Experimental Study on Mechanical Property and Fatigue Failure of the Bamboo-based Composites

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Abstract. Bamboo is a kind of advanced bio-material and has good mechanical behaviour. Bamboo-based composites have been rapidly developing for use in engineering, especially in wind turbine structures. In the present study, a series of experiments were performed and the results were presented concerning the monotonic tension and compression mechanics properties and fatigue life of bamboo-based composites. The stress-life curve was shown and the failure models of laminates were discussed. The results suggest that the bamboo-based composites have different fracture models under tension, compression and reverse fatigue loading. The composites can support load more abidingly under compression loading. However, higher strength values can be obtained under tensile loading.

1. Introduction

Bamboo is a kind of bio-material and has good mechanical behaviour. As an economic and friendly material, bamboo has got increasing use in a wide range of application in engineering [1]. The properties of outside strip of bamboo are better than those of inside. Thus the grading process was developed, which can make the laminated bamboo strip lumber of grading [2]. The advanced bio-composite, compared with other materials, can replace GFRP and wood/epoxy, and be used in wind turbine blades as a new generation of materials [3]. These materials have many advantages, such as renewable, less dissipation of energy, low cost, no waste and the worn-out product s can be disposed easily.

Synthetic fiber/resin composites have been concentrated on all the time, and most of the current studies focused on their chemical and mechanical properties [4-5]. However, the research and discuss on the natural fiber composites are relatively new. As more and more interest in and attention to natural fiber composites, a study on the static and fatigue properties of theses composites is timely and important. Since bamboo has often been used in engineering structures, some previous research has been carried out on the basic mechanical and fracture properties of nature bamboo and bamboo fiber reinforced composites [6-10]. However, bamboo culms or structures made of bamboo sometimes bore the cyclic forces, such as wind loading. The fatigue damage and failure mode in bamboo-based composites need to be given serious thought.

Some authors have been focusing on the fatigue properties of bamboo culms [11], structural bamboo materials [12], textile or biodegradable composites [13-14]. The results show that such composites did not suffer fatigue damage at stresses well below their static strength, normal and

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shear strains at the fiber/resin interface could cause deterioration leading to fatigue failure [15]. Static failure and fatigue damage in such composites take the form of fiber breakage, matrix cracking, debonding, transverse ply cracking, and delaminating [16]. These processes sometimes occur interactively or independently depending on the types and properties of the composites. Testing conditions and material variables may sometimes influence the predominance of one mechanism over another [17-18].

In order to understand the mechanical properties and fatigue behaviour of bamboo-based composites, a series of experiments were performed concerning the monotonic tension and compression mechanics properties and fatigue life of the laminated bamboo lumber used for wind turbine structures. The stress-life curve was shown and the failure modes of the laminated bamboo lumber were discussed.

2. Materials and experimental procedure

A novel type of laminated bamboo lumbers was chosen for the present study. The laminate was comprised of moso bamboo curtain mats which were formed to panels using one-time vacuum infusion processes. Rectangular slices selected from outside strip of bamboo were used to form the bamboo curtain mats. Epoxy resin was used as the adhesive. The chemical components of outer layers in the moso bamboo culm are listed in the Table 1. The processed bamboo laminate has the physical properties with the bending modulus of elasticity (MOE) 28GPa/gm^3, specific strength 140MPa/gm^3, and density 1150kg/m^3. The specimen was cut with precision machine tools. The geometric configuration of the specimen employed is shown in Figure 1. according to ISO 527-4, which is also a common standard used for wood-based products. The bamboo slices were aligned in the axial direction.

All tests were carried out on an MTS Landmark servo-hydraulic machine as shown in Figure 2. at room temperature. To obtain the monotonic strength of the laminated bamboo lumber, the specimens were loaded to failure at a fixed displacement rate of 1mm/minute. The fatigue life tests were performed utilizing the same specimen geometry used for monotonic tests. All the tests were under load control at stress ratio R=-1 and the loading frequency f=5Hz.

Table 1. Chemical components of outer layers in the moso bamboo culm.

