Physico-Mechanical and Joint Performance of Bamboo Veneer Products Manufactured by Mould Pressing

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Bamboo can be processed into engineering materials with excellent properties by reasonable processing methods. In this study, the performance of mould-pressed bamboo (MBP) veneer products was examined. The physical mechanical properties and connection properties of MPB were tested, and the application performance of the MPB was analyzed. The results show that MPB has a comprehensive property of high internal bonding and good dimensional stability, and its density and mechanical properties are similar to those of wood dimensional stock. The overall bending strength, bending modulus, and compression strength of MPB were 29.0 MPa, 6.83 GPa, and 15.6 MPa, respectively. While the overall carrying capacity was relatively low, the connection performance of BPM was good. Thus, it can be used as a connector or substructure.

Keywords: Bamboo moulds-profile; Dimension stock; Physical mechanics properties; Connection properties

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INTRODUCTION

Bamboo is a natural engineering material with high strength, good toughness, and good wear resistance. It offers the advantages of green environmental protection and special cultural elements, suggesting that it can serve as a suitable substitute for building materials such as bricks and rocks (Janssen 2000; Lugt *et al*. 2016). The unique structural characteristics of bamboo equip it with excellent longitudinal mechanical properties and processing properties. According to the longitudinal characteristics of bamboo, it can be processed into bamboo strips to make bamboo floors (Sharma *et al.* 2015; Fang *et al.* 2018), as bamboo bundles to make reconstituted materials (Chen *et al.* 2017), and as bamboo slivers to make bamboo slivers-based panels (Feng *et al.* 2013; Deng and Wang 2018). Consequently, its characteristics and good longitudinal mechanical properties can be fully utilized. However, bamboo easily splits longitudinally and has no transverse organizational unit, which results in a weak transverse structure and great difficulty in horizontal processing. By processing bamboo into bamboo veneers, a mould-pressed bamboo (MPB) structure can optimize the characteristics of a layered structure. Using a mould pressing system, bamboo is processed into a bamboo composite material with reasonable structure that conforms to building material specifications.

In recent years, the development speed of light wood structure houses in China has been relatively fast; however, their number is still below 1% of the annual construction volume of other countries such as North America, Europe, and Japan. Most frame materials that are being incorporated into light wood structure houses in China are almost exclusively imported from Canada and the United States. The design and construction technology of wood structures also comes from abroad. Both the promotion and localization of light wood structure houses are limited (Yuan *et al*. 2010). MPB retains the characteristics of good mechanical properties and natural appearance of bamboo, and it avoids the defects of high density of bamboo engineering materials that have caused problems in the past. MPB can replace wood specifications as light bamboo and wood structure building materials. MPB alleviates the current situation that the materials of light wood structure houses in China depend on imports from overseas, reduces the cost of raw materials of light wood structure houses, and promotes the development of light wood structure houses.

The properties of wood specification and bamboo structural material (Zhao 2010; Guo *et al.* 2011; Bhavna *et al.* 2015; Zhong *et al.* 2015, 2016) and the joining properties of wood specification, plywood, and reconstituted bamboo (Fei *et al.* 2008; Xu *et al.* 2011; Zhang *et al.* 2012; Zhou *et al.* 2012; Zhou *et al.* 2016) are well known. However, as a new type of building material, MPB has not been reported in the context of light wood structure. There is less information available concerning the physical and mechanical properties of MPB that it is unsafe in building structures without establishing the suitable design mechanical performances. In this paper, the physical mechanical properties and connection properties of MPB were studied, and the performance characteristics of MPB were analyzed to provide reference for its practical application.

EXPERIMENTAL

Materials and Equipment

A commercial bamboo veneer (*Phyllostachys pubescens*) with a moisture content ranging from 6% to 8% and urea formaldehyde resin (UF) with a solid content of 48% were respectively supplied by Dashan Bamboo Industry Co., Ltd. (Fujian Province, China) and Taier Co., Ltd. (Beijing, China). The experimental equipment included a mechanical testing machine (Instron 5582, Instron, Norwood, MA, USA), Jinan gold assay mechanical testing machine (WDW-300E, Jinan, China), field emission environment scanning electron microscope (FEG-ESEM; XL30, ThermoFisher Scientific, Hillsboro, OR, USA), body microscope with INFINITY analysis software (Lumenera Corporation, Ottawa, Canada), sliding table saw (FESTOOL-CS70, Festool, Wendlingen, Germany), dicing saw (J1G-355, DongCheng company, Qidong, China), electric drill, oven, water bath kettle, and electronic digital caliper.

