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ADHESIVE BOND PERFORMANCE IN GLUE LINE SHEAR AND BENDING FOR GLUED LAMINATED GUADUA BAMBOO

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CORREAL JF & RAMIREZ F. 2010. Adhesive bond performance in glue line shear and bending for glued laminated guadua bamboo. An adhesive experimental programme was developed in order to establish the adhesive performance for glued laminated guadua bamboo (GLG) and to determine the best type of adhesive and its optimal spread rate. Static bending and glue line shear tests were performed on GLG specimens assembled with four types of adhesives and using the manufacturer's recommended spread rate. Urea-formaldehyde (UF), melamine-formaldehyde (MF), melamine-urea-formaldehyde (MUF), and a mixture of 50% of UF and 50% MF (MIX) were the selected adhesives. Differences in shear bond strength, modulus of rupture (MOR) and modulus of elasticity (MOE) among all the adhesives were not significant when using the spread rate recommended by the manufacturer. Finally, glue line tests were performed using six different adhesive spread rates of the MIX adhesive. Optimum adhesive spread rates of 300 and 150 g m^{-2} on the wide and narrow faces respectively are recommended based on the bond shear strength and percentage of bamboo failure. Additional delamination and long-term tests should be performed in order to validate the recommended spread rates.

Keywords: *Guadua angustifolia*, spread rate, internal shear bond strength, mechanical properties, laminated bamboo, melamine-urea-formaldehyde (MUF)

CORREAL JF & RAMIREZ F. 2010. **Prestasi ikatan perekat dalam ricih garis glu dan lentur untuk buluh guadua berlapis yang berglu.** Satu program eksperimen dibangunkan untuk menentukan prestasi buluh guadua berlapis yang berglu (GLG). Hasil keputusan diguna pula untuk menentukan jenis perekat yang terbaik serta kadar sapuan yang optimum. Ujian lentur statik dan ujian ricih garis glu dijalankan terhadap spesimen GLG yang disapu empat jenis perekat mengikut kadar sapuan yang disyorkan pengilang. Urea-formaldehid (UF), melamin-formaldehid (MF), melamin-urea-formaldehid (MUF) dan 50% UF serta 50% MF (MIX) merupakan perekat yang dipilih. Perbezaan kekuatan ikatan ricih, modulus kepecahan (MOR) dan modulus keanjalan (MOE) antara semua perekat yang diuji tidak signifikan apabila kadar sapuan yang disyorkan oleh pengilang digunakan. Akhirnya ujian garis glu dijalankan menggunakan enam kadar sapuan berbeza bagi perekat MIX. Kadar sapuan optimum bagi perekat iaitu 300 g m^{-2} dan 150 g m^{-2} masing-masing disyorkan untuk permukaan buluh yang luas dan kecil berdasarkan kekuatan ricih ikatan serta peratusan kegagalan buluh. Delaminasi tambahan serta ujian jangka panjang harus dijalankan untuk mengesahkan kadar sapuan ini.

INTRODUCTION

Bamboo is regarded as an interesting construction material because of its high strength to weight ratio, relatively low cost and fast growing rate. It also helps with oxygenation of the environment and captures carbon dioxide. A giant species of bamboo called *Guadua angustifolia* grows naturally in Colombia, Venezuela and Ecuador and it has been introduced to other Andean and Central American countries. One of the most frequently encountered problems in the use of round guadua as construction material is the variability of its geometry, mechanical properties and anatomical composition that makes this material difficult to characterise, thus, preventing its use in large structures.