Components	Moisture	Ash	Hot Water solubility	Alcohol-benzene solubility	Lignin	Pentosan	Cellulose
(%)	13.7	1.22	8.31	7.15	24.77	31.54	42.59

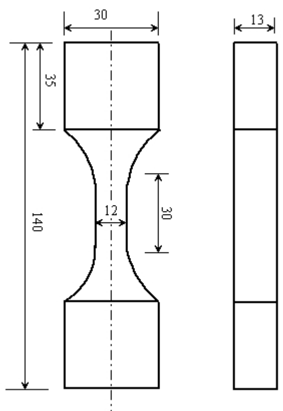


Figure 1. Details of the specimen geometry.

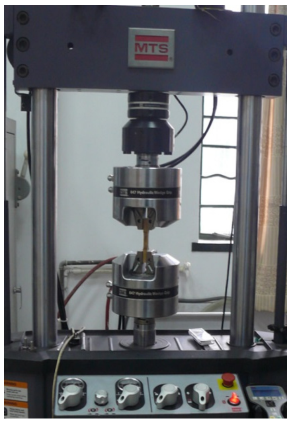


Figure 2. Specimen installed in fatigue machine..

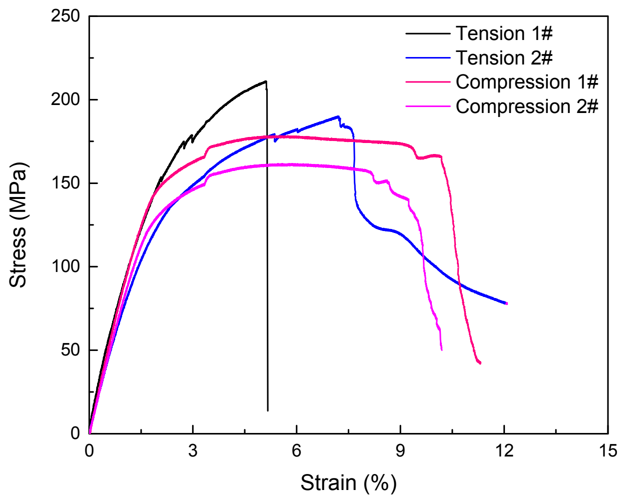


Figure 3. Stress-strain curves under tension and compression loading.

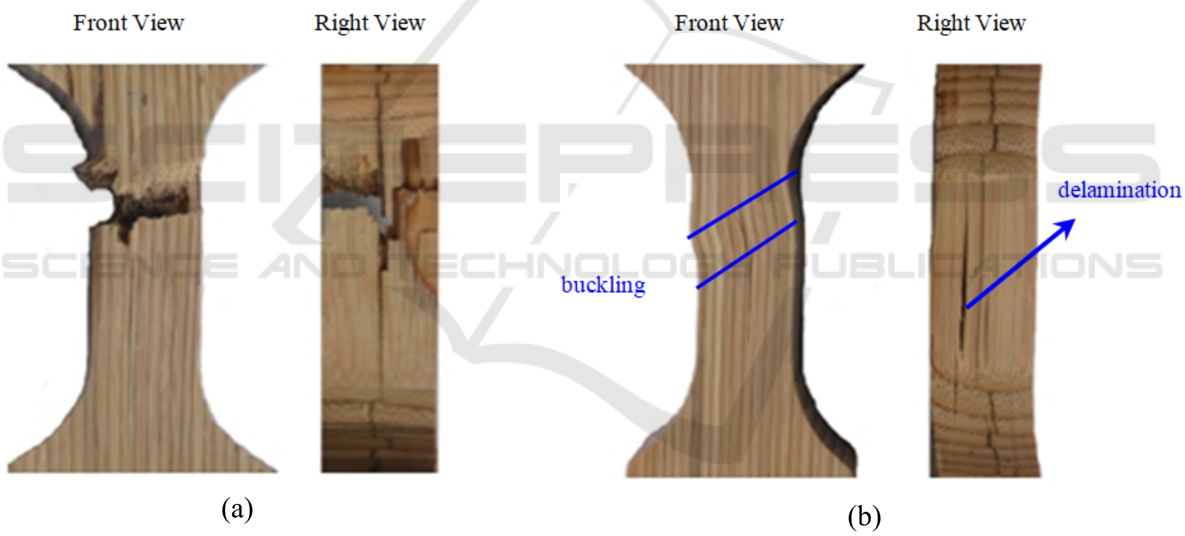


Figure 4. The failure mode and evolution for the laminated bamboo lumber: (a) under monotonic tension loading; (b) under compression loading.

