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COMPARATIVE PERFORMANCE OF PHENOL FORMALDEHYDE-BONDED LAMINATED BAMBOO LUMBER AND BAMBOO STRAND LUMBER PREPARED FROM FOUR DIFFERENT BAMBOO SPECIES

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Bamboo is an eco-friendly lignocellulosic material which gained much interest for its utilisation as structural material in the composite form after processing. The processing method used for bamboo composite fabrication has significant effect on its performance. The current work emphasises on studying the effect of fabrication method and species on the important physical and mechanical properties of bamboo composites. In the present study, two types of composites namely laminated bamboo lumber and bamboo strand lumber were prepared using four bamboo species such as *Dendrocalamus brandisii*, *Bambusa vulgaris, Bambusa bambos* and *Guadua angustifolia*. Various physical and mechanical properties were evaluated. The results showed the physical properties such as water absorption, thickness swelling and volumetric swelling of laminated bamboo lumber were significantly lower as compared to bamboo strand lumber composites after 2 and 24 hours of exposures. The mechanical properties such as MOR, MOE and compressive strength parallel to grain were observed to be significantly higher in laminated bamboo lumber as compared to bamboo strand lumber composites. The results also revealed that the method of fabrication as well as species significantly affect the physical and mechanical properties of the bamboo composites.

Keywords: Engineered bamboo composites, density, physical properties, mechanical properties, compressive strength

INTRODUCTION

Engineered bamboo has recently gained high importance as structural materials in modern green buildings, especially in the tropics. The reason was due to their environmental benefits, excellent strength properties and high CO_2 sequestration capability (Mahdavi et al. 2011, Liu et al. 2016). Bamboo has a rapid growth rate and vast availability which allows the material to be harvested and processed at a faster rate as compared to other timber yielding species (van der Lugt et al. 2006, Yiping et al. 2010). Bamboo can be considered as a suitable substitute to high quality wood and wood based products (Chaowana 2013). There are over 1200 species of bamboo found around the world and natural variations within the species as well as within the bamboo culm may have adverse effect on the uniformity and overall performance of the processed composite material. (Harries et al. 2012). The proper selection of species helps in facilitating the use of the locally available material at optimal level. In order to address the difficulties appearing during the utilisation of round bamboo, the engineered bamboo composites are considered as a viable alternative with additional benefits of being a sustainable material compared to traditional high quality timbers. The engineered bamboo composite provides a highly uniform material with practicable cross-sections when compare to the round tapering natural structure of bamboo. The engineered bamboo composites are produced using processed round bamboo culms into materials such as mats, strands, splits, strips and bonded with structural grade adhesives (Liu et al. 2016). These bamboo composites provide several advantages over round bamboo and subsequently facilitate its use as a sustainable alternative for commercially used timber species (Sharma et al. 2015b). However, the performance of these bamboo composites may be influenced by the processing methodologies adopted during the fabrication (Mahdavi et al. 2011, Sharma et al. 2015a). Therefore, improving the methodology of production can certainly lead to a material providing uniformity and optimum performance in its anticipated application.

There were many preliminary studies regarding fabrication process and estimation of various physical and mechanical properties of different types of bamboo lumber. Their work involved fabricating bamboo laminates using zephyr bamboo mats, bamboo strips and longitudinally split-half bamboo culms respectively (Lee et al. 1998, Nugroho & Ando 2001, Sulastiningsih & Nurwati 2009). Mahdavi et al. (2011) reported that the processing methodology used for fabrication of bamboo composite had significant effect on the performance of bamboo laminates. Sharma et al. (2015a) studied the mechanical properties of semi-caramelized and bleached bamboo lumber and reported that the properties were significantly affected due to pre-processing treatments.

Various studies were carried out to evaluate the mechanical properties of bamboo based composite materials for their utilisation as a structural material. Zhao and Zhang (2019) studied the effect of size on the compressive strength of the structural bamboo scrimber prepared from moso bamboo. They reported that the size effect on bamboo compression was significantly higher than wood due to the higher uniformity of bamboo as the presence of internal defects and variations was negligible as compared to wood. Tan et al. (2020) studied the mechanical performance of parallel bamboo strand lumber under axial compression and reported that the axial compressive strength and type of failure occurrences had significantly affected the slenderness ratio of the material. Li et al. (2019a) investigated the behaviour of parallel strand bamboo lumber under quasi static and dynamic compression loading and stated that the deformation capacity and energy absorption ratio were not affected by the fibre direction of the specimen as reported in natural materials like wood and bamboo. Li et al. (2019b) studied the compression behaviours of parallel bamboo strand lumber under static loading and reported that the compressive strength parallel to grain was double as compared to compressive strength perpendicular to grain. The mechanical properties of bamboo composites such as laminated bamboo lumber and bamboo strand lumber were comparable or higher than the traditionally used structural timber (Sharma et al. 2015b). Fabrication methodology as well as the raw material used have significant effect on the performance of bamboo based composites in structural applications. There were few reported studies on the comparative performance of laminated bamboo lumber and bamboo strand lumber composites and effect of using different bamboo species on the physical and mechanical properties of laminated bamboo lumber and bamboo strand lumber composites. The current study emphasised on comparing important physical and mechanical properties of two bamboo composites such as laminated bamboo lumber and bamboo strand lumber prepared using four bamboo species namely *D. brandisii, B. bambos, B. vulgaris, and G. angustifolia.*

