Effects of Structural Configurations on the Bending Performance and Dimensional Stability of Laminated Bamboo Made from Two *Gigantochloa* Species

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GRAPHICAL ABSTRACT

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Engineered laminated bamboo plays a crucial role in structural applications, addressing challenges such as bamboo's natural variability, species differences, adhesives, and loading direction. This study examines the bending performance of three-layered laminated bamboo configurations using two species, *Gigantochloa scortechinii* and *G. levis*, bonded with phenol-resorcinol-formaldehyde (PRF) and polyurethane (PUR) adhesives. Laminated bamboo was assembled with lay-up patterns (parallel and perpendicular) and arrangements (vertical, horizontal, and mixed). Four-point bending tests under flatwise and edgewise loading were used to determine flexural performance and failure modes. Results showed that PUR-bonded bamboo had lower thickness swelling (TS) and water absorption (WA). While bamboo species did not significantly affect bending performance, the adhesive type, lay-up pattern, and arrangement were influential. Flatwise loading improved the modulus of elasticity (MOE) by 5% but reduced the modulus of rupture (MOR) by 10% compared to edgewise loading. PRF-bonded bamboo outperformed PUR in strength, making it preferable for structural use. Vertical arrangements with PRF and PUR adhesives yielded optimal bending performance, emphasizing the importance of adhesive selection and configuration in enhancing laminated bamboo's structural properties.

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Keywords: Engineered bamboo; Laminated bamboo; Bending; Configurations; Loading direction; Failure modes

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INTRODUCTION

Bamboo is an inexpensive, environmentally friendly, and long-lasting natural resource with excellent reusing and recycling capabilities (Sharma *et al.* 2021). Due to the growing demand and scarcity of wood, bamboo products are being employed as a sustainable alternative to wood in structural applications in various regions worldwide. Bamboo is renowned for its superior strength-to-weight ratio when compared to wood, structural steel, and cast iron (Mahdavi *et al.* 2011; Huang *et al.* 2016). Because of its unique characteristic of harder outer and softer inner parts, bamboo has better flexural deformations as the tensile stress is resisted by the outer part while the softer inner part could withstand considerably high compressive deformation (Liao *et al.* 2013; Richard *et al.* 2017; Bakar *et al.* 2019). Compared to the majority of commercial wood species, bamboo possesses comparable or superior physical and mechanical properties, making it a promising substitute for wood in engineering bamboo structures (Li *et al.* 2020; Chen *et al.* 2022; Zhong *et al.* 2022).

One of the new composite materials is laminated bamboo, which is made by adhering thin, flat strips of bamboo together (combination of lay-up; parallel and perpendicular and arrangements: vertical, horizontal, and mixed). Laminate bamboo, as claimed by Sharma *et al.* (2021), is an innovative building material with growing demand as a surface material and potential as a primary engineering structural component. Because the thickness and shape of laminated bamboo panels can be tailored to meet specific requirements, they may be more advantageous than bamboo culms when used in construction and building applications (Ahmad and Kamke 2011; Verma and Chariar 2012; Sharma *et al.* 2015; Huang *et al.* 2022). Laminated bamboo exhibits mechanical characteristics akin to hardwoods and demonstrates superior compressive strength in comparison to softwoods. Additionally, it possesses enhanced tensile strength and improved resistance to fluctuations in moisture and temperature, contingent upon the specific wood species employed (Tahara *et al.* 2021). Through employing efficient connections, laminated bamboo elements can be easily extended to any desired length. It is an exceptionally renewable and environmentally sustainable substance that possesses strength, lightness, and frequently does not necessitate additional processing or finishing. According to Sharma and Van der Vegte (2020), it is obtained from more sustainable sources, experiences less shrinkage, and provides better dimensional stability. Engineered laminated bamboo offers a sustainable alternative by potentially decreasing logging activities and addressing wood shortages (Anokye *et al.* 2016).

Kumar and Mandal (2022) conducted a thorough review summarizing aspects influencing the performance of laminated bamboo panels. Among the factors listed, the most prominent ones include bamboo species, moisture content of the bamboo, and adhesive type used for manufacturing laminated bamboo panels (Correal *et al.* 2010; Li *et al.* 2013). Like most lignocellulosic materials, bamboo is a hydrophilic material that absorbs moisture from its surroundings (Siam *et al.* 2023). It is recommended that the bamboo must be properly dried prior to laminated bamboo panels fabrication as the mechanical strength of the panel reduced drastically beyond moisture content of 12% (Kibar *et al.* 2010). Bamboo collectively contains over 1,400 species in 119 genera, and therefore their basic properties vary to a great extent (Lee *et al.* 2023). Wang and Guo (2003) compared the laminated panels made of two big bamboos, namely *Dendrocalamus yunnanicus* Hsueh and *Phyllostachys heterocycla* var. *Heterocycla pubescens* and found that the former had higher mechanical strength. A study by

Sulastiningsih and Nurwati (2009) stated that although the laminated bamboo composites manufactured from *Gigantochloa apus* were characterized by higher density than that of *G. robusta*, and the bending strength values did not differ significantly among these two species.

In addition to the bamboo species, the adhesive utilized in creating laminated bamboo panels is a crucial aspect that greatly impacts the qualities of the final panels. The selection of adhesives is determined by the adhesive's exceptional mechanical, bonding, and physical characteristics, as well as its cost efficiency. Adhesives play a vital role in the production of engineered bamboo, such as glued laminated bamboo lumber, laminated bamboo board, and ply bamboo. They need to provide sufficient penetration and strong bonding between the fiber layers. Laminated bamboo is a type of construction material that has a similar appearance to wood and is used for structural purposes. According to Priyosulistyo *et al.* (2020), the bonding area between the bamboo layers is identified as a vulnerability in the structure of laminated bamboo beams. Inadequate adhesive lines hinder the movement of laminated bamboo blocks. Jimenez and Natividad (2019) studied the effects of bamboo species, adhesive type, and glue spread rate on the bending performance of arc-laminated bamboo lumber. It was discovered that the bending strength of the laminated bamboo lumber was only moderately affected by the adhesive type. Modulus of rupture (MOR) values for PVAc-bonded laminated bamboo lumber were 22% lower than those for PUR-glued laminated bamboo lumber. For example, adhesives such as phenol-resorcinol-formaldehyde (PRF) and polyurea-urea (PUR) resins are frequently used in the production of laminated boards.

However, different results on which adhesive resulted in better performance are always obtained as the manufacturing process parameters of the laminated boards using these resins are highly dependent on the species used (Yusoh *et al.* 2021). Yusof *et al.* (2019) found that PRF has superior permeability to *Acacia mangium* wood, making it more effective than PUR adhesives in bonding cross laminated timber (CLT). In gluing bamboo, the requirements for the resin might differ to that of wood. In bamboo, penetration of the resin in the bamboo samples is vital to attain satisfactory bonding characteristics. The PUR resin that relies on pore filling and mechanical interlocking may be challenging when being used for gluing bamboo (Huang *et al.* 2020).

The way the bamboo strips are assembled during the fabrication of laminated bamboo panels also affects their bending performance. A study by Lee *et al.* (2012) showed that the cross-layered laminated bamboo panel had inferior bending strength values compared to that of the parallel-layered laminated bamboo panel. However, the cross-layered laminated bamboo panels exhibited lower thickness swelling due to their small orthotropic value. Another study by Verma *et al.* (2017) reported that the bending strength of the laminated bamboo was highly influenced by the configurations of the laminates. Laminates that were assembled parallelly had superior bending strength compared to that of crossed laminates. Similar trend was also observed by Ashaari *et al.* (2016), where the compreg laminated bamboo fabricated parallelly had better bending strength than those fabricated perpendicularly.

Engineered bamboo is recognized as a promising construction material, yet it is not widely utilized as the primary structural material due to the absence of reliable and uniform design standards. Although there have been reports on laminated bamboo made from various bamboo species and adhesive types, there is a scarcity of studies specifically focused on Malaysian bamboo. Furthermore, there is a lack of research on the impact of strip arrangement and lay-up pattern on the bending performance of laminated bamboo, which needs to be addressed to ensure its optimal utilization. Varying the strip arrangement and lay-up pattern will have an impact on the ultimate thickness of the laminated bamboo and, as a result, the amount of material used. Therefore, it is worth investigating the impact of various factors, including bamboo species, adhesive type, strip arrangement, lay-up pattern, and loading directions, on the bending performance of laminated bamboo panels.

The hypothesis of this study is that the bending performance of laminated bamboo panels is significantly influenced by bamboo species, adhesive type, strip arrangement, lay-up pattern, and loading directions. Specifically, it hypothesized that different bamboo species and adhesive types, along with variation in strip arrangement and lay-up pattern, result in distinct changes in the mechanical properties of the panels such as modulus of elasticity (MOE) and modulus of rupture (MOR).

EXPERIMENTAL

Converting Bamboo Culm into Strips

Two bamboo species that are highly used by the local manufacturers and crafters, namely beting (*Gigantochloa levis*) and semantan (*G. scortechinii*), were collected from a plantation close to Nami, Kedah, Malaysia. The harvested bamboo culms were cut down to a length of 2,000 mm and processed while in green condition with a moisture content of 50 to 70% which is preferred by local manufacturer for the split and strips process. The culms were initially split into 22 mm wide pieces, then trimmed and planed to a final width of 20 mm and strips with a thickness of 5 mm were obtained. Prior to the fabrication process for laminated bamboo panels, the bamboo strips were treated with 5% boric acid and were dried to 12 ± 5% moisture content using a kiln dryer to provide short-term protection against biodeterioration agents. The moisture content was assessed using a portable device and calculated based on random strips, as specified in EN 13183-1 (2002).