3. Results and discussion

3.1. Monotonic tension and compression tests

Tensile test: The standard tensile stress-strain behaviour is shown in Figure 3. In order to ensure the accuracy of the results, two specimens were chosen to test. The average ultimate tensile strength is about 190MPa. Under tensile loading, the laminated bamboo lumber failed in a progressive manner instead of abrupt failure. As shown in Figure 4a, the failure process was involved with the rupture of individual bamboo slices accompanied by progressive fracture of adjacent bamboo layers. The fracture was straight and along the plane vertical to the axial direction.

Compression test: The compressive stress-strain behaviour is also shown in Figure 3. In the same way, two specimens were tested and the average compression strength is 179MPa. Compared with the tensile stress-strain curve, the composites can support load more abidingly under compression loading. However, higher strength values can be obtained under tensile loading. The similar consults have been obtained by John W H [3].

Under compressive loading, the laminated bamboo lumber failed in a debonding/buckling manner as shown in Figure 4b. When the compressive load was up to some value, the composite buckled and delaminating subsequently occurred.

3.2. Fatigue tests and failure modes

The stress ratio means the ratio of the minimum stress to the maximum stress for a fatigue cycle, $R=\sigma_{min}/\sigma_{max}$. Because the laminated bamboo lumber has different failure mode and strength under tensile loading and compression loading, the tension-compression cycle loading with the stress ratio R=-1 were applied and analyzed. Six groups of stress levels from 65MPa to 120MPa and total 30 specimens were selected. For each stress level, five specimens were chosen to obtain the fatigue life.

The evaluation of the fatigue life for the composite is usually different with metallic materials. A critical number of cycles of fatigue failure are defined according to the damage evolution during the fatigue loading. Stiffness reduction is one of the methods more commonly used [19]. In this study, the fatigue peak displacement d_{max} was introduced as a damage parameter to describe the fatigue damage. When the peak displacement including the tension and compression values increased up to 25%, the fatigue failure was considered to happen and the corresponding number of cycles is the fatigue life.

The fatigue stress-life curve, namely S-N curve, is presented in Figure 5. The fitting formula of the maximum stress S_{max} vs. fatigue life N is as follows:

$$\log S_{\max} = 2.3452 - 0.08806 \log N \tag{1}$$

In order to predict the fatigue life of the studied bamboo-based composites more efficiently and accurately, it requires the P-S-N curve and suggests the fatigue life data follow the lognormal distribution. The P–S–N curves can be established by connecting the *Pth* percentile points of the distributions of fatigue life at different stress levels with each other. We can label N_i as the fatigue life of the *nth* specimen under the same stress level. The logarithmic life can be expressed as $x_i=\log N_i$. The mean fatigue life $\bar{x}$ and standard deviation s can be written as the following equations respectively.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

$$s = \sqrt{\frac{1}{n-1}\sum_{1}^{n}(x_i - \bar{x})^2} \tag{3}$$

For the fatigue life with the failure probability P, the logarithmic life can be expressed:

$$x_p = \bar{x} + u_p s \tag{4}$$

When the failure probability P=10%, u_p=-1.282. So we can get the final fatigue life according to the equation:

$$N_p = \log^{-1} x_p \tag{5}$$

For the S-N curve of the composite with the expression equation (1), the P-S-N curve with P=10% can be calculated. The results were shown in Figure 5. and the following equation. From the picture, we can see that the S-N curve and P-S-N curve are almost same, and the experimental data show good consistency with each other.

