Development of Bamboo Winding Composite Pipe (BWCP) and its Compression Properties

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A new bio-composite pipe structure named bamboo winding composite pipe (BWCP) was made of bamboo slivers, and its mechanical performance was investigated. Bamboo winding composite pipe that is lightweight and has high strength mechanical properties can be used in water conveyance projects as a green alternative to traditional pipeline materials. Continuous lengths of bamboo slivers were reinforced with resin matrix, which were then fed through a mechanical arch-shaped winder to fabricate the BWCP. The specific ring stiffness of BWCP was comparable to that of fiberglass reinforced plastic pipe (GFRP). The BWCP density was 46.1% to 54.9% lower than that of GFRP. The BWCP exhibited a typical ductile failure and underwent significant deformation before fracture, with the pipe radial deflection at nearly 30%, which is nine times higher than that of brittle fracture failure of GFRP. The interlaminar shearing properties of the BWCP were higher in the structural layer reinforced by bamboo than that of the inner layer made of polyurethane. The BWCP was comparable to most materials used in the pipe industry, exhibiting light weight and high strength.

Keywords: Biomaterials; Structural; Fiber technology; Polymeric composites; Mechanical properties

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INTRODUCTION

Bamboo is one of the strongest and fastest growing plants in the world. Approximately 22 million hectares of the world's surface is covered in bamboo forest (Zhang *et al.* 2013). There is a multitude of advantages to using bamboo as a material, including its fast growth cycle of three to five years and sustainable utilization; bamboo timber can be harvested multiple times from a single planting. In addition, it is easy to process and eco-friendly, and it has high strength and stiffness (about 2 to 3 times when compared to wood (Xiao *et al.* 2013; Zakikhani *et al*. 2014). During the past 20 years the field of research concerning bamboo fiber reinforced composite (BFRC) has been dedicated to developing economical, lightweight, and green composites with ever growing importance with each passing year (Chen *et al*. 2013; Ho and Lua 2014). A series of new BFRC products have appeared throughout various markets for decoration, furniture, and construction material. BFRC products include bamboo plastic composites, reconstituted bamboo timber, bamboo bundle laminated veneer lumber, bamboo plywood, particleboard, oriented strand board, laminated strand board, and parallel strand board (Nugroho and Ando 2001; Chen *et al*. 2014; Yu *et al*. 2014). Most BFRC boards are used in planar construction, which consists of compression molding, extrusion molding, vacuum molding, *etc*. These common methods of production severely limit the size and shape of bamboo-based products, which is why a breakthrough in BFRC processing technology has become essential to expanding its application to new industries (Li *et al.* 2016).

A bamboo winding composite pipe (BWCP) possesses good physical and mechanical properties. It was developed using the filament winding technology that takes advantage of bamboo's high axial tensile strength and good bending ductility (Song *et al.* 2014; Chen *et al*. 2016). BWCP is the first pressure pipe manufactured from a bio product and may serve as an alternative to traditional non-biodegradable materials used in the manufacturing of pipes (Fei *et al.* 2018). The comprehensive performance of BWCP in specific strength and stiffness, insulating property, water resistance coefficient, easy installation, and low transportation expenses makes it as a preliminary candidate. In addition to the performance of BWCP, the total production cost of pipes is reduced by 30% to 70% with the replacement of traditional pipes made from metal, plastic, glass reinforced plastics, and cement (Wang *et al.* 2016). However, the compression performance of BWCP is key important to its application in farmland irrigation, urban water supply lines, drainage lines, oilfield pipelines, telecommunication cable protection. Further investigating the mechanical properties and fracture behaviors of BWCP under compression loading is a pre-requisite. This paper investigated the compression properties and fracture behaviors of BWCP.

EXPERIMENTAL

Raw Materials

Moso bamboo stalks (*Phyllostachys pubescens*) with ages ranging from 3 to 5 years old were harvested from bamboo forest gardens in Anji, Zhejiang Province, China. The bamboo stalks were cut into 3 m length bamboo tube sections, which were then split with a hack machine into four strips of approximately the same size. An untwining machine was designed to use a multi-group of sharp blades to split bamboo strips into thin bamboo slivers. The dimensions of the bamboo slivers were 0.8 mm thick by 4 mm wide by 3 m long. A sewing approach was used to link together separate bamboo slivers into a uniform continuous bamboo sliver curtain. The bamboo sliver curtain was air-dried to a moisture content of 12 ± 1% for material preparation. The polyester resin used to manufacture BWCP was custom made by Zhejiang Xinzhou Bamboo-based Composites Technology Co., Ltd., Hangzhou, China. The control sample used was a Sand sandwiched glass fiber reinforced plastic pipe (GFRP) that was supplied by Huaqiang GRF Co., Ltd., Hengshui, China.