Fabrication of 3-layer Laminated Bamboo Panels

The production of 3-layer laminated bamboo panels used two types of adhesives. Phenol-resorcinol-formaldehyde (PRF) and polyurethane (PUR), supplied by AkzoNobel Sdn. Bhd., Petaling Jaya, were used as a binder to bond laminated bamboo panels with varying configurations (lay-up pattern and strip arrangement) in this study. The bamboo strips were arranged in a horizontal, vertical, and mixed pattern across three layers. The lay-up patterns ranged from parallel to perpendicular. The samples were labelled using three letters, where the first letter B and S represent bamboo species (B – Beting (*G. levis*) and S – Semantan (*G. scortechinii*)) while the second letter of P and U represent PRF and PUR, respectively. The last letter A and B represent parallel and perpendicular lay-up. The bamboo strips were assembled in a vertical orientation for the middle panel and in a horizontal orientation for the outer two. Layouts of all patterns were either parallel (0° to the next layer) or perpendicular (90° to the next layer). In this study, a total of six different configurations were produced. For the PRF resin, the glue spread was 250 g/cm^2, and for the PUR adhesives, it was 200 g/m^2. The PRF adhesive had a mixing ratio of 100:25 adhesive to hardener), with a viscosity ranging from 350 to 1,000 mPas, a pH of 7.5 to 8.5, and a dry content of 55 to 95%. Meanwhile the viscosity of the PUR adhesive ranged from 2,000 to 3,500 mPas. All data were obtained from the supplier's technical data sheet, which also provided recommendations for the spread rate and mixing ratio.

Following assembly, the laminates were pressed for 4 h at 75 kg/cm^2 for edge bonding and 125 kg/cm^2 for face bonding using a laboratory hydraulic press (Carver CMG 100H-15, Ontario, NY, USA) under ambient temperature. A total of 144 panels, 1220 mm long and 300 mm wide, were produced (2 species x 2 adhesives x 6 configurations x 6 replications). Vertically, the final panels measured 54 mm in thickness, while horizontally they measured 13 mm, and the mixed pattern measured 27 mm.

Physical Properties Evaluation of Laminated Bamboo Board

The test apparatus used for the physical and bending tests adheres to the European standard for the laminated bamboo board. A total of 288 specimens (12 replicates × 2 species × 2 adhesives × 2 lay-ups pattern × 3 arrangements) and 576 specimens (12 replicates × 2 species × 2 adhesives × 2 lay-ups pattern × 3 arrangements × 2 loading direction) were tested for physical properties and bending properties, respectively.

Moisture Content (MC)

Laminated bamboo panels were selected at random to measure the MC as specified in EN 13183-1 (2002) (Oven dry method). The samples were oven dried at 103 ± 2 °C for 24 h, or until the variability between two separate measurements was less than 1%. The MC was then calculated using Eq. 1,

$$MC\ (\%) = [(M_1 - M_0)/M_0] \quad (1)$$

where M_1 is the weight before dry bamboo (g); and M_0 is the weight of oven dried bamboo (g).

Density

The volume of the panels was obtained by measuring their length, width, and thickness. Next, the samples were weighed to obtain their weight. The samples' densities were determined by dividing their mass by their respective volumes. The density was expressed in kg/m^3.

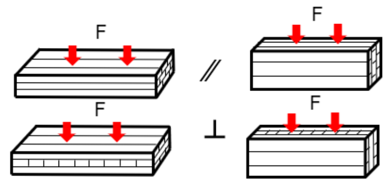
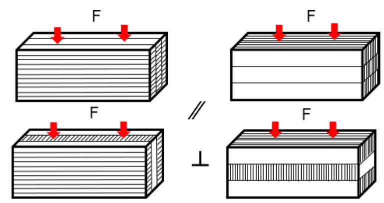
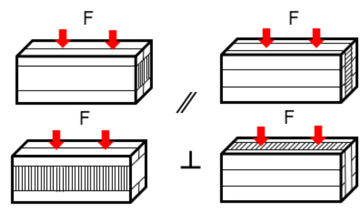
Water Absorption (WA) and Thickness Swelling (TS)

The water absorption (WA) and thickness swelling (TS) of the samples were conducted in accordance with EN 317 (1993). Rectangular samples with 20 mm x 20 mm were submerged in water at room temperature for 24 h. The water absorption and thickness swelling of the samples were then calculated based on the changes of thickness and weight before and after soaking. The results are expressed in percent (%).

Four-point Bending Test Evaluation

The test apparatus for the bending tests were set up in accordance with European standard BS EN 408:2010+A1 (2012) and referred to ISO 23478 (2022) and prEN 16351 (2015) standard. An Instron Universal Testing Machine (Norwood, MA, USA) with a force capacity of 100 kN was used. The bending tests of the laminated bamboo panels produced in this work were performed edgewise and flatwise. The dimensions and loading direction are shown in Table 1. All the strength were adjusted at 12% moisture content according to EN 384:2016+A2 (2022).

Table 1. Dimensions of Laminated Bamboo Panels for Four-Point Bending Test

Test Item	Configurations	Dimension (mm) Flatwise Edgewise
Bending	Horizontal	300 × 20 × 13 
	Vertical	1080 × 54 × 54 
	Mixed	540 × 27× 27 

The load was applied at a constant rate and the rate of movement of the loading head was not greater than 0.003h mm/s. Flexural test measures the force that required bending a beam under four- point loading conditions. The test pieces were symmetrically loaded bending at two points over a span of 18 times the depth. The bending strength (or MOR) and stiffness (or MOE) of the individual test piece was calculated using the following Eq. 2 and 3,

$$\text{Modulus of rupture (N/mm}^2\text{)} = FL/bd^2 \qquad (2)$$

where F is load at a given point on the load deflection curve, N; L is support span, mm; b is width of test specimens, mm; and d is depth of test specimens, mm.

$$\text{Modulus of elasticity (N/mm}^2\text{), global} =$$

$$(3al^2 - 4a^3)/(2bh^3 \quad [2(F_2 - F_1)/((w_2 - w_1)) - 6a/5Gbh]) \qquad (3)$$

where F_2 - F_1 is an increment of load on the straight-line portion of the load deformation curve, N; a is distance between loading position and the nearest support in bending test, mm; W_2 - W_1 is the increment of deformation corresponding to F_2 - F_1, mm; G is the shear modulus, which shall be taken as infinite; l is span in bending, or length of test piece between the testing machine grips; b is width of test specimens, mm; and h is depth of test specimens, mm.

Statistical Analysis

The study results were analyzed using analysis of variance (ANOVA) to compare means. The *post hoc* test, which is the Least Significant Difference (LSD) method, was used for mean separation at a significant level of $p \leq 0.05$. The analysis was performed with the SAS System for Windows 9.0, © 2002 SAS Institute Inc., Cary, NC, USA.

RESULTS AND DISCUSSION

Physical Properties of Laminated Bamboo Panels

Density

The density of the laminated bamboo panels manufactured in this study ranged from 733 to 803 kg/m^3 for *G. scortechinii* and 665 to 793 kg/m^3 for *G. levis*, respectively (Table 2). The density of both bamboo species is significantly influenced by the arrangement of strips in both vertical and horizontal orientations. The horizontal and mixed arrangement of *G. levis* resulted in a higher density compared to *G. scortechinii*, with an increase of 5 to 10%. These results were higher compared to the study by Brito *et al.* (2018), who determined average density values of 550 to 560 kg/m^3 for laminated bamboo panels made from *G. apus* and *G. robusta* but it is comparable to Sulastiningsih and Nurwati (2009), who found laminated bamboo from *G. apus* and *G. robusta* to have an average density of 730 kg/m^3. Despite the fact that each adhesive had a different spread rate (250 g/m^2 for PRF and 200 g/m^2 for PUR), the density of some laminated bamboo from PUR adhesive was higher than that of PRF. Ogunsanwo *et al.* (2019) determined no significant differences in density of the panels using *B. vulgaris* and PVAc adhesive with varying spread rates.

Table 2. Density of Laminated Bamboo Panels Fabricated in this Study

Label	Variable			Density (kg/m³) Adjusted at 12% MC		
	Species	**Adhesive**	**Lay-up**	**Vertical**	**Horizontal**	**Mixed**
BPA	*G. levis*	PRF	Parallel	760.55^B (26.76)	757.97^A (61.56)	777.07^A (49.73)
BPB	*G. levis*	PRF	Perpendicular	749.39^C (25.46)	780.28^A (97.54)	733.06^B (29.21)
BUA	*G. levis*	PUR	Parallel	780.87^B (32.37)	785.46^A (31.45)	776.42^A (56.47)
BUB	*G. levis*	PUR	Perpendicular	803.31^A (28.24)	651.07^C (47.42)	790.85^A (33.93)
SPA	*G. scortechinii*	PRF	Parallel	792.88^A (26.61)	665.27^B (87.36)	734.22^B (32.45)
SPB	*G. scortechinii*	PRF	Perpendicular	769.37^B (30.75)	672.41^B (37.26)	763.54^A (19.22)
SUA	*G. scortechinii*	PUR	Parallel	771.59^B (14.78)	694.21^B (64.89)	745.23^B (41.37)
SUB	*G. scortechinii*	PUR	Perpendicular	761.02^B (19.62)	716.95^B (52.45)	731.12^B (10.96)

Note: The values in parentheses represent the standard deviation
Mean followed by the same letters in the same column are not significantly different at $p \leq 0.05$

Moisture Content (MC)

As shown in Table 3, the MC values of laminated bamboo ranged from 11.1 to 13.7% (*G. scortechinii*) to 10.2 to 14.2% (*G. levis*), respectively. The moisture content values consistently fell within the acceptable range of air-dried moisture content, which is 12 ± 2%. This range is suitable for any lamination process. Due to the different thicknesses of the laminated bamboo panels, the panels with vertical arrangement exhibited higher density and MC values than the mixed and horizontally arranged panels. The density of laminated bamboo boards made from PUR resin was the highest among all configurations. Vertical laminated bamboo panels have a higher density, being 1 to 3% denser, and can retain more moisture, with a capacity 1 to 5% greater, compared to horizontal and mixed configurations.