$$\log S_{\max} = 2.34113 - 0.08933 \log N_p \quad (6)$$

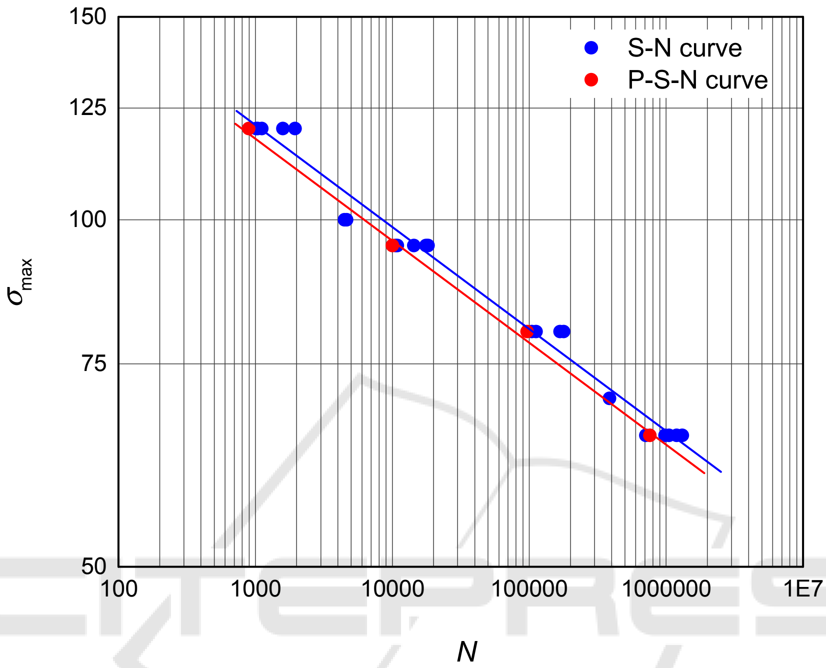


Figure 5. Stress-life curve for bamboo-based composites at R=-1.

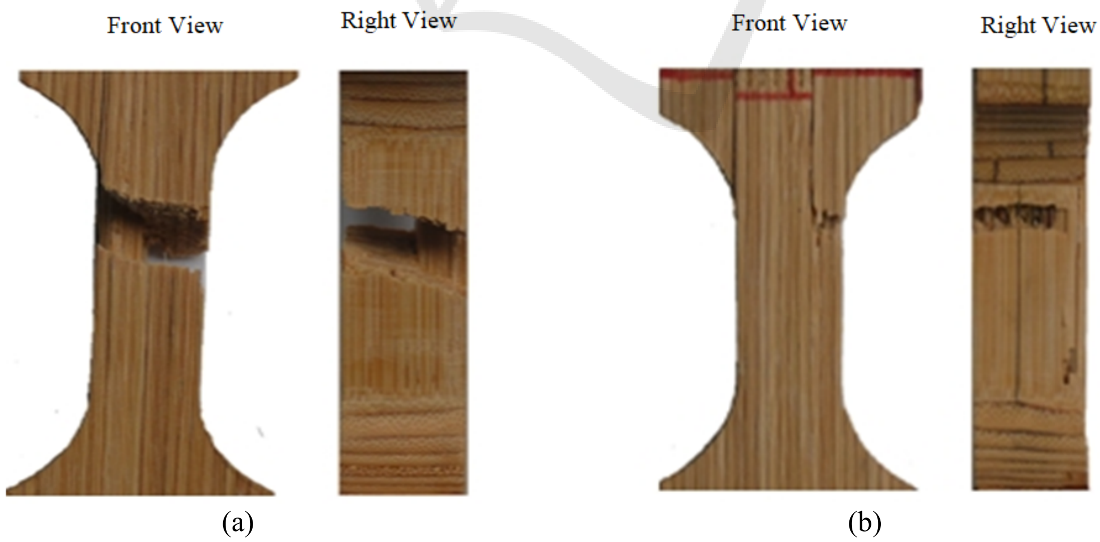
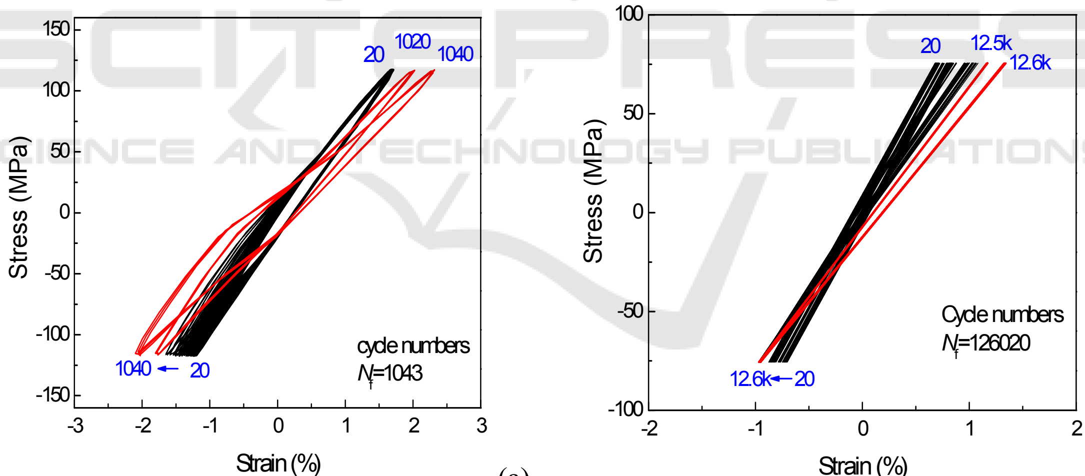


