Journal of Engineering Science and Technology Review 12 (5) (2019) 104 - 111

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Flexural Behavior of Bamboo-Reinforced Solid Timber Plate

Qiang Chen[1,2,*], Lingyong Liu[2] and Jiejun Wang[1]

[1]*Hunan Engineering Laboratory of Modern Timber Structure Engineering Materials Manufacturing and Application Technology, Central South University of Forestry and Technology, Changsha 410004, China*
[2]*College of Civil Engineering, Hunan City University, Yiyang 413000, China*

Received 13 February 2019; Accepted 22 September 2019

Abstract

The use of bamboo and timber structures has been increasing. However, the span, size, and bearing capacity of the traditional ones are sensitive to many material properties. Composite structures are commonly made of steel-timber and timber-concrete. However, bamboo-timber composite structure is rare, and its stress characteristics have been seldom discussed. In this study, a bamboo-reinforced solid timber structural model that uses square solid timber and bamboo-reinforced plates for the skeleton was proposed to reveal the relationship between the stress characteristics and bearing capacity of the structure. Three pieces each of log and bamboo-reinforced solid timber plates, which have a basically consistent structural size and characteristics, were chosen for a contrast test of flexural properties under centralized midspan loading. The failure mode, ultimate bearing capacity, and load-deflection and -strain relations of the two structures were obtained. Experimental results reveal that the solid timber plates reinforced with log and bamboo have developed brittle failures, and their bearing capacity is strongly sensitive to material defects. The longitudinal strain on the midspan section still conforms to the plane cross-section assumption, indicating that bamboo and timber can be integrated. The bamboo-reinforced solid timber plate has lower bearing capacity by 0%-10% (5.1% in average) and higher failure deflection by 1.1%-9.3% (5.7% in average) than the log plate. These percentages reflect that the bamboo sheet and square timber plate fully utilize the tensile strength and compression resistance, respectively. The flexural rigidity and bearing capacity of the bamboo sheet change slightly compared with those of the log plate. This finding supports the simple calculation formula of flexural capacity of bamboo reinforced solid timber plate. The theoretical values are compared with the experimental results, and an average error of 18.7% is obtained. This study provides some references for the design of bamboo-timber composite structure and the applications of timber structures.

Keywords: Bamboo reinforcement plate, Solid timber, Composition board, Flexural behavior, Study

1. Introduction

As the biggest country of bamboo resources in the world, China has a long history of bamboo cultivation and utilization. According to the 8th forest resource survey, China possesses more than 6 million m^2 of artificial bamboo resources. The bamboo area has an annual growth rate of at least 150,000 m^2. With regard to mass bamboo resources, China has the leading position in terms of research content and scope on bamboo-timber composite materials. Although China has achieved many outstanding accomplishments on bamboo-timber composite materials, some problems remain regarding the production and use of bamboo-timber composite materials, such as low bamboo utilization and high technological requirements. Relevant scholars have explored and studied the feasibility and mechanical properties of new materials formed by timber and other materials. They mainly focus on timber-concrete, timber-steel, and timber-bamboo composite structures, and their research results provide beneficial conditions for the processing and utilization of bamboo and timber resources in China [1].Bamboo-timber composite material refers to the composite plate or square material formed by combining and cementing bamboo and timber materials in the same or different structural units. This structure has multiple forms, such as bamboo-timber composite plywood, laminated timber, chipboard, middle-density fiber plate, and directed material [2]. In China, bamboo-timber composite container floors, which are formed by Mao bamboo and Masson pine, are the most successful bamboo-timber composite material. In this study, a new bamboo-timber structural material was proposed to further increase the utilization of bamboo and timber materials and save in engineering cost. Small-sized solid timber and bamboo reinforced plates were boned into the bamboo-reinforced solid timber plate by using a binder. This composite plate fully utilizes the tensile strength of bamboo materials and the compression resistance of square timbers. The integrated timber and bamboo have developed their own properties. The feasibility of this process was verified by a mechanical test.

2. State of the art

Composite timber structures have various forms. Bamboo-timber composite structure is a new material that is manufactured from bamboo and timber materials through modern cementation. The physical and mechanical properties of timber composite structures have been recently

