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AXIAL COMPRESSION PROPERTIES OF BAMBOO/WOOD COMPOSITE COLUMN CONSTRAINED WITH SLICED BAMBOO VENEER

Yan Yan
International Centre for Bamboo and Rattan Anhui Taiping
Experimental Station
Huangshan, China
Anhui Agricultural University, School of Forestry and Landscape Architecture
Hefei, China

Fei Benhua
International Centre for Bamboo and Rattan
Beijing, China

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ABSTRACT

The purpose of this study was to investigate the enhancement effect of composite column on axial compression. Four full-scale composite columns and one Chinese fir (*Cunninghamia lanceolata*) column were fabricated and tested under axial compression load to study the enhancement effect of composite column. The compressive, bending properties of bamboo (*Phyllostachys edulis*) rod and Chinese fir were tested respectively. The ultimate axial load capacity, midpoint lateral displacement, failure mode of composite column and Chinese fir column were also investigated. The test results indicated that the harmonious coordination between bamboo rods and Chinese fir was shown under the axial load process, and the axial compressive strength 26.21 MPa and compressive modulus of elasticity 9.46 GPa of the composite column were increased significantly meanwhile the lateral displacement at the midpoint of composite columns was reduced by 9.61 mm compared with that of Chinese fir column, and the failure patterns of two types of columns were different. The results will provide a theoretical basis for the popularization and application of bamboo and Chinese fir composite columns.

KEYWORDS: Bamboo and Chinese fir composite column, axial compression, ultimate bearing capacity, failure patterns.

INTRODUCTION

With the implementation of natural forest protection project, the development and utilization of artificial forest has become a major forestry goal in China. Artificial forest management is relatively extensive, rapid growth rate and the high output, meanwhile there are some wood defects, take timber of Chinese fir plantation as an example, such as material soft, inhomogeneous tissue structure and the higher proportion of young wood etc. which affects the wood processing industry and the performance of our products to a great extent (Lv and Bao 2000). With the development of industry and the demand for materials improved, the artificial forest Chinese fir, especially small-diameter logs and thinning timber, have been unsalable (Zhang 2006), due to its structure loose (density 370 $kg \cdot m^{-3}$) and low strength and hardness (Li et al. 1998, Chen and Wu 2000). Therefore, in addition to cultivation measures, how to improve the performance of products and increase their added value through processing technology have become the problem of the industrialization utilization of plantation timber to be solved in China.

The present study on the processing and utilization of Chinese fir artificial forest thinning timber mainly includes Chinese fir material improvement and modification (Xu et al. 2008, Wang et al. 2017), such as LVL (Xu and Jin 2001), artificial board (Yang et al. 2002, Du et al. 2009, Yao 2010), papermaking and strengthening treatment (Nie et al. 1998, Ren et al. 2006, Liu 2016) and so on. However, it is few used as structural column due to its low mechanical strength and small diameter, which is can't meet the requirements of high performance for application in wood structures (Song 2000). Wooden structure building has a long history in China (Zhou et al. 2005). In recent years, the wooden structure residential in Shanghai, Beijing and other large cities has quietly risen (Fei and Zhou 2006). The development of modern wood structure provides a wide market for plantation wood utilization, which means the higher requirements for plantation timber.

Bamboo is one of the most important forest resources, with more than 1250 species, belonging to 75 genera (Lessard and Chouiard, 1980), and is closely related to human's production and life. Its flexural strength, tensile strength and hardness are about 2 times as much as that of ordinary wood (Tommy and Lo et al. 2004). Bamboo plates can achieve higher performance grades (Yan and et al. 2017) with the further study of the microstructure and properties of bamboo, its engineering materials play an important role in people's economy and life (Jiang 2007). On the other hand, its disadvantages of small diameter and low percentage of cut-turn and low processing efficiency (Jiang et al. 2002) have increased the cost of processing, limiting its large-scale industrial utilization. Bamboo and wood composite can effectively display the excellent properties of both, which expands the use scope of artificial forest timber and bamboo. At present, this composite material has applied to artificial board, beams and decorative materials, and so on (Wang et al. 2006, Wang 2012), but it is not commonly used in building column components.

Researchers have made some progress in the field of reinforced columns by using fiber reinforced polymer (Taheriand et al. 2009, Ou et al. 2011, Wu et al. 2013, Chun et al. 2013) recently. Fiber reinforced composites are of higher specific strength and stiffness, which are used as reinforcement materials for steel structures (Wu et al. 2012). However as wood reinforced materials, its performance is excessive and uneconomical. Bamboo reinforced Chinese fir column has more advantages, they are natural biomass materials with green, energy-saving and recyclable, and the price of bamboo is cheaper than fiber reinforced polymer.

