THE CIRCUMFERENTIAL MECHANICAL PROPERTIES OF BAMBOO WITH UNIAXIAL AND BIAXIAL COMPRESSION TESTS

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The objective of this study was to investigate the effect of uniaxial and biaxial compression loadings on the circumferential-radial mechanical properties of bamboo. A novel biaxial testing device, called the 3D composite material analysis system, was developed to conduct biaxial compression tests. Strain field analysis was characterized with the help of the digital speckle correlation method (DSCM). The effects of four different environmental treatments (I. air-drying, II. constant temperature and relative humidity, III. relatively low temperature, and IV. ultra-low temperature) on the circumferential performance of bamboo were examined in the experiment. The results of this study indicated that the diametric strength of bamboo evaluated by biaxial load was as 2.4 to 2.5 times the uniaxial compression. Under biaxial load, the strength of the bamboo node was about 2.38 times higher than the internode. Failure first occurred at the outside surface of bamboo at about the 45° position between X and Y axial when conducting a biaxial compression test. The distribution of X-strain field expressed itself more uniformly than the Y-strain field. The diametric mechanical properties of bamboo ring were $\sigma_{IV} > \sigma_{III} > \sigma_{II} > \sigma_{I}$ for both the uniaixal and biaxial compression tests.

Keywords: Bamboo; Biaxial compression; Mechanical properties; Ultra-low temperature; Strain field

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INTRODUCTION

Bamboo is one of the oldest construction materials due to its excellent physical and mechanical properties. For instance, in China, bamboo has traditionally been used in scaffoldings, low-rise houses, short-span footbridges, long-span roofs, and construction platforms (Chung and Yu 2002; Mahdavi *et al.* 2012). Recently, a considerable amout of interest has been focused on bamboo because of environmental conservation and wood-based resource shortages (Wang *et al.* 2011). In addition to being an eco-friendly material, bamboo is fast becoming a promising wood substitute. One of the chief reasons for this is that bamboo can be harvested in 3 to 5 years when its mechanical strength, utilization properties, and anatomical characteristics become stable and mature (Lee *et al.* 2012; Verma and Chariar 2012).

Bamboo is also an anisotropic and heterogeneous material that possess high strength and stiffness along the axial direction, versus poor mechanical properties in the transverse direction (Ghavami 2005; Chen *et al.* 2011). This characteristic is mainly due to the structure, composed of a lignin matrix reinforced with fibers aligned in a longitudinal direction. However, the bamboo culm is a hollow and thin-walled cylinder without fiber reinforcement in the radial direction. In a practical engineering application, the circumferential direction of bamboo is often craftily installed with metal connecting pieces and reinforced hoops (Fig. 1). This bamboo construction not only suffers from uniaxial stress in a diametric direction (the weakest part) but also develops biaxial or even multi-axial stress sites, such as the interconnection parts of bamboo with each other, the fixation joints between bamboo and girder or foundation. Stresses in biaxial or multiple dimensions, in addition to the anisotropy and viscoelasticity of materials, can result in a complex fracturing process. In addition, bamboo is a hygroscopic and hydrophilic material that can absorb water from its surroundings. Bamboo is likely to be subjected to dimensional change when the ambient environment (relative humidity and temperature) fluctuates greatly. Dimensional variation is a serious and complex phenomenon, since it can have a deleterious effect on other mechanical and physical properties (Shi and Gardner 2006).

Several experimental studies on mechanical properties have been performed that mainly focused on the longitudinal elasticity modulus by executing the corresponding standardized protocol (ISO/DIS 2001). Li (1999) studied the bending properties of *Phyllostachys pubescens* and calculated the Young's modulus of bamboo culm. Chung (2002) examined the variation of compressive strengths along the length of bamboo and found that representative values of mechanical properties could be obtained, despite the variations in external diameter, wall thickness, and dry density. Few studies have been aimed at finding the circumferential mechanical properties of bamboo culm. Torres *et al.* (2007) developed a transversely isotropic law to determine the circumferential Young's modulus of bamboo with diametric compression tests. A simple test protocol was proposed by García (2012) and obtained the radial-circumferential Poisson's ratio, the circumferential Young's modulus, and the circumferential-axial shear modulus of bamboo by using ring specimens. However, studies have not been performed to determine the mechanical properties of bamboo in a radial-circumferential direction by using the biaxial compression method.