Table 3. Moisture Content of Laminated Bamboo Boards Fabricated in this Study

Label	Variable			Moisture Content (%)		
	Species	**Adhesive**	**Lay-up**	**Vertical**	**Horizontal**	**Mixed**
BPA	*G. levis*	PRF	Parallel	13.2^{C} (0.48)	13.06^{A} (0.43)	11.45^{B} (0.38)
BPB	*G. levis*	PRF	Perpendicular	13.73^{B} (0.36)	13.28^{A} (0.53)	11.1^{C} (0.28)
BUA	*G. levis*	PUR	Parallel	12.22^{E} (0.19)	12.16^{B} (0.5)	11.26^{B} (0.33)
BUB	*G. levis*	PUR	Perpendicular	12.15^{E} (0.26)	11.37^{C} (0.54)	11.89^{A} (0.20)
SPA	*G. scortechinii*	PRF	Parallel	13.59^{B} (0.55)	12.98^{A} (1.02)	10.9^{C} (0.28)
SPB	*G. scortechinii*	PRF	Perpendicular	14.19^{A} (0.65)	13.08^{A} (0.31)	11.2^{B} (0.21)
SUA	*G. scortechinii*	PUR	Parallel	12.66^{D} (0.17)	11.33^{C} (0.85)	10.6^{D} (0.5)
SUB	*G. scortechinii*	PUR	Perpendicular	12.38^{D} (0.21)	12.06^{B} (0.4)	10.15^{E} (0.3)

Note: The values in parentheses represent the standard deviation
Mean followed by the same letters in the same column is not significantly different at $p \leq 0.05$

Water Absorption and Thickness Swelling

A graphical representation of the WA and TS values of the laminated bamboo panels, fabricated in the laboratory with vertical, horizontal, and mixed arrangements, is shown in Fig. 1. After 4 h of immersion in water, the panels bonded with PRF resin exhibited WA values ranging from 7.97% to 14.33% (*G. levis* parallel), 13.18 to 25.59% (*G. levis* perpendicular), 4.97 to 19.64% (*G. scortechinii* parallel), and 12.44 to 21.65% (*G. scortechinii* perpendicular), respectively. Meanwhile, the laminated bamboo panels bonded with PUR resin displayed WA values as follows: 1.95 to 6.56% (*G. levis* parallel), 6.82 to 28.64% (*G. levis* perpendicular), 6.81 to 23.53% (*G. scortechinii* parallel), and 10.55 to 20.04% (*G. scortechinii* perpendicular), respectively, after 4 h of water immersion. After 48 h of immersion in water, WA values of 32.88 to 40.11% (*G. levis* parallel), 34.11 to 53.15% (*G. levis* perpendicular), 32.11 to 44.98% (*G. scortechinii* parallel), and 36.92 to 55.17% (*G. scortechinii* perpendicular), respectively, were recorded for the laminated bamboo panels bonded with PRF resin. The panels, bonded with PUR resin displayed WA values of 28.51 to 33.21% (*G. levis* parallel), 28.72 to 59.96% (*G. levis* perpendicular), 34.82 to 54.81% (*G. scortechinii* parallel), and 36.14 to 45.83% (*G. scortechinii* perpendicular), respectively.

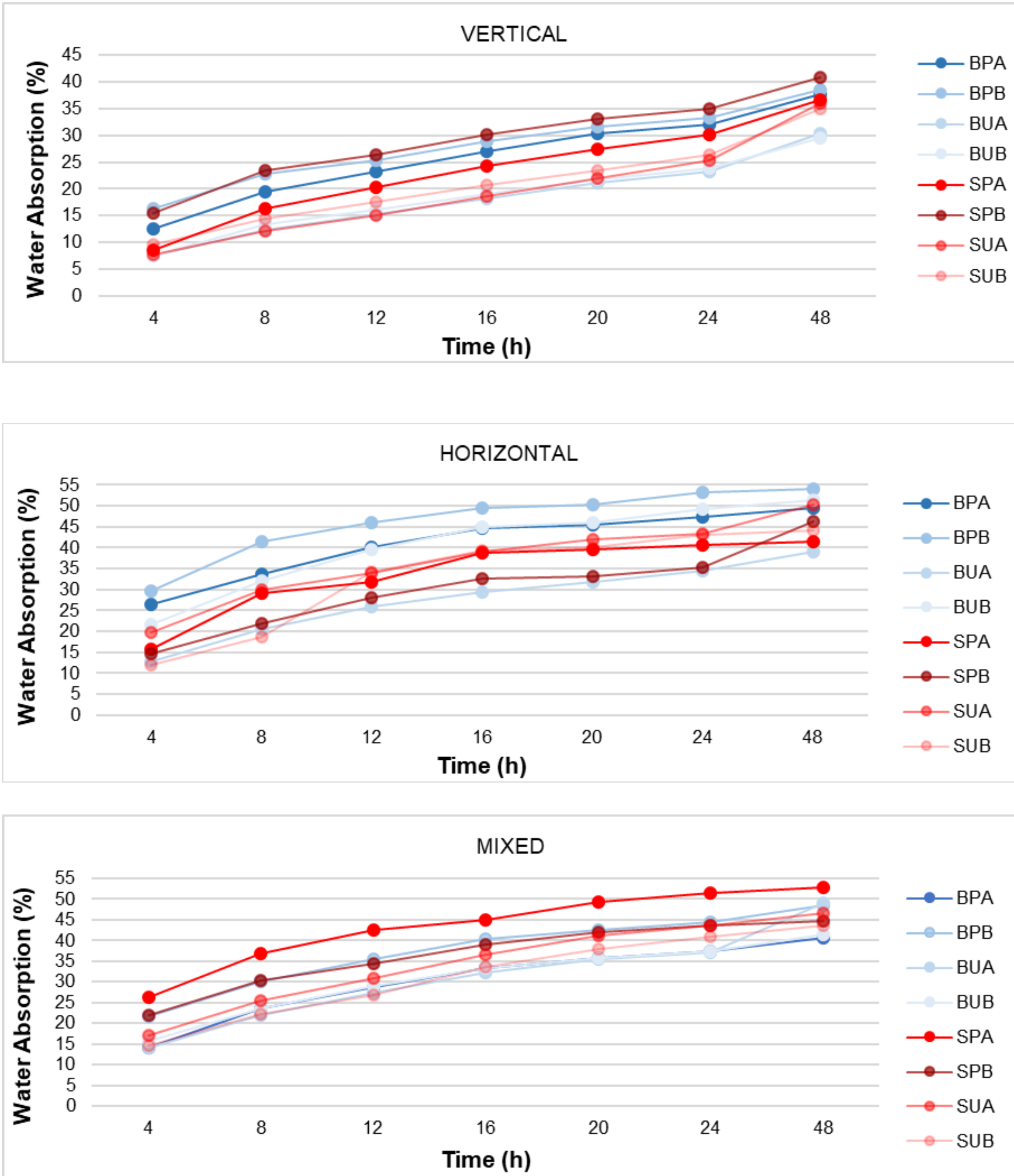


Fig. 1. Effects of bamboo species, adhesive type, and configurations on the water absorption of laminated bamboo panels

A graphical representation of the TS values of laminated bamboo panels after 4 h of immersion in water is given in Fig. 2. The panels, fabricated with PRF resin exhibited TS values of 0.32 to 0.90% (*G. levis* parallel), 0.42 to 1.39% (*G. levis* perpendicular), 0.26 to 2.55% (*G. scortechinii* parallel), and 0.40 to 0.73% (*G. scortechinii* perpendicular), respectively.

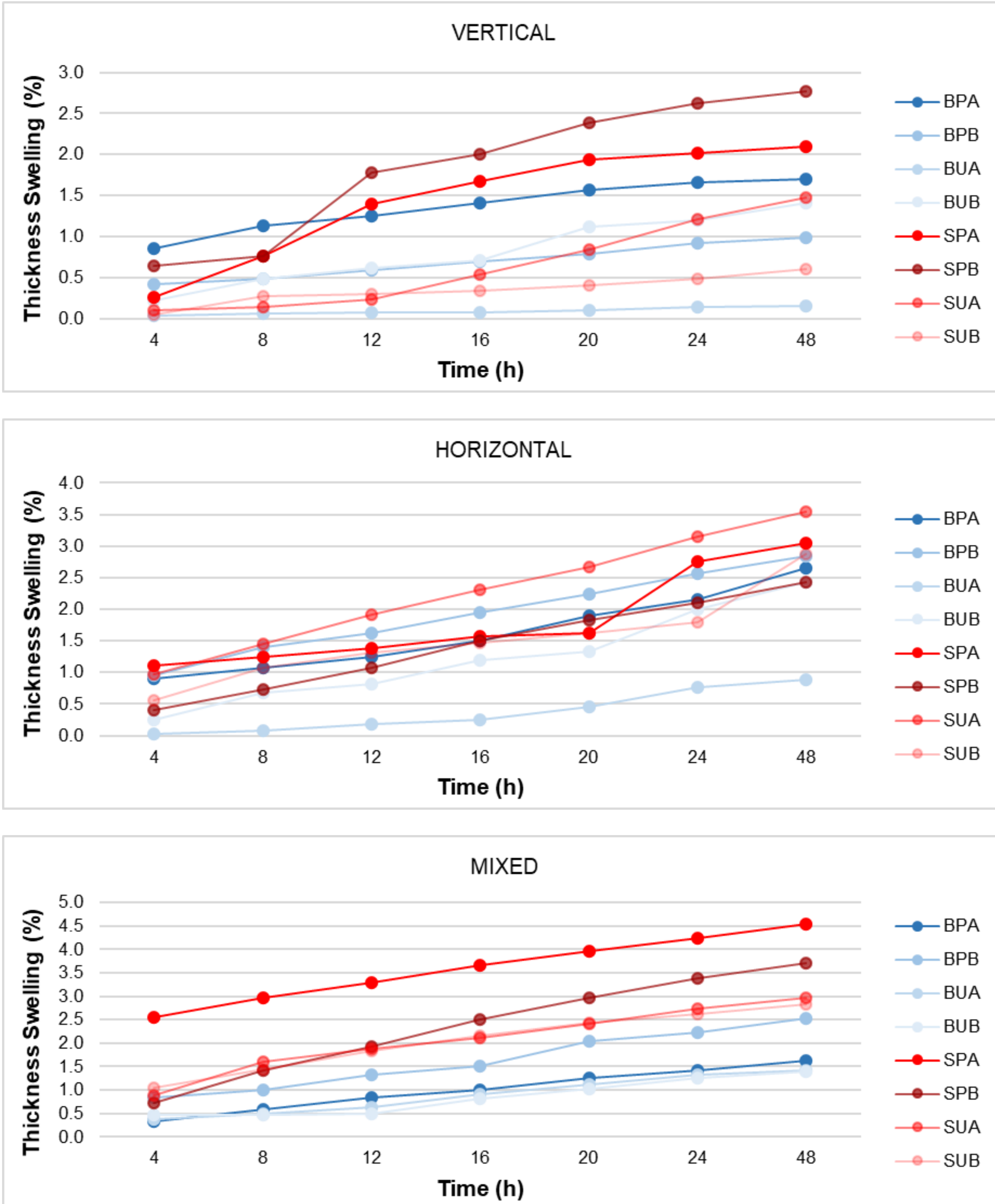


Fig. 2. Effects of bamboo species, adhesive type, and configurations on the thickness swelling of laminated bamboo panels

