., 2018). Srivaro et al. (2014), also noted that increased porosity correlates with higher WA in wood materials.

The density, porosity and WA values of the panels are interrelated. Higher-density panels typically have lower porosity, resulting in reduced water absorption, and vice versa. In this study, the hybrid laminated panel exhibited a higher WA than the bamboo mat panel, indicating that the OPT veneer has a higher saturation threshold compared to bamboo. This is consistent with Sumardi et al. (2020), who reported that WA values for hybrid panels (34%–43%) were higher than those for strip bamboo panels (29%–35%).

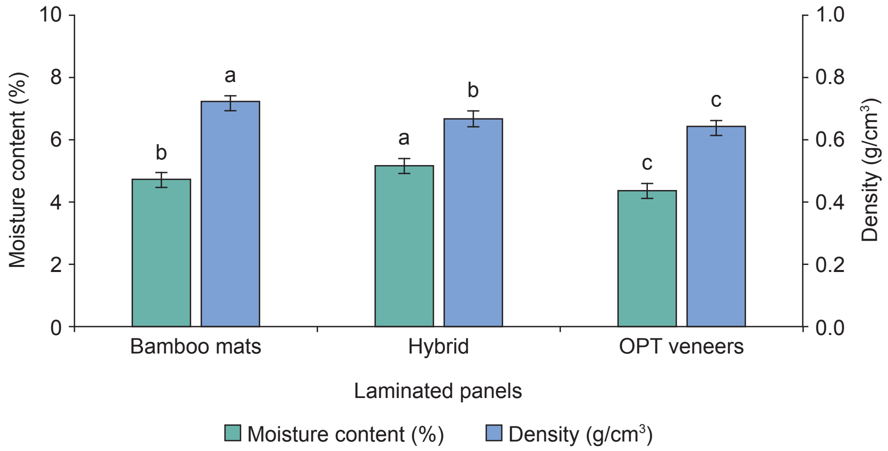


*Figure 3. Mean values of density and moisture content for each laminated panel.*

The interaction between hydrophilic fibres and adhesives can also affect water absorption. Al-Maharma and Al-Huniti (2019) found that poor adhesion between hydrophilic fibre surfaces and adhesives can create voids, increasing WA. Additionally, the pressing process, sample preparation and other fabrication steps can introduce microcracks in the panels, leading to increased water uptake (Panthapulakkal & Sain, 2007).

The mean TS values were 14.40% for hybrid panels, 19.90% for bamboo mat panels and 18.70% for OPT veneer panels (*Figure 4*). *Figure 5* shows the variation in thickness after 24 hr water soaking. TS values generally follow a trend similar to WA values, reflecting their close relationship. However, the TS value for bamboo mat panels was notably higher than for the other panels. This discrepancy may be due to gaps within the crushed bamboo mats, which become more pronounced during the pressing process and affect swelling (Srivaro et al., 2014).

Consequently, water tends to infiltrate gaps within crushed bamboo mats, causing internal swelling. However, the WA of bamboo mat panels remains low due to bamboo's inherent anatomical structure, despite these gaps. Srivaro et al. (2014) noted that pressing can induce additional swelling through densification in the core layer. In this study, the perpendicular arrangement of laminates was found to enhance dimensional stability by reducing WA and thickness changes. This arrangement effectively balances the panel's stresses, as supported by Lee et al. (2012) and Sumardi et al. (2020).

**Mechanical Properties**

***Modulus of elasticity (MOE) and modulus of rupture (MOR) of bending properties***. The mean MOE ranged from 6.6–16.6 GPa, and the MOR ranged from 53.1–108.3 MPa (*Figure 6*). Bamboo mat panels exhibited the highest MOE of 16.6 GPa, followed by hybrid panels at 16.4 GPa, while OPT veneer panels had the lowest MOE of

