Effects of Species, Adhesive, and Structural Configurations on Compression Parallel to the Grain of Laminated Bamboo

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GRAPHICAL ABSTRACT

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This study investigated the compressive performance of 24 three-layered laminated bamboo specimens made with four different parameters, primarily bamboo species, adhesive type, lay-up pattern, and arrangement of laminated bamboo. The goal for this study was to investigate the compression parallel to the grain performance of laminated bamboo. A total of 288 laminated bamboo specimens were tested. Modulus of elasticity (MOE) and compressive strength were conducted to simulate the utilization of this material into construction material. The laminated bamboo produced were comparable to wood strength group A to B for vertical and horizontal arrangements and SG D for mixed arrangements. Laminated bamboo was produced based on *Gigantochloa scortechinii* and *Gigantochloa levis* and bonded with phenol resorcinol formaldehyde (PRF) and one-component polyurethane (PUR) adhesive. Four failure types were classified. All specimens experienced the elastic stage at the beginning of the loading process and then changed to elastic-plastic stage. There was a significant difference in the parallel and perpendicular lay-up for vertical, horizontal, and mixed arrangements.

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Keywords: Laminated bamboo; Compression parallel; Modulus of elasticity; Compressive strength; Construction; Gigantochloa scortechinii; Gigantochloa levis

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INTRODUCTION

Bamboo is valued for its strength, cost-effectiveness, and market potential. It is increasingly used as a laminate in construction, furniture, and decoration due to its environmental benefits, high strength, and aesthetic appearance (Huang *et al.* 2015; Nkeuwa *et al.* 2022; Zhang *et al.* 2024). Similar to wood, optimising bamboo use necessitates a thorough understanding of its physical and mechanical properties (Ribeiro *et al.* 2017). In recent decades, various widely used bamboo engineering materials have been developed, such as laminated bamboo, parallel strand bamboo, cross laminated bamboo, and glued laminated bamboo (Dauletbek *et al.* 2023). Compression is essential in almost all construction products. Compression can occur when compressive force is applied parallel to the grain and produces stress that deforms (shortens) the cell along its longitudinal axis (Qiang *et al.* 2021). The maximum crushing strengths are referred to as compression parallel to the grain, representing the highest level of stress endured by compression in the same direction as the grain (Green *et al.* 1999). Many Malaysian studies have focused on the bending properties rather than the performance under compression with different thicknesses of laminated bamboo such as bending parallel to the fibers (Ong *et al.* 2023), physical and bending strength of bamboo (Osman *et al.* 2022), tensile and bending of layered laminated woven bamboo (Rassiah *et al.* 2018), and properties of laminated woven bamboo (Abidin *et al.* 2022). Compression strength is heavily influenced by bamboo species, lamina thickness, configurations, and adhesive types. In some studies, some of these influence factors on the compression strength properties of laminated bamboo were investigated. It was found that a parallel lay-up is the best angle for laminated bamboo (Yang *et al.* 2020). In addition, different layers affect the mechanical properties of laminated bamboo products (Suhaily *et al.* 2020), and species greatly effect strength properties (Mateus de Lima *et al.* 2023; Kumar and Mandal 2022). The type of adhesive also has been found to affect the bonding strength of laminated bamboo lumber (Sulastiningsih *et al.* 2021).

Chen *et al.* (2018) bonded moso laminated bamboo with phenol formaldehyde (PF) adhesive and investigated the effect of curing temperature, moisture content of bamboo strips, resin consumption, and hot-pressing parameters. However, the adhesive strength is the most influential factor in compression failure, with the three common failure modes being folding, glue line cracks, and bottom lamina cracks. Anokye *et al.* (2016) investigated how nodes and resin affect the mechanical properties of bamboo timber. Over PVaC, which had the highest compressive strength, PF was chosen as the best adhesive for manufacturing bamboo timbers. On laminated bamboo, adhesive types were found to differ significantly in compression strength but not in spread rate. With a 46.9% difference, PF was chosen as the best adhesive for manufacturing bamboo timbers over PVaC. The large difference could be attributed to hot pressing-induced plasticization of PF within the vascular bundles closer to the glue line.

Shangguan *et al.* (2015) investigated the effect of different load-grain angles on the compressive properties of bamboo scrimber. The ultimate compression strength was found to vary significantly with angle, with increasing angles having a greater influence on compressive strength with a lower value and less impact on failure. It was concluded that increasing lamina angles by more than 50º decreased compressive strength and caused microcracks in the samples. A small change in grain angle can cause a significant change in mechanical properties when grains are nearly parallel to the load direction. Yang *et al.* (2020) discovered that the compression strength of laminated bamboo decreased as the lamina angle increased. Sharma and Van der Vegte (2020) discovered that the direction influenced bamboo scrimber rather than laminated bamboo compressive stress. Rahman (2015) discovered that different orientation angles and layers of laminated bamboo affect compressive strength. The 3-ply and 5-ply lay-ups demonstrated higher compressive strength with combination lay-ups 0º/45º /0º and 0º/90º /0º /90º /0º compared to 45º/90º /45º and 45º/90º /45º /90º /45º lay-ups, indicating that such lay-ups are unsuitable for lamination work.

Previous research by Verma and Chariar (2012) investigated the mechanical properties of layered laminated bamboo composites using epoxy resin, as well as the effect of laminate layer orientation on strength properties, with an average compressive strength ranging from 55 N/mm^2 to 88 N/mm^2. However, as the lamina angle increased, so did the compressive properties. As a result, understanding the mechanical properties of laminated bamboo for structural applications is becoming increasingly important. The goal of this study was to investigate the destruction of compression parallel to the grain caused by a fracture of the fibre or matrix, where failure at the fibre-matrix interface resulted in delamination failure. The objective of this study was to analyze the compression MOE, compressive strength, and detailed failure modes for all specimens. The study was investigating how different factors such as species, adhesive and configurations (lay-up and arrangement) effect these properties. The test arrangements and experimental parameters are illustrated in Fig. 1. In this study, 288 laminated bamboo specimens were tested in compression parallel to the grain and the influence factors on bamboo material type, such as composition pattern, layer thickness, and lamina lay-ups type were comprehensively considered. Then, the performance of compression parallel to the grain of laminated bamboo was tested, which provided a basis for the material selection for prestressed laminated bamboo.