Glued laminated guadua bamboo (GLG) has emerged as an excellent alternative to overcome this problem. Preliminary studies (Barreto 2003, Duran 2003, Lopez & Correal 2009) indicated that GLG has mechanical properties equivalent to the best structural wood in Colombia. However, the influence of the adhesive spread rate on the mechanical behaviour of laminated bamboo has not been studied, and most of the research

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done with different species of bamboo and different types of laminated products follows the spread rate recommended by local adhesive manufacturers (Amino 2002, Barreto 2003, Duran 2003, Anwar *et al.* 2005, Voermans 2006, Lopez & Correal 2009, Sulastiningsih & Nurwati 2009). In studies involving bamboo zephyr strand mats, it has been shown that the adhesive spread rate is a significant variable for the internal bond strength (Lee *et al.* 1998, Naresworo & Naoto 2001). If the internal bond strength of any laminated structural product is not strong enough to guarantee failure of the substrate (bamboo), delamination may occur and the global structural capacity will be unpredictable. Therefore, the optimum amount of adhesive is an important variable that needs to be determined since it defines not only the mechanical performance of the laminated bamboo but also its cost.

The Universidad de los Andes in Bogotá is conducting a detailed research programme in Colombia on round guadua and GLG. The objective of the study was to understand the structural behaviour of these materials not only under static loads but also under dynamic loads such as earthquakes. This research consists of physical and mechanical characterisation, strength verification of structural elements, behaviour of typical connections and seismic validations of construction systems. As part of the mechanical characterisation of GLG, an experimental programme to study the bond performance of different types of adhesives has been developed. The effect of different adhesive types and adhesive spread rates on the GLG internal shear bond strength and flexural properties are presented in this paper. Finally, an optimum amount of adhesive is proposed based on results of the experimental programme.

MATERIALS AND METHODS

GLG production

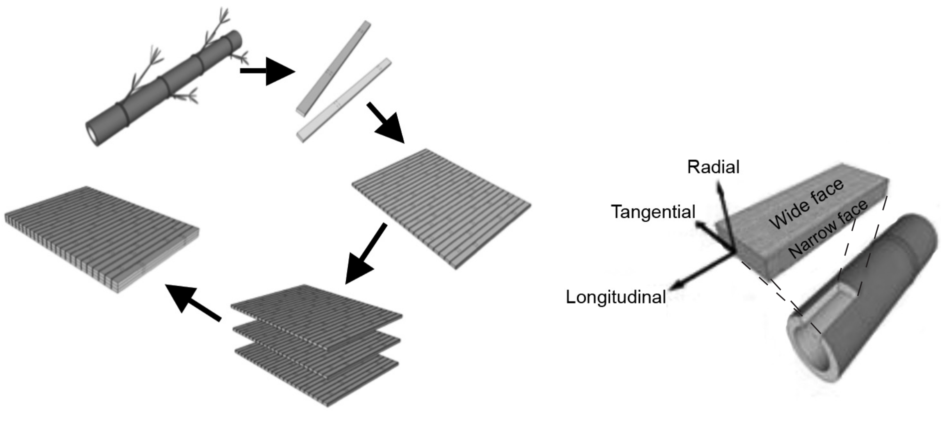
Four-year-old *G. angustifolia* bamboo culms (average base diameter of 7 to 14 cm and height, 30 m) were obtained from the region of Caidedonia-Colombia located at 1400 m asl. The average thickness of the culm wall varied from 0.8 to 2.0 cm. The culms were cut into pieces of 2 to 3 m long on site before transporting to the warehouse.

The fabrication process of the GLG is summarised in Figure 1(a). At the factory, the culm pieces were cut again into 1 to 1.5 m long pieces in order to have straight elements. Each piece was cut in the longitudinal direction to obtain eight slices, each one 20 to 30 mm wide. The quasi-flattened guadua slices were passed through a grinding machine to remove the inner and outer layers. These slices were then immersed in a fungicidal solution composed of 2% water-soluble of copper salt and then dried in an oven at 80 °C to reach an average moisture content of 5%. Once the slices were dried, their four faces were polished with a machine to flatten their surfaces, producing guadua strips. Each guadua strip was about 7 to 10 mm thick, 20 to 25 mm wide and 1 to 1.5 m long. The strips were then impregnated with adhesive resin along the narrow faces and assembled to form guadua sheeting. Each bamboo sheet comprised 24 to 30 bamboo strips. A hot press at 100 °C with a lateral pressure of 1.2 MPa was applied to the sheet. When the adhesive was cured, the guadua sheets were glued together by the wide faces in order to form boards in a hot press at a pressure of 2 MPa for 15 min at 100 °C. A minimum of six bamboo sheets made up one board, although this number of sheets and the final dimensions of the bamboo boards depended on the size of the element to be produced. Finally, the GLG specimens for testing were cut from the laminated bamboo guadua boards.