Meanwhile, the laminated bamboo panels bonded with PUR resin had TS values of 0.03 to 0.39% (*G. levis* parallel), 0.05 to 0.24% (*G. levis* perpendicular), 0.10 to 0.97% (*G. scortechinii* parallel), and 0.05 to 1.04% (*G. scortechinii* perpendicular), respectively, after 4 h of water immersion. After 48 h of water immersion, TS values of 1.62 to 2.64% (*G. levis* parallel), 0.98 to 3.15% (*G. levis* perpendicular), 2.04 to 4.54% (*G. scortechinii* parallel), and 2.42 to 3.71% (*G. scortechinii* perpendicular), respectively, were recorded for the laminated panels bonded with PRF resin. In contrast, the panels bonded with PUR resin displayed TS values of 0.16 to 1.42% (*G. levis* parallel), 1.40 to 2.74% (*G. levis* perpendicular), 1.47 to 3.54% (*G. scortechinii* parallel), and 0.60 to 2.83% (*G. scortechinii* perpendicular), respectively.

Markedly, the laboratory-made laminated bamboo panels bonded with PUR resin had lower TS and WA values than that of PRF-bonded specimens. It was also apparent that the laminated bamboo panels fabricated with vertical arrangement were more dimensionally stable as all the panels showed TS values less than 3% and absorbed less water (~ 40%) after 48 h immersion in water. The lower water uptake, attributed to the panels reduced moisture content, consequently resulted in minimal TS. These findings suggest that initial moisture content can be considered to be a key parameter in estimating both WA and TS. The PUR is known for its hydrophobic nature because of its non-polar structure; therefore, lesser water was able to infiltrate into the laminated panels (Sugahara *et al.* 2022). A study by Wimmer *et al.* (2013) showed that cured PRF resin had a moisture uptake of 18% while PUR was 3.5%. This also explained the lower WA values in PUR-bonded laminated bamboo panels. In contrast, vertically arranged panels exhibited better dimensional stability, *i.e.*, lower TS, probably due to the higher amount of adhesive in the samples. Vertical samples contained 3 layers of face-glued strips and therefore the surface contact area of the adhesive was higher than the other two arrangements, bestowing better resistance against water infiltration.

Bending Performance of Laminated Bamboo Panels

MOE and MOR edgewise

Overall, as shown in Table 4, the lay-up pattern exerted the most significant effect on bending properties of the laminated bamboo and it was the most significant factor that affects the MOE and MOR. Adhesive type also exerted significant influence on the MOE values of vertically and horizontally assembled panels and less significant on the panels with mixed arrangement.

Table 4. Summary of the Analysis of Variance (ANOVA) for the Effects of Studied Variables on the Bending Performance of Laminated Bamboo Panels of Different Configurations

Source	p-value					
	MOE			**MOR**		
	Vertical	**Horizontal**	**Mixed**	**Vertical**	**Horizontal**	**Mixed**
Species	0.0123 *	0.7572 ns	0.0016 **	<0.0001 ***	0.0112 **	0.1341 ns
Adhesive	<0.0001 ***	<0.0001 ***	0.0036 **	0.0277 *	<0.0001 ***	0.0018 **
Lay-up	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***
Loading direction	0.0249 *	<0.0001 ***	0.7690 ns	<0.0001 ***	<0.0001 ***	<0.0001 ***

Note: ns $p > 0.05$; * Significantly different at $p < 0.05$; ** Significantly different at $p < 0.01$

Bamboo species had significant effect on the panels with mixed arrangement and slight effect on the panels with vertical arrangement but did not show significant influence on the laminated bamboo fabricated with horizontal arrangement of bamboo strips. Loading direction, on the other hand, significantly affected the MOE values of the horizontal panels. It slightly affected the MOE values of the vertical panels, and had no significant effect on the panels with mixed arrangement. Regarding the MOR values, lay-up and loading direction were the most influential factors in all types of laminated bamboo panels. Adhesive type also affected the MOR values of the panels to a lesser extent compared to the former mentioned factors. Bamboo species significantly affected the MOR values of the panels fabricated with vertical arrangement.

Graphical representations of the edgewise MOE and MOR values of the laminated bamboo panels, manufactured in the laboratory with different bamboo species, adhesive types, lay-up pattern, and strip arrangement, are shown in Figs. 3 and 4. Generally, vertically arranged laminated bamboo panels exhibited higher edgewise MOE values compared to the values determined for the mixed and horizontally arranged panels. The panels with horizontal strip arrangement performed poorly in MOE edgewise. However, horizontally arranged laminated panels displayed higher MOR edgewise compared to that of the other two arrangements (vertical and mixed). The MOE edgewise of the panels with parallel lay-up was higher than that in perpendicular, particularly in the panels having mixed strip arrangement by 150% in mixed, 40% in vertical, and 30% in horizontal arrangement, respectively (Fig. 4). The MOR edgewise in the parallel lay-up panels was higher than that in perpendicular direction, particularly in the mixed arrangements by 205% in mixed, 68% in horizontal, and 29% in vertical patterns, respectively.

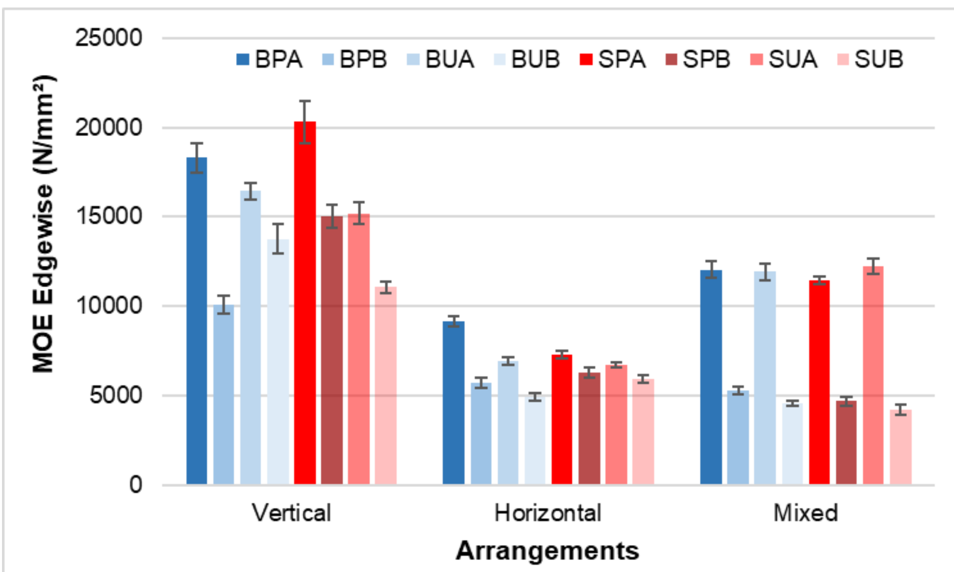


Fig. 3. Effects of bamboo species, adhesive type, and configurations on the edgewise MOE values of laminated bamboo panels

The strength and stiffness of laminated bamboo under load are largely influenced by its mechanical properties, particularly density, fiber orientation, and adhesive. Bamboo density varies by species and growth conditions and influenced its strength properties. Higher density improves bending MOE and MOR, while lower density weakens structural performance (Kadivar 2020). Proper lamination also improves load distribution and prevents failure in laminated bamboo. Sugiyama *et al.* (2017) found that aligning fibers with the load direction increased bending strength by up to 50%.

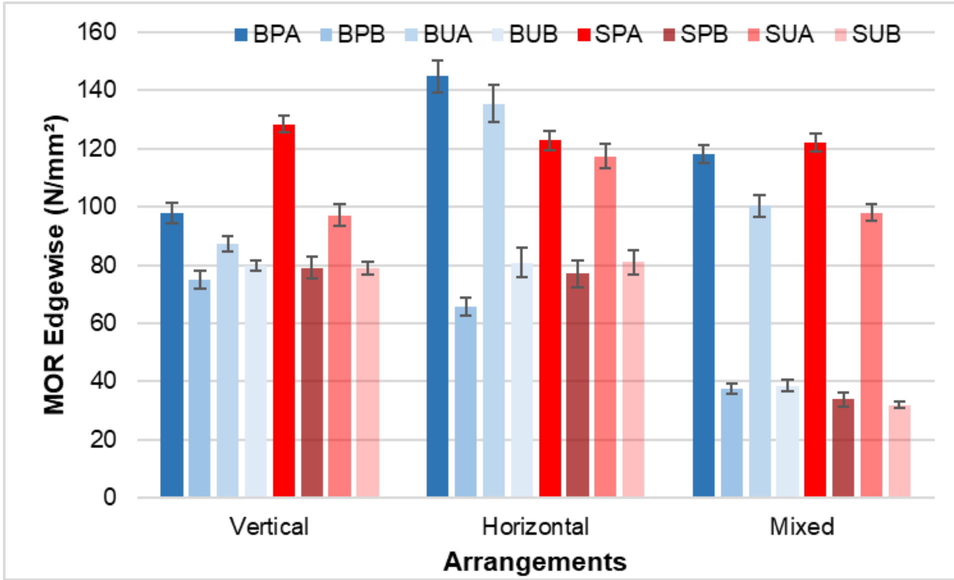


Fig. 4. Effects of bamboo species, adhesive type, and configurations on the edgewise MOR values of laminated bamboo panels

Horizontally arranged laminated bamboo panels, having the lowest thickness of 13 mm, displayed higher MOR values edgewise than the thicker panels with vertical (54 mm) and mixed (27 mm) arrangements. The results revealed that the effects of bamboo species were not obvious, but the lay-up pattern did exhibit significant effects on both MOE and MOR edgewise values of the panels. The MOE and MOR edgewise of the panels with parallel layup were higher than that in perpendicular, particularly in the panels having mixed strip arrangement. Generally, PRF-bonded panels performed slightly better compared to the PUR-bonded specimens. The quality and type of adhesive plays a crucial role in the mechanical performance of laminated bamboo, as insufficient penetration can weaken bonding strength and reduce bending capacity. However, studies by Chen and O'Kane (2019) found different results, where polyurethane-based adhesive significantly improved bending strength due to their superior flexibility and bonding properties.