MATERIALS AND METHODS

Bamboo culms

The bamboo culms of *D. brandisii*, *B. bambos*, *B. vulgaris* and *G. angustifolia* were harvested from Kodagu district of Karnataka, India. Matured culms with 3–4 years of age were selected for the study. The bamboo culms were cross cut into sections of 1 m length and further converted into thin strips of 2.5 cm width and around 8–9 mm thickness with the help of a multiple bamboo strips making machine. These strips were passed through a thicknesser to remove outer waxy-silica layer and inner soft fibrous tissue and to achieve uniform thickness. The converted bamboo strips were air dried to achieve a moisture content of 12 ± 2%. Defect free strips were selected for fabrication of laminated bamboo lumber and bamboo strand lumber composites.

Adhesive used

Phenol formaldehyde in powdered form was used during the fabrication of bamboo composites. The powdered phenol formaldehyde resin was slowly mixed with distilled water to achieve a solid content of 50% and stirred continuously to reduce coagulation during the adhesive preparation. The liquid adhesive was maintained at pH of 11.5–11.8 and flow rate of 35–40 seconds at 25 °C. In bamboo strand lumber fabrication, the resin prepared had solid content of 30% in order to reduce the viscosity and to improve resin penetration into the cells of bamboo strands.

Fabrication of bamboo composites

Fabrication process for laminated bamboo lumber

Surfaces of bamboo strips were coated with phenol formaldehyde adhesive by brushing. Glue spread rate of about 250 g m^{-2} was maintained throughout the production of laminated bamboo lumber from four bamboo species. The phenol formaldehyde adhesive-coated strips were air dried to remove excess moisture. The strips were later assembled in between layers of uncoated strips making sure that the fibre direction of the strips was parallel to each other in every layer. The assembled strips were placed inside a hydraulic press of 500 ton capacity and preheated at a temperature of 145–150 °C. Strips were subjected to hydraulic pressure applied in a vertical direction. The horizontal pressure of 20 kg cm^{-2} was also applied to reduce the occurrence of gaps which ultimately helped in improving the edge to edge adhesion of bamboo strips. A vertical pressure of 20 kg cm^2 was applied on each panel during the preparation of laminated bamboo lumber composites from four bamboo species. The final dimensions of the bamboo composites were 60 × 30 × 2.2 cm^3. The laminates were pressed for 25 minutes to assure the optimum heat transfer required for adhesive curing. Three panels were prepared for each bamboo species. The pressing parameters were kept constant during the fabrication of each replicate.

Fabrication process for bamboo strand lumber

The green bamboo strips were passed through sets of rollers mounted on a bamboo crushing machine for three times with a crushing pressure of 8–10 kg cm^{-2} to disintegrate the bamboo fibre bundles. The crushed bamboo strips were air dried to reduce the moisture content to 12 ± 2%. The crushed and dried bamboo strands were dipped in the diluted phenol formaldehyde adhesive with 30% solid content for 15 minutes. The strands were again air-dried for 7–8 hours to remove the excess amount of moisture to minimise formation of steam pocket during hot pressing. The strands were weighed after drying and prerequisite quantity was assembled in a press to achieve desired density. The hydraulic hot press was preheated at 145–150 °C and the strands were arranged in the assembly to maintain the overall uniformity in the distribution. The hydraulic press was adjusted to assure the gap between two platens was approximately 25 mm. Additional lateral pressure was also applied to remove any voids present in the assembly. Vertical hydraulic pressure of 20 kg cm^{-2} was applied to achieve the final thickness of 22 ± 1 mm and the assembly was pressed for 25 minutes. Finally, the lumber was removed and conditioned for two weeks at a temperature of 23 ± 2 °C and 65 ± 5% relative humidity. Three panels were prepared for each bamboo species.

Physical and mechanical tests

The physical and mechanical properties of raw bamboo strips were evaluated according to IS: 8242 standards (Anon 1976) and properties of laminated bamboo lumber and bamboo strand lumber composites were evaluated according to the IS: 1708 standards (Anon 1986) (Kelkar et al. 2020). Physical properties namely density, water absorption, thickness swelling and volumetric swelling were measured. A universal timber testing machine with 50 kN capacity was used to measure the mechanical properties such as modulus of rupture, modulus of elasticity, compressive strength parallel to the grain and compressive strength perpendicular to the grain. Six specimens were prepared from laminated bamboo lumber as well as bamboo strand lumber composite panels for each test.

Statistical analysis

The statistical analysis was carried out using IBM SPSS Statistics 22.0 software. In order to compare the effects of composite fabrication method, species and their interaction, data were analysed using the generalised linear model (two-way ANOVA) followed by post-hoc least significant difference analysis at 95% confidence interval.