In this paper, moso bamboo (*Phyllostachys edulis*) and plantation Chinese fir (*Cunninghamia lanceolata*) are used as experimental materials. Bamboo wood composite columns are processed and its axial stress resistance performance is tested. This study provides a basis for the application of bamboo and wood composite materials to structural engineering materials.

MATERIAL AND METHODS

Materials

Four-year-old moso bamboo culms (high 11 m ± 0.5 m, diameter at breast height (DBH) 10 cm ± 1 cm) and Chinese fir were collected in Huangshan area, Anhui province. Bamboo strips (length 2000 mm, width 20 mm, thickness 5 mm) were sliced from bamboo culms (Fig. 1). There were seven Chinese fir logs with age fifteen years, top diameter 16 ± 1 cm, length 0.8 m. The five of them were made into four composite columns and one Chinese fir column respectively, after peeled, kiln dried (65°C) to moisture content of 10% and processed into cylinders with a diameter of 15 cm by woodworking lathes. The others were used for the physical and mechanical properties specimens' preparation.

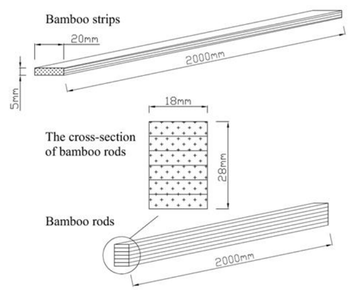


Fig. 1: Diagrammatic sketch of bamboo rods.

Bamboo veneers (length 2400 mm, width 400 mm, thickness 0.5 mm) with moisture content of 10%, purchased in market.

Phenol-formaldehyde resin (PF) (Model 16L511) was purchased from Beijing DYNEA Chemical Industry Co. Ltd, its solid content and the viscosity were 49% (3g/135°C/1h), and 20~40 cps (25°C) respectively.

Two-component epoxy resin (E-51) was purchased from Shanghai KAIPING resin Chemical Co. Ltd, which consisted of main agent CYD-128 type epoxy resin (epoxy equivalent 184.3 g/eq) and curing agent (epoxy compound and fatty amine), and the ratio of the former to the latter is 4:1.

Sample preparation

Bamboo rods: bamboo strips were impregnated into PF resin for 2 h, then air dried. Every 6 of them were hot pressed to a bamboo rod, with the arrangement of side grain contacted with each other. The temperature of upper and lower hot plate was 135°C, and the hot pressing time was 22 minutes. Then the bamboo rods with rectangular cross section were obtained by four-side planer, with their length 2000 mm, width 18 mm, height 28 mm (Fig. 1). A total of 30 bamboo rods were prepared, 12 of them were used to prepare bamboo Chinese fir composite columns, and the rest was used for mechanical properties testing.

Preparation of composite columns: six grooves were evenly distributed around the circumference of the Chinese fir columns, paralleled to the axis. The inner wall of the groove was painted with epoxy resin adhesive and embedded in the bamboo rods (Fig. 2).

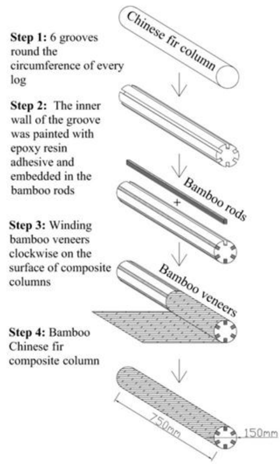


Fig. 2: Processing flow chart of bamboo Chinese fir composite column.

Then the surface of composite column was wound with bamboo veneers which thickness was 2.5 mm (5 loops), the epoxy resin as bonding between every loop. Finally, four bamboo Chinese fir composite columns (D = 15 cm, H = 75 cm) and one Chinese fir column (D = 15 cm, H = 75 cm, control sample) were prepared. Due to the thin winding layer, the Chinese fir columns and bamboo Chinese fir composite columns were regarded as equal diameter cylinder.

Experimental method

The axial compressive properties of composite columns were tested by testing machine WPS500 (Jinan SHIJIN Testing Machine Group Co. Ltd.), and the mechanical properties of bamboo, bamboo rods and Chinese fir were tested by testing machine WDW100E (Jinan SHIJIN Testing Machine Group Co. Ltd.). The breaking strength and elongation at break of bamboo veneers were tested by electronic fabric strength machine SCT-231 (Wenzhou DAIRONG Textile Instrument Co. Ltd.).

