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Effects of Adhesive Types and Structural Configurations on Shear Performance of Laminated Board from Two Gigantochloa Bamboos

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Abstract: Semantan (*Gigantochloa scortechinii*) and beting (*Gigantochloa levis*) bamboo are the two Malaysian bamboo that are suitable to be converted into laminated bamboo boards. One of the main criteria for laminated board is its good bondability, which is determined by shear performance. The shear performance of laminated board is influenced by several factors such as the species used, adhesive types and lamination configurations. Therefore, in this study, laminated bamboo boards were produced using Semantan and Beting bamboo bonded with phenol–resorcinol–formaldehyde (PRF) and polyurethane (PUR) adhesives. Different configurations (lay-up patterns and strip arrangements) were used during the consolidation of the laminated boards. The bamboo strips were arranged in three different arrangements, namely vertical, horizontal and mixed, and then assembled into a three-layered structure with two lay-up patterns, which are perpendicular and parallel. Shear performances, such as shear strength, bamboo failure and delamination of the boards, were evaluated. The results revealed that the adhesive type and lay-up pattern were the most influential factors on the shear performance. PRF-bonded laminated bamboo boards outperformed PUR-bonded laminated bamboo boards in terms of shear strength and bamboo failure but PUR bonding had better bond durability as indicated by its low delamination. Boards laminated parallelly significantly outperformed those bonded perpendicularly. As for strip arrangement, PRF-bonded laminated boards were less influenced by it compared to PUR-bonded laminated boards. The results suggested that PRF is a better adhesive for bamboo lamination due to its higher shear performance and more consistent performance across structural configurations (lay-up patterns and strip arrangements).

Keywords: semantan bamboo; beting bamboo; shear strength; strip arrangement; lay-up pattern

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1. Introduction

Laminated bamboo board is an excellent substitute for wood, with performance comparable to or exceeding that of wood [1,2]. While maintaining the benefits of round bamboo, studies have shown that laminated bamboo board can overcome round bamboo's disadvantages such as size limitations and dimensional inconsistencies [3,4]. In Malaysia, there are approximately 70 identified bamboo species [5], with 13 of them being commercially used [6]. Beting bamboo (*Gigantochloa levis*) and Semantan bamboo (*Gigantochloa scortechinii*) are two bamboo species used commercially in Malaysia [6]. In Malaysia, *G. scortechinii* has been widely used by researchers to produce laminated bamboo board [4,7], plybamboo [8] and polymeric bamboo composites [9,10]. Meanwhile, *G. levis* has also been used to produce glued laminated bamboo lumber [11], plybamboo [12] and bamboo/epoxy composite [13]. Given the abundance of these bamboos and their exceptional strength properties, both *G. scortechinii* and *G. levis* could be viable commercial candidates in the laminated bamboo board industry.

The performance of laminated bamboo boards is influenced by several factors such as the layer structure [14], adhesive type, adhesive spreading rate and clamping pressure and time [15]. Adhesive is critical in the formation of high-quality, long-lasting bonds as well as in achieving the proper interface bond and penetration between the fibre and laminas [16]. Adhesives are generally classified based on their chemistry, according to Stoeckel et al. [17]. Adhesives are classified into two types based on this criterion: in situ polymerised adhesives and pre-polymerised adhesives. Aminoplastic adhesives, phenol–resorcinol–formaldehyde (PRF), and polymeric methylene–diphenyl–diisocyanate (pMDI) are examples of in situ polymerised adhesives containing relatively rigid, highly crosslinked polymers. Meanwhile, polyurethane (PUR) and polyvinyl acetate (PVAc) are examples of pre-polymerised adhesives with flexible polymers. The ability of these two groups to distribute moisture-induced stress in an adhesive bond varies significantly, resulting in different failure mechanisms. However, the chemistry of the adhesives is not the only factor to consider when categorising adhesives. One of the primary concerns is the mechanical response of the adhesives [18]. Previous research by Guan et al. [19] discovered that the type of adhesive has a significant impact on the shear bond strength of bamboo materials. The penetration of the adhesive into the bamboo cell walls alters the bonding mechanism and has a significant impact on the mechanical properties of laminated bamboo materials from various bamboo species and densities. Dong et al. [20] studied the bonding performance of cross-laminated timber–bamboo composites and concluded that the adhesive type is the most important factor that affects its performance.

In comparison with other mechanical properties, such as compressive, tensile and bending resistance, the bonding shear strength of the laminated materials, particularly bamboo, has not been fully addressed [16]. This study focuses on investigating the effects of adhesive types and assembly configurations on the bonding shear performance of laminated bamboo made from two local bamboo species, *G. scortechinii* and *G. levis*. Phenol–resorcinol–formaldehyde (PRF) and polyurethane (PUR) were used as adhesive for the laminated bamboo boards' fabrication. The laminated bamboos were consolidated using different configurations, that is, different lay-up patterns (parallel and perpendicular) and strip arrangements. Three strip arrangements, namely horizontal, vertical and mixed, were used during the consolidation of the laminated bamboo boards. The bamboo strips were consolidated into a three-layer structure horizontally, vertically and a combination of horizontal and vertical, called a mixed pattern, in this study. Shear strength, bamboo failure and delamination were evaluated as functions of the above-mentioned parameters.

