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Bonding characteristics of *Gigantochloa scortechinii*

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Abstract—The adhesion and bonding properties of bamboo, *Gigantochloa scortechinii*, were studied. The variables studied were adhesive types, grain orientation (parallel-ply or cross-ply) and bonding properties of strips taken from different parts of bamboo culm, i.e. strips taken near the periphery or near the inner layer or a combination of both. Commercially available adhesives, phenol formaldehyde (PF), urea formaldehyde (UF) and melamine urea formaldehyde (MUF), were used to bond the bamboo strips. The bonded specimens were subjected to plywood shear test in both dry and wet conditions. The study showed that PF resin formulation suitable for the production of tropical plywood was found to be most compatible for bonding bamboo strips; nevertheless, a slightly longer press time is required to ensure sufficient curing of resin. All shear strengths and wood failure percentage of the PF-bonded laminates met the minimum requirement of British standards. The bonding properties of UF-bonded laminates achieved the standard only when tested in dry conditions. Hot press parameters employed for pressing the MUF-bonded laminates was not sufficed to cure the resin. The grain orientation (parallel or cross-ply) of the strips bonded with either PF or UF had no significant effect on the glue bond quality when tested dry. In extreme wet conditions, the parallel-ply laminates were apparently more stable than the cross-ply laminates. Different parts of the bamboo culm significantly affect the resulting glue bond quality. In all conditions, laminates made from peripheral strips gave more stable products than those made either from inner strips or from the combination of both.

Key words: Bamboo; *Gigantochloa scortechinii*; strips; bonding parallel-ply; cross-ply.

INTRODUCTION

Bamboo has been getting attention as a substitute material for wood [1]. It has similar morphological properties to wood. Due to its fast growth and availability,

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having an attractive and unique appearance this material can be converted into engineered products such as composites, laminated boards and plywood. These products have gained commercial importance in China and Japan. In Malaysia, this material has been used intensively in cottage industry like poultry cage, vegetable basket, incense stick and joss paper, skewer and chopstick and handicraft [2, 3].

Due to the nature of the plants, the utilization of bamboo culm can only be through lamination. In wood lamination, bonding characteristics, i.e. the surface wettability, buffering capacity and adhesive formulation, are important, since they determine the rate of adhesive penetration into the wood surface, the rate of adhesive curing and the degree of adhesion developed between the substrate and the adhesive.

Wettability of a wood surface refers to the rate or how fast a liquid can wet and spread on it. The study of the wetting of solids by the contact angle measurements has become an important tool in the study of adhesion. According to Minford [4], wetting can be quantified by the equilibrium contact angle formed by the intersection of the solid, liquid and gas phases. When good wetting occurs, the contact angle becomes very small and the liquid spread or flows spontaneously across the surface. Earlier study showed that the wetting angle of *Gigantochloa scortechinii* (Buluh semantan) was 15° [5], compared to 39° for rubberwood after 1 min of water droplet spreading [6].

Buffering capacity measures the resistance of wood to change in acidity or in alkalinity. Both the pH and buffering capacity of the wood at the glueline affect the cure of the resin. Knowing the buffering capacity of wood helps determine the amount of buffering agent required in the adhesive to prevent changes in pH at the glueline. These changes, if not prevented, will influence the rate of curing of the resin. Subsequently, the working parameters, i.e. assembly time, press time, and press temperature, will have to be adjusted and this could be very costly.

This paper reports the bonding characteristics of bamboo strips (*Gigantochloa scortechinii*) in terms of adhesion properties of the bamboo and the glue bond quality of the laminated board made from it. An understanding of the bonding characteristics of this species is essential to ensure good bond quality is achieved, and for bamboo to be able to complement wood.

MATERIALS AND METHODS

Materials

Three-year-old culms of *Gigantochloa scortechinii* (Buluh semantan) were obtained from Forest Research Institute, Kepong. Only culms having at least 7 mm wall thickness were selected to produce a minimum of 4-mm-thick strips after final dressing. The culms were cross cut into 1.25 m long and converted into splits of 20 mm wide using a splitting machine. The epidermis and the inner parts of the splits were removed. Strips of 4 mm thickness were prepared from two separate zones of the split, i.e. close to the periphery, and close to the inner side. All strips were initially air-dried and then equalized in a conditioning room until it reached 12% MC.

Determination of buffering capacity of bamboo

Bamboo strip was ground to pass through a sieve with 53 μm mesh. The aqueous bamboo extract was prepared by refluxing 1 g bamboo particle in 100 ml distilled water for 1 h. After refluxing, the mixture was filtered using filter paper. The distillate was diluted to 400 ml and cooled to room temperature before titration. Fifty ml was drawn from the solution and it was again diluted to 500 ml (concentration: 0.02%). Then 50 ml was taken and the initial pH of the solution was recorded. The solution was titrated first with 0.01 M HCl until it reached pH 3.0. The procedure was repeated using another sample titrated with 0.01 M NaOH until it reached pH 11.0. The pH value was recorded at every 5 ml of titration. The experiment was done in triplicates and the values were maintained less than 5% deviation.