*E-mail address: liulingyong2003@163.com
ISSN: 1791-2377
doi:10.25103/jestr.125.12

explored. However, the research on bamboo-timber composite structure started relatively late. With aim to develop the timber-concrete composite structure, Chen Chun et al. [3] significantly strengthened the cemented the timber-concrete composite beam by using a carbon fiber composite. Chen Wei [4] performed a finite element numerical simulation and a push out test on the stress properties of angle iron, which is a rigid joint of the timber-concrete composite structure through which the shear capacity and stiffness of the angle iron were obtained. Qin Kai [5] analyzed the long-term stress mechanism of the timber-concrete composite beam. Yuan Shuai et al. [6] designed and manufactured an 8 m×3.5 m full bridge model with timber-concrete composite as a simple support beam. The load-slippage curve, load-deflection curve, and midspan sectional strain distribution under normal loads were obtained finite element numerical analysis and model test. However, only the stress characteristics of timber and concrete were studied. Li Denghui [7] proposed a composite beam with new sections. In this composite beam, a welded H-shaped steel beam was used as the skeleton. The upper and lower flanges of the steel beam were cemented with Pinus sylvestris plates to form a steel-timber composite beam with an H-shaped section. Moreover, a flexural test and a theoretical analysis of the steel-timber composite beam were conducted. To lower the utilization of steel materials and improve the comprehensive environmental quality, Y. Xiao, Y. Wu, J. Li, et al. [8-9] prepared cemented timber and bamboo structures based on modern cementation and processing. Furthermore, experimental and theoretical studies of the cemented timber and bamboo structures were performed. They claim that although both cemented timber and bamboo structures are applicable to buildings and bridges, these materials have certain limitations and increase the binder usage and manufacturing cost. Therefore, the steel-timber composite structure alone was experimentally investigated. Zhu Yixin [10] studied the horizontal shearing strength of the bamboo-timber composite plate through a short beam method and found that the span of bamboo-timber composite plate specimens is a major factor that influences the testing of horizontal shear strength. The horizontal shear strength decreases significantly with the increase in span, and the reasonable span is four times the plate thickness. The horizontal shear strength range of the bamboo-timber composite plate is 3.2-11.1 MPa. Yao Lihong [11] cemented bamboo materials with different surface roughness and a single fir plate, analyzed the influences of surface roughness on the bonding strength of the bamboo range of timber composite plate, and concluded that roughness significantly influences the bonding strength of the bamboo range of timber composite plate. Han Jian [12] studied the tensile and flexural properties of a composite material of bamboo mat, bamboo curtain, and poplar veneer by using a dynamic resistance strain instrument and a computer-controlled mechanical tester. A significant linear correlation found between the longitudinal and transverse tensile strain and the loads of the bamboo-timber composite plate and the nonlinear relations of Poisson’s ratio and elasticity modulus and loads proves the elastic-plastic characteristics of the bamboo-timber composite plate. Tadashi Kawai et al. [13] replaced the reinforcing steel bar with bamboo and prepared a bamboo-concrete cemented plate and beam and proved the feasibility of the bamboo reinforced concrete structure through outdoor exposure and bending tests. Basing on the effective utilization of natural resources, Hiroyuki Kinoshita et al. [14] developed a green composite material using biodegradable resin as the bonder, bamboo fiber as the reinforced fibers, and timber sheet as the base and performed four-point bending and impact tests to test the flexural and impact strengths. Ting Tan et al. [15] introduced a series of multi-scale test results and numerical models of the mechanical properties of the bamboo structure with functional gradient. Matthew Penellum et al. [16] argued that the microstructure of bamboo-laminated timber materials could be simulated as a fiber-reinforced composite material and compared the analysis results on fiber volume scores with the bending test results, revealing that fiber volume score analysis is an effective method to determine non-destructive evaluation bamboo beam stiffness. Suzana Jakovljević et al. [17] analyzed the influences of humidity on the quality changes and mechanical properties (bending and toughness) of Mao bamboo and obtained a parameter prediction model under wet conditions. Nonetheless, these studies only discussed the bonding and mechanical properties of bamboo-reinforced composite timber and the bamboo-concrete composite structure. Several scholars investigated the mechanical properties of bamboo-reinforced solid timber composite beam and plate. Sinha Arijit et al. [18] studied the bending and shearing characteristics of the bamboo-timber hybrid laminated timber to evaluate the feasibility of using laminated bamboo layers (LBLs) in structures as laminated timber beam. They concluded the high bonding strength of isocyanate resin. Viviana Paniagua et al. [19] tested the flexural properties of an H-shaped beam composed of LBL and cemented plate and reported that the modulus of rupture, modulus of elasticity (MOE), and shear strength were 39.45, 17.05, and 5.95 MPa, respectively. The H-shaped beam has mechanical properties that satisfy the structural design standards and thus is applicable to buildings with 2-7 m span. Chen and Qiang et al. [20] performed a comparative test of the flexural properties of the bamboo-log composite beam and concluded that the flexural strength of the bamboo-log composite beam was 17.5%-75.6% higher than that of the log beam. Xiao Bo and Chen Qiang et al. [21] studied the mechanical properties of bamboo-reinforced solid timber plate and found that the strain of the bamboo-reinforced solid timber plate during the small deformation stage presents a linear growth with uniformly distributed loads. The growth is consistent with the plane cross-section assumption.

