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Flexural performance of bamboo scrimber beams strengthened with fiber-reinforced polymer

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HIGHLIGHTS

- A new type of bamboo scrimber beams is proposed.
- The failure of the strengthened beams starts with tensile fractures.
- Load-carrying capacity and rigidity of the strengthened beams are increased.
- A theoretical method for predicting the load carrying capacity is developed.

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ABSTRACT

This study presents a new type of bamboo scrimber beams that are strengthened by fiber-reinforced polymer (FRP) composite sheets embedded in the internal tensile region with an additional bamboo plate. To investigate the flexural performance of the bamboo scrimber beams, four-point bending tests were conducted to determine the failure modes, the load-displacement relationship, the load carrying capacity and the flexural rigidity of reinforced bamboo scrimber beams. The main parameters in the tests were the number of FRP layers and the type of FRP. The results indicated that the failure of the strengthened beams started with tensile fractures on the bottom bamboo plates, and no slipping was observed between the strengthening materials and the original bamboo beams prior to the rupturing of the bamboo plates. The flexural load-carrying capacity and the flexural rigidity of the strengthened beams effectively increased due to the FRP composite sheets and an additional bamboo plate. The strengthening method has a beneficial effect on promoting the compression behavior in the compression zone of the cross-sections of bamboo beams. Based on a simple stress-strain model of bamboo scrimber, a theoretical method for predicting the flexural load carrying capacity was developed. The predicted results are consistent with the test results.

1. Introduction

Wood structures are extensively employed for short-span bridges, lightweight residential buildings and landscape architecture; studies of wood structures are relatively extensive and thorough [1]. However, numerous problems of wood structures remain: their development is accompanied by vast consumption, and wood is characterized by a long growth cycle, slow regeneration, a significant shortage of resources and a low utilization rate of raw materials [2,3]. Consequently, feasible and appropriate materials should be explored. Bamboo has been extensively applied in composite industries because it is fast-growing material that has a high specific strength and specific rigidity and a relatively low water swelling ratio compared with wood [4,5]. Bamboo can serve as a replacement for wood in appropriate places because it is biodegradable, has a low carbon content, and contributes to sustainable and recyclable energy conservation [6]. Bamboo scrimber and laminated bamboo are common and typical bamboo fiber-based composite products; an increasing number of studies have investigated the selection of raw materials, manufacturing process and material properties of these products [7–12]. Bamboo scrimber has high density, excellent mechanical stability and corrosion resistance, however, larger raw materials consumption and higher cost are its disadvantages for the engineering application. The flexural performance of bamboo beams has also been recently analyzed by many researchers [13,14]. Existing experimental results illustrate that the failure modes of bamboo beams are often revealed as a fracture of the tensile fibers and a large mid-span

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deformation under flexural loads. Therefore, potential strengthening technology to enhance the insufficient stiffness of cross-sections and insufficient spanning capacity of bamboo beams needs to be explored.

In previous studies of wood structures, a variety of strengthening techniques have been proposed by researchers [15–19]. For instance, Luca et al. [15] investigated the flexural behavior of reinforced and reinforced-prestressed glue laminated timber beams with steel bars. The experimental results demonstrated that flexural strength can be improved by strengthening beams with simple or prestressed steel bars. The strengthened solution is effective. A remarkable observation in the study was a pronounced ductile zone in a reinforced beam and a completely brittle zone in an unreinforced beam. However, a distinct defect of a metal-material-reinforced wood structure is susceptibility corrosion compared with fiber-reinforced polymer (FRP) composite material. Numerous studies have demonstrated that FRP composite sheets are ideal for the tension reinforcement of wood beams. Commonly, FRP composite material is employed for reinforcement in the form of sheets or plates. For instance, Nadir et al. [20] discussed the flexural properties of laminated wood beams that are strengthened with carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) composite sheets. The results indicated a significant increase in the flexural strength and stiffness of FRP-wood composite beams. Li et al. [21] investigated the performance of the CFRP sheets that adhered to the tensile side of two different species of wood beams; the different layers of FRP were employed as the research parameters. They explored experimental load-displacement relationships and discovered that flexural strength increased and middle vertical displacement decreased for wood beams that were retrofitted with CFRP composite sheets compared with wood beams without CFRP sheets and that the middle vertical displacement of the composite decreased as the layers of CFRP composite sheets increased. Glišović et al. [3] tested glulam beams reinforced with two different layers of CFRP plates on the tension side to assess the effectiveness of flexural reinforcement. According to the experimental results, this method is effective for reinforcing the glulam beams by externally bonding CFRP in the tensile region. The results indicated that an increase in reinforcement may not provide a substantial increase in flexural strength characteristics but may increase the rigidity of the cross-section. Borri and Corradi [22,23] externally epoxy-bonded or embedded CFRP and GFRP composite materials in the tensile region to study their enhancement effect on the mechanical characteristics of the reinforced wood elements. The results indicated that composite sheets can increase the flexural stiffness characteristics. In addition, FRP composite material is also employed as reinforcement in the form of bars or rods. Johnsson et al. [24] investigated the short-term behaviors of glulam beams with flexural reinforcement using CFRP in the form of pultruded rods that are referred to as near-surface mounted reinforcement (NSMR). The method of NSMR is successful for wooden members because the method does not increase the height of the cross-section and shields the reinforcement from outer damage. Existing studies illustrated that the wood beams could be reinforced by sheets, bars or pultruded elements fabricated with composite material (e.g., FRP), metallic materials (e.g., steel) and additional wood or other material-based layers or patches.