MOE and MOR flatwise

Similar to the trend observed in MOE edgewise, vertically arranged laminated bamboo panels demonstrated higher MOE flatwise than horizontally and mixed panels (Fig. 5). The flatwise MOE values of the panels manufactured with parallel lay-up were higher compared with the panels having perpendicular lay-up, while the effects of bamboo species and adhesive type were not significant. The value of MOE flatwise (Fig. 5) for the parallel panels was from 24% to 70% higher than the respective value in perpendicular. Because of its thickness, the panels with vertical arrangements performed better than horizontal and mixed arrangements. Arranging the strips in horizontal pattern resulted in an almost similar flatwise MOE value as in the mixed arrangements despite having almost two times less thickness compared to the panels produced with mixed arrangement. As seen from Fig. 6, the flatwise MOR value of the panels having parallel lay-up was higher than the respective value of the panels fabricated with perpendicular lay-up in all strip arrangements by 240% in mixed, 100% in horizontal, and 47% in vertical patterns, respectively.

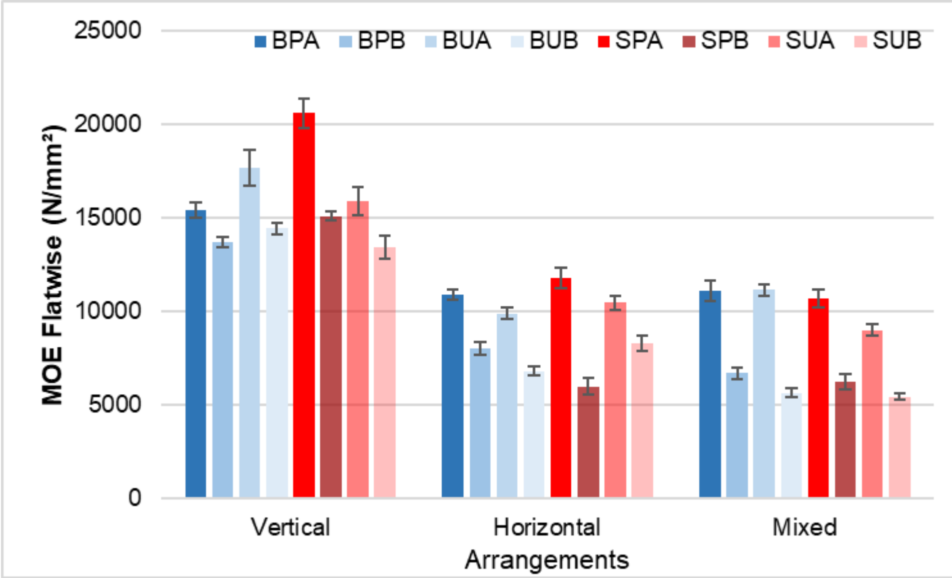


Fig. 5. Effects of bamboo species, adhesive type, and configurations on the flatwise MOE values of laminated bamboo panels

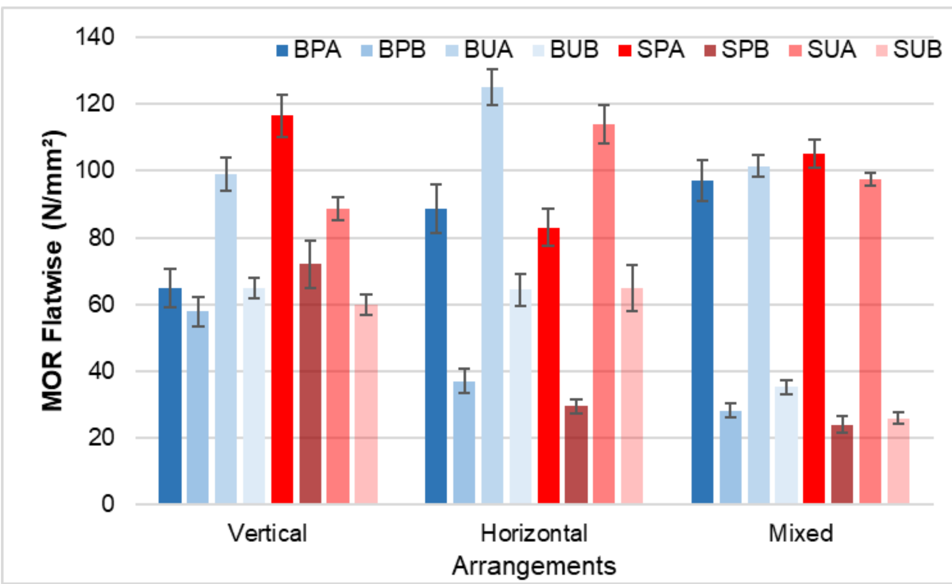


Fig. 6. Effects of bamboo species, adhesive type, and configurations on the flatwise MOR values of laminated bamboo panels

Overall, laminated bamboo panels have strong mechanical properties in both configurations, but their bending performance varies due to difference in bamboo characteristics, adhesives and manufacturing processes. Variation in density, species and fiber orientation affect the strength, with bamboo's natural anisotropy causing inconsistencies (Deng *et al.* 2014; Li *et al.* 2016; Sharma and Vegte 2020). Adhesive bonding is crucial as poor penetration or improper selection weakens structural integrity (Syaifudin *et al.* 2022). Manufacturing factors such as pressure curing temperature and layer arrangement also significantly impact performance which influencing load distribution and mechanical stability (Almeida *et al.* 2017; Darmo and Sutanto 2023). By optimizing material selection, adhesive and precise manufacturing control is essential for improving reliability of MOE and MOR laminated bamboo panels.

Effects of Single Variable on the Bending Strength

The bending strength of the laminated bamboo board did not show significant variation between *G. levis* and *G. scortechinii*, as indicated by the MOE and MOR values (Table 5), which is consistent with the findings of Sulastiningsih and Nurwati (2009). For this study, bamboo from the same *Gigantochloa* genus was utilized, suggesting that it is expected to result in minimal variation in bending strength. The PRF-bonded laminated bamboo panels displayed significantly higher MOE but lower MOR values than the PUR-bonded counterparts, indicating that the adhesive types are an influential factor. PUR is a foaming adhesive, while PRF resin is characterized by good permeability. The PUR resin can penetrate wood cell walls under high pressure, while PRF can penetrate even under low pressure (Li *et al.* 2021). Therefore, despite many studies have reported the inferiority of PUR in gluing wood and bamboo (Yusof *et al.* 2019; Yang *et al.* 2022; Dong *et al.* 2023), in this study it has been confirmed that the PUR could yield a satisfactory mechanical properties provided sufficient pressure is applied.

Table 5. Comparison Between Effects of Variables on the Bending Performance (MOE and MOR Values) of Laminated Bamboo Panels

Variable	**Bending**	
	MOE (N/mm²)	MOR (N/mm²)
Species		
Beting (*G. levis*)	10,444.7^{A}	80.20^{A}
Semantan (*G. scortechinii*)	10,556.2^{A}	81.21^{A}
Adhesive		
PRF	10,913.5^{A}	79.44^{B}
PUR	10,087.4^{B}	81.97^{A}
Lay-up		
Parallel	12,606.8^{A}	106.26^{A}
Perpendicular	8,394^{B}	55.15^{B}
Arrangement		
Vertical	15,402^{A}	84.19^{B}
Horizontal	7,818.6^{C}	89.46^{A}
Mixed	8,280.7^{B}	68.46^{C}
Loading direction		
Flatwise	11,019.1^{A}	72.68^{B}
Edgewise	9,981.8^{B}	88.73^{A}

Both lay-up patterns and strip arrangements significantly affected the bending performance of the laminated bamboo panels. The laminated bamboo panels with parallel lay-up outperformed those with perpendicular lay-up. These findings are consistent with the reported results in previous studies (Ashaari *et al.* 2016; Verma *et al.* 2017; Mnaik *et al.* 2021) as wood or woody materials generally have the highest strength when the fiber's inclination angle with respect to the length axis is zero and *vice versa* when the angle was 90°. Manik *et al.* (2021) found that laminated bamboo panels with parallel lay-up or on-axis laminas direction (0°) exhibited matrix fracture first, followed by laminate fracture during bending tests. Laminated panels with perpendicular lay-up or off-axis direction (90°) failed by matrix fracture and lamina fracture at the bottom of the specimen, followed by delamination in the 90° direction. The poorer bending strength of perpendicularly lay-up laminated bamboo panels compared to parallel panels is attributed to debonding of adhesion between laminas caused by delamination.