RESULT AND DISCUSSION

Physical properties

Density

The densities of bamboo strip and bamboo composites were recorded in Table 1. The lowest mean density at 0.663 ± 0.08 g cm^{-3} was observed in the specimens prepared from *G. angustifolia*, whereas the highest density at 0.732 ± 0.05 g cm^{-3} was observed in *B. bambos*. The density of laminated bamboo lumber prepared using four bamboo species varies from 0.749 ± 0.05 to 0.790 ± 0.03 g cm^{-3}. Density of bamboo strand lumber was significantly higher as compared to laminated bamboo lumber composites and ranged between 0.984 ± 0.01 and 1.021 ± 0.07 g cm^{-3}. Earlier studies on bamboo strand lumber composites also showed similar results (Chung & Wang 2018). In laminated bamboo lumber and bamboo strand lumber composites, highest density was observed in composites prepared from *D. brandisii* followed by composites prepared from *B. bambos* and *B. vulgaris* respectively. The lowest density was observed in both panels prepared from *G. angustifolia*. The higher density observed in the BSL composites was attributed to the fabrication method adopted during the production of the panels. The adhesive-soaked fibre bundles when subjected to high temperature and pressure resulted in compression of cell walls of parenchymatous tissues and vascular bundles leading to reduced porosity and improved density (Takagi et al. 2008). Thermosetting adhesives such as PF resin had significantly plasticise cell walls, which aided in achieving better compression of the cells during the fabrication of composites (Anwar et al. 2008, Shams et al. 2004). The two-way ANOVA results revealed that method adopted during the fabrication as well as bamboo species had significant effect on density of the composites. The post-hoc results for physical properties were recorded in Table 2 and 3 for multiple comparisons for type of material and bamboo species respectively. Results revealed that the density of bamboo strip, laminated bamboo lumber and bamboo strand lumber were significantly different. Within the bamboo species, comparison between the density of *B. bambos* and *G. angustifolia* was significantly different.

Water absorption

The water absorption for bamboo strip, laminated bamboo lumber and bamboo strand lumber were recorded in Table 4. The average water absorption after 2 hours for bamboo strips varied between 13.78 ± 2.53 and 18.49 ± 2.14%. Water absorption after 2 hours of exposure for laminated bamboo lumber composites varied between 10.81 ± 0.61 and 11.91 ± 0.65% whereas for bamboo strand lumber composites water, absorption ranged between 17.54 ± 1.85 and 19.49 ± 1.26% after 2 hours of exposure. The water absorption after 24 hours ranged between 30.68 ± 4.38 and 41.81 ± 5.50% for bamboo strips, whereas it varied from 21.11 ± 0.57 to 22.71 ± 0.85% and 30.67 ± 2.46 to 32.59 ± 2.16% for laminated bamboo lumber and bamboo strand lumber composites

Table 1 Density of bamboo strips, laminated bamboo lumber and bamboo strand lumber

Species	Density (g cm^{-3})		
	Bamboo strips	Laminated bamboo lumber	Bamboo strand lumber
D. brandisii	0.695 (0.04)	0.790 (0.03)	1.021 (0.07)
B. vulgaris	0.689 (0.08)	0.757 (0.18)	0.994 (0.12)
B. bambos	0.732 (0.05)	0.781 (0.36)	1.005 (0.02)
G. angustifolia	0.663 (0.08)	0.749 (0.05)	0.984 (0.01)

Values in parenthesis represent standard deviation

Table 2 Multiple comparisons least significant difference between bamboo strips, laminated bamboo lumber and bamboo strand lumber for physical properties

Material (I)	Material (J)	Density	Water absorption		Volumetric swelling		Thickness swelling	
			After 2 hours	After 24 hours	After 2 hours	After 24 hours	After 2 hours	After 24 hours
		Mean difference (I-J)						
Bamboo strips	Bamboo strand lumber	-0.325*	-2.393*	6.177*	-2.358*	-5.239*	-4.626*	-4.413*
Bamboo strips	Laminated bamboo lumber	-0.086*	4.794*	13.938*	2.719*	0.986	-1.172*	-3.807*
Bamboo strand lumber	Laminated bamboo lumber	0.238*	7.187*	7.761*	5.077*	-6.225*	3.453*	0.607*
	Mean sum of square	0.003	3.656	11.645	2.512	3.575	0.783	0.870

* The mean difference is significant at the 0.05 level

Table 3 Multiple comparisons least significant difference between species for various physical properties

Species (I)	Species (J)	Density	Water absorption		Volumetric swelling		Thickness swelling	
			After 2 hours	After 24 hours	After 2 hours	After 24 hours	After 2 hours	After 24 hours
		Mean Difference (I-J)						
D. brandisii	*B. vulgaris*	-0.004	-1.524*	-2.377*	-0.790	-.0781	0.189	0.326
	B. bambos	-0.021	-0.683	2.514*	-1.925*	-2.150*	-0.506	-0.614*
	G. angustifolia	0.020	-0.957	1.367	-2.522*	-2.476*	-0.701*	-0.835*
B. vulgaris	*B. bambos*	-0.017	0.841	4.891*	-1.135	-2.072*	-0.695	-0.940*
	G. angustifolia	0.024	0.567	3.744*	-1.732*	-2.398*	-0.890*	-1.161*
B. bambos	*G. angustifolia*	0.041*	-0.274	-1.146	-0.597	-0.3259	-0.195	-0.221
Mean sum of square		0.003	3.656	11.645	2.512	3.575	0.783	0.870

* The mean difference is significant at the 0.05 level.