Profile Preparation

The processing of MPB is shown in Fig. 1(a). The MPB were hot pressed with a removable core mold and moulded platen at a platen temperature 130 °C for 10 min.

The cross-section specification of MPB was 90 × 40 mm. The length of MPB depended mainly on the mould and processing procedure. The MPBs of different lengths were produced by lengthening the mould or by intermittent mould pressing procedure. Figure 1 shows that the wall structure of the materials was composed of nine layers, and the adjacent layers were assembled in the form of billets having a rectangular cross-section.

In the process of billet assembly, splicing or butt joints were adopted to connect the bamboo veneers. Generally, splicing gaps occurred easily in the overlapping longitudinal billet layers, as shown in Fig. 2(a), layers 1, 3, 5, 5, 7, and 9. Transverse billet layers were jointed at the corner or easily broken at the corner, as shown in layers 2, 4, 6, and 8 in Fig. 2(b).

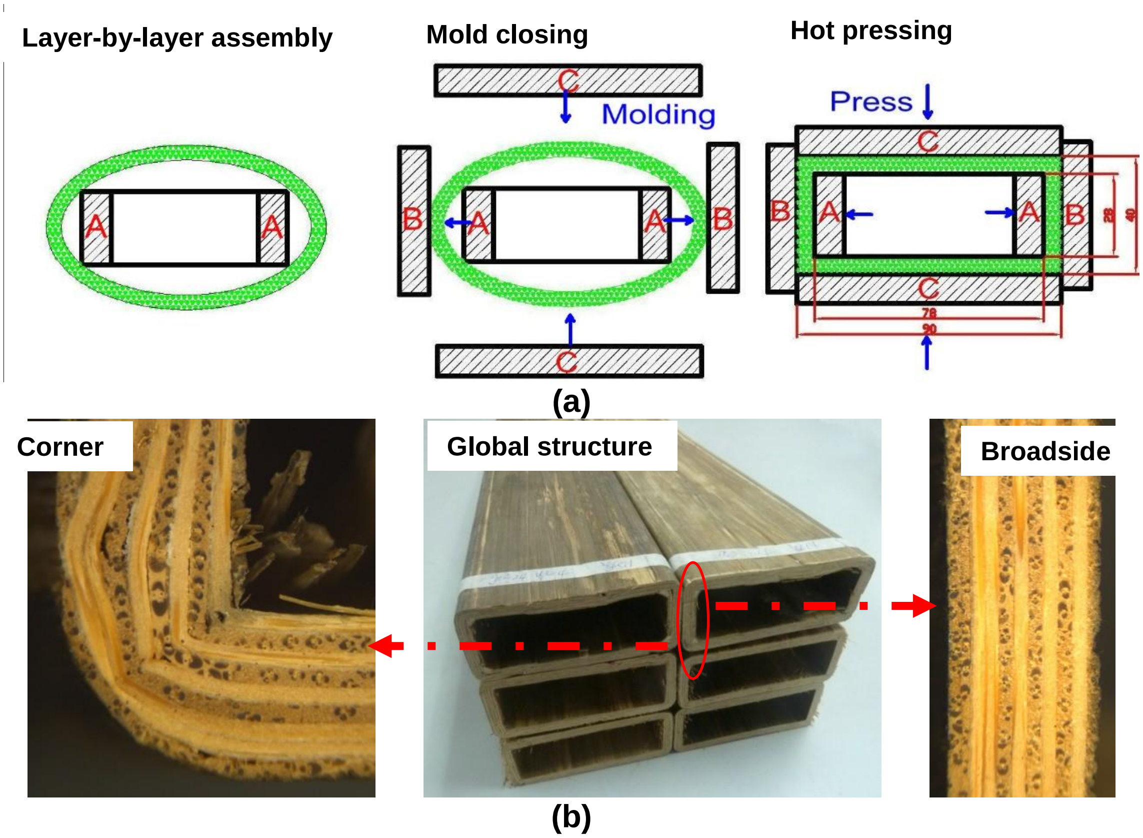


Fig. 1. Process and structure of MPB. (a) Process, (b) Structure

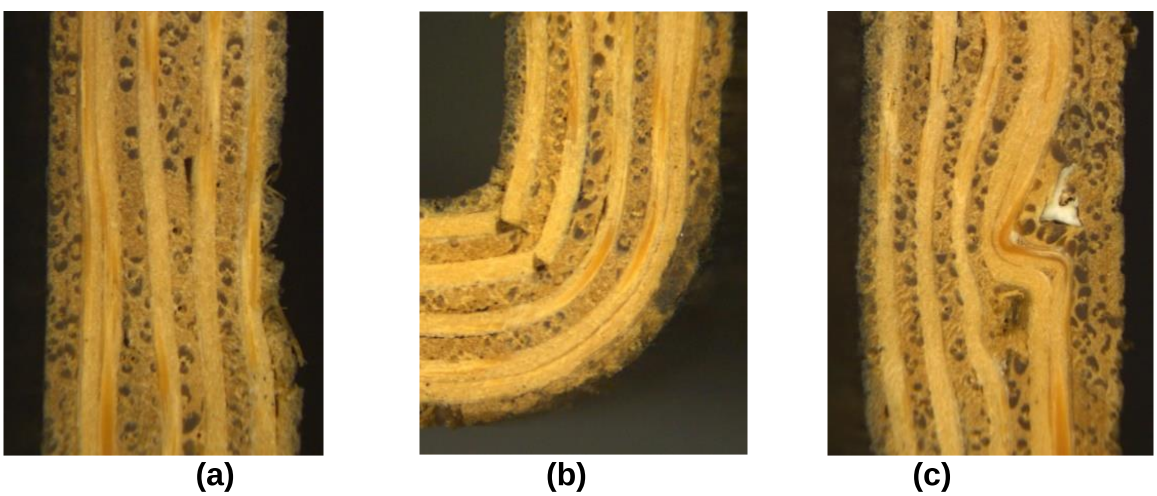


Fig. 2. Structure defects of MPB. (a) Lap defects, (b) docking defects, and (c) accumulative defects

Moisture Equilibration

The MPB were put in the lab with a constant temperature of 20 °C and relative humidity of 65% for at least two weeks. For each experimental condition, 6 and 12 specimens were tested for physical, mechanical, and connection properties, respectively.

Physical Properties Test

The volume density (*i.e.*, bamboo profiles are recognized as solid wood to calculate density), material density (*i.e.*, the density calculated by removing the hollow volume of bamboo profiles), and the wall thickness swelling rate and cross-sectional width dimensions swelling rate were measured according to GB/T 17657 (2013).

Mechanical Properties Test