Experimental programme

The experimental programme developed in this study consisted of two phases. The objective of phase I was to determine the best type of adhesive in terms of strength of the GLG specimens based on glue line shear and static bending tests. In this phase, four types of adhesives and two adhesive spread rates were applied to the narrow and wide faces of the laminae (Figure 1b). The adhesives used, manufactured by Akzo-Nobel and provided by Interquim S.A in Colombia, were urea-formaldehyde (UF), melamine-formaldehyde (MF), melamine-urea-formaldehyde (MUF) and mixture of 50% UF and 50% MF (MIX). The characteristics of these adhesives are shown in Table 1.

As specified and recommended by the manufacturer, two different adhesive spread rates



(a) GLG manufacture (b) Local directions

Figure 1 Manufacturing process and local directions of GLG

Table 1 Characteristics of the adhesives used in this study

Resin type	Solid content (%)	Viscosity (mPa s)*	PH at 25 °C	Proportions by weight
UF	64.0–79.0 (105 °C)	200–600	8.0–8.6	Resin:ammonium salt = 9:1
MF	76.5–79.0 (25 °C)	530–730	8.5–9.5	Resin:Cat CFM40 = 9:1
MUF	65.0–70.0 (25 °C)	9000–11 000	9.5–10.5	Resin:hardener 2542 = 100:20
MIX	NA	NA	NA	UF:MF:wheat flour:Cat CFM40 = 45:45:5:5

*Brookfield LVT viscosity, spindle type 4, 12 rpm, 25 °C; UF = melamine-formaldehyde; MF = melamine-formaldehyde; MUF = melamine-urea-formaldehyde; MIX = 50% UF + 50% MF

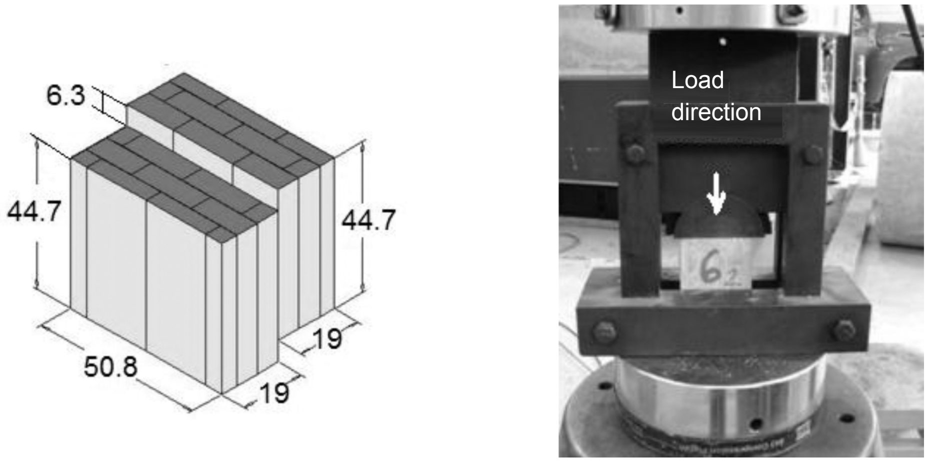
on a single face of the laminae (single glue line) were applied. The spread rates recommended over the wide faces were 400 and 450 g m^{-2}, while the rates along the narrow faces were 200 and 250 g m^{-2}. The wide face needed a higher speed rate because its area was more than three times the area of the narrow face, thus the contribution of bond strength was more important.

