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Bending properties evaluation of newly designed reinforced bamboo scrimber composite beams

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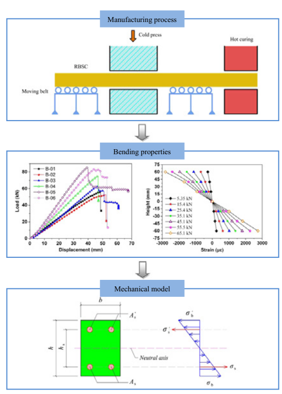
HIGHLIGHTS

- A newly designed reinforced bamboo scrimber composite (RBSC) beam is developed.
- The ultimate load capacities and bending stiffness of the RBSC beams are significantly improved.
- A simplified mechanical model is proposed to predict the bending properties of RBSC beams.

GRAPHICAL ABSTRACT



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ABSTRACT

To meet the material requirements of a large span structural beam, a newly designed reinforced bamboo scrimber composite (RBSC) beam combining the bamboo element and the reinforcement element was developed. The RSBC beam was compared with other un-reinforced beams to evaluate its bending properties. Results indicated that the reinforcement and the bamboo elements could firmly form an integrated composite cross-section. The failure modes, ultimate load and cross-section stiffness of the RBSC beams were significantly correlated to the diameter of reinforcement as well as the heat treatment of bamboo bundle. A simplified mechanical model was also proposed according to the superposition principle, and the predicted deflection and load capacity matched well with the experimental results. This preliminary study is beneficial for the design, manufacture and application of bamboo-based structural composite materials in practical engineering.

1. Introduction

With increasing demands on green buildings, bamboo is becoming an interesting and promising construction material owing to its environmental friendliness, sustainability, and easy recovery and utilization [1,2]. Bamboo not only has a fast growing rate, being ready for harvest in 3–5 years; it also has a high strength-to-weight ratio, compared with other common building materials such as wood, wood-based composite, concrete, and steel [3,4].

However, the use of natural bamboo as construction material is limited mainly because of the small diameter of bamboo culms and the high variability of its mechanical properties. To overcome these

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constraints, bamboo-based composites have been developed and further investigated [5–9]. The bamboo scrimber, which is manufactured by a mechanical treatment without any chemicals and by moving the inner and outer layers of the bamboo, exhibits a great potential for application as a construction material because of its high manufacture efficiency, utilization and good mechanical properties [9–11]. However, the length of the bamboo scrimber is limited to no more than 2.5 m because of the lack of continuous cold pressing equipment; this limitation hinders the further application of bamboo scrimber as a large scale structural member, such as large-span beams or long columns. Therefore, a number of researchers [12–14] have devoted themselves to developing the large scale members by using the veneer-joint or finger-joint methods. These joints have been proven to significantly reduce the strength and stiffness of the whole member, rendering the structural safety requirements difficult to satisfy.

In addition, beams strengthened with the reinforcement element have been widely applied in concrete structures [15]. In this study, a bamboo scrimber composite (RBSC) beam was firstly developed and manufactured using an intermittent cold pressing process (Fig. 1). The RBSC consists of a bamboo element as the main bearing members and a reinforcement element as the strengthening member. Six types of beams with different configurations including the un-reinforced and reinforced bamboo scrimber composite were manufactured.

This study aimed to investigate and compare the bending properties (the ultimate load capacity, bending stiffness and strain distribution) of the reinforced and un-reinforced bamboo scrimber composite beams, and to propose a simplified mechanical model of RBSC beams to predict the deflection and load capacity.

2. Materials and methods

2.1. Materials

Generally the manufacturing process of RBSC beams includes three main stages: (a) preparation of the bamboo element; (b) preparation of the reinforcement element; and (c) molding of the reinforced bamboo scrimber, as shown in Fig. 2. For the un-reinforced bamboo scrimber composite beams, no reinforcement elements were added in its cross-section.

First, the Moso bamboo (*Phyllostachys pubescens*), aged 3–4 years, was harvested from Guangde county, Anhui province, in the southeast part of China. These culms, with an average diameter of 100–150 mm and an average thickness ranging from 12 to 20 mm, were cut into long pieces. They were then split into two semi-circular or more bamboo tubes, and the inter nodes were removed. Without moving the inner layer and outer layer, the bamboo tubes were passed through a rolling machine along the grain direction, and then were flattened along the longitudinal fiber direction to obtain the oriented bamboo bundle [10,11,16]. In this study, some of bamboo bundles were heated using steam at 175 °C for 140 min (Table 1) to evaluate the effects of heat treatment on the bending properties of RBSC beams. Both unheated and heated bamboo bundles were immersed in resin for about 10–15 min at room temperature (20 °C) and were dried for 8 h at 45–50 °C.

Second, the reinforcement used is a common construction material, which is a Q235-B grade steel bar with a nominal yield strength of 235 MPa and a nominal modulus of elasticity of 206 GPa. These data were provided by the manufacturer. To enhance the bonding strength between the bamboo element and reinforcement element, the reinforcements were wrapped with a 2–3 mm thick linen. Thereafter, the reinforcements were immersed in resin for about 3–5 min at room temperature and then dried for 8 h at a temperature 45–50 °C.

After the bamboo (Fig. 2(a)) and reinforcement elements (Fig. 2(b)) were prepared, both were paved along the grain direction and cold pressed with a pressure of 37 MPa for 3 min, and then hot cured for 12 h at a temperature 130–140 °C, as shown in Fig. 2(c).