Manufacturing Process of BWCP

BWCP is a multi-layered pipe constructed from bamboo sliver curtain that has gone through a high-tension winding process. BWCP is manufactured when a bamboo sliver curtain that is reinforced with melamine-modified urea-formaldehyde resin (UF) is fed through a mechanical arch shaped winder (Fig. 1). The arch shaped winder takes advantage of bamboo's high tensile strength as well as its good bending toughness because it is able to wind the bamboo so that it is free of stress defects. A layer of polyester film tape (0.022 mm thick by 190 mm wide) is uniformly wound about a metal winding mandrel, which allows the tape to function as a mold release agent. Modified polyurethane resin is painted on the polyester film tape. In order to construct the inner seepage control layer of the pipe structure a layer of alcohol soluble polyurethane resin layered onto the winding mandrel. Once the resin is applied, a layer of nonwoven bamboo fabric is applied to the mandrel, followed by a glass fiber mat layer, then a synthetic mesh layer. The resulting control layer has a thickness of 1.2 mm. Reciprocating-cross-winding technology is used to apply a 0.8 mm thick by 190 mm wide continuous length bamboo slivers curtain impregnated with UF resin to create the pipe's reinforced structure layer. The pipe is then placed in a drying kiln at 80 to 100 °C for 2 to 3 h while the seepage control layer and structural layer cure. After the pipe has cured, a 1.2 mm thick external protection layer made of asphalt-rubber waterproofing coating (AR) or phenol-formaldehyde resin (PF) is applied to the structural layer of BWCP. With the final layer of the pipe applied, the winding mandrel is removed using an automatic thruster.

Compression Properties

The mechanical properties of the BWCP were evaluated in accordance with GB/T 5352 (2005) and GB/T 21238 (2007) for pipe ring stiffness and bearing capacity by parallel-plate loading. The interlaminar shear strength of BWCP was tested using a group of custom disk-shaped pressure plates with groove and convex ladder types. The samples were conditioned in 65 ± 5% relative humidity and a temperature 23 ± 2 °C for 40 h. The specific testing speed for BWCP was determined by formula (1) and initial ring stiffness was calculated following formula (2),

$$V = 3.50 * 10^{-4} D^2 / t \tag{1}$$

where V is the testing speed (mm/min), D is the dameter of pipeline (mm), where D=DN+t, and t is the thickness of the pipe wall (mm).

$$S_0 = 0.01935 \times \triangle F / \triangle y \tag{2}$$

In Eq. 2, S_0 is the initial stiffness of the ring (N/m^2), $\triangle y$ is the variation of pipe diameter, generally taking 1.25% of D (m), and $\triangle F$ is the static line load corresponding to $\triangle y$ (N/m).

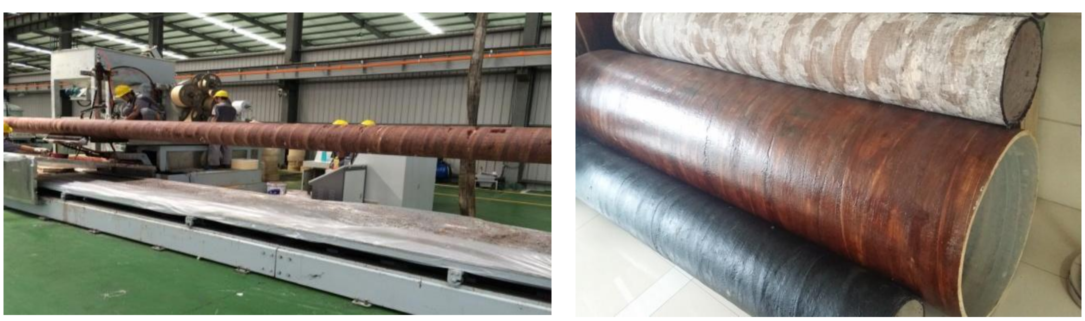

Fig. 1. Bamboo winding composite pipe (BWCP) (a) manufacturing process and (b) products

RESULTS AND DISCUSSION

The average density of the BWCP used was a comparison of three types of BWCP and GFRP as a control (Table 1). BWCP samples consisted of one sample with no external protection layer, one with asphalt rubber coating, and the other with phenol-formaldehyde resin coating. Of the three BWCP samples, the sample without any coating exhibited the lowest average density of 0.76 g/ cm^3.