Fig. 1. The specimen for compression parallel to the grain test arrangements

EXPERIMENTAL

Material Preparation

This study focused on two bamboo species, *G. scortechinii* and *G. levis*, which are often utilized in Malaysia for the production of laminated bamboo board. These species were chosen due to their abundant availability and remarkable strength. This was based on the results of the authors' previous studies on the physical and mechanical properties of the bamboo strips of the selected species (Yusof *et al.* 2023). The harvested matured bamboo culms with an average age 3–5-year-old were cut to 2,000 mm and split to 22 mm width. Splits were trimmed to 20 mm width and 5 mm thickness were obtained. Prior to laminated bamboo manufacturing, bamboo strips were treated for 24 h with 5% boric acid to provide short-term protection against biodeterioration agents. The bamboo was harvested in Kedah, Malaysia.

Laminated bamboo from *G. scortechinii* and *G. levis* using phenol resorcinol formaldehyde (PRF) and polyurethane (PUR) adhesive were fabricated. Adhesive were supplied by AkzoNobel Sdn. Bhd., Petaling Jaya. The glue spread rate was 250 g/cm² for PRF and 200 g/cm² for PUR. The bamboo strips were arranged in a horizontal, vertical and mixed arrangement with two lay-up patterns namely parallel and perpendicular. Laminated bamboo was pressed for 4 hours 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). The test apparatus of the compression parallel to the grain tests used according to the European standard BS EN 408 (2010) and ISO/TC 165 N1242 (2024) was referred to for the bamboo structures. This standard is certified for determining the stiffness and strength properties of laminated wood based on the BS EN 16351 (2015) standards. A total of 288 specimens (12 samples × 2 species × 2 adhesives × 6 configurations) was tested. The test was performed on Instron Universal Testing Machine 8802 and 5582 (250 kN and 100 kN). All the strengths were adjusted at 12% moisture content according to EN 384 (2016). The chosen adhesive was based on its superior mechanical, bonding physical properties, and cost effectiveness which are criteria frequently used in the production of laminated boards.

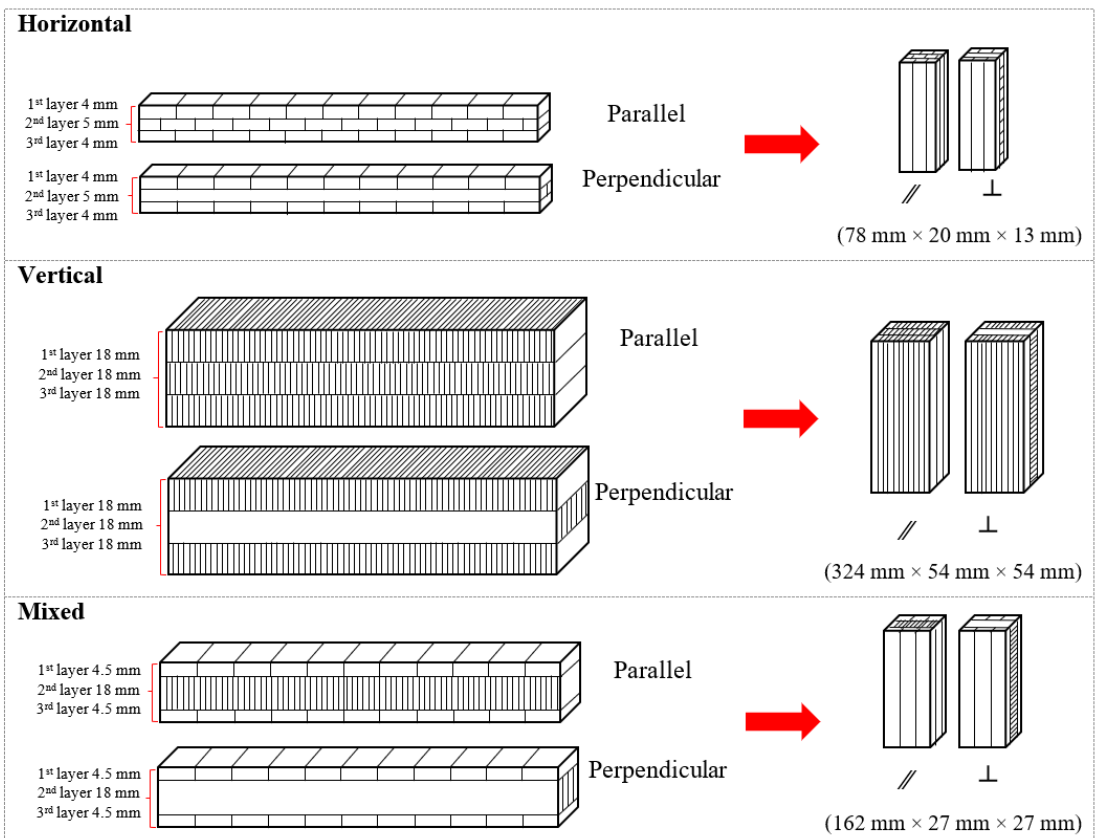

Fig. 2. Dimensions of compression parallel to grain for laminated bamboo

This section examines the effects of species, adhesive, and configurations (direction: parallel and perpendicular; arrangements: vertical, horizontal, and mixed) on compression and compressive strength of three-layer laminated bamboo boards.

Specimen Preparation

Figure 2 shows the size of the specimen was 6*h* with different thicknesses of 54 mm, 27 mm, and 13 mm.

Test Method

The test pieces were full cross sections and length of six times (6 × *h*) the smaller cross-sectional dimension. The end-grain surfaces were accurately prepared to ensure that they were aligned and parallel to one another and perpendicular to the axis of the piece. The MOE and MOR calculations were based on the measurement values from the gross cross-section of tested samples according to BS EN 408 (2010).

The test pieces were loaded concentrically using spherically seated loading heads or other devices, where the compressive load was applied without inducing bending. The load was applied at a constant rate and the rate of movement of the loading head shall be not greater than 0.00005 *l* mm/s.