The strengthening techniques of bamboo structures are not very mature compared with the strengthening techniques of wood. The majority of the strengthening methods proposed for bamboo structures are referring to the studies of strengthened wood structures. Wei et al. presented a bamboo structure that was reinforced with bars [25]. Four test beams were subjected to four-point bending tests to investigate their failure modes and load carrying properties. The application of bars in the tensile regions of bamboo beams significantly increased the load-carrying capacity and section stiffness and improved the utilization of the compression plastic behavior of bamboo. Subsequent research assessed the load-bearing capacity and rigidity of unreinforced and reinforced glulam bamboo beams that were strengthened with steel bars [26]. In this paper, fiber-reinforced polymer (FRP) composite sheets are proposed to strengthen bamboo scrimber beams; as a result, the flexural performance of the bamboo scrimber beams are expected to be improved. Four-point bending tests were conducted to characterize the flexural performance of the bamboo scrimber beams that were strengthened by FRP sheets with various layers and types. The failure modes, the load-displacement relationship, the load carrying capability and the flexural rigidity of these strengthened beams were investigated in the test. A theory of flexural strengthened bamboo scrimber beams using FRP composite material was derived and verified by the test results.

2. Materials

2.1. Bamboo scrimber

Bamboo scrimber is a new engineering material that is manufactured via defibring and compositing technology. Bamboo scrimber has been extensively employed in flooring, furniture, and building. The key manufacturing process of bamboo scrimber is shown in Fig. 1. Moso bamboo culms are processed into interconnected and longitudinally continuous bamboo fibers by flattening, defibring and caramelizing. The bamboo fibers are subsequently processed into an engineering material with high strength, high density, excellent uniformity, natural texture and stable mechanical properties by drying, dipping and hot pressing [27].

In this paper, the bamboo scrimber was manufactured by Anhui Hongyu Bamboo Technology Co. Ltd. The amount of impregnated adhesive is approximately 5–10% of the dry mass of the bamboo fibers, the moisture content ranges between 6% and 8%, and the mean density is 1100 kg/m^3. The bamboo scrimber is simultaneously processed by the same batch of raw materials, which reduces the variability of the material properties due to different environmental conditions during growth.

To obtain the tensile strength, compression strength and corresponding longitudinal elastic modulus of the bamboo scrimber, uniaxial tension and compression tests are performed. Referencing ASTM D143-09 "standard test methods for small clear specimens of timber" [28], the dimensions of the tension specimens are shown in Fig. 2, where the length parallel to the grain is 460 mm. The dimensions of the compression specimens were designed as 50 mm $\times$ 50 mm $\times$ 150 mm, where 150 mm is the length parallel to the grain. Ten specimens with identical dimensions were prepared and tested in tension and compression tests, respectively.

The mechanical properties are listed in Table 1. The ultimate tensile strength (f_{bt}) and elastic modulus (E_{bt}) of bamboo scrimber are 149.5 MPa and 16.1 GPa, respectively. The ultimate tensile strain (ε_{tu}) is 0.010. As shown in Table 1, the coefficient of variation of tensile strength is low as 9.3%. The subscript b and subscript t represent the bamboo scrimber and tension mechanical properties,

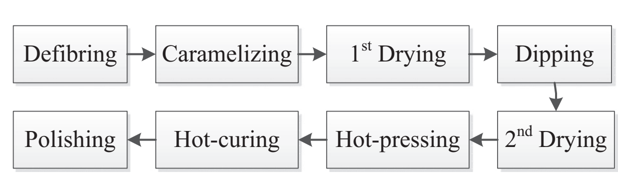

Fig. 1. Production of bamboo scrimber.