2. Materials and Method

2.1. Preparation of Bamboo Strips

Gigantochloa levis, locally called Beting bamboo, and *Gigantochloa scortechinii*, locally called Semantan bamboo were used to make 3-layer laminated bamboo in this study. Three-year old bamboo culms were selected from a bamboo plantation near Nami, Kedah. *G. scortechinii* and *G. levis* have average densities of 700 kg/m^3 and 751 kg/m^3, respectively. The modulus of rupture and modulus of elasticity of the former are 125 N/mm^2 and 10,039 N/mm^2, while those of the latter are 163 N/mm^2 and 13,185 N/mm^2, respectively. *G. levis* is a large species of bamboo with an average culm size of 11–13 cm and a wall thickness of 11–15 mm, with estimated height and length of 18–23 m and 35 cm, respectively. The height of *G. scortechinii* is between 17 and 20 m. This bamboo's internode is 42 cm long and has a culm length of 9–11 cm. The wall thickness ranges from 6 to 10 mm. The culms were transported to Saudagar Bamboo Enterprise located in Kuala Nerang, Kedah, for further processing. The culms were cut to 2 m long then ripped into splits of 22 mm wide (Figure 1). The bamboo splits were then flattened and shaped using thicknesser machine before being planed to a final thickness of 5 mm using a double-sided planer. The final dimensions of the bamboo strips was 2000 mm long × 20 mm wide × 5 mm thick. The bamboo strips were then soaked in 5% boric acid solution for 24 h and kiln dried to a 12 ± 2% moisture content. The densities of the bamboo strips after conditioning are 685.51 kg/m^3 and 689.91 kg/m^3 for *G. scortechinii* and *G. levis*, respectively.

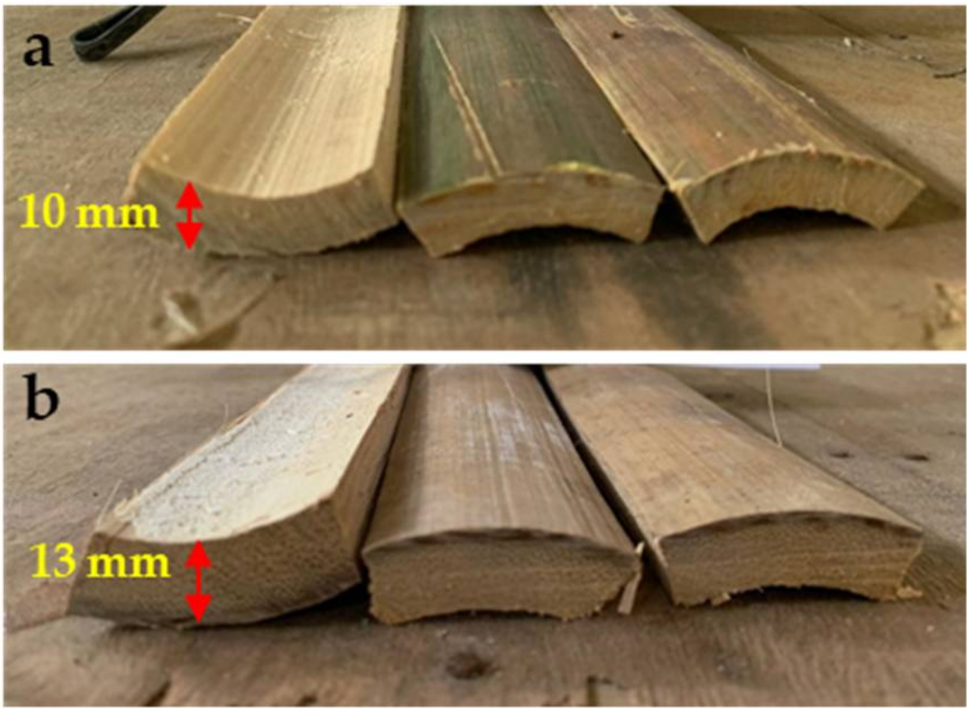

Figure 1. Splits of: (**a**) *Gigantochloa scortechinii* and (**b**) *Gigantochloa levis*.

2.2. Fabrication of 3-Layer Laminated Bamboo Boards

Prior to fabrication of laminated bamboo boards, the bamboo strips were sorted into three categories, which are: (i) straight and square strips for edge bonding, (ii) slightly curved and square strips for face bonding and (iii) reject strips due to being highly curved, bent or not meet the desired size. The bamboo strips were consolidated by using different configurations (lay-up patterns and strip arrangements) as shown in Figure 2. Three strip arrangements, namely horizontal, vertical and mixed, were used during the consolidation of the laminated bamboo boards. The bamboo strips were consolidated into 3-layer structures horizontally, vertically and a combination of horizontal and vertical, called mixed pattern, in this study. In the mixed arrangement pattern, the bamboo strips were assembled horizontally in the 2 outer layers of the boards and vertically in middle layer. All arrangement patterns were laid parallelly (oriented at 0° to the adjacent layer) and perpendicularly (oriented at right angles to the adjacent layer) (Figure 2). Therefore, laminated bamboo boards with a total of 6 configurations were fabricated.