Load was applied at a constant loading head movement and the maximum load is reached within (300 ± 120 s). The time to failure of each test piece was recorded and its average reported. Any single piece diverging more than 120 s from the target of 300 s was reported. The MOR and MOE for compression were calculated using the following Eqs. 1 and 2,

$$\text{MOR (N/mm}^2\text{)} = \frac{Fmax}{A} \tag{1}$$

where F_{max} is the maximum load, N; A is the cross-sectional area, mm^2, and

$$\text{MOE (N/mm}^2\text{)} = \frac{I1(F2-F1)}{A(w2-w1)} \tag{2}$$

where F_2 - F_1 is an increment of load on the straight-line portion of the load deformation curve (N); W_2 - W_1 is the increment of deformation corresponding to F_2 - F_1 (mm); l_1 is the gauge length for the determination of modulus of elasticity (mm); and A is the cross-sectional area (mm²).

Statistical Analysis

The data were tested for potential differences in group mean characteristics of the compression parallel to the grain for laminated bamboo that had eventually been analyzed using the Analysis of Variance (ANOVA).

Meanwhile, mean separation was carried out using the Least Significant Difference (LSD) method. The level of significance (α) was set for all the statistical tests at 0.05 so that probability values less than 0.05 were taken as indicatives of statistically significant difference.

RESULTS AND DISCUSSION

Analysis of Variance

The analysis of variance (ANOVA) of the effects of species, adhesive, and lay-up in the different arrangements on compression parallel to the grain MOE and compressive strength is shown in Table 1. The results showed that lay-up had the greatest impact on both compression MOE and compressive strength. Aside from that, with the exception of mixed arrangements for values compression MOE and compressive strength, both vertical and horizontal arrangements had a significant effect in species. Meanwhile, only horizontal arrangement had a significant effect on compression MOE in adhesive. In compressive strength, horizontal arrangement was found to be significantly affected by adhesive types in both values, followed by vertical arrangement. Except in mixed arrangements, there was an interaction effect between the species and the adhesive on vertical and horizontal arrangements for compression parallel to the grain for both values. Table 1 shows the results of further analysis of these effects using the least significant difference (LSD) method.

Table 1. ANOVA for the Effects of Species, Adhesive, Direction, and Configurations for the MOE in Compression and Compressive Strength of Laminated Bamboo

Source	df	p-value					
		MOE			Compressive Strength		
		Vertical	Horizontal	Mixed	Vertical	Horizontal	Mixed
Species	1	< 0.0001 ***	0.0050 **	0.9889 ns	0.0078 **	< 0.0001 ***	0.0607 ns
Adhesive	1	0.3512 ns	< 0.0001 ***	0.3814 ns	0.0010 ***	< 0.0001 ***	0.7824 ns
Lay-up	1	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***
Species* adhesive	1	0.0087 **	< 0.0001 ***	0.0606 ns	< 0.0001 ***	< 0.0001 ***	0.0387 *
Species* lay-up	1	0.3236 ns	0.7233 ns	0.9945 ns	0.0435 *	0.0003 ***	0.0137 *
Adhesive * lay-up	1	< 0.0001 ***	0.3664 ns	0.2563 ns	0.0077 **	0.1282 ns	0.5089 ns
Species* adhesive* lay-up	1	0.0649 ns	0.0003 ***	0.0966 ns	0.0002 ***	< 0.0001 ***	0.5709 ns

Notes: ns p > 0.05; * Significantly different at p < 0.05; ** Significantly different at p < 0.01; *** Significantly different at p < 0.001

Compression MOE and Compressive Strength of Laminated Bamboo

The value of compression parallel to the grain in three different arrangements of laminated bamboo samples from this study is tabulated in Table 2. The evaluation included the compression MOE and compressive strength. The average values for MOE and compression strength in parallel lay-up was 20% higher compared with perpendicular lay-up irrespective of strips arrangement. This is due to the layer of parallel lay-up connecting three longitudinal layers, which offer sufficient compression capacity (Wei *et al.* 2019). Table 2 displays the highest and lowest values from 24 types (6 configurations × 2 bamboo species × 2 adhesive types) of laminated bamboo boards. Despite being 4.2 times thinner than that of the vertical arrangement, laminated bamboo made by arranging the strips horizontally exhibited strength two-thirds to three-quarters of the former mostly in the compressive strength.

Table 2. MOE in Compression and Compressive Strength of Laminated Bamboo Boards Fabricated with Different Configurations

Arrangement	Vertical		Horizontal		Mixed	
	MOE (N/mm^2)	Compressive Strength (N/mm^2)	MOE (N/mm^2)	Compressive Strength (N/mm^2)	MOE (N/mm^2)	Compressive Strength (N/mm^2)
BPA	9,553.13 ^{C} (1,032.69)	53.15 ^{B} (2.31)	5,781.96 ^{A} (731.32)	49.87 ^{A} (5.52)	6,327.09 ^{A} (1,587.84)	50.81 ^{A} (7.09)
BPB	6,548.96 ^{G} (403.58)	36.9 ^{D} (1.8)	4,947.51 ^{B} (861.7)	49.87 ^{A} (6.99)	2,170.44 ^{C} (295.22)	15.78 ^{C} (3.33)
BUA	9,041.39 ^{D} (470.88)	55.65 ^{B} (3.4)	4,691.43 ^{B} (683.78)	43.33 ^{B} (4.93)	6,061.78 ^{A} (354.47)	53.34 ^{A} (3.18)
BUB	7,470.92 ^{F} (621.5)	37.85 ^{D} (4.12)	2,421.10 ^{D} (548.71)	21.64 ^{C} (8.94)	2,087.95 ^{C} (337.7)	16.26 ^{C} (2.71)
SPA	11,260.6 ^{A} (271.34)	59.18 ^{A} (2.92)	4,872.11 ^{B} (1,035.2)	48.63 ^{A} (9.46)	5,713.87 ^{B} (1,159.27)	49.37 ^{B} (4.72)
SPB	8,462.45 ^{E} (637.39)	35.2 ^{E} (5.35)	2,772.79 ^{D} (626.36)	20.46 ^{C} (5.74)	2,131.48 ^{C} (427.39)	17.55 ^{C} (1.69)
SUA	10,557.69 ^{B} (343.21)	48.75 ^{C} (1.9)	4,820.27 ^{B} (873.16)	40.76 ^{B} (6.56)	6,667.8 ^{A} (1,055.96)	47.48 ^{B} (4.88)
SUB	8,314.54 ^{E} (465.79)	33.38 ^{E} (1.57)	3,595.3 ^{C} (568.41)	25.20 ^{C} (7.78)	2,124.5 ^{C} (277.15)	15.51 ^{C} (1.85)