In phase II, the optimal spread rate for the adhesive that provided the best performance in phase I was estimated. GLG specimens with adhesive spread rates of 260, 280, 300, 400 and 450 g m^{-2} on the wide faces were manufactured and tested. The spread rates used along the narrow faces were 130, 140, 150, 200 and 250 g m^{-2}.

Static bending and glue line shear tests were conducted on GLG specimens for the adhesive performance programme. Samples were tested in the Structural Model Laboratory of the Universidad de Los Andes in Bogotá, Colombia. Test procedures followed specifications given by the Colombian Institute of Standards Techniques (ICONTEC) for woody materials which are based on the ASTM standards D1037 (ASTM 2006) and D143 (ASTM 2007), for glue line shear and static bending tests respectively. Specimens for the static bending test were 760 mm long and had cross sections measuring 50 × 50 mm. Load was applied at the center of the 710 mm clear span with a rate of 2.5 mm min^{-1}. The failure load and displacement at the middle of the span were recorded, and the modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated. Figure 2 shows dimensions of the specimen and testing setup for the glue line shear test. Load was applied at a rate of 0.6 mm min^{-1} and shear strength was determined based on failure at maximum load. Tests were conducted in five replicates giving a total of 160 samples for phase I and 40 in phase II.

RESULTS AND DISCUSSION

Average values obtained in both experimental phases for bond shear strength (BS), MOE, MOR and their corresponding coefficients of variation (CV) are presented in Table 2 along with the average moisture content (MC), density and bamboo surface failure (BF). Although specimens spread with MF and MUF



(a) Specimen dimensions (in mm) (b) Test setup

Figure 2 Glue line shear test

Table 2 Summary of the average physical and mechanical properties of glued laminated guadua bamboo (GLG)

Adhesive		MC	Density	MOE	MOR	BS	BF
Type	Spread rate ($g\ m^{-2}$) on wide/ narrow faces	(%)	($kg\ m^{-3}$)	(MPa)	(MPa)	(MPa)	(%)
			PHASE I				
UF	400/200	9.0 (2.0)	756 (2.8)	13 821 (5.8)	112 (8.6)	12.3 (3.3)	93 (2.8)
	450/200	9.3 (0.8)	758 (4.4)	13 645 (4.5)	116 (7.7)	12.9 (4.0)	97 (4.0)
	400/250	12.9 (4.3)	672 (3.7)	14 125 (4.1)	117 (6.8)	12.3 (6.0)	92 (5.6)
	450/250	9.1 (1.3)	739 (7.7)	13 676 (4.8)	114 (3.4)	12.7 (7.7)	94 (5.4)
MF	400/200	9.0 (5.4)	761 (4.6)	13 190 (3.0)	113 (9.0)	12.9 (7.1)	96 (3.9)
	450/200	13.1 (1.8)	743 (3.6)	14 163 (6.6)	118 (9.0)	13.0 (2.8)	98 (2.8)
	400/250	11.3 (1.5)	735 (10.1)	14 077 (5.2)	116 (7.2)	12.0 (2.9)	92 (5.0)
	450/250	9.1 (7.6)	756 (2.0)	13 778 (4.3)	117 (8.7)	13.0 (6.4)	97 (4.9)
MUF	400/200	9.9 (0.5)	732 (3.4)	13 373 (2.9)	110 (5.2)	12.9 (4.9)	96 (3.2)
	450/200	10.1 (3.1)	746 (3.0)	13 301 (4.8)	116 (3.2)	13.1 (3.3)	98 (2.1)
	400/250	10.4 (2.6)	728 (0.9)	13 599 (4.6)	113 (7.2)	13.0 (6.4)	97 (4.5)
	450/250	10.2 (1.9)	748 (2.9)	13 451 (4.0)	117 (6.9)	13.1 (2.3)	99 (1.6)
50% UF + 50% MF	400/200	9.7 (3.3)	766 (3.2)	13 737 (4.2)	113 (6.9)	12.7 (4.8)	96 (4.6)
	450/200	9.4 (2.2)	700 (4.3)	13 974 (7.6)	116 (7.7)	12.8 (4.2)	96 (3.7)
	400/250	8.8 (1.7)	743 (6.2)	14 022 (7.8)	115 (6.1)	12.8 (5.2)	96 (5.1)
	450/250	11.3 (0.8)	780 (3.6)	14 095 (4.7)	117 (6.4)	12.9 (5.6)	96 (3.8)
			PHASE II				
50% UF + 50% MF	260/130	8.5 (10.4)	643 (3.9)	13 220 (4.9)	103 (7.4)	9.6 (12.9)	66 (7.0)
	280/140	8.9 (8.9)	707 (3.7)	13 058 (7.0)	104 (8.7)	9.5 (12.3)	66 (8.4)
	300/150	10.0 (8.6)	771 (3.2)	13 732 (6.2)	113 (6.8)	13.1 (7.7)	96 (6.6)
	350/175	10.9 (5.8)	756 (3.3)	13 658 (6.4)	113 (6.5)	12.9 (7.5)	95 (4.1)