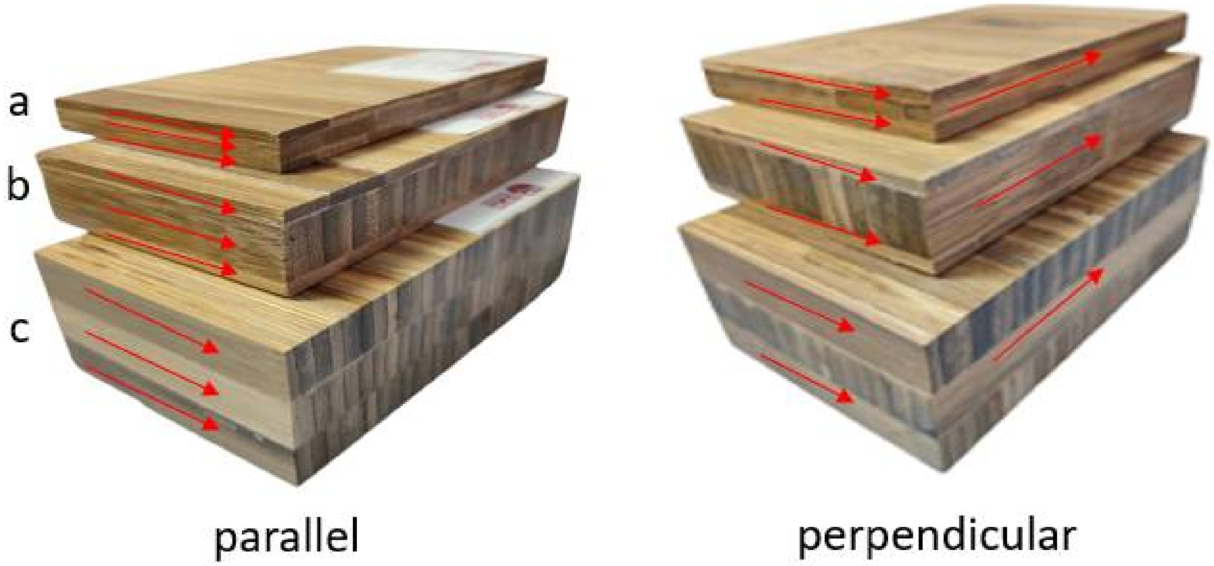

Figure 2. Parallel and perpendicular lay-up patterns of bamboo strips with different arrangements: (a) horizontal; (b) mixed; and (c) vertical.

Two cold setting adhesives, phenol–resorcinol–formaldehyde (PRF) and polyurethane (PUR) (supplied by AkzoNobel Sdn. Bhd., Petaling Jaya, Selangor), were used as bonding agents for the laminated bamboo boards. The glue spread rate used was 250 g/m^2 and 200 g/m^2 for PRF and PUR, respectively, as recommended by the supplier. Each layer of bamboo strips was edge glued firstly using a pressing pressure of 75 kg/cm^2. The formed layers were then face glued into a 3-layer structure using a pressing pressure of 125 kg/cm^2. Edge trimming and sanding were performed on the 3-layer laminated bamboo boards to remove squeezed out adhesive for smooth and flat surfaces. A total of 144 boards (2 species × 2 adhesives × 6 configurations × 6 replications) with dimensions of 300 wide × 1220 mm long were fabricated. The thicknesses of the final boards were different according to different configurations, which were 54 mm vertically, 13 mm horizontally and 27 mm mixed.

2.3. Evaluation of Shear Strength of Laminated Bamboo Boards

The shear strengths of the glue lines of the laminated bamboo boards produced in this study were evaluated based on British Standard (BS) EN 392: 1995—Glued laminated timber—Shear test of glue lines. Samples with dimensions of 40 mm wide × 40 mm long with various thicknesses were prepared. Prior to testing, the samples were conditioned at a temperature of 20 ± 2 °C and relative humidity 65 ± 5% until contact mass was achieved. The conditioned samples were placed on a shear machine and load was applied at the glue line between the laminations of the laminated bamboo until failure occurred (Figure 3). The load was applied under a displacement control rate of 3 mm/min, ensuring failure after no less than 20 s. The shear strength *fv* was determined for every tested glue line and was calculated in accordance with the following formula:

$$fv = k\frac{Fu}{A} \quad (1)$$

where:

Fu is the ultimate load (in N);
A is the sheared area (in mm^2);
k is factor: kv = 0.78 + 0.0044 t;
t is thickness (in mm).

Figure 3. Shearing machine set up for shear strength test.

Twelve replications were tested for each species, adhesive and configuration. A total of 288 samples (2 × 2 × 6 × 12) were tested. The shear strengths of the glue lines obtained were then compared with EN14080:2013—Timber structures—Glued laminated timber and glued solid timber—Requirements for parallel arrangement and EN16351:2021—Timber structures—Cross laminated timber—Requirements for perpendicular arrangement. It is stipulated in the standard that the minimum requirements for parallelly arranged laminated boards shall be at least 4 N/mm^2 (EN14080) and at least 2 N/mm^2 for laminated boards arranged perpendicularly.

2.4. Estimation of Bamboo Failure

The estimation of bamboo failure was performed on the sheared area specimens as shown in Figure 4. Each failure surface was measured and the results were averaged. The bamboo failure percentage was estimated to the nearest 5% by examining the total area covered by the bamboo fibre (signifying bamboo failures) on the sheared area in comparison to the area covered with glue failure.

Figure 4. Sheared samples for failure estimation after shear test.

2.5. Evaluation of Delamination of Laminated Bamboo Boards

Three-layer laminated bamboo samples with dimensions of 75 mm wide × 130 mm long and various thicknesses were prepared for delamination evaluation. The delamination test was conducted according to the procedures specified in EN 391:2002—Glued laminated timber—Delamination test of glue lines. The test cycle for method B was chosen. The samples were placed in a pressure vessel as shown in Figure 5 and submerged in water at ambient temperature. A vacuum of 60 kPa was applied and held for 30 min. Subsequently, the vacuum was released and a pressure of 550 kPa was applied and retained for 2 h. Once the vacuuming was completed, the test pieces were dried for a period of approximately 10–15 h in a circulating oven at 65 ± 10 °C. Delamination was observed and recorded when the mass of the test pieces had returned to within 100% to 110% of the original mass. After removal from the oven, the samples were examined for the occurrence of delamination or open glue lines. The length of the open glue lines was determined by first inserting a thin metal probe between the two delaminated surfaces. Measurements count if the depth of the delamination is less than 2.5 mm and more than 5 mm. Two attributes were determined, (i) total delamination and (ii) maximum delamination of a test piece, according to Equations (2) and (3):

$$Delam\ tot = 100\,\frac{ltot,\ delam}{ltot, glueline}\ (\%) \tag{2}$$

$$Delam\ max = 100\,\frac{lmax,\ delam}{2l, glueline}\ (\%) \tag{3}$$

where:

$ltot,\ delam$ = the total delamination length (in mm);
$ltot, glueline$ = the sum of the perimeter of all glue lines in a delamination specimen (in mm);
$lmax,\ delam$ = the maximum delamination length (in mm);
$l, glueline$ = the perimeter of one glue line in a delamination specimen (in mm).