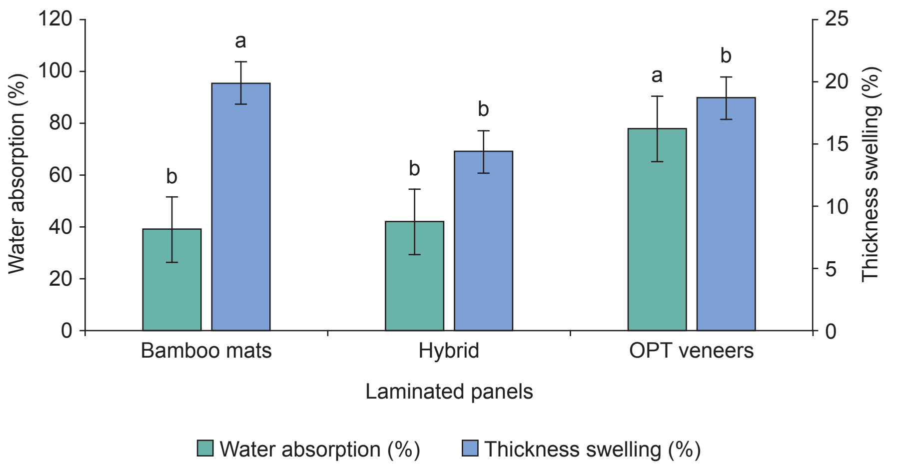


*Figure 4. Mean values of water absorption (WA) and thickness swelling (TS) for laminated panels according to the configuration.*

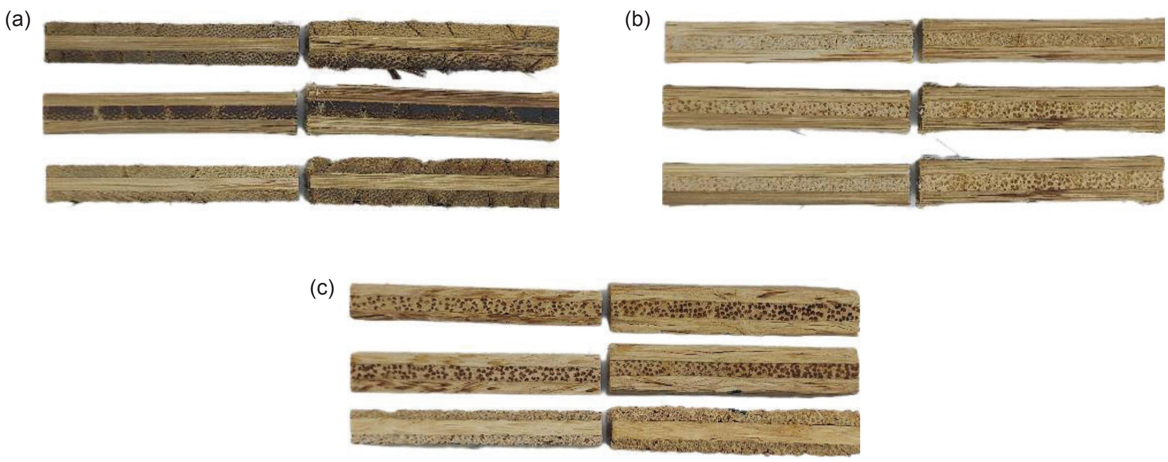


*Figure 5. Changes in the thickness of test specimens after soaking in water for 24 hr. (a) Bamboo mat panels, (b) hybrid panels and (c) OPT veneer panels.*

6.6 GPa. The minimal MOE difference between bamboo mats and hybrid panels contrasts with the larger difference from OPT veneers, indicating superior mechanical properties in bamboo-based and hybrid panels. Statistical analysis confirmed significant differences between the MOE of bamboo mats and hybrid panels compared to OPT veneers.

These results indicate that the MOE of the hybrid panel was nearly as high as that of the bamboo mats panel, despite the hybrid's inclusion of OPT veneer. While OPT veneer has lower strength than bamboo, its role in the hybrid panel only slightly reduces bending strength compared to the bamboo mat panel, suggesting effective compatibility between the crushed bamboo mat and OPT veneer. Trisatya et al. (2021) similarly found that hybrid composite beams of bamboo and damar exhibited superior MOE compared to damar-only composites, demonstrating that hybrid laminates can match or exceed the strength of single-material panels.

The bamboo mats panel achieved the highest MOR at 108.3 MPa, followed by the hybrid panel at 90.9 MPa, with the OPT veneers panel showing the lowest MOR at 53.1 MPa (*Figure 6*). This is consistent with Sumardi et al. (2020), who reported lower MOR for hybrid bamboo panels compared to all-bamboo panels. The OPT core in the hybrid panel was less effective at resisting bending stress due to inherent strength differences, as reflected in the failure modes observed (*Figure 7*). Bamboo's natural strength and stiffness contribute to higher bending strength (Abdullah et al., 2017) in panels made entirely of bamboo mats (Nkeuwa et al., 2022). Conversely, the lower stiffness of the OPT veneer impacts the bending strength of the hybrid panel (Nuryawan et al., 2022). Thus, while the MOE and MOR of the hybrid panel were comparable to or slightly lower than those of the bamboo mats panel, they were higher than those of the OPT veneers panel.