The above research results mainly focus on the mechanical properties of timber-concrete and steel-timber composite structures. Few studies on the relationship between the stress characteristics and bearing capacity of the bamboo-timber composite structure exist. Particularly, studies on the bamboo-reinforced solid timber composite structure are rare. In this study, a new bamboo-timber composite structure was manufactured using a small-sized solid timber and a bamboo-reinforced plate through cementation. The flexural properties of the structure under midspan loading were tested. We hypothesized that the tensile force of the composite structure is assumed by bamboo reinforcement, and the wood beam only undertakes pressure. A calculation model and a simple calculation formula of bearing capacity were constructed. The synergistic deformation ability of bamboo and timber was tested. Moreover, the variations of failure mode, deflection, bearing capacity, flexural rigidity, and strain of the specimens during the loading process were tested. The results provide references for the experimental and theoretical analyses of the applications of the new bamboo-timber composite plate.

The remainder of this study is organized as follows. Section 3 describes the structure of the bamboo-reinforced solid timber plate, the material test, the loading test design, and the test methods. Section 4 presents the comparative analysis between the theoretical results and actual values of stress characteristics and bearing capacity according to the test phenomenon, test data, and computation model hypothesis. On this basis, the stress characteristics and the calculation formula of bearing capacity of the proposed structure were obtained. Section 5 provides the conclusions.

3. Methodology

3.1 Design of specimens

In this experiment, a group of bamboo-reinforced solid timber plates (A1-A3) and one group of log plates (B1-B3) were designed. The dimensions of the specimens were set to 60 mm×600 mm×2000 mm. The bamboo-reinforced solid timber plates were composed of several small solid timber beams with different lengths. Moreover, one layer of a 5 mm-thick bamboo-reinforced plate was pasted onto the upper and lower surfaces of the timber plate (Figs. 1 and 2). The solid timber plate was composed of two 60 mm×300 mm×2000 mm log plates (Fig. 3).

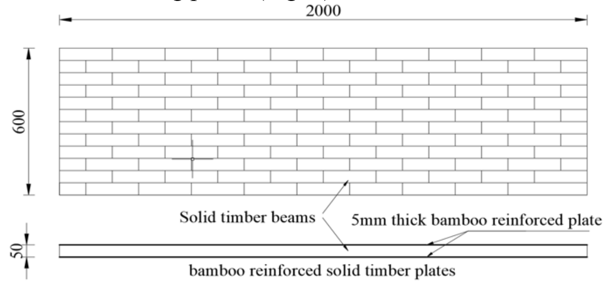


Fig. 1. Bamboo-reinforced solid timber plate specimen size (unit: mm)

Fig. 2 Physical specimen

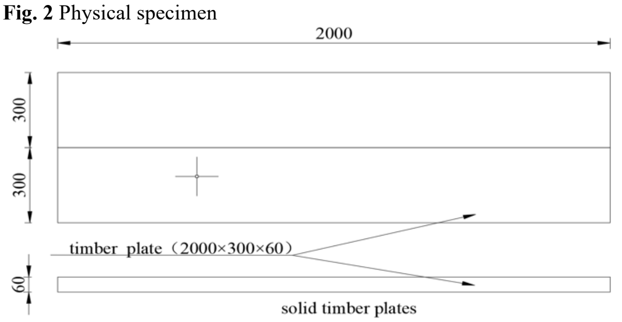


Fig. 3 Solid timber plate specimen size (unit: mm)

3.2 Test materials

P. sylvestris was chosen as the timber sample. The small 50 mm×50 mm timber beams were designed with the length ranging from 10-80 cm. The timber plate dimension was 60 mm×300 mm×2000 mm. The density, moisture content, and modulus of elasticity parallel to the grain of the timber plates were 432 kg/ m^3, 10%-12%, and 6622 MPa, respectively. The assembled bamboo materials were collected from Hunan Province Yiyang Taohuajiang Bamboo Industrial Corporation as the bamboo-reinforced plates. These materials were processed into 5 mm×600 mm×2000 mm specimens using 4- to 6-year-old Mao bamboo. The density, moisture content, and modulus of elasticity parallel to the grain of the bamboo-reinforced plates were 820 kg/ m^3, 10.7%, and 10150 MPa, respectively. An AB type epoxy resin glue was used as the bonder. The tensile and shear strengths of the steel-steel structure were higher than 40 and 18 MPa, respectively. When the compression strength was higher than 50 MPa, the preliminary curing time was set to 3 h, and the complete curing time was 24 h.