Note: *Adjusted at 12% moisture content;; BPA- Beting PRF parallel; BUA- Beting PUR parallel; BPB- Beting PRF perpendicular/ cross; BUB- Beting PUR perpendicular/ cross; SPA- Semantan PRF parallel; SUA- Semantan PUR parallel; SPB- Semantan PRF perpendicular/ cross; SUB- Semantan PUR perpendicular/ cross; Mean followed by the same letters in the same column are not significantly different at $p \leq 0.05$ according to LSD; Values in parenthesis are standard deviation

All samples were adjusted at 12% moisture content based on BS EN 384 (2016) (Eq. 2). Based on the Table 2, the mean compression MOE and compression strength was

5,240 to 9,300 N/mm², 46.6 to 54.4 N/mm² (*G. levis* parallel), 2,130 to 7,010 N/mm², 16.0 to 74.8 N/mm² (*G. levis* perpendicular), 4,850 to 10,900 N/mm², 44.7 to 54 N/mm² (*G. scortechinii* parallel), 2,130 to 8,480 N/mm², and 16.5 to 34.3 N/mm² (*G. scortechinii* perpendicular), respectively. The highest value in parallel (A) lay-up from vertical arrangements from *G. scortechinii* with 11,300 N/mm² and 59.2 N/mm² and the lowest was perpendicular (B) lay-up from mixed arrangements from *G. levis* with 2,090 N/mm² and 16.3 N/mm².

The compression results were primarily influenced by the density of the laminated bamboo. Table 3 provides a summary of the density of laminated bamboo boards made from two species (*G. scortechinii* and *G. levis*), two types of resin (PRF and PUR), two lay-up (parallel and perpendicular), and three strip arrangements (vertical, mixed, and horizontal). The density ranged from 665 to 793 kg/m³ for *G. scortechinii* and from 651 to 803 kg/m³ for *G. levis*. These ranges apply to different parallel and perpendicular lay-up arrangements, as well as vertical, horizontal, and mixed arrangements. The densities were adjusted to 12% moisture content.

Table 3. Density of Laminated Bamboo Boards Fabricated with Different Configurations

Arrangement	Vertical	Horizontal	Mixed
BPA	760.55	757.97	777.07
BPB	749.39	780.28	733.06
BUA	780.87	785.46	776.42
BUB	803.31	651.07	790.85
SPA	792.88	665.27	734.22
SPB	769.37	672.41	763.54
SUA	771.59	694.21	745.23
SUB	761.02	716.95	731.12

Note: BPA- Beting PRF parallel; BUA- Beting PUR parallel; BPB- Beting PRF perpendicular/ cross; BUB- Beting PUR perpendicular/ cross; SPA- Semantan PRF parallel; SUA- Semantan PUR parallel; SPB- Semantan PRF perpendicular/ cross; SUB- Semantan PUR perpendicular/ cross; Mean followed by the same letters in the same column are not significantly different at $p \leq 0.05$ according to LSD; Values in parenthesis are standard deviation

In comparison to the adhesive types, the effect of the bamboo species parameters appears to be influenced by the arrangements, particularly in vertical arrangement. In both parameters, *G. scortechinii* performed better than *G. levis* (lay-ups and adhesive types). However, when bonded with PRF adhesive, *G. levis* surpassed *G. scortechin*ii in both horizontal and mixed arrangements. In contrast, laminated bamboo bonded with PUR adhesive produced the opposite result for horizontal and mixed arrangement. The density of laminated bamboo was comparable to Malaysian medium hardwood categories, with an average density of 720 to 880 kg/m³. In MOE compression, the density of *G. levis* was higher compared to *G. scortechinii* values of horizontal and mixed arrangement, but compressive strength was closely related for both species. In all parameters (species, lay-up, and arrangements), laminated bamboo bonded with PRF adhesive produced better results and density than PUR. The compression strength parallel to the grain of laminated bamboo was significantly affected by the lay-up patterns in all arrangements.

In comparison to Malaysian wood strength classification (Table 4), the compression strength parallel to the grain value of laminated bamboo was comparable to wood strength group (SG) A for vertical in parallel lay-up (A), and SG C for perpendicular lay-up (B). Meanwhile, except for perpendicular lay-up (B) laminated bamboo bonded with PUR, horizontal arrangement was mostly in SG B. Despite having a lower density than heavy hardwood (800 to 1,120 kg/m^3), laminated bamboo had a higher compression strength in both species, adhesive, and arrangements. Most medium hardwood timber belongs to either SG B or SG C, with a few exceptions in SG A. Light hardwood timber (400 to 720 kg/m^3) is typically found in strength groups C and D. However, despite having a high-density value, some laminated bamboo had the weakest compression strength parallel to the grain. Particularly, this was true for mixed arrangements in perpendicular lay-up (B) for both species and adhesive in SG D. Meanwhile, for laminated bamboo in mixed arrangement for parallel lay-ups in SG B it was significantly higher than that of mixed arrangements in perpendicular lay-up.

Table 4. Strength Grouping Table

Strength Group (SG)	Compression Strength Parallel to the Grain (N/mm²)
A	Greater than 55.2; extremely strong
B	41.4 to 55.2; very strong
C	27.6 to 41.4; moderately strong
D	Less than 27.6; weakest

Note: Determined using the test procedure described in ASTM D143-52 (1967)

As compared, the result in parallel lay-up (A) was higher than in perpendicular/ cross lay-up (B). This was in line with a previous study by Zheng and Guo (2003), who made laminated bamboo panel from *Heterocycla pubescens* and *Dendrocalamus yunnanicus* Hsueh with compressive strength of 85.5 and 89.4 N/mm² for parallel, and 72 and 82.4 N/mm² for perpendicular/ cross lay-up (B), respectively. In addition, the value for parallel lay-up (A) for all arrangements was close to that of CLT from Munis *et al.* (2018) and Buck *et al.* (2016) using European Norway spruce with an average of 5,500 to 7,100 N/mm², but in vertical arrangement in both lay-ups it was higher than CLT. However, the value in vertical parallel for compressive strength was close to the glulam from European beech (*Fagus sylvatica* L.*)* between 58.2 to 65.8 N/mm² (Ehrhart *et al.* 2020).