The failure mode of each test specimen from each group is displayed in *Figure 7*. Most of the bamboo mat panel specimens (*Figure 7a*) displayed horizontal shear failure. Bamboo is a highly anisotropic material with excellent strength along the grain (Verma & Chariar, 2012) but lesser strength across the grain. Shear pressures concentrate on the weaker transverse grain direction at the interfaces and within the cores (Bahari & Wan Jaafar, 2011). Because it is perpendicular to the load's direction, the core layer is the most vulnerable to shear stresses, resulting in visible horizontal shear failure. Similarly, hybrid panel specimens (*Figure 7b*) are subjected to significant stress at the interface of the bamboo and OPT layers due to their different mechanical properties. Failure will occur at the interface if the adhesive bond is weaker (Sewar et al., 2024) than the OPT or bamboo layers. The majority of OPT veneer panels exhibit splintering tension (*Figure 7c*). The reason for this is that OPT is not as compressive or tensile as bamboo (Nuryawan et al., 2022), and it fails when the OPT's weaker fibres are subjected to excessive tensile pressure.

The load-displacement graph for the bamboo mat panel (*Figure 8a*) demonstrates a steep elastic area with a drop at failure. This behaviour suggests a high stiffness and brittle failure mechanism. The observed horizontal shear failure correlates with the abrupt load decrease, which occurred because the panel's transverse layers were unable to effectively withstand shear pressures (Yusof et al., 2023).

The hybrid panel's graph (*Figure 8b*) shows intermediate stiffness with a sharp decline at failure. The sturdy bamboo outer layers and the softer OPT core each contribute to this behaviour. The horizontal shear failure in the core corresponds to the graph's sudden load decrease. OPT is more flexible and ductile (Wahab et al., 2008), it can withstand more deformation before failing, as shown by the slow fall following the peak load

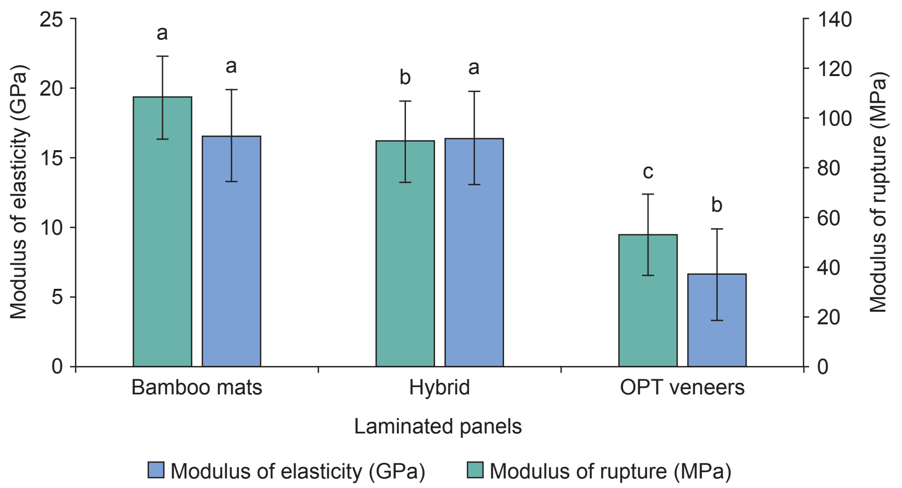


*Figure 6. Mean values of modulus of elasticity (MOE) and modulus of rupture (MOR) for laminated panels according to the configurations.*


*Figure 7.* *The failure mode of the test specimens after the bending test. (a) Bamboo mats panels, (b) hybrid panels and (c) OPT veneer panels.*

(*Figure 8c*), which is indicative of splintering tension failure. This is in line with the bending test's observed failure mode (*Figure 7c*).

***Compressive strength***. Compressive strength denotes the ability of a material to withstand applied loads that cause fracture or crushing. *Figure 9* shows the compressive strength results, ranging from 17.0–36.4 MPa, with a slight deviation from the bending test trend. The hybrid panel displayed the highest compressive strength (36.4 MPa), followed closely by the bamboo mats panel (34.2 MPa) and the OPT veneers panel again had the lowest value (17.0 MPa).

