Reliability of Compression Strength of Hennon Bamboo-reinforced Extruded Tubular Particleboard

Haiyang Zhang,* Hai Luo, and Xiaoning Lu*

This paper presents a new kind of composite produced with small-diameter bamboo (*Phyllostachys glauca* McClure) and extruded tubular particleboard. The mechanical properties of the composite are significantly affected by the properties of the bamboo. First, the compression strength of the bamboo was studied. It was found that the compression strength (f_c, MPa) and the maximum force of compression (F_{max}, kN) of the bamboo are strongly, linearly related to its outer diameter (D, mm): f_c = -0.5D+79.37 and F_{max} = 0.83D–0.59. The compression strength of the composite made with the bottom part of the bamboo was larger than that of composites made with the middle and top parts. In addition, its reliability was also the best of the three groups due to the variation of the outer diameter of the bamboo from the bottom to the top. The bottom part of the bamboo is the best choice for manufacturing bamboo-reinforced extruded particleboard (BREP).

Keywords: Hennon bamboo; Tubular particleboard; Compression strength; Reliability analysis; Distribution model

*Contact information: College of Wood Science and Technology, Nanjing Forestry University, 159# Longpan Road, Nanjing, 210037, China; *Corresponding author: zhanghaiyangnjfu@gmail.com (Haiyang Zhang); luxiaoning-nfu@126.com (Xiaoning Lu)*

INTRODUCTION

Bamboo grows in most tropical and subtropical regions. People originally used bamboo as a hunting tool. Currently, it is used for paper, mat materials, plywood, particleboard, fiberboard, and so on (Tang 1998; Shen *et al.* 2002). More recently, several new kinds of composites, such as oriented strand board (OSB), parallel strip lumber (PSL), and oriented strand lumber (OSL) (Sumardi *et al.* 2006, 2007, 2013; Ahmad and Kamke 2011; Malanit *et al.* 2011; Febrianto *et al.* 2012), have been invented for structural use.

The bamboo industry is the backbone of many rural economies in China, especially in the Zhejiang, Anhui, and Fujian provinces. Studies in the past have focused on large- and middle-sized bamboos, especially Moso bamboo (*Phyllostachys pubescens*) (Yu *et al.* 2008; Abe and Yano 2010; Fu 2011). Bamboo can be divided into three groups, based on its outer diameter: large (greater than 8 cm), middle (between 4cm and 8 cm), and small (smaller than 4 cm).

There has been little research regarding the industrial use of small bamboo. It is typically used by farmers for fences (Zhang *et al.* 2013). The production of small-diameter bamboo is the second largest (Fu 2011), so finding efficient uses for it is essential. In this study, a new composite was developed using small-diameter bamboo-reinforced extruded particleboard (BREP). The reliability of BREP was also studied.

EXPERIMENTAL

Materials

Extruded tubular particleboard manufactured with the wood of ginkgo (*Ginkgo biloba* L.), a widely cultivated tree in China, was used in all experiments. It was produced by Kaixuan Wood Co., Ltd. in Jiangsu province. Common particles with dimensions of (10 to 20 mm length)×(0.2 to 0.6 mm thickness)×(3 to 6 mm width) and UF were used to manufacture the tubular particleboard. The thickness of the tubular particleboard was 33 mm and the diameter of the tube was 22 mm. The web thickness was 5 mm. The moisture content of the panels was 11%. The solid density and the average density of the particleboard were (0.65±0.04)g/cm^3 and (0.28±0.02)g/cm^3, respectively. The static bending strength and internal bonding strength of the particleboard with E1 grade performance were 1500 MPa and 0.23 MPa, respectively.

Small-diameter bamboo (*P. glauca* McClure) of differing ages was harvested from a bamboo garden in Zhenjiang, in the Jiangsu province of China. The height of the bamboo was about 4 m, and the outer diameter was in the range of 10 mm to 25 mm. The bamboo was air dried to a moisture content of 12±1%.