Table 4 Water absorption of bamboo strips, laminated bamboo lumber and bamboo strand lumber

Species	Water absorption (%)					
	Bamboo strips		Laminated bamboo lumber		Bamboo strand lumber	
	2 hours	24 hours	2 hours	24 hours	2 hours	24 hours
D. brandisii	14.01 (2.63)	36.98 (2.06)	10.81 (0.61)	21.11 (0.57)	17.54 (1.85)	30.67 (2.46)
B. vulgaris	16.43 (3.92)	41.81 (5.50)	11.18 (0.89)	22.27 (1.4)	18.80 (1.40)	31.83 (7.15)
B. bambos	13.78 (2.53)	30.68 (4.38)	11.14 (0.74)	21.95 (1.25)	19.49 (1.26)	31.64 (2.53)
G. angustifolia	18.49 (2.14)	34.35 (2.19)	11.91 (0.65)	22.71 (0.85)	18.34 (1.32)	32.59 (2.16)

Values in parenthesis represent standard deviation respectively. Similar results were also observed for water absorption in bamboo scrimber made from strands extracted from culms of Moso bamboo (Kumar et al. 2016). Nugroho and Ando (2001) reported water absorption varied between 12.70 and 13.50% and 24.10 and 26.10% for 2 and 24 hours of exposure respectively for bamboo lumber made from compressed bamboo mats which was lower as compared to the observed values recorded in the current study. After 2 and 24 hours of exposure, the lowest water absorption was observed in laminated bamboo lumber as well as bamboo strand lumber composites prepared from *D. brandisii* whereas, the highest water absorption was observed in panels prepared from *G. angustifolia.* The higher water absorption in *G. angustifolia* was attributed to the lower density of laminated bamboo lumber as well as bamboo strand lumber panels. In the bamboo strand lumber composites, water absorption was found significantly higher as compared to laminated bamboo lumber, even though the density of the bamboo strand lumber was higher as compared to laminated bamboo lumber. Fadhlia et al. (2017) reported the influence of soaking and impregnation of medium molecular weight phenol formaldehyde resin on physical and mechanical performance of plybamboo prepared from *Gigantochloa scortechinii* slivers and reported that the penetration of phenol formaldehyde resin was higher in bamboo slivers subjected to vacuum-pressure impregnation as compared to soaking treatment. The phenol formaldehyde penetration was limited to only few voids in bamboo slivers and was not effective as compared plybamboo prepared with vacuum-pressure impregnated plybamboo. Moreover, the crushing of bamboo during the fabrication process provided higher availability of free hydroxyl groups present on cellulose chains in bamboo as compared to laminated bamboo lumber composites. ANOVA results confirmed that the water absorption at 2 and 24 hours were significantly affected by type of fabrication method as well as bamboo species. The post-hoc results showed that the mean differences for water absorption of bamboo strip, laminated bamboo lumber and bamboo strand lumber were significantly different. Furthermore, the results confirmed that the bamboo species had significant effect on water absorption of the composite as the mean difference between species was found significantly different.

Thickness and volumetric swelling

The average values for thickness swelling for bamboo strips, laminated bamboo lumber and bamboo strand lumber were recorded in Table 5. The average thickness swelling for bamboo strips ranged from 2.78 ± 0.65 to 3.30 ± 0.70% and 5.74 ± 0.91 to 6.59 ± 0.79% after 2 and 24 hours of exposure respectively. The thickness swelling of laminated bamboo lumber varied from 3.54 ± 0.74 to 4.36 ± 0.62% and 9.51 ± 0.93 to 10.63 ± 0.76% after 2 and 24 hours of exposure respectively. Thickness swelling was significantly higher in the bamboo strand lumber as compared to laminated bamboo lumber specimens and ranged from 6.36 ± 1.17 to 8.46 ± 1.15% and 9.50 ± 0.80 to 11.21 ± 0.91% after 2 and 24 hours of exposure respectively. Thickness swelling at 2 and 24 hours was significantly affected by species as well as the method of preparation of the composite. The mean differences between the bamboo strip, laminated bamboo lumber and bamboo strand lumber were found significantly different for thickness swelling after 2 and 24 hours of exposure. After 2 hours of exposure, the mean differences between the percentage thickness swellings of *G. angustifolia* were significantly different from *D. brandisii* and *B. vulgaris.*