The prior study reported a range of 5,500 to 7,100 N/mm² for MOE compression and 58.2 to 89.4 N/mm² for compressive strength. Despite the variation in specimen size, these results were almost the same in the current study. The strength properties of laminated bamboo were influenced by a few factors such as portion of bamboo, presence of nodes, and size of specimens. Sulastiningsih *et al.* (2017) found that the compression strength of bamboo strips is reduced by the presence of nodes. This is because the vascular cells in the nodes are more complex compared to those in the internodes. In contrast, another research conducted by Li *et al.* (2013) indicated that practical structural size specimens can be used to minimize the growth effects of various parts (bottom, middle, and top) of bamboo. However, to control the portion and reduce the presence of nodes was difficult, especially for bigger specimens due to several problems such as cost for raw materials, workers, time, experts in bamboo production, *etc.*

Previous study by Chen *et al.* (2020), Ni *et al.* (2016), Li *et al.* (2013), and Xiao *et al.* (2008) using the same species *P. pubescens* with different products showed quite similar results. Research from Rahman *et al.* (2015) and Razak *et al.* (2002) used the same species of this study, *G. scortechinii*, and achieved higher results in MOE compression and compressive strength compared to this study in perpendicular (B) lay-up. However, in parallel (A) lay-up the value was slightly higher compared to previous study. Shangguan *et al*. (2015) stated that the mean values were influenced by the different angles between load and grain on compressive properties and the angles ≤ 10º have higher value. Luna *et al*. (2010) gave two mean values of MOE compression due to the difference in percentage of moisture content and the density of the laminated bamboo. That finding is supported by Brito *et al*. (2018), where moisture content is the main factor that influenced the properties of laminated bamboo. Based on the comparison of compression MOE and compressive strength in this study and previous studies, it was shown that laminated bamboo from both species *G. scortechinii* and *G. levis* bonded with PRF and PUR using different configurations (lay-ups and arrangement) is suitable for construction material for engineering structures with various applications.

Figures 3 and 4 give the effects of species, adhesive, lay-up, and arrangements in the compression parallel to the grain. The overall performance is shown for 24 types of three-layer laminated bamboo board produced in this study. Even though the final thickness of the boards differed (*i.e.*, vertical strip arrangement was 54 mm, horizontal was 13 mm, and mixed was 27 mm), the strength properties were plotted for comparison purposes. As shown in Figs. 3 and 4, most of the highest performance came from the board with parallel lay-up and vertical arrangement.

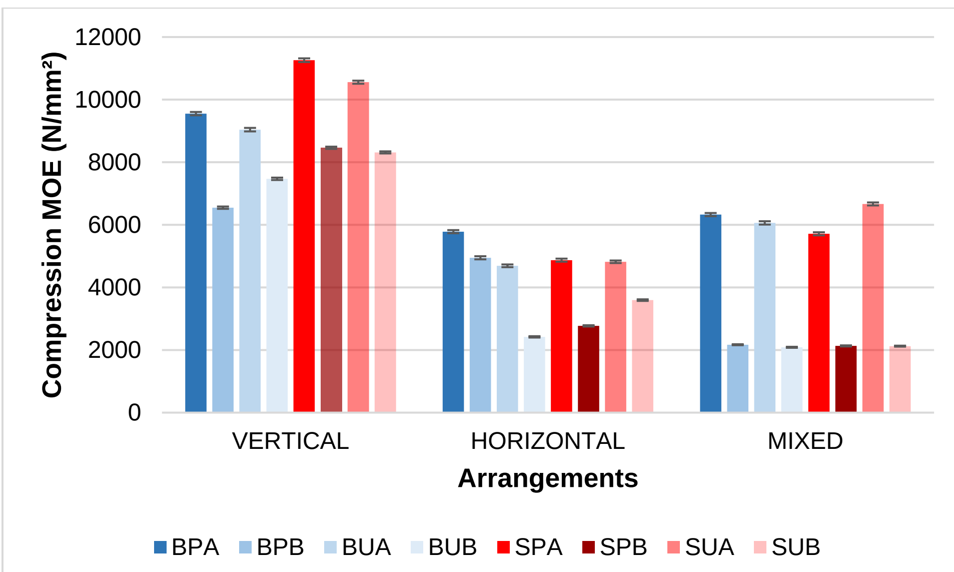

Fig. 3. Effects of species, adhesive, and configurations on the compression MOE for laminated bamboo boards

Surprisingly, mixing the vertical and horizontal arrangement resulted in the poorest strength, especially in perpendicular lay-up. This is clearly indicated by the lowest performance that came from this type of arrangement. It appears that parallel (A) lay-up consistently gives higher compression MOE than perpendicular (B) lay-up for vertical (by 31%), horizontal (by 47%), and mixed (by 49%) arrangement. This effect can be seen in all arrangements in compression MOE. Both species performed extremely well with close performance that may be attributed to having stronger strips. The difference between these two species was less than 10%, which was not a significant difference, especially in mixed arrangements.

As shown in Fig. 4, the compressive strength value in parallel (A) lay-up is higher than in perpendicular (B) lay-up by 50%, with a value of 203%, particularly in mixed arrangement. In mixed arrangement, all parallel (A) lay-ups consistently had much greater compressive strength compared to cross-laminated bamboo or perpendicular (B). The compressive strength of laminated bamboo in parallel lay-up surpasses that of LVL, WPC, plywood, and OSB and is comparable to similar bamboo-based materials, softwoods, and hardwoods like glulam, CLT, *etc.* The compressive strength below was influenced by the lay-up of laminated bamboo either parallel (A) and perpendicular (B) but it is not influenced by the adhesive types even though different amount of adhesive were used and the spread rate for PRF and PUR was 250 g/m² and 200 g/m², respectively. However, a study by Ogunsanwo *et al.* (2019) found that the trend of compressive strength increased with increasing glue amount using *Bambusa vulgaris* at different amounts of spread rate (150 g/m², 200 g/m², and 250 g/m²) with differences less than 10% that shows there is no significant differences in the means.