Figure 5. Samples placed inside a pressure vessel for delamination tests.

2.6. Statistical Analysis

Analysis of the obtained data were performed using statistical software IBM-SPSS version 25.0 by employing one-way analysis of variance (ANOVA). Meanwhile, mean separation was carried out using the Least Significance Difference (LSD) method.

3. Results and Discussion

3.1. Shear Strength and Bamboo Failure

Table 1 summarises the analysis of variance (ANOVA) results for the effects of species, adhesive and lay-up on the shear strength and failure of laminated bamboo arranged vertically, horizontally and in a mixed pattern. The shear strength of the laminated bamboo in the horizontal and mixed arrangements is affected by the species ($p \leq 0.05$). The bamboo species had no effect on shear strength in the vertical arrangement. Meanwhile, the shear strength of the laminated bamboo in all arrangements is significantly affected by adhesive type and lay-up ($p \leq 0.01$). On the other hand, adhesive type was discovered to have a significant effect on bamboo failure, whereas species had no influence on bamboo failure. Only the bamboo failure of laminated boards manufactured in a mixed arrangement was significantly influenced by the lay-up pattern.

Table 1. Analysis of variance (ANOVA) for the effects of species, adhesive and lay-up on the shear strength and failure of laminated bamboo arranged vertically, horizontally and in a mixed pattern.

Source	*p*-Value					
	Vertical		Horizontal		Mixed	
	Shear Strength	Bamboo Failure	Shear Strength	Bamboo Failure	Shear Strength	Bamboo Failure
species	0.4477 ns	0.7913 ns	0.0135 *	0.0041 **	0.0347 *	0.470 1ns
adhesive	<0.0001 **	<0.0001 **	<0.0001 **	<0.0001 **	<0.0001 **	<0.0001 **
lay-up	<0.0001 **	0.3030 ns	0.0068 **	0.0674 ns	<0.0001 **	0.0095 **

Note: ns not significant. * Significantly different at $p \leq 0.05$. ** Significantly different at $p \leq 0.01$.

Shear strength and bamboo failure of laminated bamboo of different configurations bonded with PRF and PUR adhesives are tabulated in Table 2.

Table 2. Shear strength of laminated bamboo boards fabricated with different species, adhesives and configurations.

Label	Variable			Shear Strength (N/mm^2)		
	Species	Adhesive	Lay-Up	Vertical	Horizontal	Mixed
BPA	Beting	PRF	Parallel	5.52 ^{B} (1.58)	4.21 ^{B} (1.97)	7.99 ^{A} (2.42)
BPB	Beting	PRF	Perpendicular	2.34 ^{D} (0.82)	3.07 ^{C} (1.68)	2.36 ^{C} (0.80)
BUA	Beting	PUR	Parallel	4.05 ^{C} (1.78)	7.55 ^{A} (3.33)	5.64 ^{B} (2.35)
BUB	Beting	PUR	Perpendicular	3.31 ^{C} (0.39)	6.87 ^{A} (1.77)	2.63 ^{C} (1.07)
SPA	Semantan	PRF	Parallel	7.91 ^{A} (1.08)	6.69 ^{A} (3.58)	6.41 ^{B} (2.57)
SPB	Semantan	PRF	Perpendicular	2.44 ^{D} (0.50)	1.54 ^{D} (0.63)	3.32 ^{C} (0.59)
SUA	Semantan	PUR	Parallel	3.71 ^{C} (1.51)	3.47 ^{C} (0.97)	3.16 ^{C} (1.91)
SUB	Semantan	PUR	Perpendicular	1.86 ^{D} (0.31)	5.6 ^{B} (1.20)	2.66 ^{C} (0.99)

Note: Mean followed by the different letters $^{A, B, C, D}$ in the same column are significantly different at $p \leq 0.05$ according to LSD; Values in parentheses ( ) are standard deviation.

Laminated bamboo boards of vertical, horizontal and mixed arrangements recorded shear strength values ranging from 1.86 to 7.91 N/mm^2, 1.54 to 7.55 N/mm^2 and 2.36 to 7.99 N/mm^2, respectively (Figure 6). The highest shear strength was observed in the samples fabricated parallelly with a mixed arrangement using *G. levis* (Beting bamboo) bonded with PRF resin. Meanwhile, the lowest shear strength was recorded in the laminated bamboo boards fabricated perpendicularly with horizontal arrangement using *G. scortechinii* (Semantan bamboo) bonded with PRF resin.