Volumetric swelling for bamboo strips, laminated bamboo lumber and bamboo strand lumber were recorded in Table 6. The volumetric swelling for bamboo strips ranged from 7.34 ± 1.07 to 11.81 ± 1.82% and 10.82 ± 1.49 to 14.36 ± 1.97% after 2 and 24 hours of exposure respectively. The lowest values were observed in the specimens prepared from bamboo strips of *D. brandisii* after 2 and 24 hours of exposure. Volumetric swelling for laminated bamboo lumber varied from 5.60 ± 0.98 to 7.40 ± 1.42% and 10.46 ± 0.50 to 13.12 ± 0.86% after 2 and 24 hours of exposure respectively. The bamboo strand lumber showed significantly higher values for volumetric swelling and ranged from 11.06 ± 1.49 to 12.55 ± 1.40% and 16.44 ± 3.51 to 19.33 ± 1.12% after 2 and 24 hours of exposure respectively. After 2 hours of exposure the laminated bamboo lumber as well as bamboo strand lumber prepared from *D. brandisii* showed the least amount of volumetric swelling. In the case of 24 hours exposure, *D. brandisii* and *B. vulgaris* showed the least volumetric swelling for laminated bamboo lumber and bamboo strand lumber respectively. *G. angustifolia* showed the

Table 5 Thickness swelling of bamboo strips, laminated bamboo lumber and bamboo strand lumber

Species	Thickness swelling (%)					
	Bamboo strips		Laminated bamboo lumber		Bamboo strand lumber	
	2 hours	24 hours	2 hours	24 hours	2 hours	24 hours
D. brandisii	2.90 (0.67)	5.74 (0.91)	3.54 (0.74)	9.78 (0.71)	7.54 (0.96)	10.49 (1.49)
B. vulgaris	2.78 (0.65)	5.92 (0.67)	4.00 (0.86)	9.51 (0.93)	6.36 (1.17)	9.50 (0.80)
B. bambos	3.30 (0.70)	6.13 (1.06)	4.36 (0.62)	10.04 (0.94)	7.83 (1.43)	11.21 (0.91)
G. angustifolia	2.96 (0.42)	6.59 (0.79)	4.29 (0.70)	10.63 (0.76)	8.46 (1.15)	10.83 (1.00)

Values in parenthesis represent standard deviation

Table 6 Volumetric swelling of bamboo strips, laminated bamboo lumber and bamboo strand lumber

Species	Volumetric swelling (%)					
	Bamboo strips		Laminated bamboo lumber		Bamboo strand lumber	
	2 hours	24 hours	2 hours	24 hours	2 hours	24 hours
D. brandisii	7.34 (1.07)	10.82 (1.49)	5.60 (0.98)	10.46 (0.50)	11.06 (1.85)	17.04 (2.76)
B. vulgaris	8.05 (1.25)	11.22 (1.35)	6.64 (1.27)	11.18 (1.33)	11.67 (1.70)	16.44 (3.51)
B. bambos	10.50 (1.85)	13.93 (2.04)	7.40 (1.42)	11.68 (0.68)	11.97 (2.54)	18.72 (2.61)
G. angustifolia	11.81 (1.82)	14.36 (1.97)	7.30 (1.20)	13.12 (0.86)	12.55 (1.40)	19.33 (1.12)

Values in parenthesis represent standard deviation

highest volumetric swelling after 2 and 24 hours of exposure for laminated bamboo lumber and bamboo strand lumber composites. Volumetric swelling after 2 and 24 hours of exposure were significantly affected by the bamboo species used as well as the method of fabrication as the mean differences for volumetric swelling between bamboo strips, laminated bamboo lumber and bamboo strand lumber were significantly different.

Mechanical properties

Static bending

The modulus of rupture and modulus of elasticity of bamboo strips, laminated bamboo lumber and bamboo strand lumber composites made from four bamboo species were recorded in Figure 1 and 2. The modulus of rupture value for bamboo strips ranged between 94.52 ± 13.29 and 116.39 ± 9.87 MPa. *D. brandisii* showed the highest modulus of rupture value whereas the lowest value was observed in bamboo strips of *G. angustifolia*. The modulus of rupture value for laminated bamboo lumber varied from 107.83 ± 21.42 to 137.62 ± 21.86 MPa, whereas modulus of rupture value for bamboo strand lumber ranged between 43.62 ± 8.98 and 53.88 ± 8.50 MPa. The bamboo strand lumber composites showed significantly lower modulus of rupture value as compared to laminated bamboo lumber. The laminated bamboo lumber prepared using *D. brandisii* showed the highest modulus of rupture value, whereas the lowest modulus of rupture value was observed in laminated bamboo lumber prepared from *G. angustifolia*. In bamboo strand lumber composites, *B. vulgaris*