In terms of MOE, the panels fabricated with vertical arrangement performed much better than the horizontal and mixed pattern specimens. The highest MOE values were observed in the vertically arranged laminated bamboo panels, which might be attributed to their higher bamboo volume fraction. Vertical arrangement panels are constituted of three-layer face-glued laminae compared to mixed (2 face-glued laminae on face and back and 1 edged-glued laminae as core) and horizontal ones (3 edged-glued laminae). Face-glued laminae consist of more strips per length unit and, therefore, the vertically arranged laminated bamboo panels would have higher bamboo volume fraction. Penellum *et al.* (2018) found a significant correlation between the bamboo volume fraction and the bending stiffness of the panels. According to the authors, the increased bending stiffness was most likely due to the increased bamboo volume fraction. Contrarily, for MOR, horizontal panels outperformed those with vertical and mixed arrangements. Sikora *et al.* (2016) reported that the thinnest 3-layered panels had the highest bending strength while the thickest 3-layered panels had the highest bending stiffness, which is consistent with this study's findings.

Laminated bamboo panels had higher MOE values in flatwise direction and higher MOR values in edgewise direction. In accordance with the findings of Burdurlu *et al.* (2007), the flatwise loading direction of laminated veneer lumber (LVL) exhibited a higher MOE than the edgewise loading direction. In contrast, LVL in edgewise direction has higher MOR than flatwise. However, dissimilar with the current study where the effect of loading directions is significant, in their study Burdurlu *et al.* (2007) reported that the load direction is not a significant influential factor that affects the bending strength of the laminated products. Hou *et al.* (2022) also found that the MOE in the flatwise direction is slightly higher than the MOE in edgewise direction.

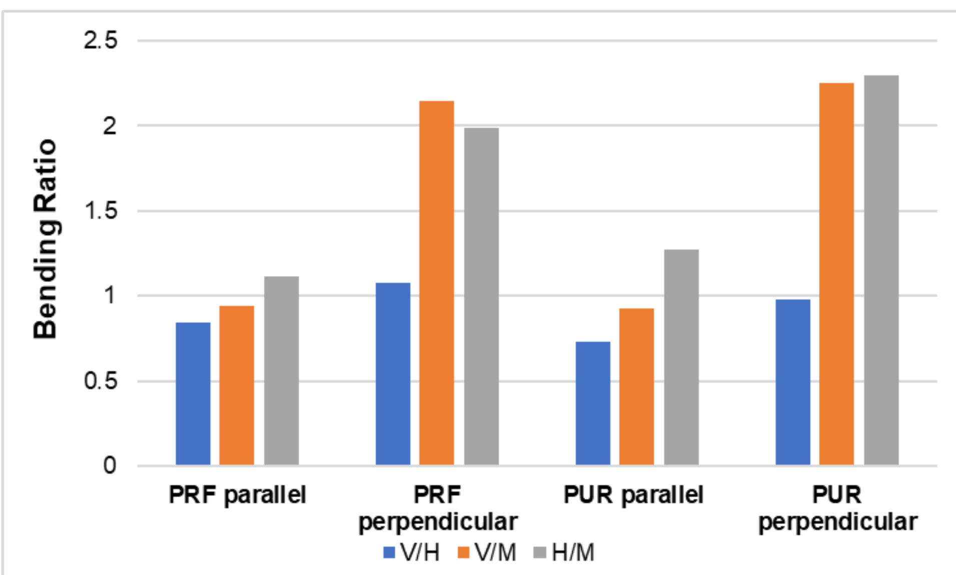


Fig. 7. Edgewise bending strength ratios of each arrangement of vertical (V), horizontal (H), and mixed (M) pattern

Graphical representations of the edgewise and flatwise bending ratios of each arrangement are depicted in Figs. 7 and 8 to examine the effects of strips arrangements in a more detailed manner.

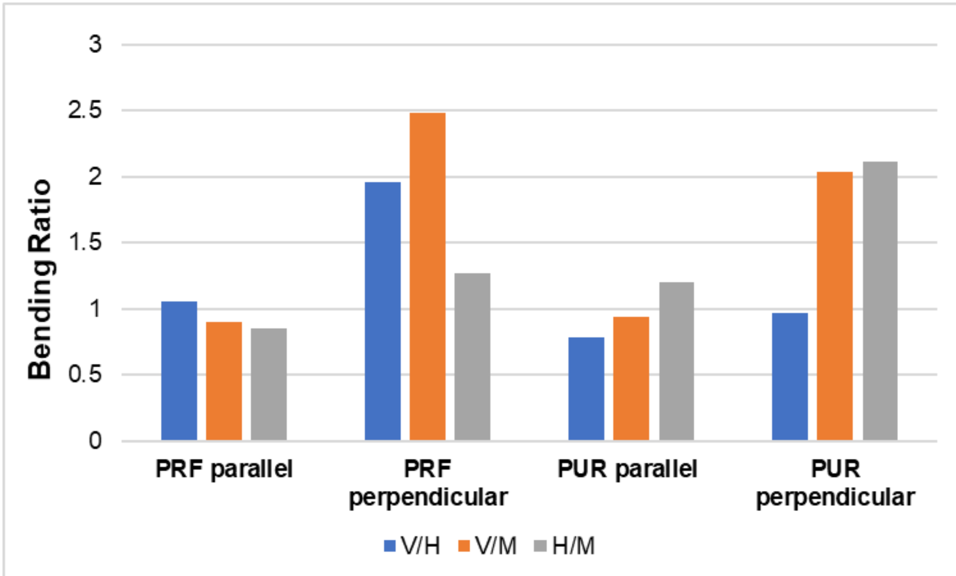


Fig. 8. Flatwise bending strength ratios of each arrangement of vertical (V), horizontal (H), and mixed (M) pattern

For edgewise bending, the bending strength ratios of parallelly lay-up laminated bamboo panels ranged from 0.85 to 1.11 for PRF-bonded boards and from 0.73 to 1.27 for PUR-bonded boards, respectively. The bending strength ratios of laminated bamboo panels that were assembled perpendicularly ranged between 1.08 to 2.15 for PRF-bonded boards and 0.98 to 2.30 for PUR-bonded boards. Meanwhile, for flatwise bending, the bending strength ratios of parallelly lay-up laminated bamboo panels ranged from 0.85 to 1.06 for PRF-bonded boards and 0.78 to 1.20 for PUR-bonded boards, respectively. The bending strength ratios of laminated bamboo that were assembled perpendicularly varied from 1.27 to 2.48 for the PRF-bonded panels and from 0.96 to 2.11 for PUR-bonded specimens. The results revealed that the strip arrangement exerted different effects on the laminated bamboo panels with different lay-up pattern. Because the bending ratios of the laminated bamboo panels were close to 1, the effect of the strip arrangement was minimal. The perpendicularly assembled laminated panels exhibited a much broader variation in bending strength to parallel panels due to strip arrangement. For PUR-bonded laminated bamboo panels, the horizontal arrangement provided the highest bending resistance both edgewise and flatwise.

Specific MOE and MOR

It was noted that the density of the laminated bamboo panels fabricated in the study ranged between 672.8 and 898.8 kg/m^3, which may have exerted significant effect on MOE and MOR values of the panels. Therefore, to eliminate the density effect, specific MOE (SMOE) and specific MOR (SMOR) values were calculated and presented in Table 6. Laminated bamboo panels bonded parallelly with PRF and PUR adhesives in vertical arrangement represent the most reasonable combinations when considering the

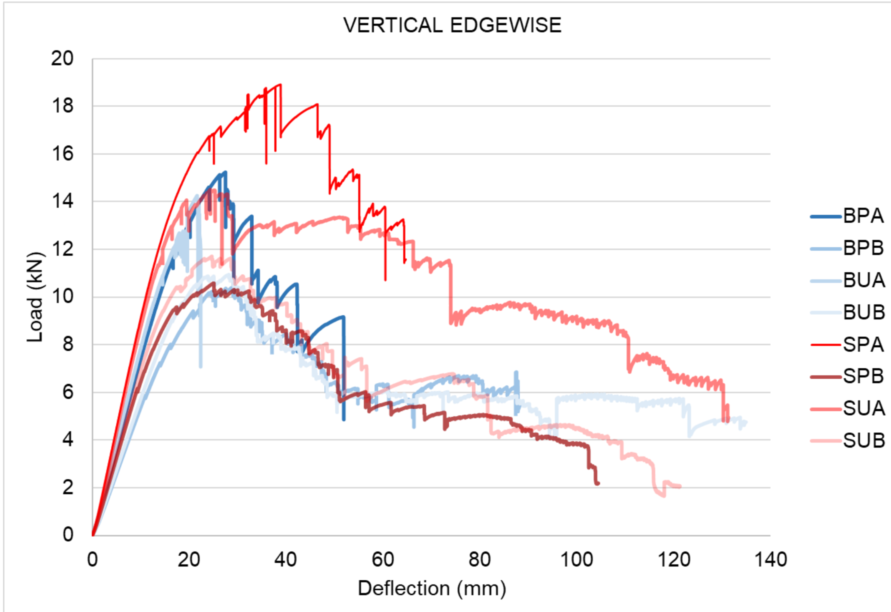
SMOE and SMOR values. However, it should be noted that the thickness of the vertically arranged laminated bamboo was 54 mm. In fact, laminated bamboo panels produced with horizontal arrangement (13 mm thickness) might be a promising alternative as they demonstrated better SMOR values in comparison with the vertical counterparts. Despite its 4-time smaller thickness than vertical panels, horizontal boards showed less than 2 times lower SMOE values. Therefore, with regard to raw material optimization, the horizontal panels outperformed the panels fabricated with vertical and mixed arrangements.