3.3 Parallel-to-grain compressive strength test of timber materials

According to the test method of parallel-to-grain compressive stress-strain curve of timber in the Standard Test Method for Timber Structure [22], five groups of 90 mm×90 mm×270 mm cubic specimens were chosen. Using a universal testing machine at room temperature of 20 ℃, the axial compressive strengths of the specimens were obtained: 24.914, 26.366, 20.730, 25.477, and 23.619 MPa (Fig. 4a). The average compressive strength was 24.221 MPa. Given that the bamboo-reinforced solid timber plate was manufactured through the cementation of small timber beams with different sizes, all samples were deduced according to the Code for Design of Masonry Structures [23]:

$$f_c = k_1 f_1^{\partial}(1+0.07f_2)k_2 \tag{1}$$

The parameter values of the solid timber composite structure were determined with reference to the values of concrete blocks, light aggregate concrete blocks, $k_1 = 0.46, \partial = 0.9, k_2 = 1$. $f_1 = 24.221, f_2 = 50$. Hence, the calculated results must be multiplied with a coefficient ($1.1-0.01f_2$). The calculated result was $f_c = 21.87\text{MPa}$, which was used as the strength of the solid timber composite structure.

3.4 Tensile strength test of bamboo reinforcement

According to the Test Methods for Physical and Mechanical Properties of Bamboo Materials [1], the bamboo assembled materials, which were processed from 4- to 6-year-old Phyllostachys pubescens from Hunan Province Yiyang Taohuajiang Bamboo Industrial Corporation, were chosen. The average density and moisture content of the 4 mm×31 mm×300 mm bamboo specimens were 820 kg/ m^3 and 10.7%, respectively. Nine groups of bamboo specimens were set. The tensile strength test of the bamboo specimens was performed on a universal tester at 20°C at 5 mm/min (Fig. 4b). The measured failure load and tensile strength of the bamboo reinforcement are listed in Table 1.

The standard deviation of the material samples ($S = \sqrt{\frac{\sum (X_i - \bar{X})^2}{n-1}} = 5.46$), the average standard deviation of the specimens ($S_t = \frac{S}{\sqrt{n}} = 1.82$), the variance coefficient of test ($v = \frac{S}{\bar{X}} \times 100 = 4.2 \le 20$), and the tensile strength parallel to the grain of the bamboo reinforcement ($f_t = \frac{\sum X_i}{n} = 128.5\text{Mpa}$) were calculated based on the data in Table 1.

(a) (b)

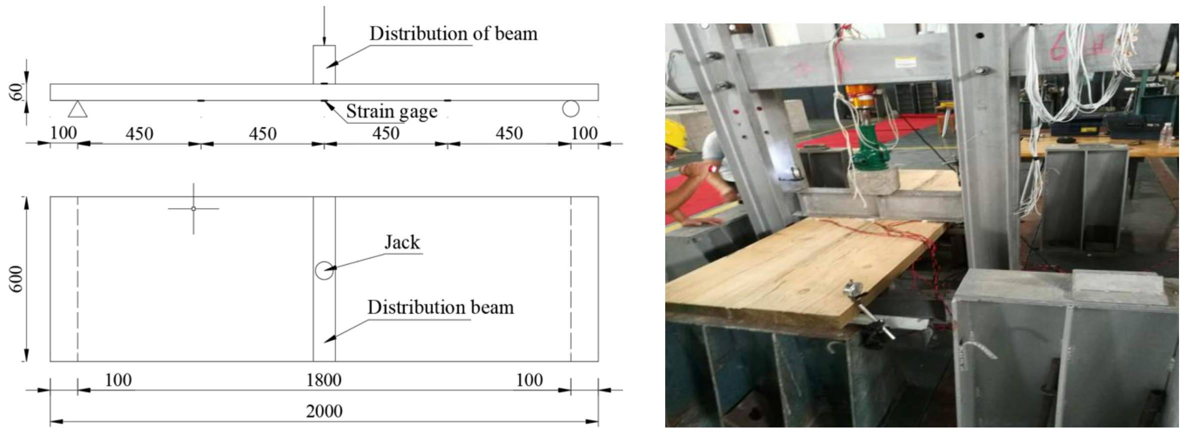
Fig. 4. Material test. (a) Parallel-to-grain compressive strength test of timber materials. (b) Tensile test of timber materials

Table 1. Failure Load and Tensile Strength of Bamboo Reinforcement

Specimen number	C1	C2	C3	C4	C5	C6	C7	C8	C9
failure load (kN)	15.1	14.8	16.9	15.5	16.7	15.9	16.8	15.9	15.8
tensile strength (MPa)	121.8	119.4	136.3	125.0	134.7	128.2	135.5	128.2	127.4

3.5 Loading device and distribution of measuring points

Nine displacement meters were installed on the supports at the two ends, at the L/4 of the plate, at the 3L/4 of the plate, and at the midspan position of the plate to record the vertical displacement and strain of the specimens during loading. Furthermore, 22 strain gages were installed at the bottom surfaces of L/4 and 3L/4 and the top and bottom surfaces of the midspan positions. A DH3818 static strain tester was used as the data acquisition system. Vertical loads were transmitted to the specimens through the distribution beam, which was connected with load sensors (Fig. 5a). All specimens were preloaded before the official loading by the loading device (Fig. 5b).