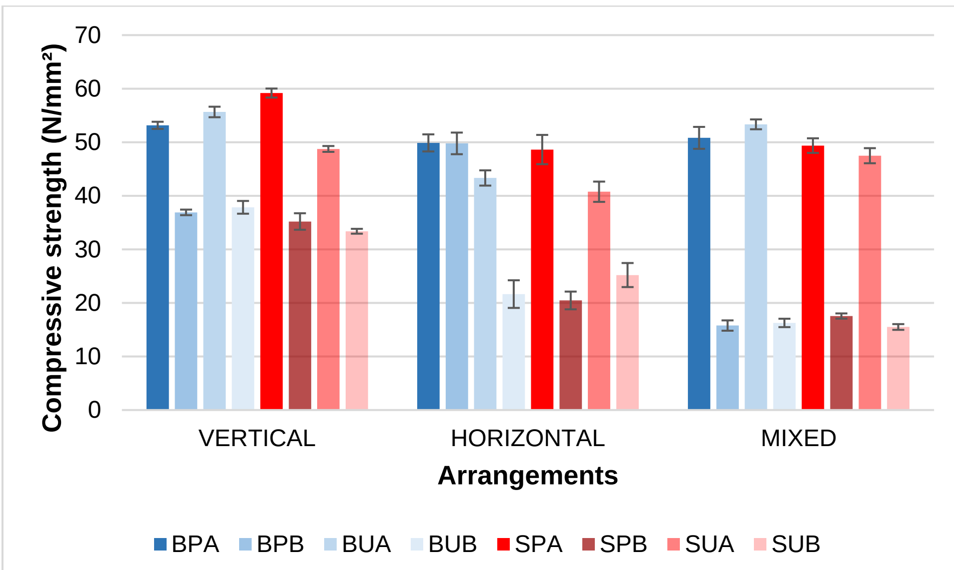

Fig. 4. Effects of species, adhesive, and configurations on the compression strength for laminated bamboo boards

Finally, the compression parallel to the grain of laminated bamboo showed different trends for both MOE and compressive strength specimens. Vertical arrangements had the highest and greatest elasticity modulus, higher compressive strength, and the best overall compression performance of the three types of arrangements. For both species and adhesive in all arrangements, the parallel lay-up (A) outperformed the perpendicular lay-up (B). There is only a 20% difference in results between the two bamboo species, and of the two adhesive types, PRF has the highest value compared to PUR due to the higher strength of PRF bonded laminated bamboo and the bonding between the adhesive and bamboo, which has shown better performance.

Effect of Single Variable on the Compression Parallel to the Grain of Laminated Bamboo Board

Table 5 compares the effects of single variable on the compression parallel to the grain of the laminated bamboo boards produced in this study. Bamboo species affects the compression parallel to the grain of the laminated bamboo board significantly as the compression MOE and compression strength values between *G. levis* and *G. scortechinii* differ. *G. scortechinii* has higher compression MOE value by 3 to 5% more compared with *G. levis.*

Table 5. Comparison Between Effects of Variables on the Properties of Laminated Bamboo Board

Variable	Compression Parallel to the Grain	
	MOE (N/mm²)	Compression strength (N/mm²)
Species		
Beting (*G. levis*)	5,591.97^{B}	40.36^{A}
Semantan (*G. scortechinii*)	5,941,15^{A}	36.79^{B}
Adhesive		
PRF	5,878.53^{A}	40.56^{A}
PUR	5,654.59^{B}	36.6^{B}
Lay-up		
Parallel	7,112.46^{A}	50.03^{A}
Perpendicular	4,420.66^{B}	27.13^{B}
Arrangement		
Vertical	8,901.2^{A}	45.01^{A}
Horizontal	4,237.8^{B}	37.46^{B}
Mixed	4,160.6^{B}	33.26^{C}

Note: Mean followed by the same different letters $^{A, B, C}$ in the same variable category is not significantly different at p ≤ 0.05 according to LSD

While *G. levis* bamboo has higher compression strength than that of *G. scortechinii.* This could be the reason for the density and moisture content of laminated bamboo from *G. levis* being higher compared to that made from *G. scortechinii*. Even though it is slightly different in density by less than 10%, the properties were significantly different. It was discovered that moisture content and the density of laminated bamboo is the main factor that influenced the properties of laminated bamboo (Luna *et al.* 2010; Brito *et al.* 2018). Because the density and moisture content between these two species were a little different, it could be the other factors influenced the properties of laminated bamboo, such as portion of bamboo and presence of nodes. The presences of nodes in bamboo strips decreased the value of compression strength due to the vascular cells of the node being more complicated than the internode, according to Sulastiningsih *et al.* (2017). *G. levis* has more nodes present compared with *G. scortechinii* due to the difference in internode length (35 cm and 42 cm, respectively). This could be the reason the compression performance of the laminated bamboo boards made from this bamboo differs significantly. However, to reduce the presence of nodes was difficult especially for bigger specimens due to the several problems, such as cost for raw materials, workers, time, and expert in bamboo production (Li *et al.* 2013).

Similarly, adhesive types also significantly affect the compression parallel to the grain of laminated bamboo. Laminated bamboo boards bonded with PRF resin were found to perform better with 3 to 5% than PUR in compression parallel to the grain due to the better bonding performance of PRF resin. The PRF was able to penetrate the bamboo cell wall while PUR resin did not, as investigated by Konnerth *et al.* (2008). Studies by Aicher *et al.* (2013) reported the same observation that PRF has better gap- filling properties, while PUR sealed the gaps of bonding materials, improving the mechanical properties of laminated bamboo. The bonding performance of laminated bamboo was greatly affected by the penetration of adhesive. Yang *et al.* (2022) stated that PRF resin is a flexible adhesive that has bond line facilitating counteracting stresses associated with expansion or contraction, thereby improving bonding and mechanical properties of laminated bamboo compared with PUR resin.