Numbers in parentheses are coefficients of variation; MC = moisture content; MOE = modulus of elasticity; MOR = modulus of rupture; BS = bond shear strength; BF = bamboo failure; UF = melamine-formaldehyde; MF = melamine-formaldehyde; MUF = melamine-urea-formaldehyde adhesives exhibited slightly higher values of bond shear strength, there were no significant differences in these values between the four adhesives used, with an average strength of 12.8 MPa. It has been reported that the shear bond strength for *Phyllostachys pubescens* (Voermans 2006) using the adhesive spread rate suggested by the manufacturer (500 g m^{-2}) was 13.3 MPa which was 4% higher than the present study value for *G. angustifolia*. This suggested that bond shear strength was not affected by bamboo species with similar densities and adhesive spread rates. Also, the amount of the adhesive applied on the wide and narrow faces did not affect the value of bond shear strength.

A similar trend as the bond shear strength was observed for MOE and MOR in the bending tests. Failure of the substrate (guadua) was observed in all specimens in glue line shear and bending tests (Table 2). GLG failure > 96% indicated that spread rate specified by the adhesive manufacturer is, at least, enough to guarantee failure of the substrate. Results of the analysis of variance (ANOVA) performed for the data from phases I and II are shown in Table 3. Values obtained for MOE, MOR, BS and BF for the adhesives and spread rates used in phase I were not significant. Therefore, it was concluded that these mechanical properties were not affected by the adhesive type and spread rates used.

Based on results of phase I, it seemed that all adhesives tested in this study performed satisfactorily. Thus, the choice of adhesive used for phase II was based on strength, durability and cost. UF adhesives have low water resistance and should be used only for interior applications. On the other hand, combined UF and MF, i.e. MUF adhesives have higher resistance to water attack compared with UF adhesives but they are usually more expensive. MIX, a combination of UF and MF, may be a more practical and economical solution for exterior applications.

For spread rate at wide/narrow faces of ≥ 300/150 g m^{-2}, bond shear strength remained generally constant with an average value of 13 MPa (Figure 3), while GLG values were ≥ 96% (Figure 4). Combined failure of the adhesive and substrate was observed with a maximum of 66% GLG failure at spread rates of ≤ 280/140 g m^{-2} for wide/narrow faces (Table 2). This combined failure is achieved because the value of shear bond strength provided by the adhesive is almost the same as the value of shear strength parallel to the grain of GLG (Lopez & Correal 2009). In general, these results indicated that an adhesive spread rate of 300/150 g m^{-2} at wide/narrow faces was the optimum amount of adhesive to be used to avoid failure along the glue line while allowing bonding strength to be left unchecked in the structural design process.