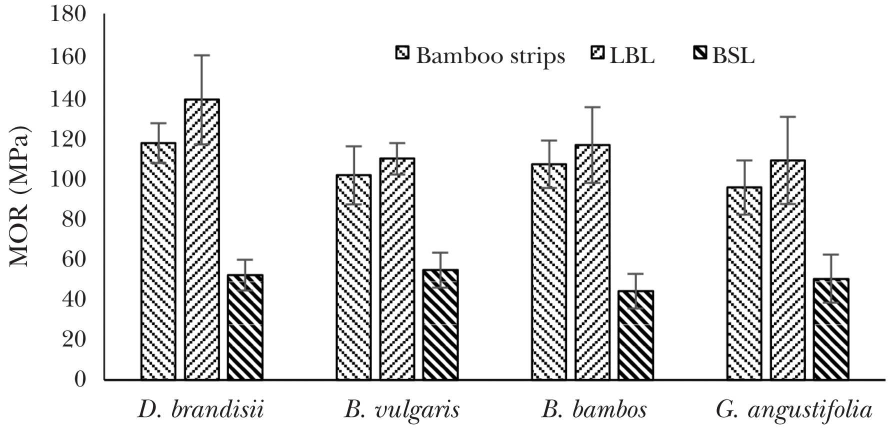

Figure 1 Modulus of rupture (MOR) of bamboo strips, laminated bamboo lumber (LBL) and bamboo strand lumber (BSL)

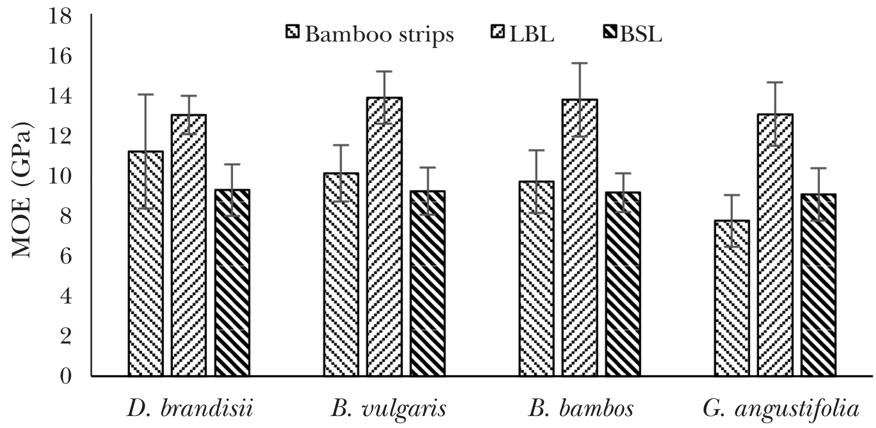

Figure 2 Modulus of elasticity (MOE) of bamboo strips, laminated bamboo lumber (LBL) and bamboo strand lumber (BSL)

showed highest values of modulus of rupture value followed by *D. brandisii, G. angustifolia* and *B. bambos* respectively. The significant improvement in the modulus of rupture value was observed in laminated bamboo lumber composites as compared to the modulus of rupture values of raw bamboo strips. Two-way ANOVA confirmed that the type of fabrication method used as well as the bamboo species used for fabrication of composites had a significant effect on the modulus of rupture ($p < 0.01$). The post-hoc least significant difference analysis results for mechanical properties were recorded in Table 7 and 8. The post-hoc least significant difference analysis results confirmed that the modulus of rupture value of bamboo strips and laminated bamboo lumber were not significantly different. Similarly, for the pairwise comparison in bamboo species revealed that mean difference for modulus of rupture value of *D. brandisii* and *B. vulgaris* were not significantly different.

Similar trend was observed for modulus of elasticity value of the bamboo composites. The laminated bamboo lumber showed significantly higher values for modulus of elasticity as compared to bamboo strand lumber panels. The modulus of elasticity value varied between 13.0 ± 1.30 and 13.84 ± 1.57 GPa for laminated bamboo lumber. The highest modulus of elasticity value was observed in laminated bamboo lumber prepared from *B. vulgaris.* The lowest modulus of elasticity value was observed in *D. brandisii* and *G. angustifolia* for laminated bamboo lumber and bamboo strand lumber respectively. For bamboo strand lumber, the modulus of elasticity value ranged between 9.03 ± 1.30 and 9.25 ± 1.28 GPa. The average modulus of elasticity value for bamboo strand lumber panels fabricated using the four bamboo species was comparable to

Table 7 Multiple comparisons least significant difference between bamboo strips, laminated bamboo lumber and bamboo strand lumber for mechanical properties

Material (I)	Material (J)	Modulus of rupture	Modulus of elasticity	Compressive strength parallel to grain
		Mean Difference (I-J)		
Bamboo strips	Bamboo strand lumber	66.895*	1.127*	1.636
Bamboo strips	Laminated bamboo lumber	-1.178	-4.023*	-17.938*
Bamboo strand lumber	Laminated bamboo lumber	-68.072*	-5.150*	-19.574*
Mean sum of square		185.076	3.791	44.037

* The mean difference is significant at the 0.05 level
The compressive strength perpendicular to grain was not performed for bamboo strips, the post-hoc ANOVA analysis was not possible

Table 8 Multiple comparisons least significant difference between species for various mechanical properties