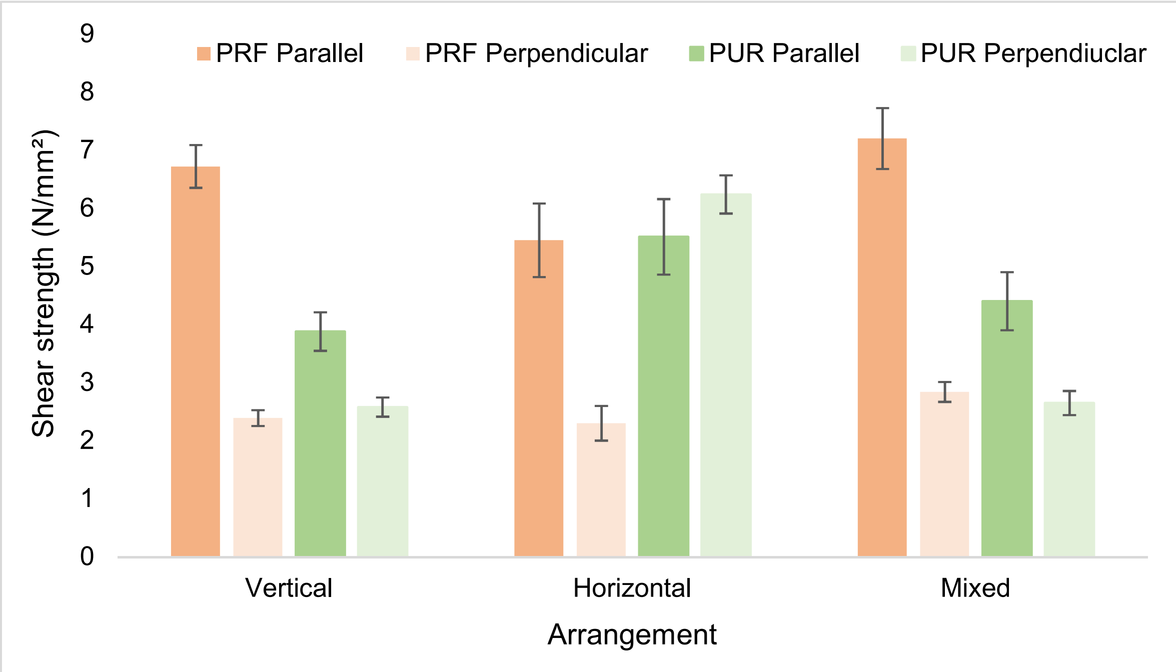

Figure 6. Effects of adhesive and lay-up pattern on the glue line shear for three different strip arrangements. Note: Vertical line in every bar represents the standard deviation.

It was observed that the shear strength of the laminated bamboo boards with parallel arrangements were greater than the minimum requirements ($\geq$4 N/mm^2) as specified in EN14080, with the exception of SUA (Semantan bamboo bonded parallelly with PUR resin) for all arrangements (vertical, horizontal and mixed). Meanwhile, the shear strengths of the laminated bamboo with perpendicular arrangements were relatively lower compared with those using parallel arrangements, but still fulfilled the minimum requirements of shear strength specified in EN16351, which is $\geq$2 N/mm^2. The only exception was found in SUB (Semantan bamboo bonded perpendicularly with PUR resin) in the vertical arrangement and SPB (Semantan bamboo bonded perpendicularly with PRF resin) in the horizontal arrangement.

The ANOVA results indicated that the interaction between adhesive and lay-up pattern are significant on the shear strength of laminated bamboo boards. Figure 6 shows the effects of adhesive and lay-up pattern on the shear strength of the boards.

The bamboo failure of laminated bamboo boards in a vertical arrangement ranged between 3.75 and 80.67% (Table 3). For the horizontal arrangement, the bamboo failure ranged between 5.08 and 92.0%, while for the mixed arrangement, the bamboo failure ranged between 0.83 and 39.67%. The bamboo failure was higher in the laminated bamboo boards bonded with PRF compared to that of PUR in all configurations. The average bamboo failure was 22%–92% for laminated bamboo bonded with PRF and 3%–22% for laminated bamboo bonded with PUR. Sikora et al. [21] discovered that the PRF has a very good durability performance compared to that of PUR resin. The visual appearance of the sheared samples is shown in Figure 7.

Table 3. Bamboo failure of laminated bamboo boards fabricated with different species, adhesives and configurations.

Label	Variable			Bamboo Failure (%)		
	Species	Adhesive	Lay-Up	Vertical	Horizontal	Mixed
BPA	Beting	PRF	Parallel	76.17 ^{A} (17.21)	77.67 ^{B} (13.54)	28.25 ^{A} (14.85)
BPB	Beting	PRF	Perpendicular	75.75 ^{A} (13.01)	87.42 ^{A} (5.16)	39.67 ^{A} (17.79)
BUA	Beting	PUR	Parallel	3.33 ^{B} (6.16)	5.08 ^{D} (6.19)	4.17 ^{C} (11.45)
BUB	Beting	PUR	Perpendicular	7.5 ^{B} (9.31)	16.33 ^{C} (7.11)	18.08 ^{B} (23.48)
SPA	Semantan	PRF	Parallel	75.75 ^{A} (18.9)	86.33 ^{A} (10.46)	35 ^{A} (15)
SPB	Semantan	PRF	Perpendicular	80.67 ^{A} (10.55)	92 ^{A} (4.97)	22.25 ^{B} (13.14)
SUA	Semantan	PUR	Parallel	3.75 ^{B} (5.28)	21.92 ^{C} (14.81)	0.83 ^{C} (1.95)
SUB	Semantan	PUR	Perpendicular	5.17 ^{B} (7.1)	10.5 ^{D} (12.71)	22.67 ^{B} (20.02)

Note: Mean followed by the different letters $^{A, B, C, D}$ in the same column are significantly different at $p \leq 0.05$ according to LSD. Values in parenthesis ( ) are standard deviation.

Figure 7. Sheared samples of laminated bamboo boards fabricated with different species, adhesives and configurations. Note: SPA—Semantan PRF parallel; SPB—Semantan PRF perpendicular/cross. SUA—Semantan PUR parallel; SUB—Semantan PUR perpendicular/cross; BPA—Beting PRF parallel; BPB—Beting PRF perpendicular/cross; BUA—Beting PUR parallel; BUB—Beting PUR perpendicular/cross; v—vertical arrangement; h—horizontal arrangement; m—mixed arrangement.

3.2. Delamination

Table 4 tabulates the analysis of variance (ANOVA) of the effect of species, adhesive and lay-up pattern on the delamination of laminated bamboo boards. Species exert slightly significant ($p \leq 0.05$) effects on the shear strength of vertically and horizontally arranged boards, and the effects on mixed arrangement boards were highly significant ($p \leq 0.01$). Meanwhile, adhesive types had significant effects on the delamination of horizontally and mixed arranged boards. The lay-up pattern was found to be significantly affected vertically ($p \leq 0.01$) and horizontally ($p \leq 0.05$) arranged boards.