(a) (b)

Fig. 5. Test loading device (unit: mm). (a) Schematic of loading device. (b) Loading device

4 Results and Discussion

4.1 Failure mode

Bamboo reinforced solid timber plates (A1-A3) produced subtle sounds in the early loading stage, indicating the existence of cracks on the contact surface of the solid timber. The contact surface in the tensile region cracked with the increase in loads. The contact surface of the solid timber and that between the bamboo reinforcement and the solid timber in the tensile region were peeled locally due to excessive deformation as the ultimate load was approached. The tensile stress was assumed by solid timber and bamboo reinforced plate together and then undertaken by the bamboo reinforced plate only. Consequently, the strength of the timber materials was underdeveloped. The shear failures at the contact surface between the bamboo-reinforced plate and the solid timber below the loading point are shown in Figs. 6a and 6b.

A comparative study on B1-B3 was conducted. When the vertical load was increased to 40%-50% of the ultimate loads, stress concentration was observed in the tensile region at the bottom of the solid timber plate, further inducing cracks. These cracks extended along the 45° direction. With the increase in loads, the cracks further propagated. Consequently, the timber fiber in the tensile region reached the ultimate tensile strain, and tensile failure developed at the tree nodes (Fig. 6c).

4.2 Flexural rigidity

The experimental results of the three groups of bamboo-reinforced solid timber plates are shown in Fig. 3. The dimensions of the beams are 90 mm×135 mm×2000 mm, and 70 mm is reserved at the two ends. In other words, a = 70 mm, and the actual span (L) between the two supports is 1860 mm. According to the experimental results and the formula,

$$E=\frac{23}{108}\times\left(\frac{L}{a}\right)^3\times\left(\frac{\Delta F}{\Delta e}\right)\times\frac{1}{b} \tag{2}$$

where ΔF is the load increment, Δe is the midpoint deflection produced by the beam under ΔF, and b is the sectional width of the plate). The MOEs of B1-B3 were calculated as 6508.49, 5906.75, and 5549.29 MPa, respectively. The average MOE was 5988.18 MPa. Given that $\frac{|x_i - \bar{x}|}{\bar{x}}\times 100\% \le 10\%$, the MOE of the composite structure was 5988.18 MPa. Hence, the flexural rigidity ($E_1 I$) of the bamboo-reinforced composite plate was 64.67×10^6 N· mm^2, while the flexural rigidity ($E_2 I$) of the solid timber was 71.51×10^6 N· mm^2. The flexural rigidity of the bamboo-reinforced solid timber plate was 9.56% lower than that of the solid timber.


(a) (b) (c)

Fig. 6. Typical failure mode. (a) Bamboo-reinforced plate and solid timber are peeled above the composite plate. (b) Bamboo-reinforced plate and solid timber above the composite plate are peeled and deboned. (c) Tensile failure at the bottom of the timber plate

4.3 Load-midspan deflection curve

Concentrated loading tests were performed on the bamboo-reinforced solid timber and log plates. During the tests, the midspan deflection of different specimens was tested. The load-midspan deflection curves of six plates are shown in Fig. 7.

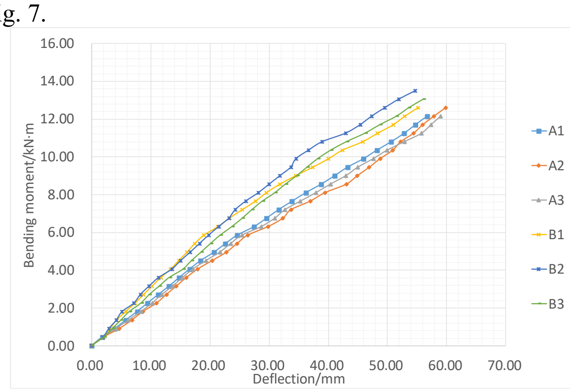
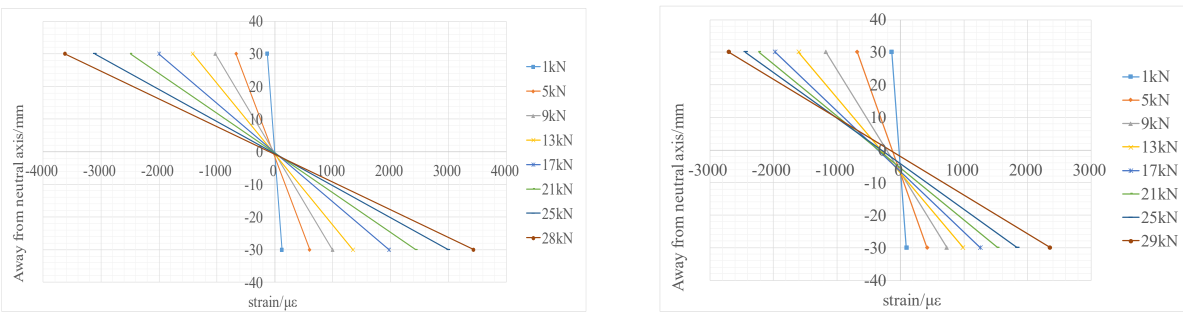