The method for measuring moisture content of bamboo strips and Chinese fir were carried out according to standard GB/T 15780-1995:1995 and GB1931-2009, 2009, respectively. The test method for axial compressive strength and elasticity modulus of bamboo, bamboo rods and Chinese fir were referenced to the standards GB/T 15780-1995, 1995, GB/T1929-2009, 2009, GB/T1935-2009, 2009 and GB/T 15777-1995, 1995 respectively. In total 60 samples were measured for the compressive strength and compressive elasticity modulus of bamboo and Chinese fir, respectively. The testing conditions were as follows: machine load sensor 100 kN (accuracy ± 10 N), indoor temperature 25°C, moisture content 65 %.

The test method of the bending strength and elasticity modulus of bamboo, bamboo rods and Chinese fir were referenced to the standards GB/T 15780-1995, 1995, GB/T1936.1-2009, 2009 and GB/ T1936.2-2009, 2009, respectively. In total 30 samples of bamboo rods and Chinese fir were prepared respectively. The bending strength and elasticity modulus were measured by the same specimen. The test was carried out on electronic universal mechanical testing machine, and conducted with a load cell capacity of 100 kN (accuracy ± 10N) under an environment of indoor temperature 25°C at moisture content 65 %.

The breaking strength and elongation at break of bamboo veneers were tested according to standard GB/T 3923.1-2013, 2013. The test method of composite column under axial loading was reference to the standard GB/T 50329-2012, 2012. The ultimate bearing capacity was achieved within 5~10 min by continuous and uniform loading. The test was carried out using 1000 kN load sensor (accuracy ± 100 N), under an environment of indoor temperature 25°C at moisture content 65%.

RESULTS AND DISCUSSION

The difference of density, mechanics performances of bamboo rods and Chinese fir

Fig. 3 showed the physical and mechanical properties of bamboo rods and Chinese fir. The testing results indicated that the density of bamboo rods was 700 kg·m^{-3}, and its compression strength, elasticity modulus of parallel to grain, bending strength and elasticity modulus were 40.31 MPa, 10.73 GPa, 131.15 MPa and 11.26 GPa, respectively. Meanwhile the above properties of Chinese fir were 330 kg·m^{-3}, 34.48 MPa, 10.45 GPa, 66.14 MPa and 9.89 GPa, respectively (Tab. 1).

Tab. 1: Density, compressive strength and modulus, bending strength and modulus of bamboo, bamboo rods and Chinese fir.

Properties / Material	Density (x 10^3 kg·m^{-3})			Parallel-to-grain compressive strength (MPa)			Parallel-to-grain compressive modulus (GPa)			Bending strength (MPa)			Bending modulus (GPa)		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Bamboo	0.71	0.04	5.6%	52.11	1.91	5.01%	12.53	0.26	9.81	155.73	8.54	6.78	11.58	2.01	16.23
Bamboo rods	0.70	0.03	4.6%	40.31	1.77	4.40%	10.73	0.24	9.37	131.15	7.02	5.35	11.26	1.19	10.58
Chinese fir	0.33	0.04	12.18%	34.48	3.80	11.01%	10.45	0.31	12.34	66.14	11.41	17.25	9.89	1.75	17.70

The density, compressive strength and bending strength of bamboo rods were higher than those of Chinese fir, while their compressive elastic modulus parallel to grain was similar (Fig. 3a, 3b). The reason for differences was closely related to the unlike anatomical structure of bamboo and Chinese fir. Bamboo is composed by vascular bundle and parenchyma; while the Chinese fir is consist of tracheae, parenchyma and ray. The vascular bundles distributed inside the bamboo are arranged parallel to the axial direction, which play a bearing role under axial compression, and the parenchyma cells between them act as transfer loads. Their combined action endows the bamboo with a high axial compressive resistance (Xian et al 1995, Shao 2004). Due to bamboo hasn't transverse ray cells (Huang, 2007), its structure is relatively simple compared with that of Chinese fir. It is also one of the reasons that the coefficient of variation of strength and modulus of bamboo or its rods are smaller than those of Chinese fir. Notably, their compressive modulus of elasticity parallel to grain are similar, and the bending modulus of bamboo rods are slightly higher than that of fir (Figs. 3b, 3c), which makes the two kind of materials have good matching and cooperative effect.