Table 4. The analysis of variance (ANOVA) for the effects of species and adhesive for the delamination of parallel laminated bamboo in different configurations.

Source	df	*p*-Value		
		Vertical	Horizontal	Mixed
species	1	0.0126 *	0.0343 *	0.0025 **
adhesive	1	0.0657 ns	<0.0001 **	0.0050 **
lay-up	1	<0.0001 **	0.0106 *	0.1720 ns

Note: ns not significant. * Significantly different at $p \leq 0.05$. ** Significantly different at $p \leq 0.01$.

Table 5 shows the effect of species, adhesive and lay-up on the delamination of laminated bamboo in three different arrangements. The delamination for vertically arranged boards ranged from 0.78% to 26.66% The highest delamination was found in SUB (Semantan bamboo bonded perpendicularly with PUR resin) samples while the lowest was observed in SUA (Semantan bamboo bonded parallelly with PUR resin) samples. For horizontally arranged samples, the delamination varied between 1.16% and 38.01%. The highest delamination was observed in BPB (Beting bamboo bonded perpendicularly with PRF resin), and the lowest was observed in BUB (Beting bamboo bonded perpendicularly with PUR resin) samples. Meanwhile, for the mixed arrangement, the delamination ranged from 6.34% to 24.27%. The highest delamination was recorded in BUA (Beting bamboo bonded parallelly with PUR resin) samples while the lowest delamination was recorded in SPA (semantan bamboo bonded parallelly with PRF resin). Generally, the vertical arrangement has better glue line durability compared to those of the mixed and horizontal arrangements, as shown by lower delamination values.

Table 5. Delamination of parallel laminated bamboo boards fabricated with different configurations.

Label	Variable			Shear Strength (N/mm^2)		
	Species	Adhesive	Lay-Up	Vertical	Horizontal	Mixed
BPA	Beting	PRF	Parallel	6.31 ^{B} (5.49)	28.32 ^{B} (6.54)	16.83 ^{B} (9.62)
BPB	Beting	PRF	Perpendicular	7.64 ^{B} (3.94)	38.01 ^{A} (18.11)	17.28 ^{B} (4.8)
BUA	Beting	PUR	Parallel	2.73 ^{C} (3.6)	4.27 ^{D} (3.62)	6.34 ^{C} (3.23)
BUB	Beting	PUR	Perpendicular	10.42 ^{B} (5.34)	1.16 ^{D} (2.71)	16.9 ^{B} (9.75)
SPA	Semantan	PRF	Parallel	5.42 ^{B} (6.4)	16.85 ^{C} (6)	24.27 ^{A} (10.17)
SPB	Semantan	PRF	Perpendicular	9.82 ^{B} (6.11)	31.3 ^{B} (4.5)	19.12 ^{A} (10.38)
SUA	Semantan	PUR	Parallel	0.78 ^{C} (1.62)	6.98 ^{D} (6.52)	15.75 ^{B} (5.92)
SUB	Semantan	PUR	Perpendicular	26.66 ^{A} (16.75)	2.78 ^{D} (2.9)	19.14 ^{A} (8.68)

Note: Mean followed by the different letters $^{A, B, C, D}$ in the same variable category are significantly different at $p \leq 0.05$ according to LSD.

Based on ANOVA, the interaction between adhesive types and lay-up were found significantly affected the delamination percentage of boards in all arrangements. Figure 8 illustrates the effects of adhesive and lay-up pattern on the delamination of laminated bamboo of all arrangements.