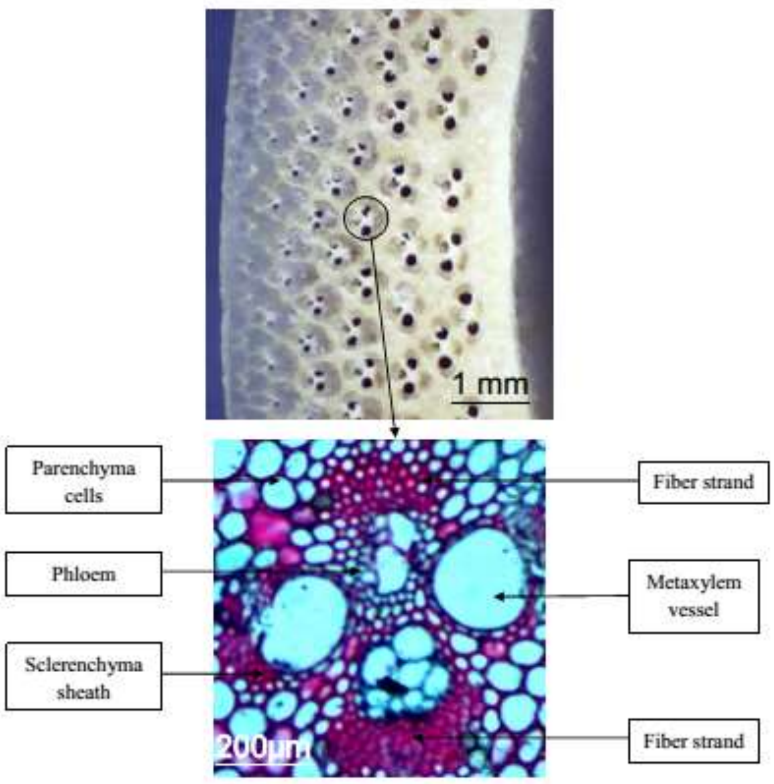

Fig. 1. Distribution and microstructure of vascular bundles and parenchyma cells of hennon bamboo (*P. glauca* McClure)

One-component polyurethane adhesive (HB S309) manufactured by Purboand Co., Ltd., which reacts with moisture in the air, was used in this study. It is the adhesive used for the production of structural wood products. It has an assembly time of 30 min and a curing time of 75 min.

Methods

The outer and inner diameters of the bamboo were measured in two perpendicular directions, and then the average wall thickness was calculated. The longitude of the bamboo was divided into three parts measuring about 1.2 m: top part, middle part, and bottom part. A t-test carried out with the experimental results showed that neither of the outer diameters and the thickness of the bamboo changed after three years of age. Therefore, all the bamboo samples were divided into two groups, young bamboo up to two years old and old bamboo with three or more years of age. The compression strength of the bamboo was tested according to JG/T 199-2007. Before the mechanical tests, all the samples had been put in a testing chamber with 25 ℃ and 65% relative humidity for two weeks to reach a constant quality. The distribution of vascular bundles from the outer to the inner surface and the structure of parenchyma and vascular bundle are shown in Fig. 1.

In order to improve the bonding strength between the panel and the bamboo, the outer skin of the bamboo was removed using a sanding machine. The adhesive was liberally applied to the surface of the sanded bamboo with a specially designed gluing machine. The thickness of the glue layer was about 1 mm. Next, the glue-covered bamboo was inserted into the holes inside the extruded tubular particleboard panels. The panels were stacked horizontally to allow the adhesive to foam and cure. After the bonding, the assemblies were conditioned for 7 days in the standard atmosphere (20 ℃ and 65% relative humidity).

The compression strength of the small diameter bamboo-reinforced extruded tubular particleboard (BREP) was tested. Compression strength was tested because it is the most important property of BREP and it will be employed in the load-bearing component for axial compressive forces. A cross section of BREP is shown in Fig. 2. The length of the samples was 100 mm. The compression tests were conducted in a universal mechanical experiment machine at a pressing speed of 2 mm/min in order to reach failure between 30 s and 90 s. Then the compression strength were calculated by the maximum force divided by the transverse area of the samples without subtracting the hollow structure.

Fig. 2. Cross section of BREP for the compression strength test

RESULTS AND DISCUSSION

Properties of the bamboo

The outer diameters of the young bamboo and old bamboo were 12 to 21 mm and 17 to 24 mm, respectively. The wall thicknesses were 2.1 to 3.1 mm and 2.7 to 3.5 mm, respectively. There was a positive correlation between wall thickness and outer diameter.

Compression tests on the small-diameter bamboo were then conducted (Table 1). The bamboo failed *via* splitting and buckling of its outer wall. This kind of failure is similar to that of fiber-reinforced composites. When the maximum force was reached, cracks appeared and propagated along the bamboo fibers in the longitudinal direction, resulting in buckling and failure.