The remarkable improvement of the composite column axial compressive properties

The axial compressive tests of columns were showed that the axial ultimate compressive load, compressive strength and elasticity modulus of Chinese fir column were 269.88 kN, 15.28 MPa and 8.13 GPa, respectively, and that of Bamboo Chinese fir composite columns were 463.01 KN, 26.21 MPa and 9.46 GPa, respectively (Tab. 2).

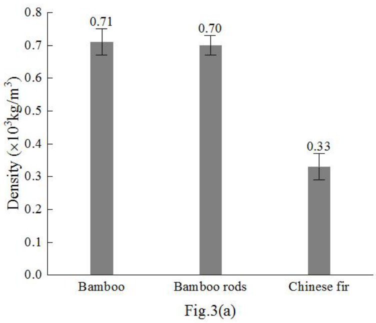


Fig. 3a: Comparison of properties of bamboo, bamboo rods and Chinese fir. Comparison of density.

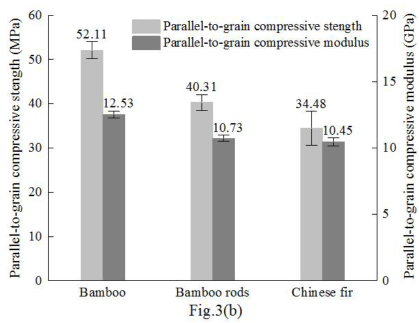


Fig. 3b: Comparison of properties of bamboo, bamboo rods and Chinese fir. Comparison of compressive strength and modulus.

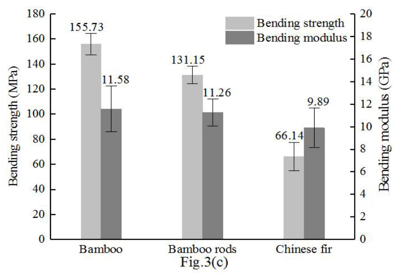


Fig. 3c: Comparison of properties of bamboo, bamboo rods and Chinese fir. Comparison of bending strength and modulus.

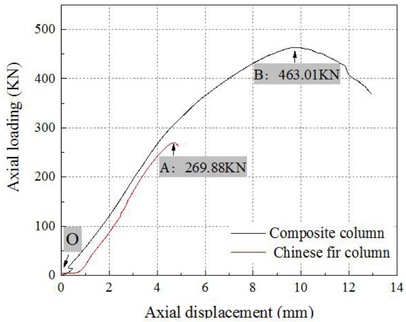
The results indicated that compared with the Chinese fir column, the axial ultimate compressive load of composite column was increased by 71.6%, and the compressive strength and elasticity modulus were increased by 71.5% and 16.4% respectively. It is preliminary evidence that the composite columns have been obviously improved in axial ultimate bearing capacity, compressive strength and elasticity modulus due to the inlay of bamboo rods and the winding restraint of bamboo veneers which breaking strength is 376 N (longitudinal), and 37 N (transverse), elongation at break is 0.9% (longitudinal), and 1% (transverse) respectively.

Tab. 2: Axial compressive performances of columns.

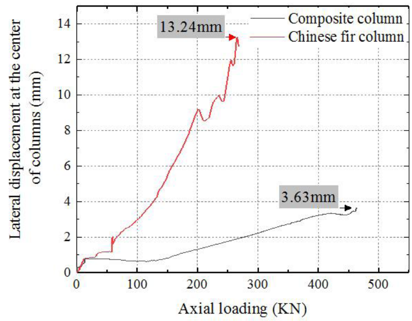
The types of column	Axial compressive ultimate load (kN)	Axial compressive strength (MPa)	Axial compressive modulus of elasticity (GPa)
Chinese fir column	269.88	15.28	8.13
Bamboo and Chinese fir composite column	463.01	26.21	9.46

Differences in failure patterns of axial compression

The axial load-deformation curve of columns was recorded in Fig. 4a. Points O, A and B were the initial loading, the ultimate load of Chinese fir column and the ultimate load of composite column, respectively. In the stage of O-A, with the increasing of axial compressive load, the deformation of the Chinese fir column changed from elastic to plastic accompanied by buckling, and the maximum lateral displacement of middle column reached to 13.24 mm (Fig. 4b), meanwhile the surface wood fibers outward crushed (Fig. 5a) and the sound of broken were observed, then the ultimate load of Chinese fir column reached at the point A.



a) Axial load-axial displacement diagram.



b) Axial load-axial displacement diagram.