The compressive strength difference between the hybrid and bamboo mat panels was 2.1 MPa and statistically insignificant. This superior compressive strength in the hybrid panel may result from effective bonding between crushed bamboo and OPT veneer, enhancing overall performance. The load-displacement graph (*Figure 10b*) revealed a sharp slope in the elastic area, indicating that bamboo contributed significantly to stiffness (Rassiah et al., 2018). The slope in the plastic zone is somewhat increased because of the ductile OPT core, allowing the panel to withstand greater deformation before failing. The use of stiff and ductile materials maximises load-bearing capability for compressive strength (Selamat et al., 2019).

Conversely, slightly lower compressive strength in the bamboo mat panel compared to the hybrid panels might be due to gaps filled with brittle resin in the outer layers. In addition, due to the stiffness of bamboo, the slope is comparable to the hybrid panel (*Figure 10a*), but the plastic region is brief due to the absence of considerable ductility (Syaifudin et al., 2022). When the elastic limit is surpassed, the panel collapses due to crushing or buckling. The lower compressive strength observed in the OPT veneer panel could be attributed to the anatomical structure of OPT fibres, which generally have lower compressive strength compared to bamboo due to their higher proportion of vessels and parenchyma cells (Osman et al., 2022). *Figure 10c* shows a short elastic slope as the panel deforms greatly because of OPT's low rigidity. The plastic region will be longer since OPT is more ductile before the fibres in the compressed zone collapse gradually.

Sulastiningsih et al. (2018) reported higher compressive strength for all-bamboo composites compared to hybrid wood plank cores. This difference may be due to better compatibility between bamboo and OPT veneer in this study compared to their bamboo and wood plank study. The use of crushed bamboo mats, which differ in processing from bamboo strips, might also contribute to the observed results. Additionally, a study by Getu et al. (2021) found that bamboo and sisal fibre hybrids exhibited higher compressive strength. *Figure 11* shows the crushing appearance of the test specimens' post-compression. Overall, both hybrid and bamboo mat panels showed similar and superior compressive strength compared to the OPT veneers panel.

***Shear strength and wood failure percentage (WFP)***. *Figure 12* shows the mean values of shear strength and WFP for each panel type, tested in dry conditions following the type of resin used. The shear strength test measures the force required to break the bond between two materials, with the bamboo mats panel exhibiting the highest shear strength at 2.6 MPa, followed by the hybrid panel at 2.3 MPa and the OPT veneers panel at 1.5 MPa. These values indicate significant shear strength, influenced by adhesive penetration and the inherent properties of the materials. The WFP was highest in the hybrid panel (62.7%), followed by the OPT veneers (46.0%) and the bamboo mats panel (30.3%).

The bamboo mats panel exhibited superior performance due to the unique characteristics of bamboo. Bamboo's vascular bundles are rich in cellulose fibres distributed throughout the culm, enhancing resistance to various forces, including shear (Mili et al., 2023). While both bamboo and oil palm materials are less dense than hardwoods, bamboo has a higher density than oil palm.