Table 6. SMOE and SMOR Values of Laminated Bamboo Panels Fabricated with Different Bamboo Species, Adhesive Types, and Configurations

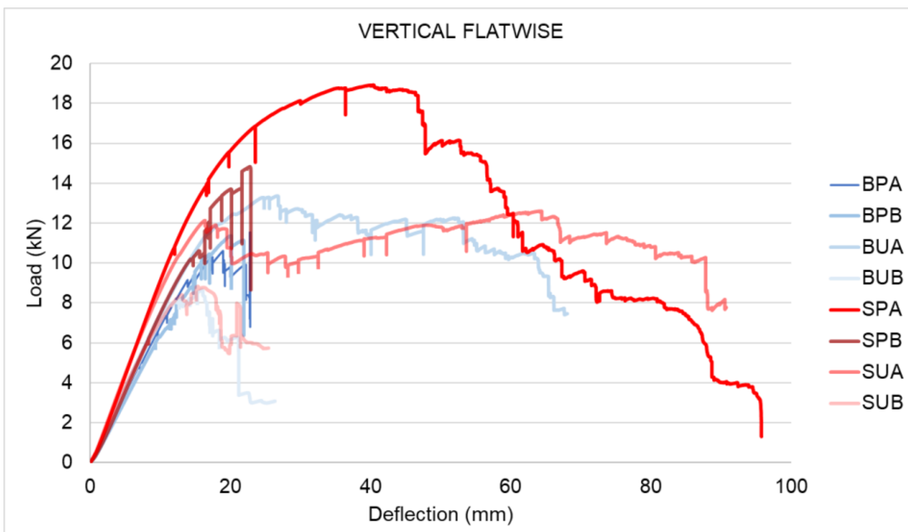
Label	Variable			Loading Direction	SMOE			SMOR		
	Species	Adhesive	Lay-up		Vertical	Horizontal	Mixed	Vertical	Horizontal	Mixed
BPA	Beting	PRF	Parallel	edgewise	26.18	10.45	13.17	0.17	0.18	0.14
				flatwise	26.54	16.94	12.28	0.15	0.12	0.12
BPB	Beting	PRF	Perpen-dicular	edgewise	19.60	9.34	5.88	0.10	0.11	0.04
				flatwise	19.66	8.90	7.81	0.09	0.04	0.03
BUA	Beting	PUR	Parallel	edgewise	20.29	9.49	13.62	0.13	0.17	0.11
				flatwise	21.22	14.79	10.01	0.12	0.16	0.11
BUB	Beting	PUR	Perpen-dicular	edgewise	14.54	7.95	5.43	0.10	0.11	0.04
				flatwise	17.64	11.16	7.05	0.08	0.09	0.03
SPA	Semantan	PRF	Parallel	edgewise	24.00	11.93	14.23	0.13	0.19	0.14
				flatwise	20.21	14.23	13.13	0.09	0.12	0.11
SPB	Semantan	PRF	Perpen-dicular	edgewise	13.69	8.00	6.95	0.10	0.09	0.05
				flatwise	18.58	11.23	8.78	0.08	0.05	0.04
SUA	Semantan	PUR	Parallel	edgewise	21.59	9.51	14.36	0.11	0.18	0.12
				flatwise	**23.22**	**13.54**	13.44	**0.13**	0.17	0.12
SUB	Semantan	PUR	Perpen-dicular	edgewise	17.70	6.92	5.71	0.10	0.11	0.05
				flatwise	**18.60**	**9.60**	**7.10**	0.08	0.09	0.04

Load-deflection Characteristics of Laminated Bamboo Boards

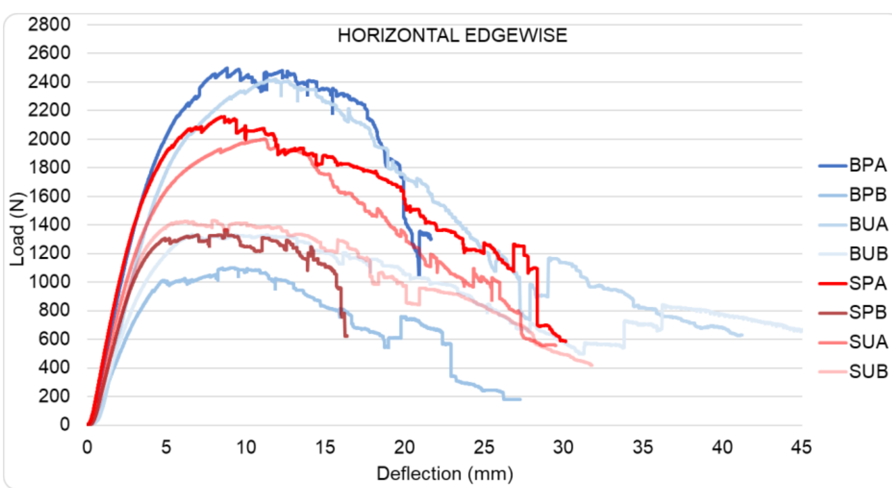
Figure 9 displays the load-deflection curves of laminated bamboo from various species, adhesive types, loading direction, lay-up patterns, and strips arrangement. There was no substantial difference between species and adhesive in terms of bending strength qualities. The load-deflection relationship was influenced by the species size. The specimens exhibited elastic-brittle behavior, with the load increasing consistently as the mid-span deflection progressed. Chen *et al.* (2020) conducted a study that compared the behavior of bamboo and wood.


VERTICAL EDGEWISE
Load (kN)
Deflection (mm)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
BPA
BPB
BUA
BUB
SPA
SPB
SUA
SUB

A


VERTICAL FLATWISE
Load (kN)
Deflection (mm)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
BPA
BPB
BUA
BUB
SPA
SPB
SUA
SUB

B


HORIZONTAL EDGEWISE
Load (N)
Deflection (mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
0
5
10
15
20
25
30
35
40
45
BPA
BPB
BUA
BUB
SPA
SPB
SUA
SUB

C

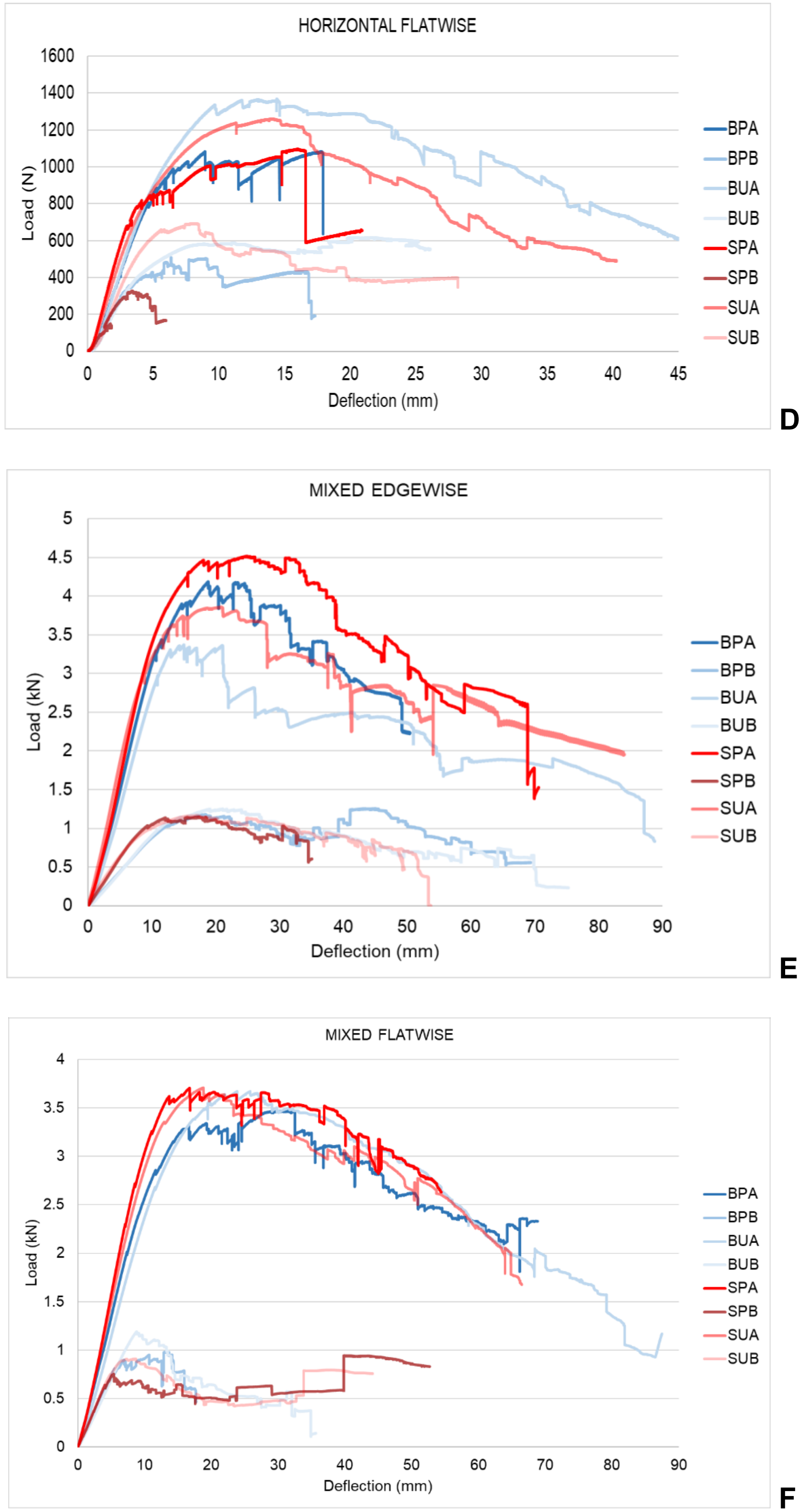


Fig. 9. Load deflection line graph in laminated bamboo specimen: (a) Vertical edgewise, (b) Vertical flatwise, (c) Horizontal edgewise, (d) Horizontal flatwise, (e) Mixed edgewise, (f) Mixed flatwise

The study discovered that wood is a fragile material that quickly breaks with modest non-linear deformation. Bamboo had partially malleable characteristics. Bamboo demonstrated greater resilience to plastic deformation compared to wood prior to breaking. The specimens in this investigation exhibited linear behavior until exceeding the yield threshold, followed by nonlinear deformation and failure in the plastic-elastic stage, similar to a recent study on laminated Moso bamboo by Sharma *et al.* (2017).