Species (I)	Species (J)	Modulus of rupture	Modulus of elasticity	Compressive strength parallel to grain	Compressive strength perpendicular to grain
		Mean Difference (I-J)			
D. brandisii	*B. vulgaris*	2.529	-0.703	-2.635	-1.339
	B. bambos	-14.780*	-0.857	5.795*	0.941
	G. angustifolia	9.194*	-0.334	0.647	3.802*
B. vulgaris	*B. bambos*	-17.329*	-0.153	8.430*	2.280*
	G. angustifolia	6.665	0.368	3.282	5.140*
B. bambos	*G. angustifolia*	23.994*	0.522	-5.149*	2.860*
Mean sum of square		185.076	44.037	44.037	3.853

* The mean difference is significant at the 0.05 level

the results reported by Lee et al. (1998) on laminates fabricated from quasi-flattened Moso bamboo laminates and Nugroho & Ando (2001) on zephyr mat-based bamboo laminates bonded with resorcinol based adhesives. Kumar et al. (2016) reported the physical and mechanical properties of bamboo scrimber prepared using phenol formaldehyde impregnated Moso bamboo and found that the modulus of rupture value varied from 131.83 MPa to 166.5 MPa and modulus of elasticity value varied from 14.68 GPa to 18.65 GPa for scrimber prepared with various densities. The findings were significantly higher as compared to the observed values of modulus of rupture and modulus of elasticity for bamboo strand lumber composites in the present study. The two-way ANOVA results confirmed that the type of fabrication process used ($p < 0.01$) as well as species ($p < 0.05$) had significant effect on modulus of elasticity value of the composites. The post-hoc results confirmed that the mean difference between the modulus of elasticity value of bamboo strips, laminated bamboo lumber and bamboo strand lumber were significantly different.

The higher modulus of rupture and modulus of elasticity values of laminated bamboo lumber composites were attributed to the unidirectional arrangement of fibres which was undisturbed during the fabrication. However, during the production of bamboo strand lumber, bamboo fibres were subjected to mechanical separation when passed through sets of rollers. The mechanical separation caused lower flexural strength and stiffness. The laminated bamboo lumber maintained the inherent characteristics of longitudinally aligned fibres in lignin matrix present in bamboo during the fabrication, leading to higher mechanical properties of these composites (Sharma et al. 2015b).

Compressive strength parallel to grain

The compressive strength of bamboo strips, laminated bamboo lumber and bamboo strand lumber were recorded in Figure 3. The compression strength value ranged between 43.48 ± 6.60 and 45.29 ± 8.39 MPa for bamboo strips of all four bamboo species. The compression strength value for laminated bamboo lumber ranged between 52.57 ± 6.53 and 71.41 ± 3.35 MPa. The bamboo strand lumber showed significantly lower compression strength value and varied between 40.97 ± 2.57 and 47.75 ± 12.84 MPa. Li et al. (2013) studied the compressive performance of laminated bamboo lumber using strips obtained from Moso bamboo bonded with phenol formaldehyde resin. The study revealed that mean compressive strength parallel to grain was 60.9 ± 5.2 MPa, which was lower than the compressive strength parallel to grain observed in laminated bamboo lumber prepared from *D. brandisii* and *B. vulgaris*. However, the results were comparable to compressive strength parallel to grain of laminated bamboo lumber prepared using strips of *B. bambos* and *G. angustifolia*. Ogunsanwo et al. (2019) studied the mechanical properties in glulam of *B. vulgaris* bonded with polyvinyl acetate glue and reported that the compressive strength of glulam was between 47.70 ± 0.47 and 48.70 ± 0.15 MPa, which was lower than the observed compressive strength parallel to grain of laminated bamboo lumber prepared from *B. vulgaris*. There was a significant improvement in the compressive strength parallel to grain of laminated bamboo lumber as compared to the compressive strength parallel to grain of bamboo strips. The functionally graded microstructure of bamboo comprised of the vascular bundles embedded in the parenchyma matrix surrounded by cellulose fibres. These fibres were accountable for providing excellent mechanical properties to bamboo. During the fabrication of laminated bamboo lumber the unidirectional fibres embedded in soft parenchymatous tissues were compressed at high pressure resulting into a denser material with improved mechanical properties. Whereas in bamboo strand lumber, the unidirectional structure of fibres were disrupted. The adhesive-soaked fibre bundles compressed at high pressure and temperature did not provide sufficient resistance to the force acting parallel to the fibre length resulting into a lower compressive strength parallel to grain. The two-way ANOVA confirmed that the compressive strength parallel to grain was significantly affected by the method of fabrication as well as the species. The post-hoc least significant difference analysis revealed that mean difference for compressive strength parallel to grain between laminated bamboo lumber and bamboo strips was significantly different. Similar result was observed in the pairwise comparison between the compressive strength parallel to grain of bamboo strand lumber and laminated bamboo lumber. The mean difference between the species was found significant.