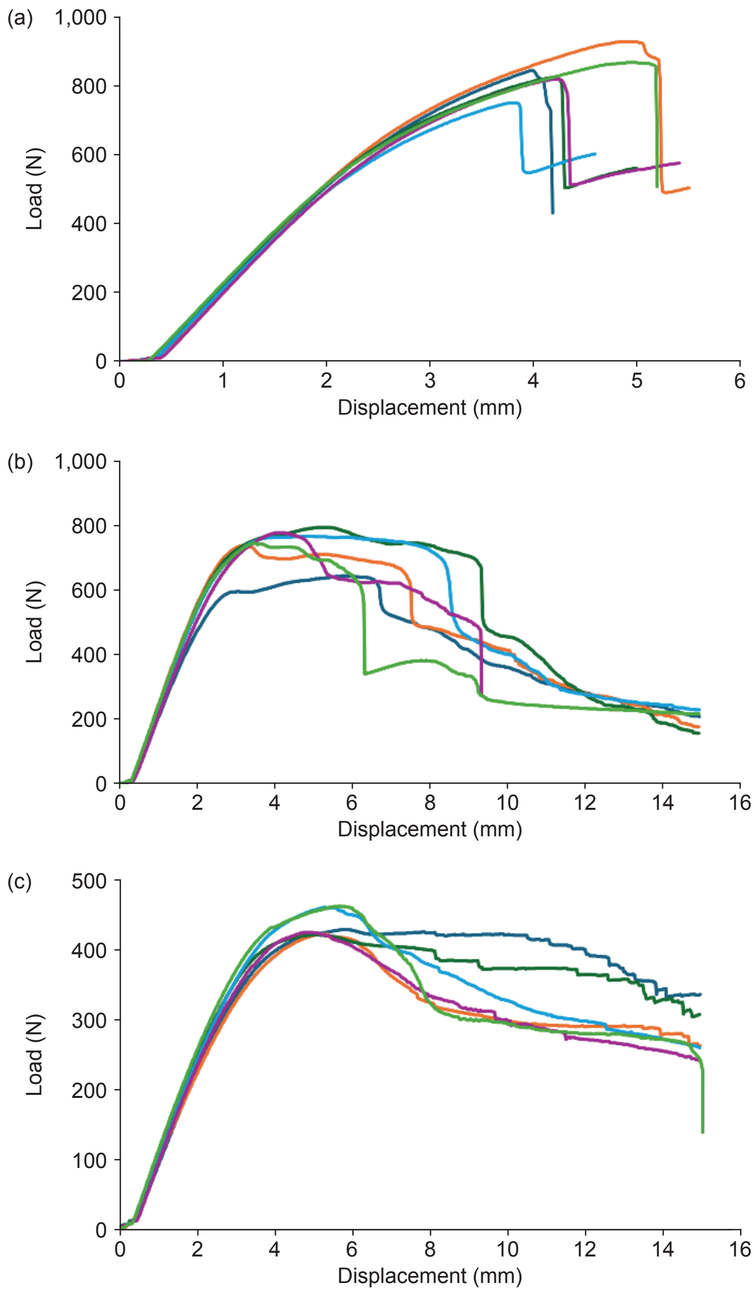


*Figure 8. Comparison of the load-displacement values obtained by each panel. (a) Bamboo mat panels, (b) hybrid panels and (c) OPT veneer panels for bending test.*

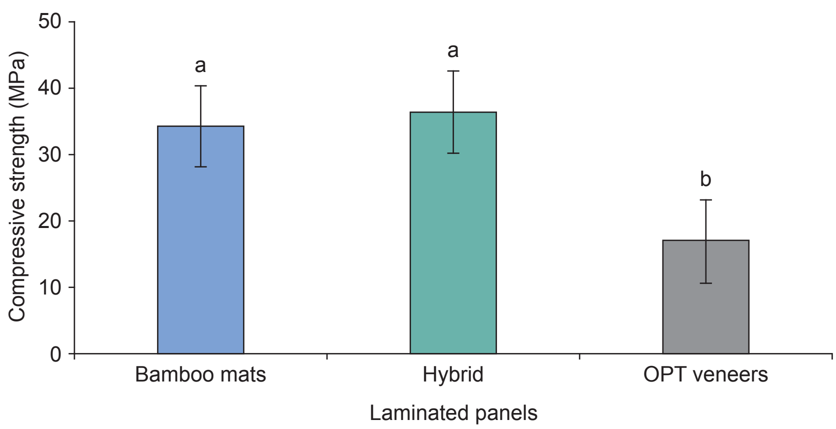


*Figure 9. Mean values of compressive strength for laminated panels according to the configurations.*