The adhesive used in bamboo and reinforcement elements was a commercially available low molecular weight phenol formaldehyde resin (PF16L510) and its parameters were 6–49% of solid content, 20–40 CPS of viscosity, 10–11 pH, and ability of dissolve in water in 7 times, supplied by Beijing Dynea Chemical Industry Co. Ltd.

2.2. Preparation of reinforced bamboo scrimber beams with six different types

Six types of beams (Table 1) with a dimension of length × width × height (3600 mm × 150 mm × 150 mm), were used for bending tests. The diameters of the reinforcement bars used in building structures usually range from 8 mm to 30 mm in China. Therefore, three different diameters (12, 16 and 20 mm) were selected in this study. For smaller or larger reinforcement bars, the mechanical properties of these composite beams can be analyzed using a mechanical model, which was proposed in the following study, or a finite element numerical simulation method. The RBSC beams (B-01 ~ B-06) contained three kinds of reinforcement and two kinds of bamboo bundle (un-heat and heat treatment). The cross-section of B-01 and B-02 beams as the un-reinforced type contained no reinforcement element, whereas that of B-03 ~ B-06 beams as the reinforced type contained four steel bars. In addition, the bamboo bundles used in B-02 and B-06 beams as the heat treatment type were heated using steam at a temperature of 175 °C for 140 min to prepare the bamboo element (Fig. 2(a)), whereas the B-01 and B-03 ~ B-05 beams were the un-heat treatment type.

Fig. 3 presents the details of a reinforced bamboo scrimber composite beam. The bamboo elements with two different lengths, 1.2 m and 1.8 m, were paved along the grain direction (Fig. 3(a)). Thus, the assembling joints appeared in three locations along the beams, and the center joints were placed in the mid-span during the bending test. The cover thickness of reinforcement (a_s) was set to 22 mm, as presented in Fig. 3(b).

The mechanical properties of individual materials, such as the tension strength (TS), compression strength (CS) and shear strength (SS) parallel to grain of the bamboo scrimber composite, as well as the yield strength of steel, were tested in accordance with the Chinese national standards. The mean value and standard deviation of mechanical properties are shown in Table 2.

2.3. Bending test

A universal test machine with a load capacity 250 kN supplied by MTS System Corporation (Minnesota, USA) was used to investigate the mechanical performances of the RBSC beams under bending. The schematic drawing and photos of the bending test were shown in Fig. 4(a) and (b), respectively. A four-point method was adopted in accordance with Chinese national standard GB/T 50329–2012. The distance (l) between two supports was 3150 mm and the distance (b) between two loading points was 900 mm, i.e. six times of the section height of RBSC beam. Three displacement transducers with a capacity of 50 mm (Model: CDP-50, Tokyo Sokki Kenkyui Co., Ltd., Japan) were placed at the mid-span and supports. Seven strain gauges (Model: BX120-80AA, Xingtai Jin Li Co., Ltd., China) were attached on one side of the beam at mid-span along the height direction to measure the strain distribution. The data were collected simultaneously using the TDS-530 multi-channels data acquisition equipment (Earth Products China Co., Ltd, China). The specimens were loaded until failure with a loading speed 5 mm/min.

For the bending test, the equivalent modulus of rupture (MOR) and equivalent modulus of elasticity (MOE) of the whole RBSC beams can be calculated by Eqs. (1) and (2) according to bending theory in mechanics of materials [17].

$$MOR = \frac{M}{W} \quad (1)$$

$$MOE = \frac{a\Delta P}{48I\Delta w}(3l^2 - 4a^2) \quad (2)$$

where M represents the bending moment at the cross-section (N·mm); W is the cross-sectional resistance moment (mm^3) equal to $bh^2/6$; I is the cross-sectional moment of inertia (mm^4) equal to $bh^3/12$; b and h are the width and the height of the whole cross-section (mm), respectively; ΔP is the load increment in the elastic stage (N); Δw is the corresponding deflection at the mid-span cross-section (mm).

3. Experimental results

3.1. Failure modes

Fig. 5 presents the final failure of all six beam types. The initial failure of each beam type is located on the outermost tension side of mid-span cross-section, which may have resulted from the failure of bamboo element to exceed the ultimate tensile strain. All six beams failed once the initial failure occurred, and the ultimate loads (P_{max}) of the six beams were 55.8, 52.9, 62.5, 75.2, 85.2, and 83.7 kN, respectively (Table 3).

After the initial failure, a crack occurred and developed along the longitudinal direction of bamboo element with an increase of the applied load, as shown in Fig. 5(a). The load capacity of the beams (B-01 and B-02) decreased abruptly because of such failure mechanism. For the B-03 ~ B-05 beams, the load capacity dropped sharply because of a crack that passed through the entire cross-section along the vertical direction of bamboo element, as shown in Fig. 5(b). Compared with the un-reinforced beams (B-01 and B-02), the crack along the longitudinal direction of bamboo element for the B-03-B-05 beams was hindered owing to the reinforcement element. Unlike other beams, shear failure was observed in the B-06 beam, as shown in Fig. 5(c). When the load capacity reached the ultimate load, a crack suddenly occurred and developed quickly along the longitudinal direction near the intermediate layer. This occurrence mainly contributed to a significant decrease in SS for the B-06 vs. B-05 (near 35%, Table 2) caused by the heat treatment of bamboo bundle.