Table 1. Basic Mechanical and Physical Properties of BWCP

Types	Inner Diameter	Wall Thickness	Testing Length	Average Density	Initial Ring Stiffness	Specific Ring Stiffness	Diameter Range	Working Pressure	Medium Temperature
	(mm)	(mm)	(mm)	(g/cm^3)	(kN/m^2)	(kN*mm/kg)	(m)	(MPa)	(°C)
BWCP	300	13.8 (0.54)	50	0.76	8.36(0.89)	10.93	0.15-3.0	0.4-1.6	≤80
AR-BWCP	300	13.6 (1.35)	50	0.90	7.49(2.90)	8.26			
GFRP	300	13.4 (0.19)	50	1.67	23.98 (3.90)	14.35	0.1-4.0	0.1-2.5	≤50

Note: AR-BWCP is the BWCP protected with asphalt rubber. The standard deviations are in parentheses.

The BWCP sample with the AR coating had the highest density of the BWCP samples at 0.9 g/cm^3, and the sample coated with PF resin had a density of 0.87 g/cm^3, which was just below that of the AR-coated sample. The GFRP control sample had the highest density of 1.67 g/cm^3, which shows that the weight of the BWCP samples was 46.1% to 54.9% lighter. The specific ring stiffness for the BWCP was 11 kN*mm/kg which is almost the same level of the GFRP, which is at 14 kN*mm/kg. This result suggested that the specific mechanical properties of BWCP are comparable to that of GFRP. BWCP can be designed to meet many specifications from a diameter of 3 m and up, a working pressure class less than 1.6 MPa, and a medium operational temperature up to 80 °C (Table 1).

The load-displacement values of BWCP and GFRP under circumferential compression were tested, and there was a difference in the fracture mechanics model in both brittle fracture and ductile fracture for both materials (Fig. 2). The load-displacement curve of GFRP displayed a good linear elasticity, but there was an abrupt failure that occurred at the layer of sand sandwiched glass fiber where a breaking displacement of 8.4 mm occurred in the diameter direction. The load-displacement curve of the BWCP showed a steep linear increase until 35 mm of displacement, after which the displacement in the BWCP slowly increased until it remained constant. At 84.3 mm, the breaking displacement occurred on BWCP load-displacement curve, which shows that the pipe radial deflection of BWCP was nearly 30% and was nine times higher than that of the GFRP. The circumferential load bearing capacity per unit length for BWCP and GFRP was comparable, with BWCP at 12.1 N/mm and GFRP at 13.7N/mm. These analyses indicated an excellent flexural ductility for bamboo-based winding composite pipe.