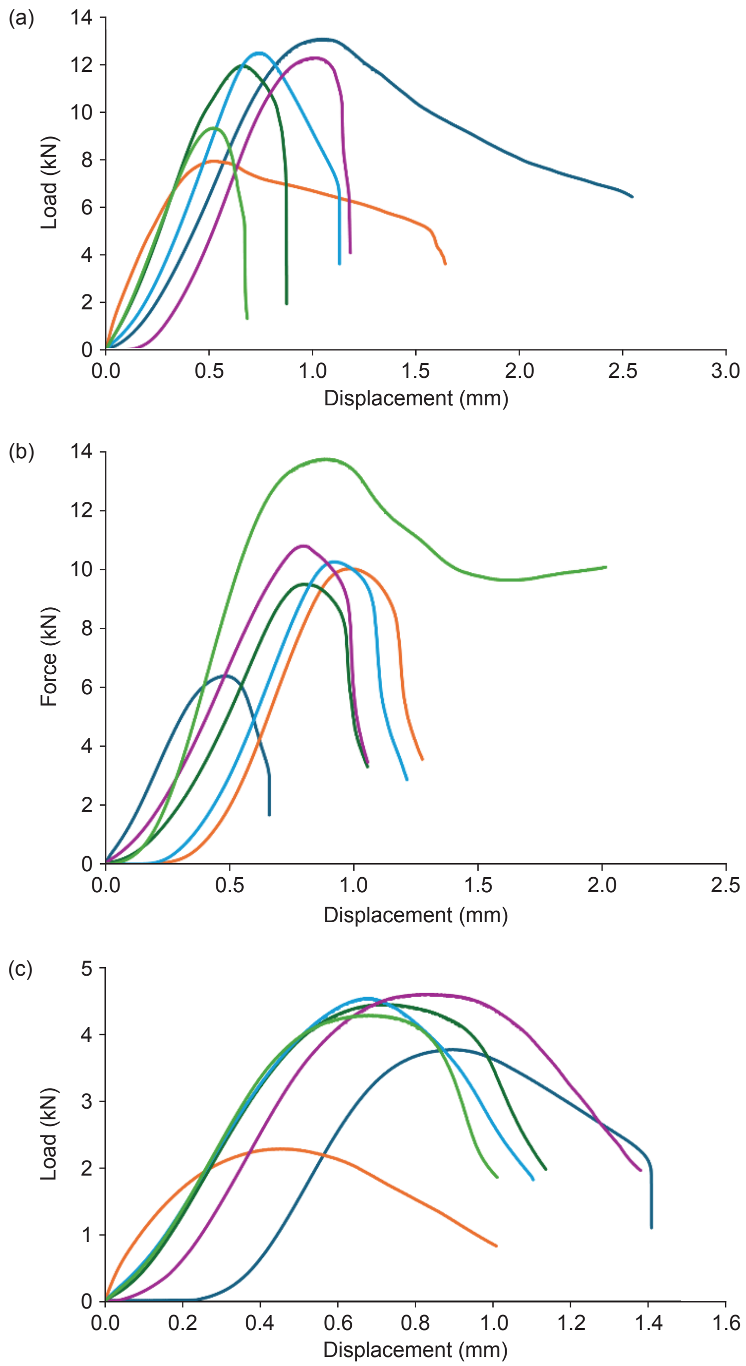


*Figure 10. Comparison of the load-displacement values obtained by each panel. (a) Bamboo mat panels, (b) hybrid panels and (c) OPT veneer panels for compression test.*

Li et al. (2021) found that bamboo woven panels (BMCP) significantly improved shear strength when incorporated into Hem-fir cross-laminated timber (CLT), thanks to the strategic placement of bamboo fibres in the inner layers to resist in-plane shear stresses. Similarly, Zhang et al. (2023) reported that CLT panels with hybrid bamboo-wood layers exhibited superior interlaminar shear strength compared to those made solely from wood. These findings highlight the potential of bamboo-wood composites to enhance the shear performance of beam structures.

The OPT veneer panel has the lowest shear strength among the other panels. Wahab et al. (2008), reported similar findings, noting that OPT LVL has lower shear strength compared to rubberwood LVL. This is attributed to OPT's lower density, which results in reduced intrinsic strength and stiffness, thereby affecting adhesive bonding efficiency (Wahab et al., 2008). Additionally, the shorter and less oriented fibres in OPT lead to weaker inter-fibre connections and a less cohesive structure, making it more susceptible to shear forces (Nordin et al., 2013). Furthermore, OPT