Table 1. Results of Outer Diameter, Wall Thickness, Compression Strength, and Maximum Force Testing of Hennon Bamboo (*P. glauca* McClure)

Age	Position	Diameter (mm)	Wall Thickness (mm)	f_c (MPa)	F_{max} (kN)
Young bamboo	Top	13.08	2.37	73.64	5.87
	Middle	16.27	2.82	69.81	8.32
	Bottom	19.39	2.98	71.23	10.94
Old bamboo	Top	19.02	2.82	68.36	9.81
	Middle	20.66	3.13	69.64	12.00
	Bottom	21.62	3.37	68.32	13.20

The most interesting discovery was that the compression strength of this type of small diameter bamboo decreased as the outside diameter increased. This was true for all data for both young and old bamboo, as shown in Fig. 3. In other words, the compression strength of the bottom of the bamboo was smaller than that of the upper parts. This result was unexpected.

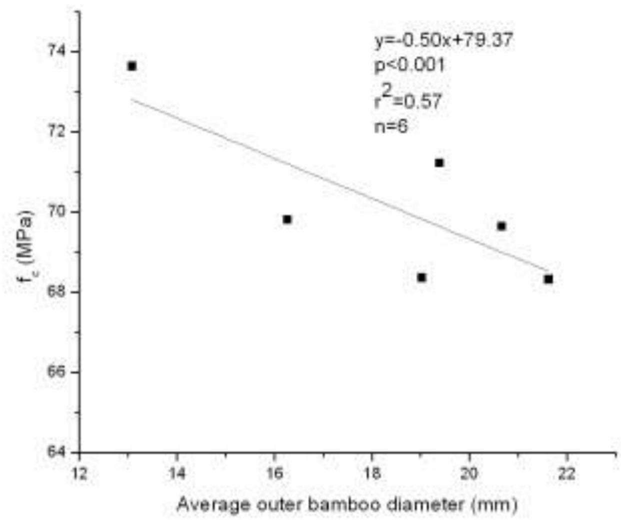

Fig. 3. The relationship between the compression strength of hennon bamboo (*P. glauca* McClure) and its average outer diameter

It was hypothesized that, since the bottom part of the bamboo has had the most time to mature, its strength would be greatest. This was not the case. And by measuring the average per unit area distribution of the vascular bundles, it was found that the area ratio of vascular bundles in the top of bamboo was 15% higher than in the bottom. In other words, the volume ratio of the vascular bundles decided the final compression strength of the bamboo.

The maximum force and the compression strength change differently as functions of the outer diameter of the bamboo. The outside diameter was larger at the bottom of the bamboo. Figure 4 shows the relationship between F_{max} and the outer diameter.

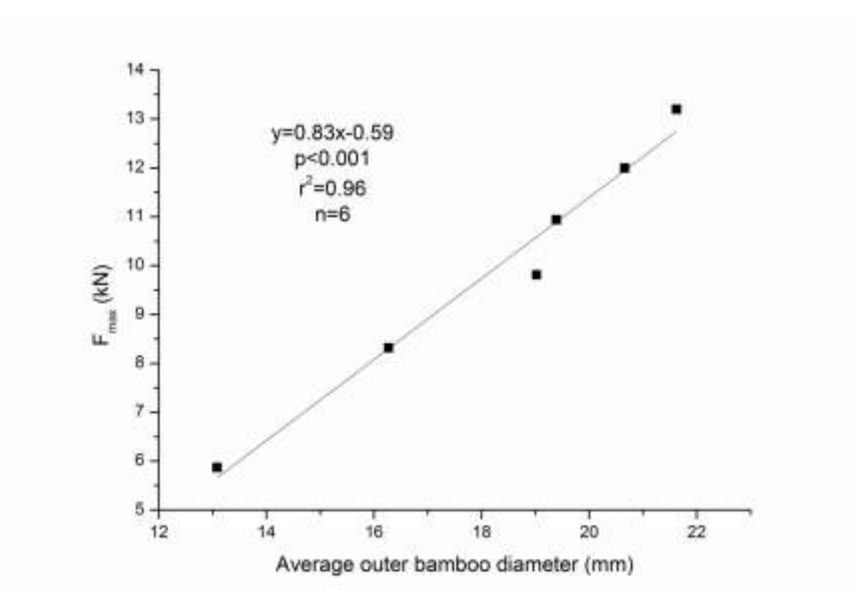

Fig. 4. The relationship between the maximum force of compression of hennon bamboo (*P. glauca* McClure) and its average outer diameter

The relationships between outer diameter and f_c and F_{max} are described by the equations,

$$f_c = -0.5D + 79.37 \tag{1}$$

$$F_{max} = 0.83D - 0.59 \tag{2}$$

where f_c is the compression strength of the bamboo (MPa), F_{max} is the maximum force of compression of the bamboo (kN), and D is the average outer diameter of the bamboo (mm).