The bending and compression properties of bamboo profiles were tested according to GB/T 28987 (2012). The bending strength, bending modulus, and compression strength of the whole material (including the hollow volume) and the solid material (removing the hollow volume) were calculated. Referring to ISO/TR 22157-2:2004(E) (2004), the shearing strength of materials was tested (Deng *et al.* 2016). The test of the internal bonding (IB) strength of the material followed the GB/T 17657 (2013) standard.

Connection Properties Test

According to GB/T 50329 (2002), the test symmetrical double shear single bolt connection properties of the material were tested. An M 10 bolt was selected for connection. The bolt connection strength was calculated using Eq. 1,

$$\sigma = F_{max} / (D * t) \quad (1)$$

where σ, F_{max}, D, and t represent the bolt connection strength (MPa), maximum failure load (N), hole diameter (mm), and main material thickness (mm), respectively. The screw holding force and screw holding force of the material were evaluated according to GB/T 17657 (2013).

RESULTS AND DISCUSSION

Physical Properties of MPB

Table 1 shows the volume density, material density, wall thickness swelling extent, and the cross-sectional width dimensions swelling rate of MPB. The average volume density of MPB was 0.370 g/cm^3, which is similar to the air-dry density of SPF Chinese fir (Guo 2007) and meets the density requirement of a light wood structure. The material density of MPB was 0.687 g/cm^3, which was lower than that of raw bamboo (0.81 g/cm^3), ply-bamboo, and reconstituted bamboo (Cheng *et al*. 2009; Feng *et al.* 2013). The MPB consisted of bamboo veneers with layer-by-layer assembly, and the cladding layer material around MPB was ply-bamboo. The extent of wall thickness swelling of the MPB was 4.40%, which was superior to the performance of ply-bamboo (Gao *et al.* 2012). The cross-sectional width dimensions swelling extent of MPB was 3.03%, which was superior to the performance of wood dimension stock and achieved a better dimensional stability.