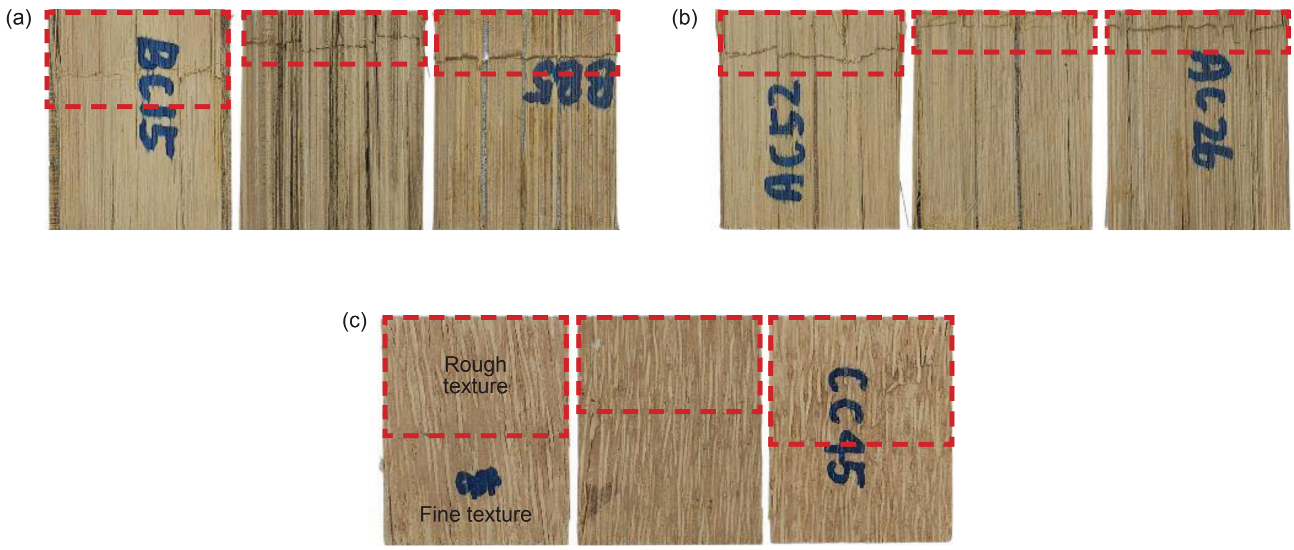


*Figure 11. The failure mode of the test specimens after the compression test. (a) Bamboo mat panels, (b) hybrid panels and (c) OPT veneer panels.*

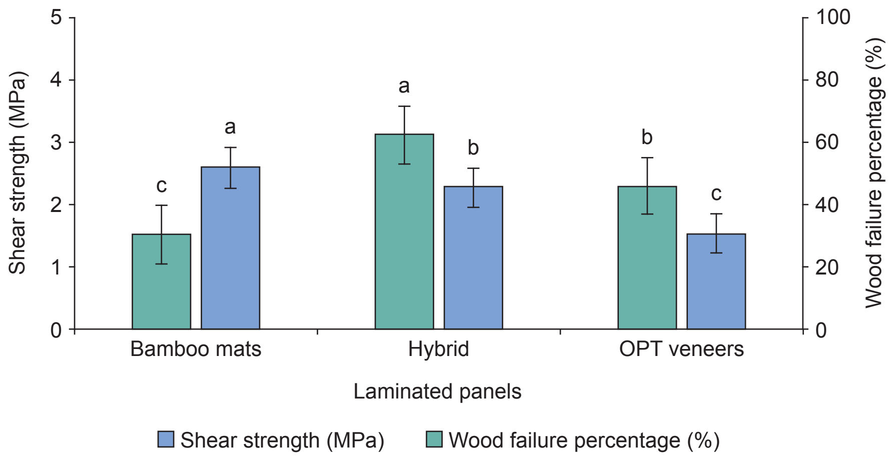


*Figure 12. Mean values of shear strength and wood failure percentage (WFP) for laminated panels according to the configurations.*

samples contain a larger proportion of parenchyma compared to bamboo, contributing to their lower shear strength.

Each panel initially failed with micro-cracks forming at the centre, which expanded under increasing load, notably in the hybrid and OPT veneer panels. This pattern is consistent with the WFP results, particularly for panels with OPT veneers, as shown in *Figure 13*, where most failures occurred in the parenchyma region. Additionally, higher content of extractives and oils compared to bamboo may disrupt adhesive bonding, leading to weaker joints and reduced shear strength (Prabuningrum et al., 2020).