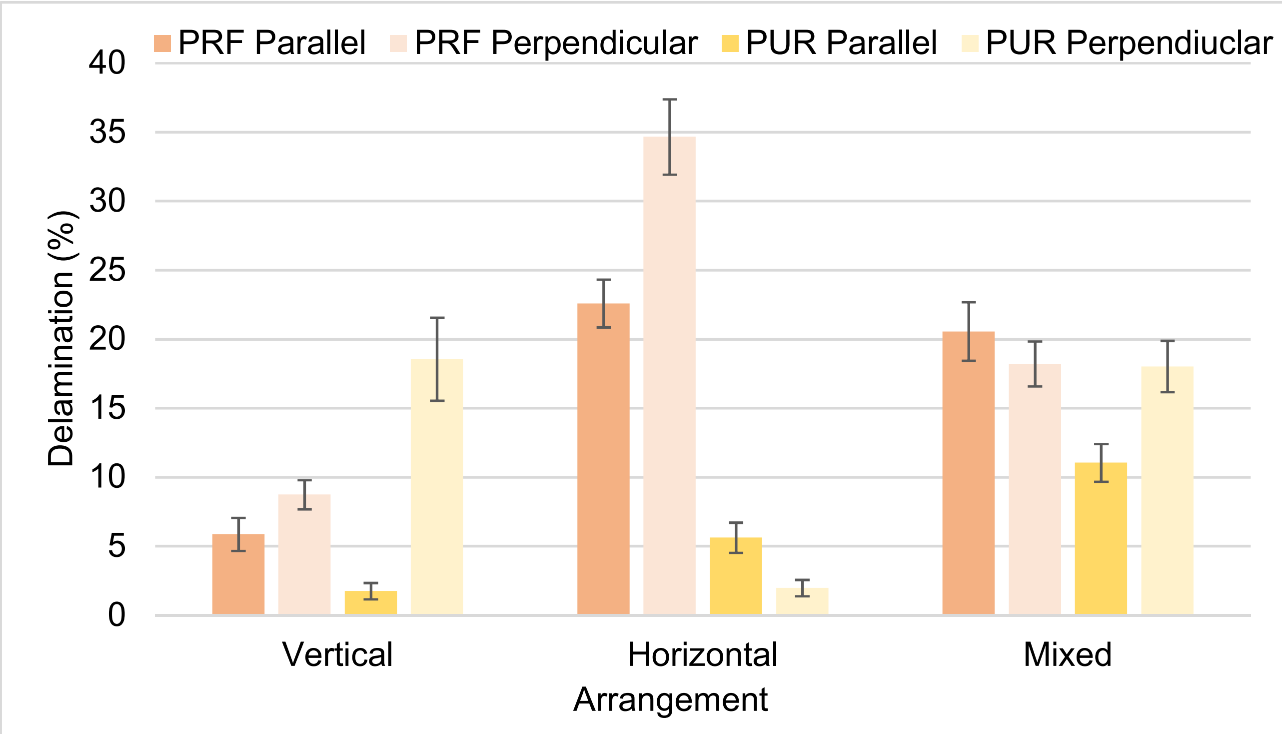

Figure 8. Effects of adhesive and lay-up on the delamination of laminated bamboo boards of all arrangements. Note: Vertical line in every bar represents the standard deviation.

Adhesive types had the most influence on the delamination of samples. PRF-bonded laminated bamboo has a lower delamination percentage as compared with PUR-bonded laminated bamboo in vertical arrangements. However, in the horizontal and mixed arrangements, this relationship was reversed. The parallel lay-up pattern had a generally lower percentage of delamination as compared with the perpendicular lay-up in all arrangements. Although the delamination results varied significantly between samples, it was observed that the mechanism causing delamination in the glue line was the same for all specimens, i.e., delamination occurred in a single glue line on one side for vertical arrangements and both sides for horizontal and mixed arrangements. Overall, PUR adhesive has a more durable bond than PRF adhesive, despite better shear strength and bamboo failure shown by PRF resin. A study by Lu et al. [22] also made a similar observation that PUR-bonded samples displayed the lowest delamination. PUR is a flexible polymer; therefore, its capability to withstand moisture-induced stress might be better than PRF resin and thus lead to better bond durability.

3.3. Effects of Variables on the Shear Strength of Laminated Bamboo Board

Table 6 compares the effects of single variables on the shear strength of laminated bamboo boards. It can be observed that laminated bamboo boards made from Beting bamboo have significantly higher shear strengths than those made of Semantan. Both Semantan and Beting bamboo are members of the Gigantochloa family and thus have similar anatomical structures. Both Semantan and Beting bamboo have type III vascular bundles, according to Abdullah Siam et al. [6]. The study by Abdullah Siam et al. [6] stated that Beting bamboo had higher density and mechanical properties compared to Semantan bamboo. It was discovered that wood density positively affected the apparent shear strength of the wood [23]. However, the difference in density between the bamboo strips used in this study is very small (685.51 kg/m^3 for Semantan and 689.91 kg/m^3 for Beting). Therefore, the density did not play a prominent role in this study and the difference in shear strength could be caused by other factors that require further investigation.

Table 6. Comparison between effects of variables on the properties of laminated bamboo board.

Variable	Glue Line Shear (MPa)
Species	
Beting (*Gigantochloa levis*)	4.63 ^{A}
Semantan (*Gigantochloa scortechinii*)	4.06 ^{B}
Adhesive	
PRF	4.48 ^{A}
PUR	4.21 ^{A}
Lay-up	
Parallel	5.53 ^{A}
Perpendicular	3.17 ^{B}
Arrangement	
Vertical	5.19 ^{B}
Horizontal	6.50 ^{A}
Mixed	5.70 ^{B}

Note: Mean followed by the different letters $^{A, B}$ in the same variable category are significantly different at $p \leq 0.05$ according to LSD.

Similarly, the effects of adhesive types also did not exert significant effects on the shear strength of laminated bamboo boards. However, laminated bamboo boards bonded with PRF resin was found to perform slightly better than those bonded with PUR resin. Studies have shown that PRF performed better than PUR in bonding materials owing to superior gap-filling properties of PRF resin [24]. Studies by several researchers also reported the same observation that the PRF-bonded samples exhibited superior shear performance than those of PUR-bonded samples [25–27]. Konnerth et al. [28] stated that PRF resin is able to penetrate into the wood cell wall, therefore resulting in better bonding performance compared to PUR resin, which is unable to penetrate into the wood cell wall.

On the other hand, the lay-up pattern of the bamboo strips was found to have significantly affected the shear strength of the laminated board. Boards arranged parallelly performed significantly better than those arranged perpendicularly. Because wood is anisotropic, the fibre direction of the bonding interface has a significant impact on shear strength. According to Qin [29], the shear strength of a perpendicular fibre direction is two-thirds to three-quarters that of a parallel fibre direction. Several studies, for instance, Ashaari et al. [30] and Rabi'atol Adawiah et al. [31], also found that the laminates assembled parallelly displayed significantly superior mechanical performance than those assembled perpendicularly. In terms of arrangement, laminated bamboo boards that were assembled horizontally outperformed those assembled vertically and in a mixed pattern. The shear strength for laminated boards constructed by arranging the strips horizontally is generally high despite having lower thicknesses (13 mm) than the vertical (54 mm) and mixed (27 mm) arrangements. This could be due to the size effect, where laminated bamboo boards in vertical and mixed arrangements with higher thicknesses had larger bamboo volumes loaded under shear stresses and thus experienced more critical strength-reducing defects than laminated bamboo boards arranged horizontally [32]. Therefore, the shear strength for parallel lay-up boards is notably higher than perpendicular ones. The same observation was also made by several researchers. For instance, Sikora et al. [33] stated that the thickness of cross-laminated timber (CLT) has adverse effects on the rolling shear strength of the CLT panels. A study by Li (2017) also confirmed that the CLT panels with higher thicknesses had lower rolling shear strengths compared to those with lower thicknesses.