Fig. 4: Load-displacement diagrams.

In the stage of O-A for composite columns, elastic deformation occurred, with no buckling in their structure intact. In the stage of A-B, the deformation of composite column was changed from elastic segment to plastic segment with the axial load increasing, and the maximum lateral displacement of that was reached to 3.63 mm, smaller than that of Chinese fir column (Fig. 4b).

Fig. 5a: Differences in failure patterns of axial compression. Wood fibers crushed of middle part of Chinese fir column.

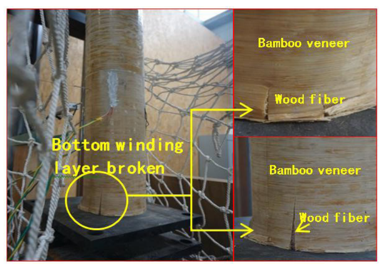


Fig. 5b: Differences in failure patterns of axial compression. Bottom winding layer broken of bamboo-Chinese fir composite column.

The rupture of the surface layer of the bottom in composite columns and exposure of internal wood fibers were observed (Fig. 5b), accompanied with rupture sounds, finally, the ultimate load of composite column was reached at the point B. Compared with Chinese fir column, the axial compressive ultimate load of the composite column was increased significantly, with its elastic stage prolonged and lateral displacement decreased. Based on the failure mode happened in the bottom of composite columns, it also infers that the ultimate bearing capacity of composite columns can be further improved by continual strengthening the winding layer of the ends of the composite columns.

The main reasons for the higher performance of the composite columns are as follow. Firstly, the bonding interfaces between the bamboo rods and Chinese fir are firm and stable because of bamboo rods embedded in Chinese fir with large slenderness ratio (Yan et al. 2016). In the process of axial loading, both of them have good coordination and shared axial load as a whole, due to the higher properties of bamboo rods, the composite column showed strong synergistic enhancement effect. Hence, the axial compressive strength of composite columns can be improved.

Secondly, the winding layers of the composite column play a radial constraint role, limiting the crushing of the wood surface fibers. In the process of axial loading, these fibers continue to bear axial load, and delay the internal fibers collapsed, which result in the elastic stage to extend and the yield point at higher stress levels (Shao et al. 2012). Lastly, the distribution of bamboo rods with higher bending modulus (Tab. 1) embedded into the column surface enhances the bending performance of the composite columns. On the contrary, the surface wood fibers of Chinese fir column crush outward, which reduces the carrying area of the column and leads to its internal wood fibers collapsed successively and buckling of fir column.

CONCLUSIONS

(1) The density, compressive strength, bending strength and bending modulus of bamboo rods were 700 $kg \cdot m^{-3}$, 40.31 MPa, 131.15 MPa and 11.26 GPa respectively, which is slightly higher than those of Chinese fir, and their compressive modulus parallel to grain is 10.73 GPa and 10.45 GPa respectively. The bending property of moso bamboo rods is better than that of Chinese fir, and the compression modulus is close to that of Chinese fir, which is the basis of the significant cooperative effect between bamboo and wood composite columns in the process of axial compression.

(2) The axial compressive ultimate load of the composite column is increased significantly with its elastic stage prolonged and lateral displacement at the middle of the column decreased, compared with the Chinese fir column. Which means that the bamboo can enhance the lateral bending resistance of the composite column and improve the axial bearing capacity without increasing the column cross-section area.

(3) The failure patterns of two types of columns under axial compression are different. The Chinese fir column shows buckling and larger lateral displacement at the middle part, its surface wood fiber on the compression-side crushed outward. The composite column is broken at the bottom, with the splits of the bottom winding layer and the exposure of inside wood fibers.

(4) In the axial compression process, the inlays of bamboo rods distributed on the composite column enhance the bending performance notably and the winding layer of the composite column constrains the horizontal deformation of the wood fiber. If the end winding layer of composite column is strengthened, the ultimate bearing capacity of composite column may be further improved.

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Yan Yan
International Centre for Bamboo and Rattan
Anhui Taiping Experimental Station
Huangshan, China
Anhui Agricultural University, School of Forestry
and Landscape Architecture
Hefei, China

Fei Benhua*
International Centre for Bamboo and Rattan
No. 8, Futong Eastern Street
Wangjing Area, Chaoyang District
Beijing, China
*Corresponding author: feibenhua@icbr.ac.cn