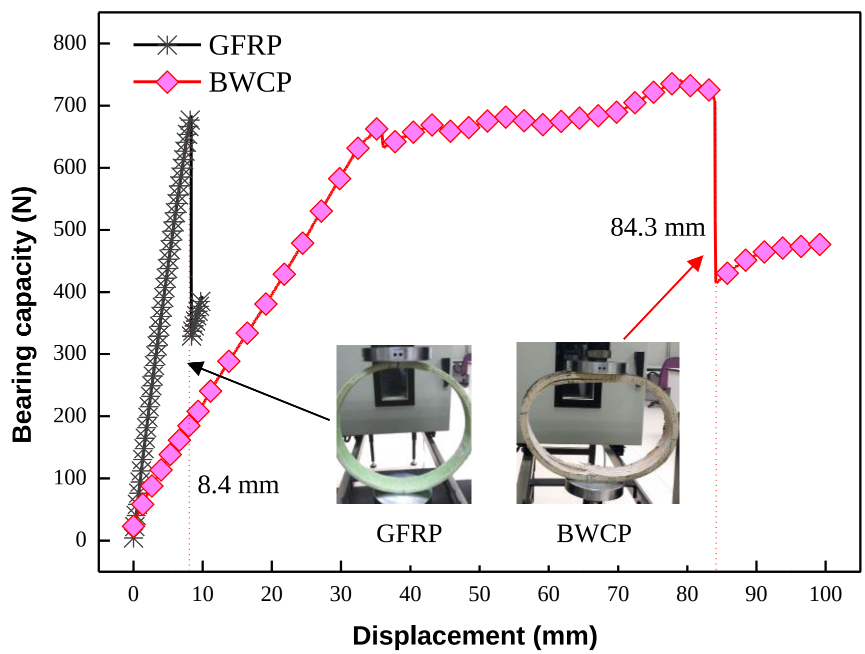

Fig. 2. The curves of compressive load *vs*. displacement for BWCP and GFRP under circumferential direction

The shear properties of the BWCP structural and inner rings were observed (Fig. 3). A maximum shear force of 27.9 kN for the structural layer was much larger than the 18.01 kN maximum shear force of the inner layer. The structural layers shearing displacement was 6.07 mm, which was higher than that of the inner layers displacement of

5.42 mm. The shear strength of the structural layer at 0.91 MPa outperformed the inner layers shearing strength of 0.67 MPa; the structural layer strength was 42.5% higher than that of the inner layer. Thus, the interface between winding bamboo slivers and UF resin is better than that between the inner layer polyurethane resin and bamboo. The improvement in the interface of BWCP, the bonding performance and internal force translating ability, is considerably crucial in the development of advanced bamboo winding composite material.

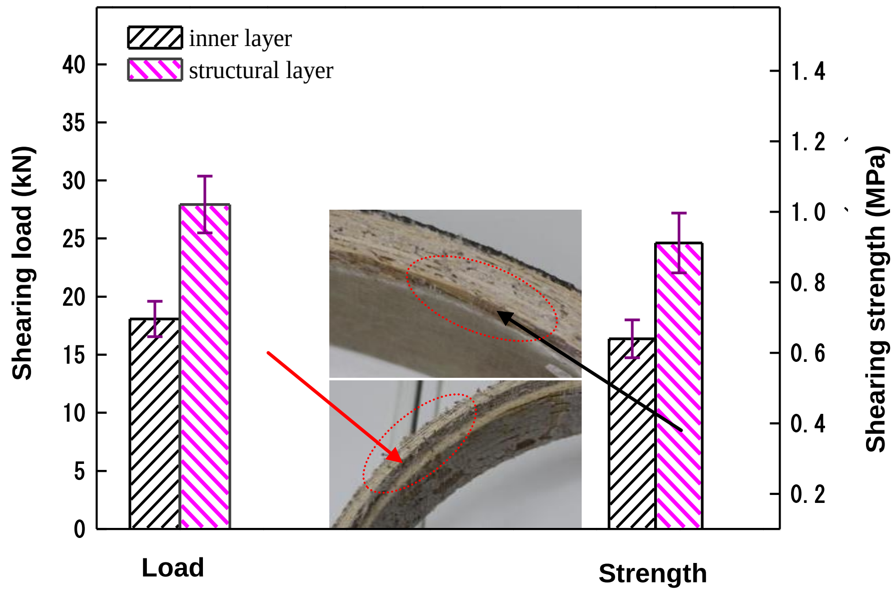

Fig. 3. Comparison of the interlaminar shearing properties of inner layers and structural layer of BWCP

CONCLUSIONS

1. Bamboo winding composite pipe (BWCP) is the first bio-pipeline made from bamboo sliver curtain then coated in resin as it is wound using filament winding technology.
2. BWCP was compared with fiberglass reinforced plastic pipe (GFRP) and found to have a lightweight, high specific strength, excellent flexural ductility with a density below 1.0 g/cm^3, initial ring stiffness over 5000 N/m, and an approximately 30% pipe radial deflection. The bonding interface of structural layer reinforced with bamboo is superior than that of inner layer.
3. BWCP can be used as a lightweight and high strength bio-pipe product in farmland irrigation and urban underground pipeline allure, modular construction and even potential application in high-speed rail carriage.

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