Figure 9 depicts the shear strength ratios of each arrangement in order to examine the effects of strips arrangements in greater detail. The shear strength ratios of V/H, V/M and H/M ranged from 0.41 to 2.36. Shear ratios revealed that strip arrangements had less effect on PRF-bonded laminated bamboo boards, with values ranging from 0.76 to 1.23, all distributed around 1.0. Meanwhile, the arrangement had a significant impact on PUR-bonded laminated bamboo boards, with strength ratios ranging from 0.41 to 2.36. Surprisingly, strip arrangements have very different effects on PRF- and PUR-bonded laminated bamboo boards. The mixed arrangement has the highest shear resistance capacity for PRF-bonded laminated bamboo boards, followed by the vertical arrangement and the lowest being horizontal. The strip arrangement had little effect on the lay-up pattern for PRF-bonded laminated bamboo boards, as both parallelly and perpendicularly assembled boards showed a fairly consistent shear strength ratio. The high variation in the shear strength ratio in PUR-bonded boards, on the other hand, revealed that the effect of strip arrangement on the board's shear strength is significant. The horizontal arrangement of PUR-bonded laminated bamboo demonstrated the highest shear resistance capacity, followed by mixed and then vertical. In comparison to parallel boards, perpendicularly assembled laminated boards were heavily influenced by strip arrangement, as shown by their extremely wide range of shear strength ratio. Xing et al. [16] speculated that the low compatibility of PUR adhesive with bamboo materials and the inferior strength of the resin itself may have contributed to the abnormal trend in PUR-bonded laminated bamboo boards.

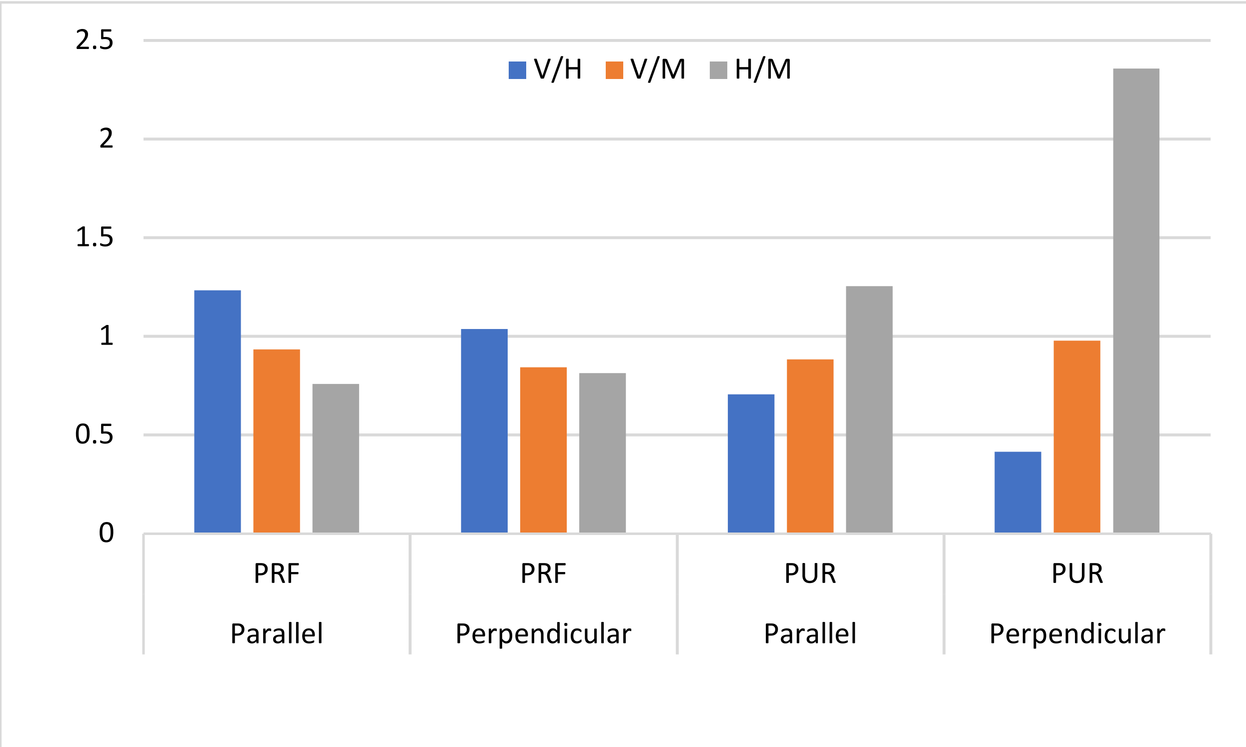

Figure 9. Shear strength ratios of each arrangement of vertical (V), horizontal (H) and mixed (M).

4. Conclusions

In this study, laminated bamboo boards with various structural configurations were fabricated from two local bamboo species, *G. scortechinii* and *G. levis*, and bonded with PRF and PUR adhesives. The shear performance of laminated bamboo boards is heavily influenced by the adhesive types and lay-up pattern (parallel and perpendicular). PRF-bonded laminated bamboo boards outperformed PUR-bonded laminated bamboo boards in terms of shear strength and bamboo failure. However, PUR-bonded laminated bamboo boards showed less delamination than PRF-bonded boards, indicating that PUR-bonded boards have better bonding durability. Furthermore, boards laminated parallelly outperformed those bonded perpendicularly. It should be noted that the arrangement of bamboo strips (vertical, horizontal and mixed) had no significant effect on the shear performance of PRF-bonded laminated boards. The strip arrangements, on the other hand, had a significant influence on PUR-bonded boards, with those assembled horizontally showing the highest shear strength compared to the other two arrangements (vertical and mixed). Furthermore, the effect is stronger in those laminated perpendicularly. According to the findings, PRF is a better adhesive for bamboo lamination due to its higher shear performance and more consistent performance across structural configurations (lay-up patterns and strip arrangements).

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