Compression strength of BREP

The BREPs were also divided into three groups according to the sections of bamboo used to create them. The solid density of BREP was about 0.70 ± 0.05 g/cm^3. Determining the reliability of materials is important when deciding what applications the materials are safe for. The compression strength is the most important mechanical property of BREP. The compression strength of BREP is affected by many factors, of which the properties of the bamboo, the tubular particleboard, and the agglutination conditions are the most important. Furthermore, genetic factors and site conditions have significant effects on the performance of the small-diameter bamboo within the composites. The mechanical properties of the extruded particleboard are functions of the raw wood particles, the adhesive, and the technology of the manufacturing. In this study, only one type of extruded tubular particleboard was used, and it was assumed that there was no significant performance difference between different particleboards used. Significant differences between different groups of BREP made with different parts of the bamboo were found, as shown in Table 2.

Table 2. One-way ANOVA of the Three Groups of BREP

Source of variation	Sum of squares	D.F.	Mean square	F ratio	P-value	F_{crit}
Between groups	12.51	2	6.26	0.51	0.60	3.28
Within groups	404.37	33	12.25			
Total	416.88	35				

As shown in Table 3, a normal distribution effectively described the distribution of the compression strength in the three groups of BREP. A logarithmic distribution was nearly as effective. A Weibull distribution did not represent the data well.

Table 3. Comparison of Different Distributions of the Compression Strength of BREP

P	Distribution	Location	Shape	Scale	AD	P	Fitting
T	Normal	18.28		4.21	0.264	0.63	**
	Lognormal	2.89		0.24	0.426	0.263	*
	Weibull		6.63	20.27	0.253	0.25	
M	Normal	18.65		3.35	0.253	0.667	**
	Lognormal	2.9		0.20	0.334	0.449	*
	Weibull		5.52	19.60	0.266	0.25	
B	Normal	19.68		2.8	0.234	0.738	**
	Lognormal	2.97		0.15	0.298	0.53	*
	Weibull		8.68	20.82	0.228	0.25	

Table 4. Reliability of the Compression Strength of the Three Groups of BREP

Positions	≥19MPa	≥18MPa	≥17MPa	≥16MPa	≥15MPa	≥14MPa
T	43.21	52.65	61.95	70.59	78.20	84.53
M	45.84	57.70	68.89	78.55	86.20	91.74
B	59.60	72.58	83.08	90.56	95.27	97.87

From Table 4 it can be seen that the probability of the compression strength of BREP manufactured with different parts of the small diameter bamboo exceeding a certain point decreased from the bottom to the top of the bamboo. There were differences between the bottom, middle, and top parts of the bamboo, but the difference between the bottom and middle sections was not very large. To explain these observations, the outer inter-node diameters of the bamboo were studied. These results are shown in Fig. 5.

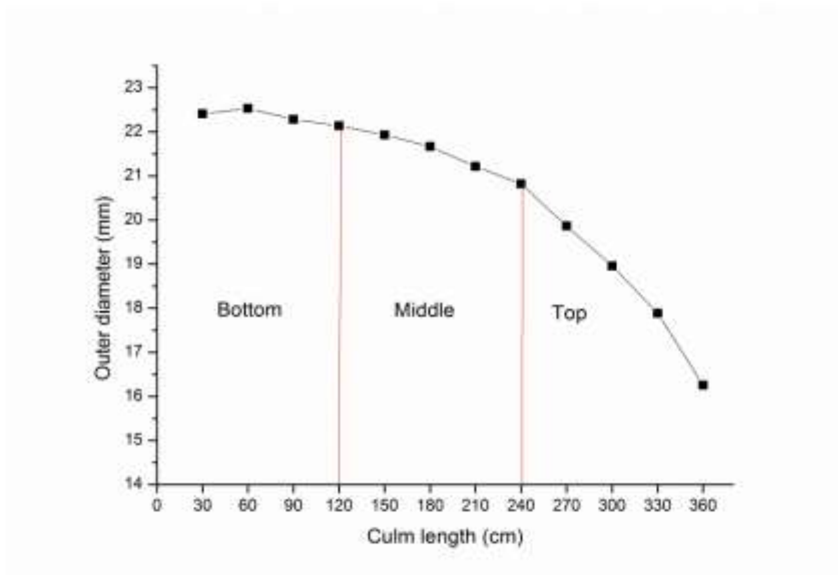

Fig. 5. The distribution of the outer diameters of hennon bamboo (*P. glauca* McClure) from the bottom to the top of the stalk