In order to successfully model and simulate the behavior of bamboo of optimum design in structural applications, a novel testing device, the 3D composite material analysis system (Fig. 1), was developed at the International Center for Bamboo and Rattan (ICBR) at the Department of Biomaterial, Key Laboratory of Bamboo and Rattan Science and Technology for State Forestry Administration, Beijing, China (Chen *et al.* 2011). This paper investigated the radial-circumferential mechanical properties of bamboo under uniaxial and biaxial compression loadings along with the comparison between the nodes and internodes, and the effect of environmental treatments on its properties.

MATERIALS AND METHODS

Materials

Two-year-old cizu bamboo (*Sinocalmus affinis* (Rendle) Mcclure) was grown in Changning, Yibing, Sichuan Province, China, with an initial 8 to 12% MC (after air drying). For testing preparation, the bamboo culm was cut into rings and then underwent different types of ambient treatments. The diametric compression tests, including uniaxial and biaxial compression, were separated into three groups of specimens. The first group compared the variation of mechanical properties of bamboo with uniaxial and biaxial compression tests. Twelve bamboo rings were taken of two different lengths (10 and 20 mm), for a total of 24 rings. For each length, six rings were used for the uniaxial test and the other six samples for the biaxial compression. The bamboo rings had an average external diameter of 62.43 mm and a culm wall thickness of 5.66 mm. The second group intended to study the effect of node on the radial-circumferential strength of bamboo under biaxial compression loading. It consisted of nine rings cut symmetrically from the node. The third group, intending to investigate the effect of ambient treatments on the diametric strength of bamboo under uniaxial and biaxial compression, was comprised of 12 rings of almost the same dimensions for each treatment. Air-drying (type I), constant temperature and relative humidity adjusted to 22 °C and 65% RH for more than two weeks (type II), a relatively low temperature of -5 °C for 48 h (type III), and an ultra-low temperature of -80 °C for 48 h (type IV) were the conditions used in this study. Three duplicates were examined for each condition.