Fig. 7. Load-midspan deflection curves of group A and Group B

Fig. 7 shows that the load-deflection curve presents a linear change throughout the loading stage. It is in the elastic deformation stage in the beginning. When the loads approached or reached the ultimate failure loads, the slope of the load-deflection curve of the log plate and bamboo-reinforced solid timber plate decreased to some extent. The loads and deflection present a nonlinear growth and enter the elastic-plastic deformation stage. The loads of the bamboo-reinforced solid timber plates in the elastic stage are basically consistent with those of the timber plates of the same size. The midspan deflection of the bamboo-reinforced solid timber plates is approximately 10% higher than the deflection of the timber plates. The slope of the timber plate changes slightly more than that of the bamboo-reinforced solid timber plates in the plastic deformation stage. The failure loads of the bamboo-reinforced solid timber plates are 0%-10% (5.1% in average) lower than those of the solid timber plates, while the failure deflection is 1.1%-9.3% (5.7% in average) higher.

4.4 Variations of longitudinal strain on midspan section

The plane cross-section assumption is verified by typical specimens of A and B. The variations of longitudinal strain on the midspan section of the bamboo-reinforced solid timber plates are shown in Fig. 8a.



(a) (b)

Fig. 8. Variations of longitudinal strain on midspan section. (a) Variation of longitudinal strain on midspan section of bamboo-reinforced solid timber plates. (b) Variation of longitudinal strain on midspan section of log plates

Fig. 8 shows that the strain of bamboo-reinforced solid timber and solid timber plates is positively related with the loads and meets the plane cross-section assumption. In Fig. 8a, the tensile force of bamboo-reinforced solid timber plates is assumed by the bamboo-reinforced plates. The bamboo-reinforced plates did not reach the tensile failure stress with the increase in loads, while the neural axis and the height of the compression zone were basically consistent. The tensile stress of the solid timber was undertaken by the lower timber plates (Fig. 8b). With the increase in loads, the lower flange of the timber plates cracked gradually, while the neutral axis rose gradually. The height of the compression region of the timber plates decreased gradually.

4.5 Calculation of flexural capacity of bamboo reinforced solid timber plates

The loads of the bamboo-reinforced solid timber plate are attributed to the bamboo reinforcement and timber plates. Given the different MOEs of bamboo and timber, the flexural capacity of the bamboo-log composite beam was calculated by the transformed section method. It basically satisfies the following hypotheses:

(1) Timber and bamboo-reinforced plates are both ideal elastomers.

(2) The connection between solid timber and bamboo-reinforced plate is reliable. Without considering the bonding thickness, the bonding between solid timber and bamboo-reinforced plate is perfect, with a relatively small slippage. This relative slippage can be ignored.

(3) Without considering the tensile strength of timber in the tensile region, the tensile stress is completely undertaken by bamboo-reinforced plates, while the compressive stress is assumed by both timber and bamboo-reinforced plates. Given that the upper bamboo-reinforced plate is thinner than the timber plates and is relatively safe, the upper bamboo-reinforced plate is equivalent to a piece of an equally thick timber plate.

Compressive failure is the basic failure mode of specimens in the loading process and is similar to the overreinforced failure of reinforced concrete. The sectional calculation diagram of the bamboo-reinforced solid timber plate using compressive strength as the control strength is shown in Fig. 9.

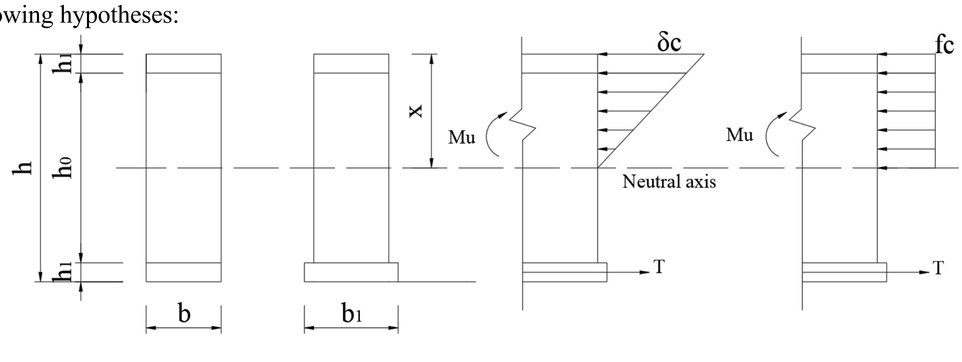


Fig. 9. Sectional calculation diagram of bamboo-reinforced solid timber plate. (a) original section. (b) transformed section. (c) stress distribution. (d) equivalent stress on midspan cracking section