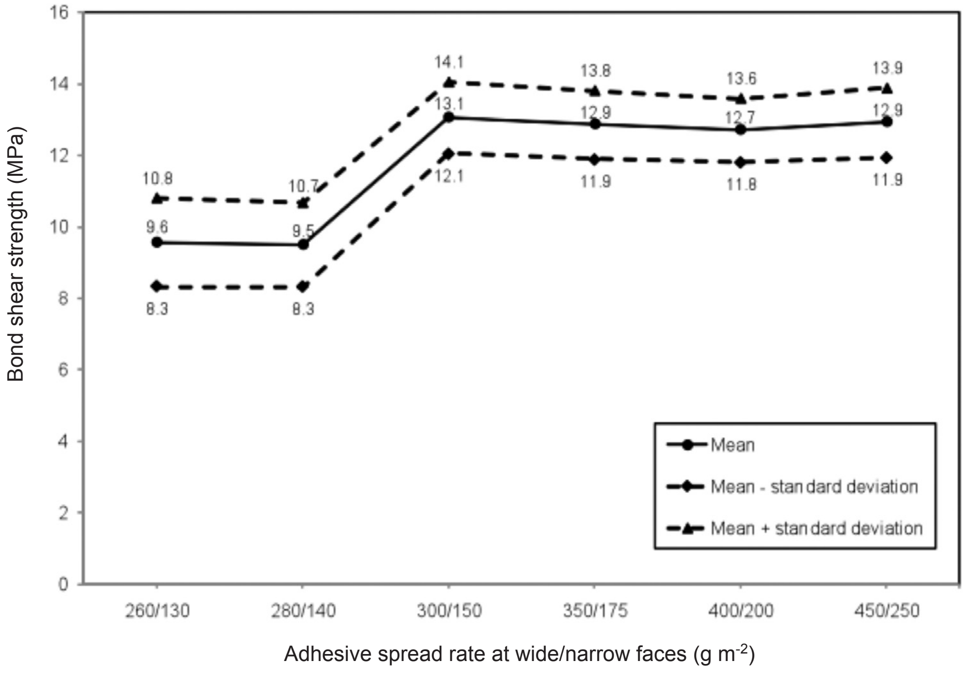
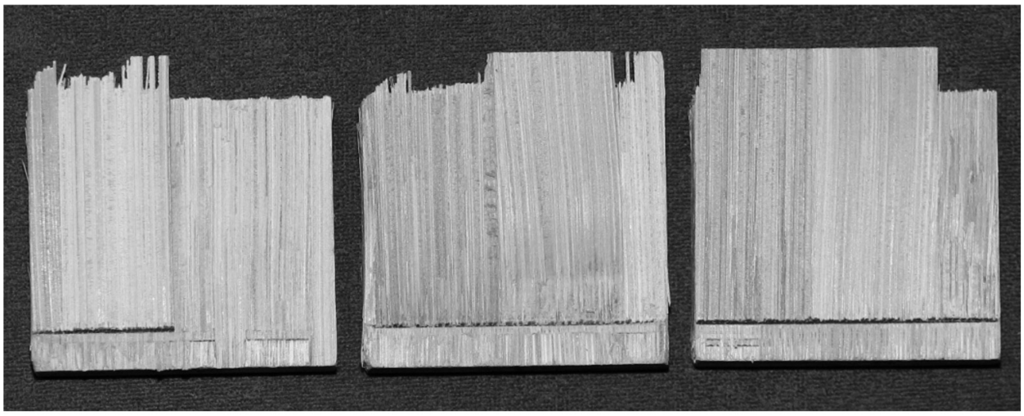