Gluing of bamboo strips

Gluing study was carried out on 150 mm long $\times$ 20 mm wide $\times$ 4 mm thick bamboo strips. The MC of the bamboo strips was maintained at about 12%. Three types of commercial adhesives were used: (a) phenol formaldehyde (PF), (b) urea formaldehyde (UF) and (c) melamine urea formaldehyde (MUF). These adhesives were supplied by a local manufacturer. The adhesive formulations were slightly modified from that of original formulation which was specifically made for plywood. The modified adhesive formulation had acceptably high viscosity to control the penetration of adhesive into the strips. Earlier study showed that surface wettability of this bamboo was markedly higher than most of the tropical hardwood [5]. Table 1 summarises the adhesive formulations.

Three layers of bamboo strips were glued at different grain combinations: (a) parallel to the grain (parallel-ply laminate), (b) perpendicular to the grain (cross-ply laminate), (c) peripheral to peripheral to peripheral layers (P-P-P), (d) inner to inner to inner layers (I-I-I), and (e) peripheral to inner to peripheral layers (P-I-P).

Table 1.
Glue mixing formulation for commercial adhesives

Material	PF	UF	MUF
Resin	65.8% (100 parts)	72 % (100 parts)	76.3% (100 parts)
Industrial wheat flour	9.9% (15 parts)	14.4% (20 parts)	15.3% (20 parts)
Hardener, NH_4Cl		1.4% (2 parts)	8.4% (11 parts)
Filler, $CaCO_3$	17.9% (27 parts)	—	—
Water	6.5% (10 parts)	12.2% (17 parts)	—
Viscosity	19	18	13

Source: Refs [5, 7, 8].

Table 2.
Requirement for shear strength and wood failure

Average shear strength, τ (N/mm^{-2})	Average wood failure (%)	Minimum average wood failure in any test piece (%)
$0.35 < \tau < 0.7$	>75	25
$0.7 < \tau < 1.7$	>50	15
$1.7 < \tau < 2.5$	>25	5
$2.5 < \tau$	>15	0

Source: Ref. [9].

To produce cross-ply laminates, a bamboo ply was first prepared. Strips were glued edge to edge using polyvinyl acetate resin to produce 15 mm × 15 mm × 4 mm ply. The ply was then glued perpendicular to each other producing three plies board. The glue spread rate was 230 g/m^2 single glue line (SGL) for PF and 390 g/m^2 for both UF and MUF resins.

The assemblies were cold pressed at 10 kg/cm^2 for about 10–20 min and hot pressed at predetermined parameters specified in the resin manufacturer's specifications [7, 8]. However, the pressing time for PF-bonded laminates was increased by 17% to ensure optimal curing of resin. The reason for this is discussed in the following section. The laminated bamboos were conditioned at 20°C and 65% relative humidity for a week.

A plywood shear test was conducted on 25 mm × 25 mm × 100 mm sheared area in accordance with BS 6566 [9]. This includes dry test, cyclic boil resistance (CBR), weather and boil proof (WBP), moisture resistance (MR) and interior immersion (INT). At least 12 specimens from each grain alignment and adhesive categories were tested.

Upon completion of the test, the specimens were dried and examined for the estimated percentage of wood failure along the glue line. The wood failures of individual specimens were recorded to an accuracy of 10% and the average shear strength and wood failure were compared with the standard requirement given in Table 2.

An analysis of variance (ANOVA) was used to detect any shear strength changes between laminates from different grain alignment and between laminates from different pattern lay-up. The means were separated using least square difference (LSD).

RESULTS AND DISCUSSION

Buffering capacity

The buffering capacity of a substrate is important in many gluing processes especially if the adhesive is pH sensitive. This property is governed by the pH of

Table 3.
Buffering capacity of *G. scortechinii*

Parameter	*G. scortechinii*	Rubberwood[a]
Initial pH	7.14	5.94
Volume of NaOH (0.01 M) required to reach pH 11	1.20 ml	1.30 ml
Volume of NaOH (0.01 M) required to change 1 unit pH	0.31 ml	0.26 ml
Volume of HCl (0.01 M) required to reach pH 3	120 ml	0.65 ml
Volume of HCl (0.01 M) required to change 1 unit pH	29 ml	0.22 ml

[a] Data for rubberwood from Ref. [6].

the material and an extreme value of wood pH had been reported to be troublesome for achieving good adhesive bonds [10].