Given that $T = \delta_s b' h', b' = \frac{E_1}{E_2} b$, the calculated tensile stresses at the midspan bottom of the bamboo plates are shown in Table 2. The tensile stress of the bamboo-reinforced plate is far lower than the tensile strength. Therefore, the upper compressive region is a controlled section. Fig. 8(a) indicates that the neutral axis of the bamboo-reinforced solid timber plate is basically kept constant and half of the height of the plates. Therefore, the compression zone, $x = \frac{h}{2}$, is shown in Fig. 9. Then,

$$
\begin{aligned}
M_u &= f_c b(h+h')\xi_b(1-0.5\xi_b) \\
\xi_b &= \frac{x}{h_0+h'}
\end{aligned} \tag{3}
$$

where E_1 is the MOE of the bamboo-reinforced plate, E_2 is the MOE of the timber plate, h is the sectional height of the composite plate, h' is the thickness of the bamboo-reinforced plate, h_0 is the height of the timber materials, b is the sectional width of the plates, b' is the transformed sectional width, σ_c is the compressive stress at the top of the composite plate, f_c is the compressive strength of the timber materials, f_s is the tensile strength of the bamboo-reinforced plate, T is the tensile stress of the bamboo-reinforced plate, and M_u is the designed sectional bending moment of the bamboo-solid timber composite beam.

According to measured results of material parameters, the bending moment of the midspan section is calculated according to Equation (3). The calculated results were compared with the test results and are shown in Table 2.

Table 2. Comparison between the calculated and test results of flexural capacity

Specimen number	Stress at midspan bottom	Tensile force of bamboo plate at midspan bottom	Calculated result (kN·m)	Test result (kN·m)	Difference (%)
A1	5719	58.048	15.12	12.15	19.6
A2	3436	34.875	15.12	12.60	16.7
A3	3154	32.875	15.12	12.15	19.6
Average	-	-	15.12	12.30	18.7

According to data in Table 2, the theoretical value is 18.7% higher than the actual calculated value in average mainly because instead of the specimen failure caused by material failure, the bonding failure among the timber beams and that between the top bamboo-reinforced plate and the timber beam become the major failure modes of the bamboo-reinforced solid timber plates. The calculation error is in the tolerance range of the project. Therefore, the actual results are basically feasible.

5. Conclusions

The cooperation between bamboo reinforcement and solid timber was disclosed to explore the stress characteristics of the bamboo-timber composite structure. The failure characteristics of the bamboo-timber composite plate, the load-deflection relationship, and the variation of the longitudinal strain on the midspan section were investigated through a flexural property test of bamboo-reinforced solid timber plates. The theoretical calculation and test results of bearing capacity were compared. The following conclusions could be drawn:

1) In the flexural performance test, the bamboo-reinforced solid timber plate develops brittle failure. The bonding failure between the bamboo-reinforced plate and solid timber and that of timber plate are major failure modes.

2) In the flexural performance test, the variations in longitudinal strain on the midspan section conform to the plane cross-section assumption. The neutral axis in the composite plate is kept basically constant before failure. Hence, the height of the compressive region is constant.

3) The flexural capacity of the composite plate is 5.1% lower than that of the log plate in average, whereas the rigidity is 9.56% lower in average. Moreover, the ultimate deflection at the midspan is 5.7% higher in average. The mechanical properties of the bamboo-reinforced solid timber plates satisfy the engineering requirements.

4) The theoretical value of flexural capacity of the bamboo-reinforced solid timber plates is 18.7% higher than the actual value. Given that the failure of the bamboo-reinforced solid timber plates is not caused by material failure but by the bonding failure between timber teams and between the timber beam and the bamboo-reinforced plates, the calculation error is within the allowable range of the project.

5) Given that the bamboo-reinforced solid timber plate is composed of small timber beams and bamboo reinforced plates, it has better applicability and universality than traditional timber plates. Moreover, the requirements on age and size of timber materials are decreased effectively, and the utilization of bamboo materials is increased. The bamboo-reinforced solid timber plate shows higher cost performance and applicability than log plates.

In this study, the failure modes, ultimate bearing capacity, load-deflection relation, load-strain relation, and displacement delay of log and bamboo-reinforced solid timber plates were gained by combining indoor experiment and theoretical study. Furthermore, a simple calculation formula of flexural capacity was proposed, and the obtained values agree with the test results. Research conclusions provide some references for the design of the bamboo-timber composite structure and exploration of the engineering applications of timber structures.