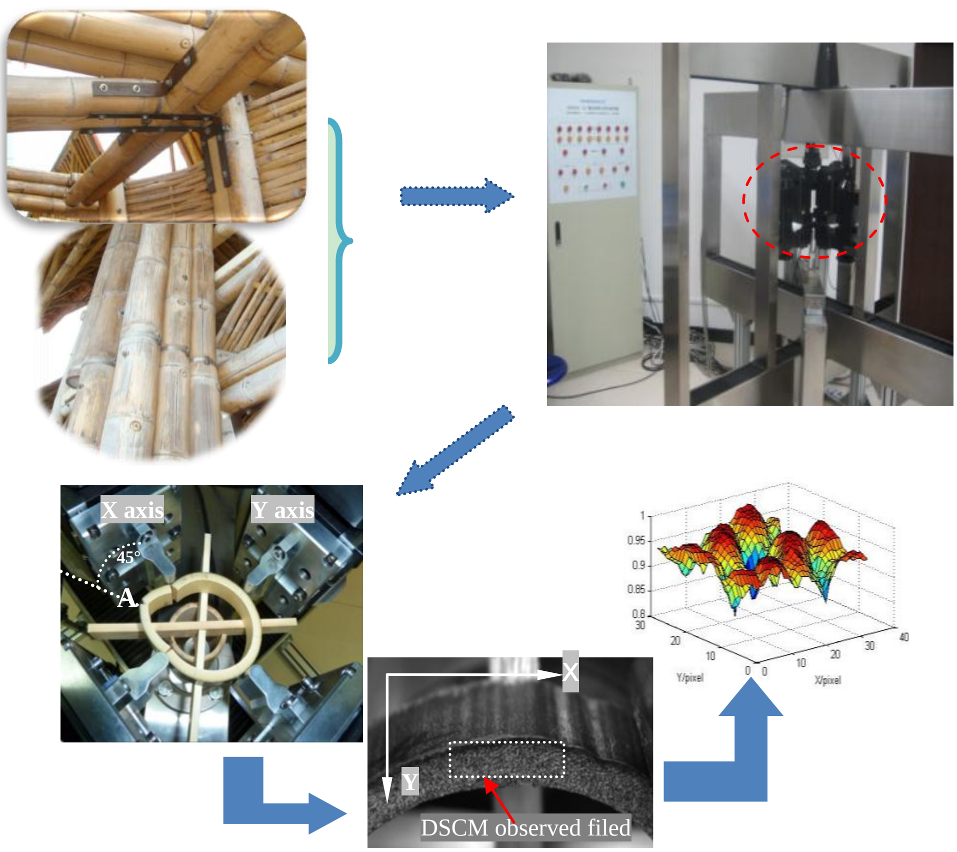


Fig. 1. Bamboo structure, 3D composite material analysis system, and visional field of specimen by DSCM. (Arrow represents the positive direction of strain-fields chosen for calculation.)

Instruments and Methods

The 3D composite material analysis system can evaluate material not only in compression or tension for the X and Y axial directions, but it can also simultaneously determine bursting in the Z direction. There are two sensors for measuring the force in X and Y directions, and each direction has two rigid heads or clamps (for compression or tension tests). The four compression heads are made of the same material and size, shaped in hemispherical cylinders with a 10 mm diameter and 40 mm length. For each direction (X/Y), its axial center is required to be correspondingly collinear. The geometric center of all heads was adjusted to the same level by using a level indicator. Such design and measures applied in the experiment can meet the requirement of linear contact and evenly bearing stress, along with decreasing the shear response in each direction. A servo-hydraulic test bench for combined loading in compression/tension and load sensor accuracy is 1.0 N, maximum load value is 5.0 kN, and drawing speed is 0.013 to 1.066 mm/s. The test bench is connected with an electronic control box, which can be manipulated by a computer with corresponding 3D software.

The system is equipped with digital speckle correlation method analysis system software (DSCM). The biaxial compression test was conducted with the modulated speckle image captured by a high-speed charge-coupled device (CCD) camera for description of the microscopic changes occurring on the surface. The pictures were saved in a file for analysis of the strain field. The observed speckle pattern included information about the object’s surface height, with varying degrees of gray reflecting the different stress-strain states of a specimen under biaxial loading (Wang *et al.* 2012). In order to form a uniform and randomly distributed speckle image, the surface of each specimen was sprayed with a layer of black glass bead paint for image enhancement.

The machine was preloaded to a value of 5 N for clamping the bamboo ring slightly. Uniaxial and biaxial compression tests were conducted at a rate of 0.013 mm/s. Strain under biaxial compression was obtained by using DSCM. A bamboo ring specimen, its visional field position by DSCM, and strain field are shown in Fig. 1. Origin 8.0 and SPSS 12.0 were used for linear fitting and the statistical analysis with a significance level of alpha=0.05.

RESULTS AND DISCUSSION

Biaxial Experiment and the Effect of Nodes

Typical experimental force-displacement curves displayed good linear elastic behavior, which was approximated in this study using two fitted linear regression lines (Fig. 2). Excellent correlations were obtained for each direction (R^2 greater than 0.95 for all bamboo ring specimens), indicating that this was a good approximation. Figure 2 shows that compression loadings in both X and Y directions increased linearly with an increase in displacement until the point of ultimate load under biaxial compression loading. Above this point, the load displacement curves showed sharp, slightly staggered decreases in load and brittle fracture for the X and Y directions simultaneously.