The samples exhibited linear growth in bending deformation and displacement of specimens in the initial stage as the load was increased. The material often reached the plastic stage when subjected to loads above 30% of its ultimate load. As the load reached its maximum, the curves displayed a steady rise in load. Cracks initially appeared at or close to the points of connection to the middle of the structure when subjected to a stress of 14 kN for vertically arranged laminated bamboo, a load of 1,200 N for horizontally arranged samples, and a load ranging from 1 to 3.5 kN for mixed arranged samples. A fracture developed in the stress zone when the load exceeded 18 kN, 1,400 N, and 1.2 to 3.7 kN. The load-bearing capacity of the specimens decreased quickly after that point. During the failure, noticeable displacement and deformation were evident in all specimens. The results indicate that most beams had displacements of more than 50 mm. The specimens rapidly broke apart with loud sounds, especially in the thicker vertical (54 mm), mixed (27 mm), and horizontal (13 mm) samples. The thinnest laminated bamboo samples exhibited the highest bending strength, whereas the thickest samples had the greatest bending stiffness because of the increase in bamboo volume fraction. Vertically arranged laminated bamboo requires a higher volume of bamboo strips and therefore it can withstand greater load than horizontal and mixed arrangements probably due to its higher volume percentage and content of vascular bundles.

Bending Failure Modes of Laminated Bamboo

Various failure types were seen in the laminated bamboo during the four-point bending tests, each exhibiting distinct behavior. Flatwise and edgewise failure modes during bending were identified by the breakage of the outer layer fibers, as shown in Fig. 10. The laminated bamboo samples were destroyed in a manner comparable to small clear bending examples, exhibiting bottom tensile fracture and glueline failure. Flatwise bending offers a greater shear failure risk than edgewise bending because the rolling (planar) shear strength is substantially less than panel shear strength (Wang *et al.* 2022).

Failure types differed among laminated bamboo specimens in four-point bending tests, and five types of failure modes were observed, which are: (1) Failure caused by the glueline between bamboo and adhesive/ delamination due to the weak structure caused by the lamina's inability to support the stress transferred from the resin polymer matrix or fracture of resin during bending, resulting in resin and fibre breakage; (2) fracture due to splintering tension slightly bends as the load force increases, but the specimens still take the additional load and form cracks; (3) failure due to compression buckling at the top and tension at the bottom caused by the bamboo strip layers, and a weak link was frequently visible between transverse layers during loading; (4) shear failure occurred when the shear was transverse to the grain; and (5) failure due to brittle fracture at the bottom caused by weak spots or defects during laminated bamboo manufacturing where tensile stress of bamboo fibre reached tensile strength and caused brittle fracture and cracks when the load reached the maximum capacity.

Gao *et al.* (2022) observed a common failure in the bottom tensile section, leading to the rupture of the matrix and fibers. The compression side collapsed due to microbuckling, and some specimens showed delamination caused by resin fracture under loading. Wei *et al.* (2011) identified four common failure modes in laminated bamboo: fracture, compressive buckling, stratified fracture of the bottom, and oblique tear. This study found similarities in various failure types, such as brittle fracture and compressive buckling. Rahman (2015) discovered the same failure in this study, where the specimens exhibit splintering, lower fibre tension, and delamination issues in the contact surface lamellae. The failure in laminated bamboo began in the compression and tension zones, where cracks progressed to the weakened zone, particularly when the presence of nodes in bamboo strips affected the strength properties of laminated bamboo. Li *et al.* (2019) discovered the same failure, which is tension, rolling shear, and delamination failure, particularly in the edgewise loading direction.

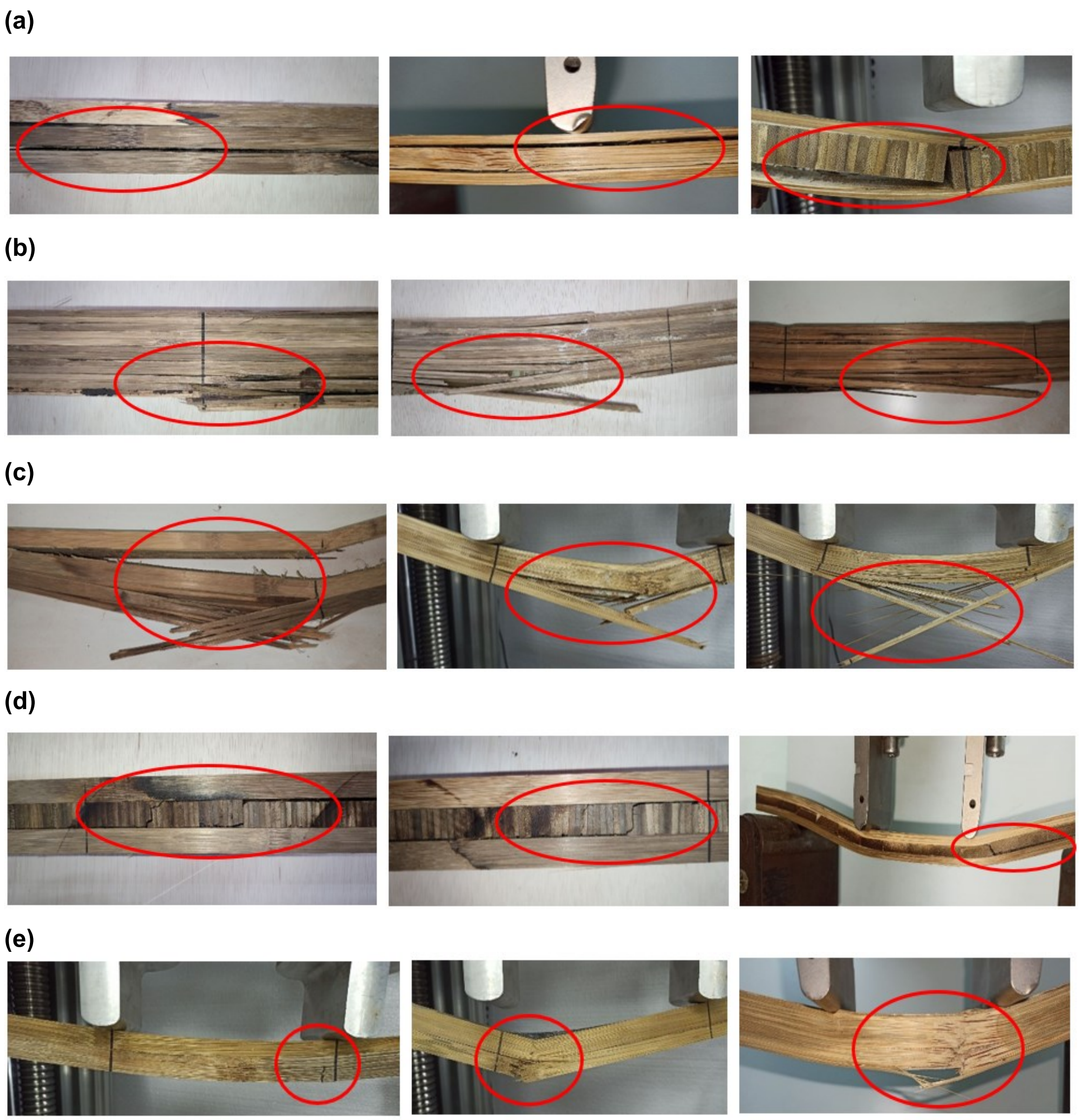


Fig. 10. Bending failure mode of laminated bamboo panels: (a) Failure caused by the glueline between bamboo and adhesive; (b) fracture due to the splintering tension; (c) failure due to compression buckling and tension; (d) rolling shear failure; (e) failure due to brittle fracture

In comparison to other studies, it is noteworthy that the MOR and MOE of the laminated bamboo in this research exceeded those of the laminated moso bamboo lumber beams as reported by Li *et al*. (2016). Nevertheless, the study examined the impact of width on bending performance, which differs from the effects of strip orientation in this research, resulting in discrepancies. Meanwhile, the specific bending strength of laminated bamboo sandwich panels constructed with various interlocking methods by Wang *et al.* (2024) closely aligns with the values presented in this study, indicating that the geometric configuration and processing technique of the core layer substantially affect the panels.

CONCLUSIONS

This study evaluated the physical properties and bending performance of laminated bamboo panels made from two different bamboo species. The panels were bonded together using phenol-resorcinol-formaldehyde (PRF) and polyurethane (PUR) adhesives, and were assembled in different loading directions, lay-up patterns, and strip arrangements.

1. It was found that the adhesive types and strip arrangement have a notable impact on the thickness swelling and water absorption of the laminated bamboo panels. The PUR-bonded laminated bamboo panels exhibited reduced thickness swelling and water absorption, indicating superior dimensional stability in comparison to PRF-bonded panels, as evidenced by thickness swelling value below 3% and water absorption around 40% after 48 hours if immersion. Vertically arranged panels were denser (by 1 to 3%) and retained more moisture (by 1 to 5%) compared to horizontal and mixed arrangements, which improved dimensional stability.
2. The vertical arrangement exhibited superior dimensional stability compared to both the horizontal and mixed arrangements. The PRF-bonded laminated bamboo panels displayed significantly higher MOE but lower MOR values than the PUR-bonded counterparts. Panels with parallel lay-up outperformed those with perpendicular lay-up with MOE and MOR values increasing by up to 150% and 240%, respectively, depending on the strip arrangement. Vertical arrangement performed much better than the horizontal and mixed pattern samples in term of MOE, while horizontal panels outperformed those with vertical and mixed arrangements in term of MOR.
3. Lay-up pattern had a relatively small effect on parallel laminated bamboo panels but significantly influenced perpendicular laminated bamboo panels. Hence, the optimal considerations were laminated bamboo panels bonded parallelly with (PRF) and PUR adhesives in vertical arrangement when considering the specific MOE and MOR values with the elimination of density effect.
4. The arrangement of horizontal panels might be a promising alternative, despite its four times smaller thickness than vertical panels because it achieved better specific MOR value and less than two times lower specific MOE values. The result of this study concluded that laminated bamboo is an effective structural material, but further research is required to understand how the effects of density and moisture impact the bending strength of laminated bamboo.

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