In contrast, lay-up pattern of bamboo strips was found to have significantly affected the compression parallel to the grain of the laminated bamboo boards as those plies with parallel lay-up performed significantly higher by 20 to 30% more than those lay-ups perpendicularly. When bamboo was arranged in parallel, the compression properties were higher due to the sufficient compression ability utilized. Several studies, Rahman *et al.* (2015), Shangguan *et al.* (2015), and Razak *et al.* (2002) also found that the laminated assembled parallel displayed significantly superior mechanical performance than those assembled perpendicularly. In terms of arrangement, laminated bamboo boards that were assembled vertically outperformed those assembled horizontally and mixed. Compression parallel to the grain of laminated bamboo assembled with vertical arrangement outperformed those assembled horizontally and mixed arrangement due to the increased thickness. Therefore, the compression parallel to the grain boards is notably higher than perpendicular. This observation was also made by several researchers. For instance, Chen *et al.* (2022) state that the lamina lay-ups of laminated bamboo had adverse effects on the compression performance of laminated glued bamboo. Based on the comparison of compression MOE and compressive strength in this study and previous studies by Mohd Yusof *et al.* (2023) on the effect of adhesive types and structural configurations that showed laminated bamboo from both species *G. scortechinii* and *G. levis* bonded with PRF and PUR using different configurations (lay-ups and arrangement) is suitable for construction material for engineering structures with various applications due to highest shear strength in samples parallel lay-up was observed with an average 3.2 to 8 N/mm^2.

Failure Modes for Compression Parallel to the Grain

Under compression parallel to the grain, four failure modes were recorded, and they were consistent for the three arrangements in laminated bamboo. Figure 5 shows the four most common failure modes. Figure 5 (a) depicts the failure caused by shearing, in which the maximum shear plane formed along the 45° in the middle of the specimen due to defects, initial eccentricity and slippage between the layers of fibers which affect structural and performance of material. While Fig. 5 (b) depicts splitting and glue line delamination failure due to lower bonding integrity between bamboo fibre and adhesive, delamination failure occurs due to loss of rigidity in specimens and is surrounded by micro-buckling in the combination of growth portion (top, bottom, and middle) of bamboo and damaged parts by deformation. Figure 5 (c) depicts buckling and crushing failure caused by specimens compressed along the grain and weak in compression and failure along the maximum line. Brooming or end rolling in Fig. 5 (d) occurs when the fibres near the end of the loaded materials bend and buckle without rupture and is most common when the MC at the end grain of the specimens is higher. Otherwise, it occurs due to instable compression and the formation of a transverse fold in the specimen surface. Yang *et al.* (2023) state that the behaviour of unidirectional laminated bamboo under compressive loading along the fibre direction is microbuckling, which includes extension and shear modes.

Chen *et al.* (2020) discovered that all specimens loaded in compression split vertically along the load direction and through the bamboo laminated. The failure phenomenon of the specimens, according to Anokye *et al.* (2016), demonstrated damages from the top and propagating either along the glue line or through the bamboo material. Most PVaC-bonded specimens, however, failed faster because their deformations could not reach the bottom. When strips from the *Gigantochloa* genus were compressed parallel to the grain, similar crushing behaviour was observed (Hamdan *et al.* 2009). Shangguan *et al.* (2015) discovered three failures in a previous study: (1) wrinkled failure or buckling along the grain due to the adhesive layer cracked severely due to the inter-laminar stresses that occurs on the surface of the fibre bundles and it happened when it reached the maximum load, (2) shearing and delamination failure occurred due to the bonding among the fibres being much lower and led to the weak areas of bonded regions, and (3) crushing horizontally along the grain directions. Buckling and crushing failure occurred more frequently in horizontal arrangements and perpendicular lay-up (B) for both species and adhesive in this study. All types of failure were cracked along the grain direction. Buckling specimens dominated compressive strength behaviour according to Sharma and Van Der Vegte (2020). The failure mode was matrix and bamboo fibre fracture.

Furthermore, Dauletbek *et al.* (2022) and Takeuchi *et al.* (2015) state that compression parallel to the grain fails in three stages: linear elastic, elastic-plastic, and descending. However, Chen *et al.* (2020) discovered that the failure process of the specimens could be divided into four stages: linear elastic, elastic-plastic, descending, and residual. Shearing, buckling, and crushing were the most common failure modes for specimens in compression, with no cracks between strips as shown in Fig. 4 (a and c). This failure occurred more frequently in vertical and mixed arrangements for both lay-ups. Because of the less than 20% difference in strength properties, the trends of mode of failure were unaffected by the types of adhesive and bamboo species. Because less than 10% glue line delamination occurred in all configurations, proper bonding and an adequate amount of adhesive were used in this study.

All of the specimens for both directions (parallel and perpendicular) behaved elastically at first, but as loading increased, the specimens showed a little plastic deformation and the stiffness of laminated bamboo was significantly reduced. Finally, as the deflection became apparent, cracks appeared on the specimen surface. Cracks were visible from various side surfaces.