Compressive strength perpendicular to grain

The compressive strength perpendicular to grain of laminated bamboo lumber and bamboo strand lumber were recorded in Figure 4. Compressive strength perpendicular to grain for laminated bamboo lumber varied between 10.82

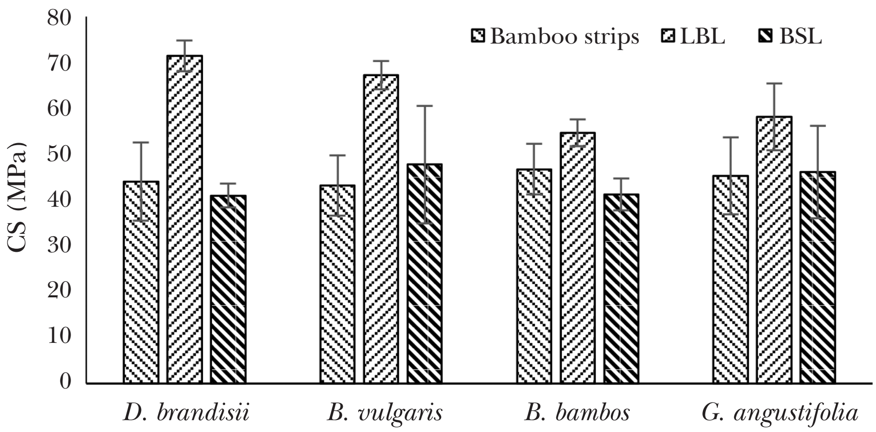

Figure 3 Compressive strength parallel to grain (CS) of bamboo strips, laminated bamboo lumber (LBL) and bamboo strand lumber (BSL)

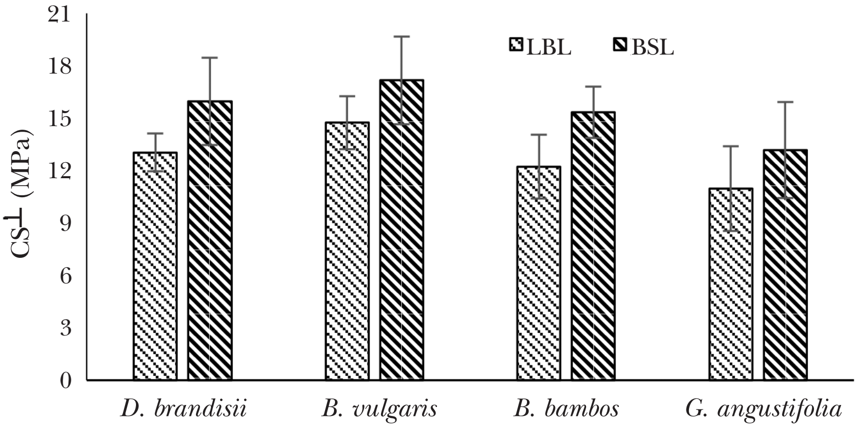

Figure 4 Compressive strength perpendicular to grain (CS⊥) of laminated bamboo lumber (LBL) and bamboo strand lumber (BSL)

± 1.47 and 14.74 ± 1.51 MPa. The compressive strength perpendicular to grain for bamboo strand lumber ranged between 10.60 ± 1.77 and 17.61 ± 2.51 MPa. The laminated bamboo lumber prepared using *B. vulgaris* showed highest compressive strength perpendicular to grain, whereas *G. angustifolia* showed the lowest values for compressive strength perpendicular to grain. Similar trend was observed in bamboo strand lumber, but it showed higher compressive strength perpendicular to grain compared with laminated bamboo lumber composites for all the species. The ANOVA results concluded that the method of preparation for laminated bamboo lumber as well as bamboo species had significant effect on compressive strength perpendicular to grain of the composites ($p < 0.01$). The post-hoc least significant difference pairwise comparison confirmed that mean difference between the *D. brandisii* was not significantly different from *B. vulgaris* and *B. bambos*. The higher compressive strength perpendicular to grain of bamboo strand lumber was attributed to the higher density of the composite. Phenol formaldehyde-coated bamboo strands were compressed at high pressure during the fabrication of bamboo strand lumber, resulting in higher density from 0.9 to 1.0 g cm^{-3}. Thus, the material used provided higher resistance to the compressive forces acting in perpendicular to direction of fibres.

CONCLUSIONS

The study evaluated the effect of four bamboo species and fabrication method on bamboo composites. Bamboo composites in the form of laminated bamboo lumber and bamboo strand lumber were prepared from four bamboo species were evaluated for their important physical and mechanical properties. In addition, properties of raw bamboo strips of the four bamboo species were also evaluated. The density of the laminated bamboo lumber was found to be significantly lower than the bamboo strand lumber. The water absorption, thickness swelling and volumetric swelling values were significantly higher in bamboo strand lumber as compared to laminated bamboo lumber composite for all four species of bamboo. A significant improvement in the mechanical properties namely modulus of rupture, modulus of elasticity and compressive strength was observed in laminated bamboo lumber as compared to the raw bamboo strips. The mechanical properties were significantly lower in bamboo strand lumber as compared to laminated bamboo lumber. The study revealed that the used of different bamboo species and the methodology adopted during the fabrication showed significant effect on the properties of the composite.

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