The outer diameter of the bamboo decreases when moving from the bottom to the top of a stalk. The curve becomes steeper with increasing height. The variability of the outer diameter was least in the bottom region of the bamboo. Therefore, the standard deviation of the compression strength of BREP was the smallest in this region. The bottom part of hennon bamboo is the most suitable part for producing BREP. BREP made with bottom-region bamboo also withstood the largest compression force, F_{max}. There was no major difference between the F_{max} values of the middle and the top parts.

CONCLUSIONS

1. Hennon bamboo, a small-diameter bamboo, can be harvested after it reaches three years of age, as its mechanical properties are stable by then. But the industrial use of small bamboo is very limited. The paper presents an efficient and effective way to use it as reinforcement.
2. The compression strength of the three-year-old bamboo was between 52 and 76 MPa. The strength of the bottom part was smaller than that of the upper parts. The compression strength was inversely proportional to the outer diameter of the bamboo, whereas the maximum force increased with the outer diameter.
3. The mechanical properties of the bamboo used in BREP determine its performance. The compression strength of BREP was between 17.6 and 20.8 MPa. BREP manufactured using the bottom part of the bamboo had the largest average compression strength with the smallest standard deviation. This was due to the decrease in the outer diameter of the bamboo from bottom to top. BREP made using the bottom part of the bamboo yielded the best and the most consistent performance.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from forestry industry research special funds for public welfare projects (201104042), national high technology research and develop program of China (2012AA03A204) and the doctoral fellowship foundation of Nanjing Forestry University (2011YB013).

REFERENCES CITED

Abe, K., and Yano, H. (2010). "Comparison of the characteristics of cellulose microfibril aggregates isolated from fiber and parenchyma cells of Moso bamboo (*Phyllostachys pubescens*)," *Cellulose* 17(2), 271-277.

Ahmad, M., and Kamke, F. A. (2011). "Properties of parallel strand lumber from Calcutta bamboo (*Dendrocalamus strictus*)," *Wood Science and Technology* 45(1), 63-72.

Febrianto, F., Hidayat, W., Bakar, E. S., Kwon, G. J., Kwon, J. H., Hong, S. I., and Kim, N. H. (2012). "Properties of oriented strand board made from Betung bamboo (*Dendrocalamus asper* (Schultes. f) Backer ex Heyne)," *Wood Science and Technology* 46(1-3), 53-62.

Fu, J. (2001). "Chinese moso bamboo: Its importance," *Bamboo* 22(5), 5-7.

Malanit, P., Barbu, M. C., and Frühwald, A. (2011). "Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (*Dendrocalamus asper* Backer)," *European Journal of Wood and Wood Products* 69(1), 27-36.

Sumardi, I., Ono, K., and Suzuki, S. (2007). "Effect of board density and layer structure on the mechanical properties of bamboo oriented strandboard," *Journal of Wood Science* 53(6), 510-515.

Sumardi, I., Suzuki, S., and Ono, K. (2006). "Some important properties of strandboard manufactured from bamboo," *Forest Products Journal* 56(6), 59-63.

Sumardi, I., and Suzuki, S. (2013). "Parameters of strand alignment distribution analysis and bamboo strandboard properties," *BioResources* 8(3), 4459-4467.

Yu, H. Q., Jiang, Z. H., Hse, C. Y., and Shupe, T. F. (2008). "Selected physical and mechanical properties of Moso bamboo (*Phyllostachys pubescens*)," *Journal of Tropical Forest Science* 20(4), 258-263.

Zhang, H., Liu, J., Wang, Z., and Lu, X. (2013). "Mechanical and thermal properties of small diameter original bamboo reinforced extruded particleboard," *Materials Letters* 2013(4), 204-206.

Article submitted: Nov. 25, 2013; Peer review completed: Jan. 25, 2014; Revised version received and accepted: March 18, 2014; Published: March 31, 2014.