Table 1. Physical Properties of MPB

Index	Volume Density (g/cm^3)	Material Density (g/cm^3)	Wall Thickness Swelling (%)	Cross-sectional Width Dimensional Swelling (%)
Average	0.370	0.687	4.399	3.034
SD	0.018	0.019	0.532	0.173
CV (%)	4.957	2.819	12.084	5.692

SD, standard deviation; CV, coefficient of variance

Mechanical Properties of MPB

Table 2 presents the mechanical properties of MPB. The overall bending strength and bending modulus of materials were 29.0 MPa and 6.83 GPa, respectively, which are lower than those of larch and Chinese fir (Zhao 2010; Guo *et al.* 2011). Compared with No. 1 Chinese fir, the bending strength and bending modulus of materials were decreased by 33% and 35%, while the bending strength and bending modulus of MPB were 41.4 MPa and 19.7 GPa, respectively, which are not less than reported values. This result showed that the bending capacity of MPB is lower than that of wood materials; however, MPB has structural advantages that improve the volume bending performance of materials. The overall compression strength of MPB was 15.6 MPa, which is lower than that of larch and Chinese fir (Zhao 2010; Guo *et al.* 2011). Compared with No. 1 Chinese fir, the compression strength of MPB decreased by 49%, while the solid compression strength of MPB was 39.0 MPa, which is higher than that of larch and Chinese fir.

Table 2. Mechanical Properties of MPB

Index	Bending Strength (MPa)		Bending Modulus (GPa)		Compression Strength (MPa)		Shearing Strength (MPa)	Internal Binding Strength (MPa)
	Global	Solid	Global	Solid	Global	Solid		
Average	28.968	41.442	6.831	19.726	15.564	39.022	7.702	1.583
SD	0.216	0.242	0.961	0.563	0.976	1.837	0.154	0.316
CV/%	0.746	0.584	14.074	2.855	6.270	4.708	2.001	19.983

Figure 3a shows that when MPB was subjected to bending load, there was no dislocation shear failure on both sides of the profiles and no obvious damage on the upper and lower surface layers. The hollow structure was broken at the loading position on the upper surface, but it did not completely lose its bearing capacity. Figure 3b shows that the failure modes of profiles under compression along the grain differed from those of wood profiles. Wood profiles were mainly crushed under compression. For MPB, there was structural damage under compression, and the hollow structure expanded outward, resulting in the circumferential force failure of bamboo veneers in all layers. The MPB properties and characteristics of bending failure and compression failure showed that the billet structure and hollow structure are more reasonable. Furthermore, the bonding between layers was closer, which improved the overall mechanical properties of profiles. This result indicated that MPB can be used to replace wood specifications as columns or secondary components.

(a) (b)

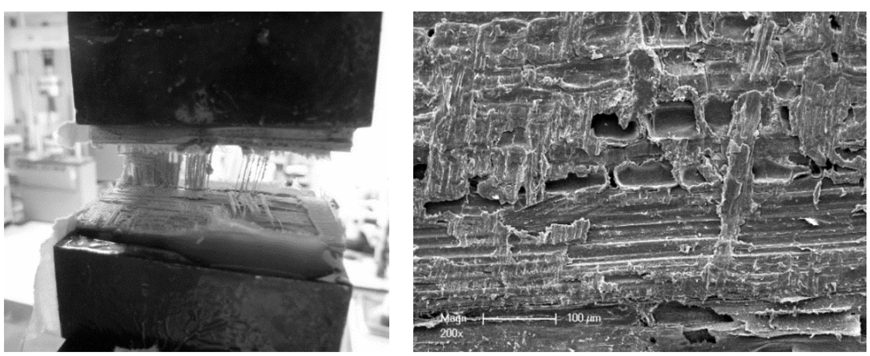
Fig. 3. Test destruction examples of MPB. (a) Bending failure; (b) Compression failure

Table 2 and Fig. 4 show the shear testing of MPB hollow structures. Four relative shear planes were formed on both sides of the profiles. The shear strength of MPB was 7.70 MPa. During the test, no apparent damage occurred on the four shear sides, and only a certain depth of indentation formed on the upper and lower end faces. This result showed that the longitudinal and transverse billet structure of MPB hinders the transmission of shear force along the grain and improves the shear failure resistance of the material along the grain.