The buffering capacity of *G. scortechinii* was found to be more sensitive towards alkali than towards acid (Table 3) implying that *G. scortechinii* has lower resistance towards a change in alkaline than in acid. Compared to rubberwood [6], bamboo has greater buffer capacity towards alkali. Since bamboo is sensitive to alkali-based adhesives, such as PF, a buffer is required in the adhesive formulation to ensure sufficient curing of the resin [11]. In this study, however, a longer press time was employed to bond the PF-based boards. The pressing time was increased to 7 min, instead of 6 min as specified by the resin manufacturer's specification for commercial plywood [7]. For acid-based adhesives, such as UF and MUF, a normal hot press time for plywood was used [8].

Effects of grain orientation on glue bond quality

Information on the shear strength and wood failure percentage is important to evaluate the glue bond quality of bonded products. Theoretically, when both the shear strength and wood failure percentage values are high, a good bonding has occurred. If one of them is high and the other is low, it indicates that either the wood or the adhesive is poor. Nevertheless, for heavy hardwood species like balau, kasai and chengal *(Shorea spp., Pometia spp., and Neobalanocarpus heimii)* low wood failure is acceptable as long as the strength is acceptable for the intended end-use [6].

The mean shear strength and wood failure percentage of the laminated bamboos bonded with different types of adhesive are summarized in Tables 4 and 5. The statistical analysis showed no significant difference ($P \leqslant 0.05$) in dry shear strengths between parallel-ply laminates (2.36 N/mm^{-2}) and cross-ply laminates (2.68 N/mm^{-2}) when bonded using PF resin (Table 4). The dry wood failure percentage however, was relatively higher in the parallel-ply laminates (75%) than in the cross-ply laminates suggesting that the former is relatively superior.

Table 4.
Performance of phenol formaldehyde adhesive on *G. scortechinii* laminated strips in dry, cyclic boiling and weather boiling conditions

Grain alignment	Dry conditions		Cyclic boiling resistance (CBR)		Weather boiling proof (WBP)	
	Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)
Parallel-ply laminates	2.36^a (0.64)	75	1.51^a (0.26)	79	1.95^a (0.35)	82
(*n*)	12		16		17	
Cross-ply laminates	2.68^a (0.38)	68	1.24^b (0.26)	62	1.45^b (0.44)	55
(*n*)	12		12		16	

Means with different superscript (a, b) across rows differ significantly at $P < 0.05$.
Values in parentheses are standard deviations.
n, number of specimens.

Table 5.
Performance of UF and MUF-bonded *G. scortechinii* laminates in dry, cold water and warm water conditions

Grain alignment	Dry conditions		Interior immersion (INT)		Moisture resistant (MR)	
	Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)
UF						
Parallel-ply laminates	1.94^a (0.61)	60	2.27^a (0.66)	52	1.03^a (0.57)	54
(*n*)	14		12		14	
Cross-ply laminates	2.36^a (0.68)	31	0.94^b (0.33)	0	0.54^b (0.31)	0
(*n*)	12		12		12	
MUF						
Parallel-ply laminates	2.91^a (0.63)	49	2.13^a (0.70)	14	1.51^a (0.76)	0
(*n*)	12		12		13	
Cross-ply laminates	1.80^b (0.57)	22	1.18^b (0.46)	0	0.82^b (0.66)	0
(*n*)	12		12		12	

Means with different superscript (a, b) across rows differ significantly at $P < 0.05$.
Values in parentheses are standard deviations.
n, number of specimens.

Table 4 also shows that there were sharp decreases in the shear bond strength and wood failure percentage after the boards were exposed to cyclic boiling test (CBR) and weather boiling proof test (WBP). This has been expected due to extensive stress developed during boiling and drying treatments specified by the tests. Strips arranged perpendicular to each other experienced a relatively higher reduction in shear strength after cyclic soaking in boil water and after long soaking in boil water. CBR test was observed to be more severe than WBP test. In terms of shear bond strength and wood failure percentage, parallel-ply laminates was relatively more stable when soaked repeatedly in boil water, with higher wet shear strength (1.51 N/mm^{-2}) and wood failure percentage (79%) compared to cross-ply laminates (1.24 N/mm^{-2} and 62%, respectively).

As shown in Table 2, all the shear strengths and wood failure percentages of bamboo laminates meets the minimum standard requirement.