In addition, it was found that fracture of a specimen firstly occurred at about the 45° position between the X and Y axial (Fig. 1). This position can be regarded as the three-point bend for 1/4 bamboo ring, whose outsider surface was subjected to tensile stress while the inner surface was subjected to compression. In the experimental process, micro-cracks in the outer side of bamboo were firstly observed at the 45° position (point A in Fig. 1), then cracks continued to develop in the inner surface of bamboo and sharply increased near compression heads.

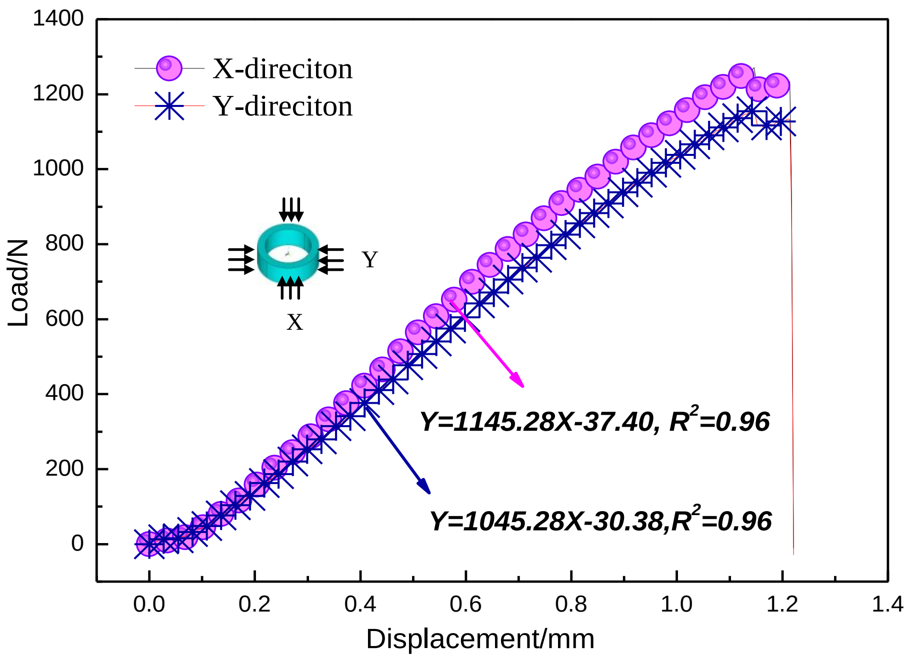


Fig. 2. Typical load displacement curves of bamboo ring under biaxial loading

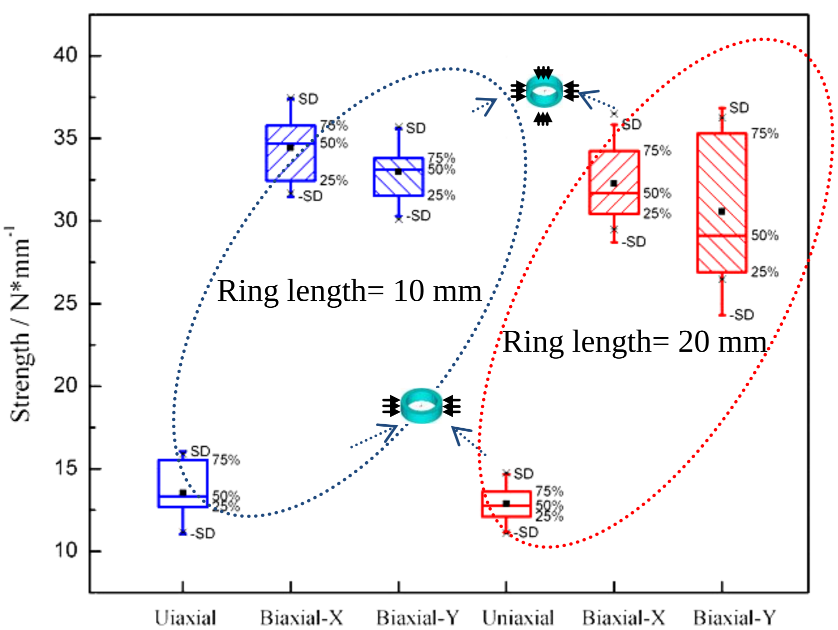


Fig. 3. The effect of loading methods on the compression strength of bamboo ring

The effects of loading methods on the compression strength and breaking time of bamboo rings are shown in Figs. 3 and 4. In general, the strength examined by biaxial compression tests was significantly higher than for the uniaxial test (P <0.01). Biaxial compression strength in the radial-circumferential direction of bamboo was about 2.4 to 2.5 times the uniaxial compression strength for 10 and 20 mm length rings. The stress field at each section of the bamboo ring is characterized by a bending moment, axial and shear forces. Due to the different internal moment and forces distributions, *i.e*. since the bamboo ring under biaxial loading is more constrained than the ring under uniaxial loading, the moments under biaxial loading will be lower than those under uniaxial loading. Using the same loading method, however, the length of ring does not have a significant effect on compression strength. The two-tailed t-test also confirmed the observation at a 95% confidence level (P=0.542). Part of the explanation of this phenomenon could be that under biaxial compression loading, the specimens with complex stress states on the circumference would have more potential to have more load-resistant capabilities, which may change or counteract the load transmission. The other possibility for the increase is that the biaxial compression test obtained higher strength at the expense of fracture time. In comparison to the uniaxial compression, the breaking time decreased by 30% and 45% for 10 and 20 mm length bamboo rings, respectively (Fig. 4). This phenomenon is completely in accordance with the principle of energy conservation,

$$E_{compression} = E - Q = \frac{1}{2}M \times V^2 = \frac{1}{2}F \times t \times V = \frac{1}{2}\frac{\sigma}{b \times L} \times t \times V \quad (1)$$

where $E_{compression}$ is the compression energy (J), E is the mechanical work (J), Q is the released thermal energy (J), σ is the compression strength (MPa), L is the effective contact length, b is width of specimen (mm), t is the breaking time (s), and V is the compression rate (mm/s). In the condition of constant compression energy ($E_{compression}$), compression strength (σ) is inversely proportional to breaking time (t).