References

1. Lin Maoyang. “Development and utilization of bamboo in China” . *Agricultural machinery in south China*, 50(02), 2019, pp.99.
2. Liu Shanshan. “Development of bamboo and wood composites” . *Forestry machinery and woodworking equipment*, 40(05), 2012, pp.8-9.
3. Chen Chun, Hu Xiamin, Wei Duyu. “Static test of composite beams reinforced with carbon fiber reinforced composites” . *Journal of nanjing university of technology (natural science edition)*, 37(6), 2015, pp.75-80..
4. Chen Wei. “*Mechanical behavior analysis and experimental research of engineering wood-concrete composite beams*” Master thesis of Central south university of forestry and technology, China, 2016.
5. Qin Kai, Hu Xiamin, Hong Wan. “Research progress on long-term mechanical properties of wood-concrete composite beams” . *Forest products industry*, 44(04), 2017, pp.6-11.
6. Yuan Shuai, He Guojing, Li Li, Peng Lening. “Experimental study on mechanical properties of wood-concrete composite beam bridge” . *Industrial architecture*, 48(05), 2008, pp.107-111.
7. Li Denghui. “*Research on flexural performance of steel-wood composite beams*” Master thesis of Beijing jiaotong university, China, 2016.
8. Xiong Haibei, Kang Jiahua,Lu Xilin. “Experimental study on flexural properties of wood composite beams” . *Journal of tongji university (natural science edition)*, 40(4), 2012, pp.522-528.
9. Y. Xiao,Y. Wu, J. Li, et al. “An experimental study on shear strength of glubam”. *Construction and Building Materials*, 150, 2017, pp.490-500.
10. Zhu Yixin, Cheng Limei, Guan Mingjie. “Study on horizontal shear strength of bamboo composite board” . *Journal of northwest forestry university*,2006(06), pp.180-182. (in Chinese with English abstract)
11. Yao Lihong, Wang Ximing, Fei Benhua, Yu Huaqiang, Tao Renzhong. “Analysis of the influence of roughness on the bonding performance of bamboo and wood composite board” . *Wood processing machinery*, 21(04), 2010, pp.28-30+42.
12. Han Jian, Zhou Wenjie, Zou Yue. “Tensile and bending mechanical properties of bamboo composite board” . *Journal of central south university of forestry and technology*, 34(10), 2014, pp.107-110.
13. Tadashi Kawai, Masashi Kawamura, Yoshio Kasai. “Properties of Bonding, Weathering, Bending of Bamboo Reinforced Soil-Cement Concrete”. *Concrete Research and Technology*, 11(2), 2000, pp.29-37.
14. Hiroyuki Kinoshita, Koichi Kaizu, Miki Fukuda, et al. “Development of the Green Composite Consists of Woodchips, Bamboo Fibers and Biodegradable”.*Advanced Materials Research*, 47, 2008, pp.322-325.
15. T. Tan, N. Rahbar, S.M. Allameh, et al. “Mechanical properties of functionally graded hierarchical bamboo structures”. *Acta Biomaterialia*, 7(10), 2011, pp.3796-3803.
16. Matthew Penellum, Bhavna Sharma, Darshil U. Shah, et al. “Relationship of structure and stiffness in laminated bamboo composites”. *Construction and Building Materials*, 165, 2018, pp.241-246.
17. Suzana Jakovljević, Dragutin Lisjak. “Investigation into the effects of humidity on the mechanical and physical properties of bamboo”. *Construction and Building Materials*, 194, 2019, pp.386-396.

18. Sinha Arijit,Clauson Milo. “Properties of Bamboo-Wood Hybird Glulam Beams”. *Forest Products Journal*, 62(7/8),2012, pp.541-544.
19. Viviana Paniagua, Roger Moya. “Flexural Performance of I-Joists Fabricated with Glue-Laminated Bamboo and Gmelina Arborea Plywood”.*Open Journal of Civil Engineering*, 4(3), 2014, pp.209-216.
20. Chen, Qiang,Lang, Jianke,Wang, Jiejun.”Flexural properties of bamboo-log composite beam”*Journal of Engineering Science and Technology Review*, 11(03), 2018, pp.104-112
21. Xiao Bo, Chen Qiang, Liu Shengxian, Zhang Hui, Shi Xintao, Liu Sunkun, Fan Jun. “Experimental study on bending performance of bamboo reinforced solid wood composite board at small deformation stage”. *Journal of hunan city university (natural science edition)*,2018.06, pp.10-13.
22. Ministry of Housing and Urban-Rural Development of the People's Republic of China “*Standards of the People's Republic of China. Standard Test Method for Timber Structure (GB/T 50329-2012)*”. Beijing: China building industry press, China, 2012.
23. Ministry of Housing and Urban-Rural Development of the People's Republic of China “*Standards of the People's Republic of China. Code for Design of Masonry Structures (GB 50003-2011)*”. Beijing: China building industry press, China, 2012.
24. State Bureau of Technical Supervision “*Standards of the People's Republic of China. Test Methods for Physical and Mechanical Properties of Bamboo Materials (GB/T 15780-1995)*” Beijing: China standard press, China, 1996.