Statistical analysis in Table 5 shows no significant difference between grain orientation in dry shear strength when bonded with UF, i.e. 1.94 N/mm^{-2} and 2.36 N/mm^{-2} for parallel-ply and cross-ply laminates, respectively. However, when bonded with MUF, the shear strength for the parallel-ply laminates (2.91 N/mm^{-2}) was significantly higher ($P < 0.05$) than cross-ply laminates (1.80 N/mm^{-2}). Dry wood failure percentage was relatively higher in the former when bonded either using UF or MUF resin. Generally, all parallel-ply laminates bonded with UF and MUF produced significantly higher wet shear strength compared to cross-ply laminates. Wood failure percentage after soaking in warm water (MR test) was 54% for UF-bonded parallel-ply laminates but no wood failure was found in UF-bonded cross-ply laminates. In most cases, MUF-bonded laminates failed at the glueline after warm water soaking even though they had considerably higher wet shear strength (1.51 N/mm^{-2} parallel-ply laminates and 0.82 N/mm^{-2} for cross-ply laminates).

Visual examination on the samples revealed solid traces of MUF adhesive in the glueline indicating that the resin was not properly cured. This phenomenon suggests that the pressing parameters used for this resin may not be suitable, since it followed that of commercial plywood manufacture. Thus, a new process parameters for bonding bamboo materials with MUF is worth investigation.

The results also show that the UF-bonded parallel-ply laminates meets the minimum shear strength and wood failure when tested either in dry or wet (both INT and MR tests) conditions (Table 2), whilst UF-bonded cross-ply met only the minimum standard of dry test.

Glue bond quality of different parts of bamboo culm

Gluing of strips from different parts of bamboo culm significantly affects ($P < 0.05$) both the dry shear strength and wood failure percentage of the laminates (Table 6). Strips cut near the peripheral layer of the culm possess higher glue bond quality (shear strength 3.17 N/mm^{-2} and 100% wood failure) than strips cut at the inner layer (2.17 N/mm^{-2} and 67%). Lower bonding quality was also found

Table 6.
Mean shear strength and wood failure percentage of parallel-ply laminates from different parts of bamboo culm when bonded with PF

Pattern lay-up	Density of individual strips (kg/m^{-3})	Dry conditions		Cyclic boil resistant (CBR)		Weather and boil proof (WBP)	
		Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)	Shear strength (N/mm^{-2})	Wood failure (%)
P-P-P	660 (0.07)	3.00^{a} (0.43)	100	1.54^{a} (0.29)	90	2.16^{a} (0.71)	100
(n)		12		12		14	
I-I-I	487 (0.07)	2.17^{b} (0.42)	67	1.66^{a} (0.39)	100	1.84^{b} (0.28)	93
(n)		13		14		12	
P-I-P		1.85^{c} (0.75)	60	1.55^{a} (0.27)	67	1.73^{b} (0.39)	63
(n)		13		14		12	

Means with different superscript (a, b, c) across rows differ significantly at $P < 0.05$.
Values in parentheses are standard deviations.
n, number of specimens.

for the mixed strips (1.85 N/mm^{-2}, 60%). In weather boil proof test, a similar trend of shear strength and wood failure percentage for the laminates was noted. The peripheral strips had the highest shear strength and wood failure percentage (2.16 N/mm^{-2} and 100%, respectively) followed by the inner strips (1.84 N/mm^{-2}, 93%) and the mixed strips (1.73 N/mm^{2}, 63%).Even though a relatively lower shear strength and wood failure percentage found in cyclic boiling test, the values among the strips did not differ significantly (1.54–1.66 N/mm^{-2}), except for a marked reduction of wood failure percentage in the mixed strips (67%).

The above results suggest that material cut at different part of the bamboo culm had a significant effect on the glue bond quality. This is true since the density at peripheral layer (660 kg/m^{-3}) of the bamboo culm was higher than at the inner layer (487 kg/m^{-3}). The higher density zone consists much higher fiber contents than the inner layer and this would provide higher cohesive bonding to the adhesive.

CONCLUSIONS

Gigantochloa scortechinii can be used in the wood lamination industry to compliment wood. A phenol formaldehyde formulation specified for commercial plywood was found suitable to be used for bonding bamboo strips. The results on buffering capacity of *G. scortechinii* shows that the bamboo is sensitive to alkali-based PF and a slightly longer press time is needed to ensure sufficient curing of resin. An urea formaldehyde formulation and hot press parameters specified for commercial plywood manufacture were found to be compatible with that of laminating bamboo. However, the MUF adhesive used in this study requires a different pressing variables than UF and PF resins.

The grain orientation of the strips bonded with either PF and UF had no effect on the glue bond quality when subjected to dry conditions. When subjected to extreme moisture conditions, regardless of adhesives used, parallel-ply laminates had higher glue bond quality.

Material cut at different parts of the bamboo culm had a significant influence on the glue bond quality. Laminates made from peripheral strips had higher glue bond shear strengths and wood failure percentages than those made either from inner strips or from the combination of both in either dry or wet conditions.

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