Differential shrinkage may contribute to the high WFP of the hybrid panel, but this is likely due to the synergistic effect between bamboo and OPT. Bamboo fibres provide inherent strength and good porosity, which benefits adhesive flow (Hoque et al., 2019). The strong bamboo fibres form a solid structural framework, while the pores facilitate adhesive penetration. The pore size in the hybrid material may optimise adhesive distribution while filtering out unwanted particles (Hartono et al., 2023). Despite bamboo's strength, variations in fibre structure and density compared to OPT can lead to mismatched shrinkage during drying, potentially causing internal stresses and cracks (Wei et al., 2019). The interaction between bamboo and OPT might primarily contribute to the lower WFP in bamboo mats and OPT veneer panels. Bamboo with a smooth, waxy surface could impair adhesive bonding compared to the rougher texture of OPT, leading to weaker bonds and increased risk of delamination, which lowers WFP.

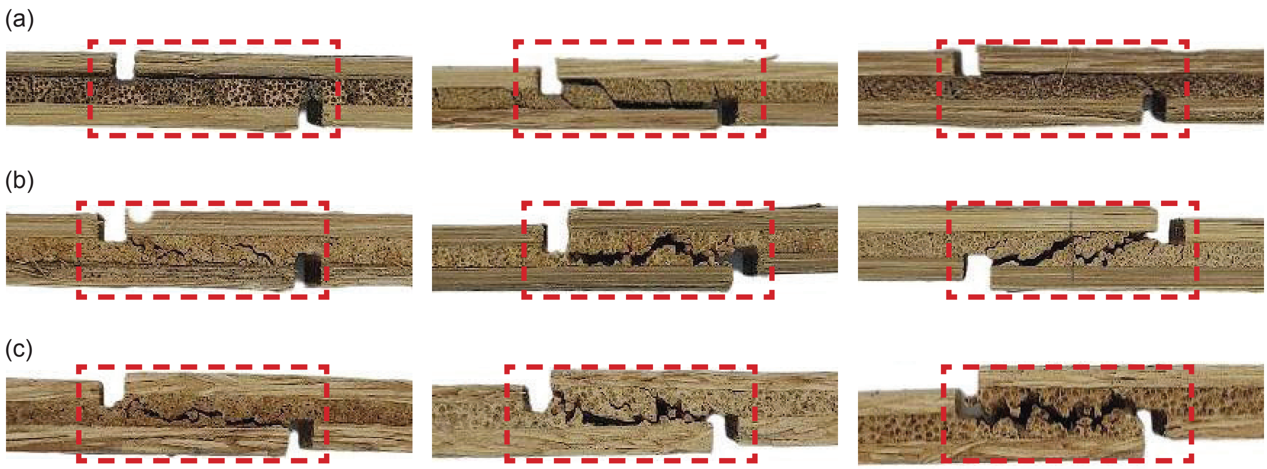

*Figure 13.* *Test specimens after the shear test. (a) Bamboo mat panels, (b) hybrid panels and (c) OPT veneer panels.*

Given that the hybrid laminated panel exhibits the highest WFP, it remains suitable for structural applications as its value meets acceptable standards. To further enhance the performance of these hybrid panels, pre-treatment of the bamboo surface through techniques like sanding, corona treatment, or chemical etching is recommended to improve adhesive bonding. Additionally, optimising pressing conditions (temperature, pressure and holding time) is essential to ensure proper adhesive activation and complete curing throughout the panel.

## CONCLUSION

In conclusion, the hybrid laminated panel, constructed from crushed bamboo mat and OPT veneer, exhibited favourable physical and mechanical properties. The bamboo mats and hybrid panels demonstrated superior performance compared to the OPT veneer panel in several physical attributes, including density, WA and TS. Specifically, the bamboo mats panel excelled in bending modulus, bending strength and shear strength, whereas the hybrid panel showed enhanced compressive strength and WFP. Statistical analysis revealed no significant difference between the bamboo mats and hybrid panels regarding bending modulus and compressive strength. Conversely, the OPT veneers panel underperformed in both physical and mechanical tests relative to the other panels.

These findings underscore the potential of hybrid laminated panels comprising bamboo crushed mat and OPT veneers as viable alternatives to solid wood for interior furniture applications, offering comparable advantages over bamboo mat panels. Combining bamboo with OPT veneers makes production more economical, especially when larger quantities are required, as it reduces dependency on bamboo alone. In addition, it addresses the underutilised potential of OPT, promoting sustainable practices.

The capacity of hybrid panels to resist fire or flame for structural purposes, as well as other layer combinations and designs, should be investigated in future studies. Furthermore, the hybrid panels enable property fine-tuning; therefore, by varying the bamboo to OPT veneers ratio, a particular strength, stiffness and cost balance may be optimal for furniture application.

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