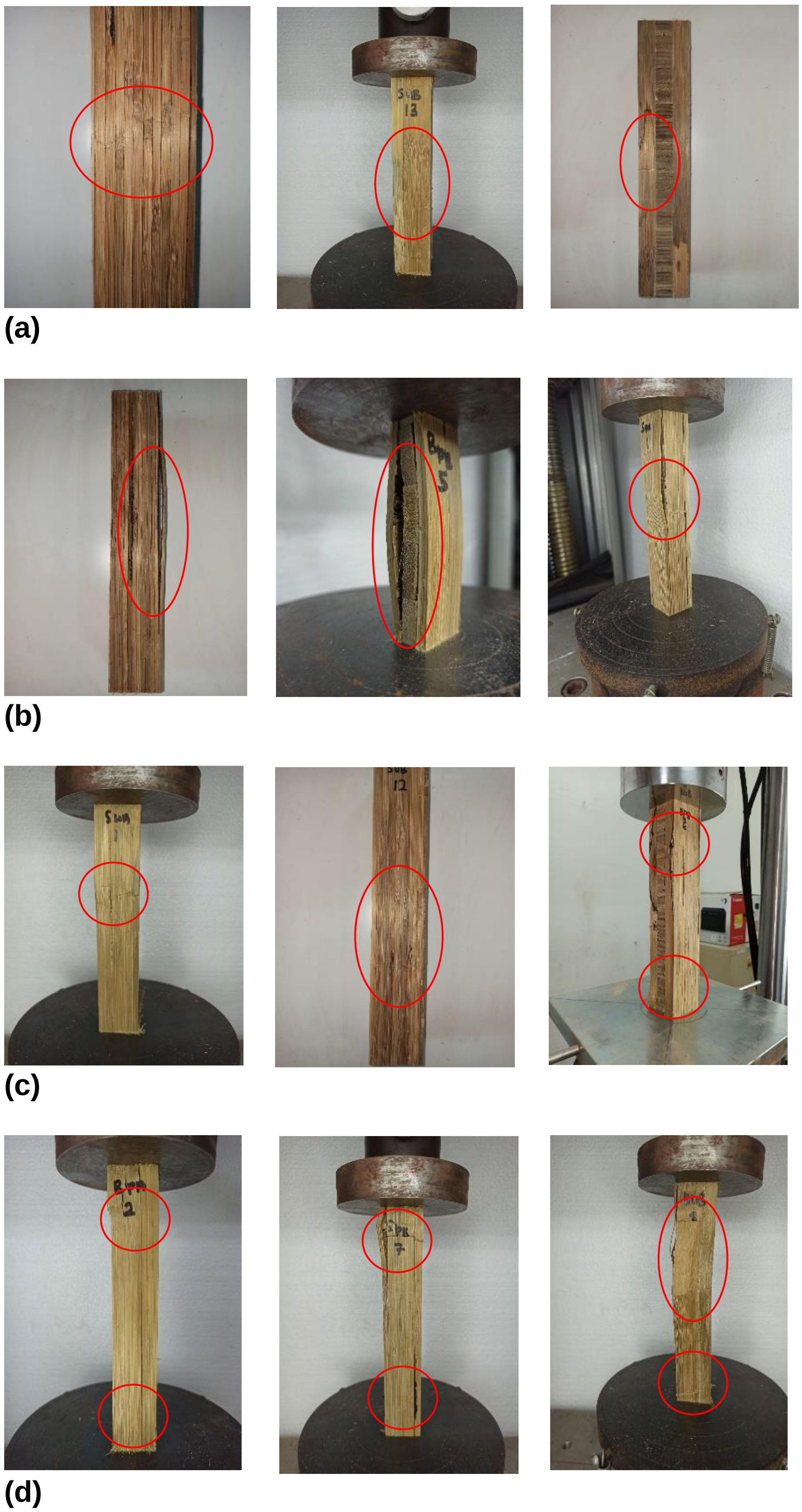

Fig. 5. Compression sample: (a) Shearing failure in LB, (b) Splitting and glue line delamination in LB, (c) Buckling and crushing in LB, and (d) Brooming or end rolling in LB

In their study, Li *et al.* (2013) discovered that the specimen was crushed at the bottom and split up the middle, and the stress-strain relationship failed in a ductile manner with quite consistent strength and stiffness, which is similar to what was found in this study for some specimens. Otherwise, the results showed that compression parallel to the grain and its failure mode were influenced by many other factors such as curing time, temperature, moisture content, resin consumption, and pressing pressure parameters (Chen *et al.* 2020). In this study, the laminated bamboo failed due to the bonding between the adhesive and the bamboo fibres. Laminated bamboo in perpendicular lay-up (B) failed faster than parallel lay-ups, with a lower load capacity for all parameters and a declining slope in the graph. Generally, shearing, buckling, and crushing in laminated bamboo occurred more frequently in vertical and mixed arrangements for both lay-ups. Parallel lay-up structures specifically supported more stress compared to perpendicular lay-up due to the longitudinal compression, and all the fibres were subjected to stress. Horizontal arrangement tended to lead to splitting and glue line delamination, with some samples exhibiting brooming and end rolling. Laminated bamboo boards from both species were nearly identical in modes of failures, indicating that the species, adhesive, and arrangement had no effect on laminated bamboo failure behaviour.

CONCLUSIONS

In this paper, the mechanical performance of laminated bamboo (compression parallel to the grain) with different species, adhesive, and configurations (lay-up pattern and strips arrangement) were studied with four modes of failures analyzed. The key conclusions are the following:

1. The compression performance of laminated bamboo was heavily influenced by the adhesive types, namely phenol resorcinol formaldehyde (PRF) and polyurethane (PUR) and lay-up pattern (parallel and perpendicular). The PRF-bonded laminated bamboo provides much superior compression modulus of elasticity (MOE) and compression strength compared to PUR-bonded laminated bamboo. Parallel lay-up outperformed those with perpendicular lay-up for both species of laminated bamboo.
2. PRF-bonded laminated bamboo exhibited superior performance compared to PUR-bonded with a 20% difference between the two combinations of bamboo species and adhesive types. This superiority was attributed to higher strength of PRF-bonded laminated bamboo and the bonding between the adhesive and bamboo, which showed better performance and more resistant performance across structural configurations (lay-up patterns and strip arrangements). This apparently was due to PRF creating strong and durable bonds between the bamboo layers. The chemical structure of PRF allows the PRF to penetrate into the wood cell wall resulting in better bonding performance. Hence, PRF adhesive was found to be the better adhesive for laminated bamboo.
3. The highest value was in parallel lay-up (A) from vertical arrangements from *G. scortechinii* of 11,300 N/mm² and 59.2 N/mm² and the lowest was perpendicular (B) direction from mixed arrangements from *G. levis* with 2,090 N/mm² and 16.3 N/mm².

4. Parallel (A) lay-up consistently gave higher compression modulus of elasticity (MOE) than perpendicular (B) lay-up for vertical (by 31%), horizontal (by 47%), and mixed (by 49%) arrangement. The alignment of bamboo strips along the grain of each layer enhanced the strength and stiffness of the material, allowing it to withstand higher loads in the same direction. This alignment also ensured uniform performance throughout the material.
5. The compressive strength value in parallel (A) lay-up was higher than in perpendicular (B) lay-up by 50%, with a value of 203%, particularly in mixed arrangement compared to the other vertical and horizontal arrangements. This arrangement is suitable for both glued laminated bamboo (GLB) and cross laminated bamboo boards (CLB) because its density range is light to medium hardwood and comparable to wood strength A to B for vertical and horizontal arrangement with an exception to D in mixed arrangement.
6. Out of 24 boards, the best strength performance came from the board with parallel lay-up (A) and vertical arrangement. Vertical arrangements had the highest and greatest elasticity modulus, higher compressive strength, and the best overall compression performance of the three types of arrangements.
7. Four main types of compression parallel to the grain failure modes could be observed in laminated bamboo boards: shearing failure, splitting and glue line delamination, buckling and crushing, and brooming or end rolling.

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