Figure 3 Bond shear strength for MIX adhesive at different spread rates



(a) Bamboo failure = 66% (b) Bamboo failure = 96% (a) Bamboo failure = 96%

Figure 4 Typical GLG failure in glue line shear test for different MIX adhesive spread rates: (a) 260/130 g m^{-2}, (b) 300/150 g m^{-2}, (c) 450/250 g m^{-2}

In contrast to bond shear strength, bending strengths were not drastically affected by the amount of adhesive. Similar to bond shear strength, MOR was consistent at adhesive spread rate of ≥ 300/150 g m^{-2}. Differences of 4.5 and 7.7% were found between adhesive spread rate at wide/narrow faces of 300/150 and 280/140 g m^{-2} for MOR and MOE respectively (Table 2). ANOVA results for phase II indicated that BS and BF were highly affected by the amount of adhesive used for the lamination process, while the effect on MOE and MOR was not significant (Table 3). MOE and MOR values were not affected by the amount of adhesive because the maximum horizontal shear stress reached in the bending tests was about 4.0 MPa. This value was only 50% of the lowest bond shear strength obtained, i.e. 8.3 MPa. As a result, all bending specimens exhibited failure of the substrate without any delamination.

Table 3 Summary of variance analysis for various properties of GLG

Property	Computed F-value			
	Phase I			Phase II
	Adhesive	Spread rate	Adhesive × spread rate	Spread rate
Density	1.10 ns	4.78**	2.69*	26.1**
	(2.75, 4.10)	(2.75, 4.10)	(2.03, 2.7)	(3.24, 5.29)
MOE	2.01 ns	1.21 ns	0.53 ns	0.8 ns
	(2.75, 4.10)	(2.75, 4.10)	(2.03, 2.7)	(3.24, 5.29)
MOR	0.17 ns	1.32 ns	0.14 ns	2.2 ns
	(2.75, 4.10)	(2.75, 4.10)	(2.03, 2.7)	(3.24, 5.29)
BS	2.01 ns	2.10 ns	0.68 ns	16.3**
	(2.75, 4.10)	(2.75, 4.10)	(2.03, 2.7)	(3.24, 5.29)
BF	1.92 ns	2.28 ns	0.51 ns	33.5**
	(2.75, 4.10)	(2.75, 4.10)	(2.03, 2.7)	(3.24, 5.29)

Numbers in parentheses are critical F-values at $\alpha = 0.05$ and $\alpha = 0.01$ respectively; MS = moisture content; MOE = modulus of elasticity; MOR = modulus of rupture; BS = bond shear strength; BF = bamboo failure; *significant, **highly significant; ns = not significant.

CONCLUSIONS

In this project, an adhesive performance experimental programme for structural GLG of *G. angustifolia* in line shear and bending was developed. Experimental results showed that at spread rates recommended by the manufacturer, bond shear strength, MOE and MOR of GLG were not affected by the types of adhesive used in this study. Based on strength, durability and cost, the 50% UF + 50% MF (MIX) adhesive is recommended for GLG structural applications, although the adequate behaviour in terms of water and weather performance needs to be studied.

Adhesive spread rates of 300 g m^{-2} on the wide faces and 150 g m^{-2} along the narrow faces were the optimum amounts to be used for GLG structural applications. These adhesive spread rates provided average bond shear strength of 13.0 MPa with a percentage of GLG failure above 96%. The optimal adhesive spread rate established in this study results in substantial savings because about 66% of adhesive can be saved when compared with the adhesive spread rate recommended by the manufacturer. Nonetheless, delamination and long-term tests should be performed in order to validate the recommended spread rates.

Bending properties (MOE and MOR) of GLG were not affected by the adhesive spread rates used in this study. This behaviour is explained by the fact that horizontal shear stresses, induced by bending tests, were lower than the bond shear strength and failure of the substrate occurs before bond failure (delamination). Experimental results also imply that mechanical properties may only have small variations among different bamboo species with similar density.

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