(a) (b)

Fig. 4. Shear test destruction of MPB. Shear properties (a) test schematic and (b) specimens

Table 2 shows the bonding properties of MPB. The bonding strength of MPB was 1.58 MPa, which is superior to that of ply-bamboo (Gao *et al.* 2012) because the thickness of each bamboo veneer unit used in MPB was 0.5 to 0.7 mm. The interlayer pavement was uniform, with the surface adhesives uniformly distributed, and there was no lack or leakage of adhesives.



(a) (b)

Fig. 5. IB test destruction schematic of MPB. (a) IB failure; (b) interface microstructure

Figure 5 shows that there was no obvious delamination damage between bamboo veneers after the internal bonding and tensile failure of MPB. Most of the damage occurred in the bamboo veneers. The stripping phenomenon occurred at the weak bonding points between the basic structure of bamboo veneers and vascular bundle fibres. The failure law of the internal bonding property of MPB was not obvious, and the bonding interface property between bamboo veneers had good performance.

Connection Properties of MPB

The bolt connection is one of the main connection modes of light wood structures. Table 3 and Fig. 6 show that bamboo profiles had better bolt connection performance, and their failure yield load reached 7.624 kN, which is close to the performance of a single-bolt connection of reconstituted bamboo (Zhang *et al*. 2012).

Table 3. Connection Properties of MPB

Index	Load (kN)	Connection Strength (MPa)		Failure Displacement (mm)	Bolt Holding Load (N)	Nail Holding Load (N)
		Global	Solid			
Average	7.624	20.085	61.591	12.177	1154.333	395.667
SD	0.829	1.470	4.119	0.389	52.776	17.009
CV/%	10.878	7.319	6.688	3.200	4.572	4.299

During the test, the bolts and connection joints were in elastic deformation at the initial stage of loading, and the load-displacement relationship increased linearly. With increased load, the force-displacement relationship developed nonlinearly. Because the bamboo profile is a hollow structure, the wall thickness of MPB and steel plates were 6 mm and 10 mm respectively, and the bolts at all bolted connection joints bore shear force. According to National Design Specification for Wood Construction (America 2018), symmetrical bolted double shear connections can be divided into four yield modes: Im, Is, IIIs, and IV. The pin groove of model I is extruded for the main material or side material, and model IIIs is bolt failure. Plastic hinges appeared in the main material on the side of the joint, and the inner and outer edges of side material were partly extruded. Model IV is bolt failure. Plastic hinges occurred simultaneously in the components on both sides of the joint, and lateral materials were subjected to compression failure at the edge of the joint. When the MPB reached the ultimate load, the compression yield occurred mainly at the bolt connection joints. The failure model was I failure, while the splitting of main timber occurred mainly in the double shear single bolt test of reconstituted bamboo, plywood, and larch specifications (Xu *et al.* 2011; Zhang *et al*. 2012). This is because MPB consists of cross-section billets, and the reasonable structure distribution ensures the performance of MPB in both vertical and horizontal directions.

(a) (b)

Fig. 6. (a) Double shear single bolt connection and (b) failure schematic

Screw and screw connections are also commonly used in light wood structures. Because bamboo profiles are hollow structures, in which the actual screw or screw insertion depth is approximately 6 mm of the profile wall thickness, which is less than the standard screw insertion depth of 15 mm. Table 3 shows that the screw holding force of screw MPB with 4.2 mm external diameter was 1154 N, which is similar to that of larch and poplar plywood fir (Que *et al*. 2014a,b). The screw holding force of bamboo profile with round steel screw was 395 N, which is similar to that of the Chinese fir (Zhao *et al*. 2010). This result shows that bamboo profiles have better screw or screw connection performance. Under the same connection thickness, the screw or screw connection performance of bamboo profiles exceeds that of specifications and has better reliability.

CONCLUSIONS

1. Mould-pressed bamboo (MPB) has a low wall thickness swelling, and the cross-sectional width dimensions swelling and high internal bonding strength. Its dimensional stability, solid bending strength, bending modulus, compression strength, and shear strength met the standard specifications. MPB has a reasonable billet structure and hollow structure design, and good application and popularization prospects.
2. Compared with No.1 Chinese fir, the volume density of MPB is similar, but the overall bending strength, bending modulus, and compression strength decreased by 33%, 35%, and 49%, respectively. Under the same density, the carrying capacity of MPB is relatively low; therefore, it is necessary to further optimize the structure and improve the carrying capacity of MPB.
3. MPB has good connection performance, high bolt connection strength, and similar connection performance than wood specifications, which can reduce the risk of bearing failure and improve design reliability.

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