Figure 6. The failure mode of the laminated bamboo lumber under cyclic tension-compression loading (R=-1): (a) in low-cyclic fatigue (N_f=1043); (b) in high-cyclic fatigue (N_f=126020).

The fatigue failure of the laminated bamboo lumber under cyclic loading was shown in Figure 6. When under low-cyclic fatigue loading, the fracture was propagated along a plane to some angle with the axial direction (Figure 6a). In some local position, the delaminating happened. The failure mechanism was similar with the “compressive mode”. Some reasons can be guessed that since ultimate tensile strength of the laminated bamboo lumber was higher than compressive strength, at the same stress value, the composite began to damage during supported the compression loading.

The stress-strain curves under low-cyclic fatigue loading are plotted in Figure 7a according to every fixed cycle numbers. It can be shown that from the beginning of fatigue test, the maximum strain was on the increase under compressive loading, but it kept unchanged in the tensile process until the last dozens of cycles. The non-linear relationship between stress and strain at the stage of compression was more obvious than tension loading. The conclusion can be suggested again that under low-cyclic fatigue loading, the damage always began to occur during compressive loading. When the damage accumulation was up to some extent, the composite was not able to bear more loading and the failure happened.

Under high-cyclic fatigue loading, the failure happened with the progressive rupture of bamboo slices, sometimes accompanied by debonding of bamboo layers. The fracture was propagated along a plane vertical to the axial direction (Figure 6b). The failure mechanism was similar with the “tensile mode”. The stress-strain curves for laminated bamboo under high-cyclic fatigue loading are plotted in Figure 7b. Contrary to the behavior under low-cyclic fatigue loading, the maximum tension strain increased more obviously than compression strain during the test. The damage introduced by tension loading contributed more to the failure of the composite. It is suggested that at the low stress level, the laminated bamboo lumber can support the cyclic compressive loading longer.



(a)

(b)

Figure 7. Stress-strain curves of the laminated bamboo lumber for every fixed cycle numbers: (a) under low-cyclic loading; (b) under high-cyclic loading.

4. Conclusions

In the present study, a series of experiments were performed and the results were presented concerning the static and fatigue mechanics properties of bamboo-based composites. The stress-life curve was obtained and the failure modes of the laminated bamboo lumber were discussed. Some conclusions were obtained.

The laminated bamboo lumber showed no exactly the same behavior under monotonic tensile and compressive loading. The laminates can support the loading more abidingly under compression condition. However, higher strength values can be obtained under tensile loading.
Under tensile loading, the laminated bamboo lumber failed in a progressive manner with a straight fracture. The process was involved with the rupture of individual bamboo slices accompanied by progressive fracture of adjacent bamboo layers. Under compressive loading, the failure was in a debonding/buckling manner.

The failure mechanism of the laminated bamboo lumber was similar with the “compressive mode” under low-cyclic fatigue loading. The fracture plane was at an angle to the axial direction. Under high-cyclic fatigue loading, the failure happened with the progressive rupture of bamboo slices, sometimes accompanied by debonding of bamboo layers.

Further investigation would be conducted on the microscopic damage mechanism and the interface strength between the bamboo slices. An effective finite element analysis model is expected to create and verify the experimental data.

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