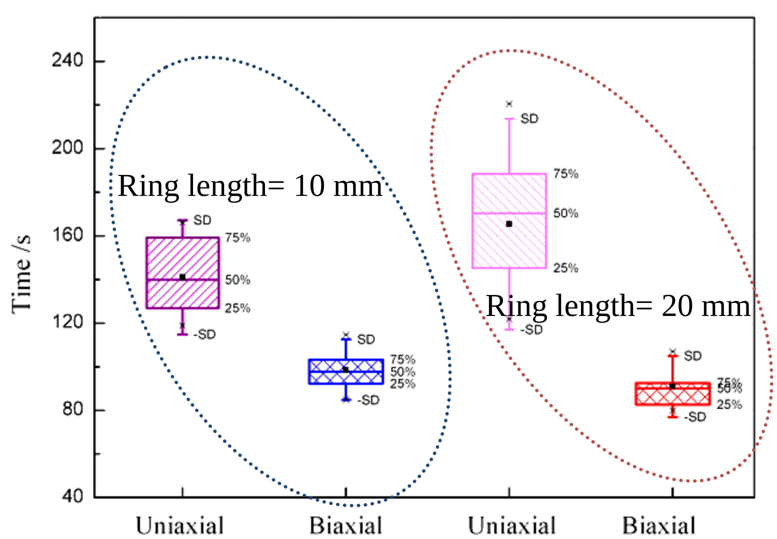


Fig. 4. The effect of loading methods on the breaking time of bamboo ring

Effect of Nodes and Internodes

The nodes irregularly distributed along the axial direction are an important characteristic of bamboo. The vascular bundle is considered the reinforcement of bamboo, which determines its basic strength. The fibers of vascular bundle are generally arranged parallel at the intermodal region, whereas they bend or flex when passing through the node. Several studies have confirmed that the tensile, bending, and compression tests along the axial direction for the node region have a lower strength than those for the internode (Zeng *et al*. 1992; Li *et al*. 1994). The influence of node on the radial-circumferential strength of bamboo was examined in this study. The results presented in Fig. 5 show a significantly increasing strength in the node for each direction (X/Y) compared with those in the internode ($P<0.05$). In comparison with the internode, the mean value of strength at the node region increased 134.99% for X direction and 149.17% for Y direction. The radial-circumference strength of the node was about 2.38 times higher than that of the internode. This mainly contributed to the function of the transversal diaphragm, which increased the loaded area considerably when conducting biaxial compression tests. These results clearly indicate that the node as a natural characteristic of bamboo has positive effects on the transverse strength and stability for engineering applications.

Figure 5 illustrates the strain field information of bamboo rings at a 45° position, corresponding to a load range of 0~300 N in Fig. 2. Figure 6a shows that the mean value of the X-strain was -0.006 with a distribution range of -0.138 to 0.096 on the well-distributed strain field. While the Y-strain field shown in Fig. 6b fluctuated more extensively, the mean value of Y-strain was 0.002 with a distribution range of -0.372 to 0.437.

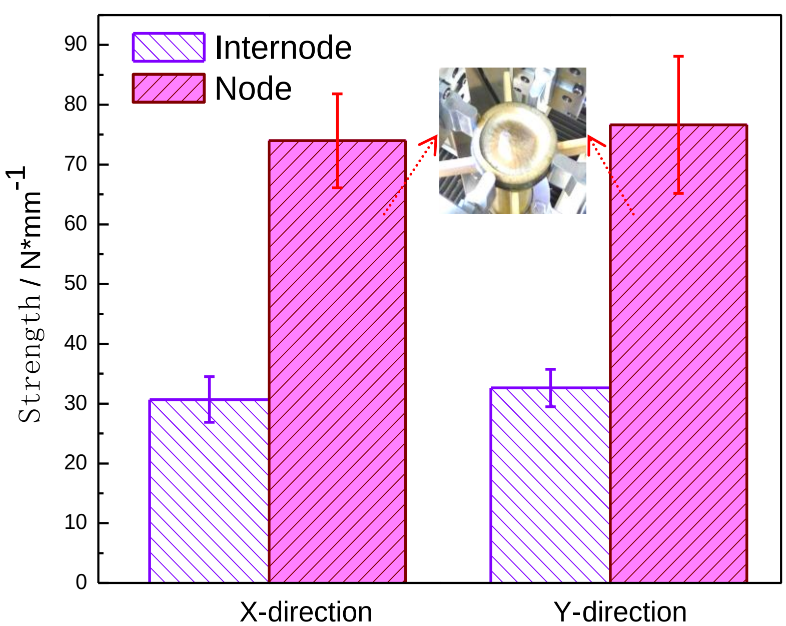
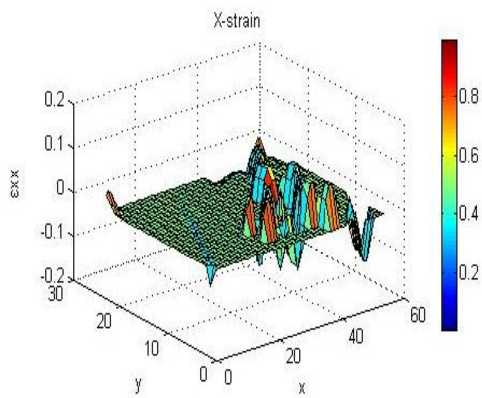


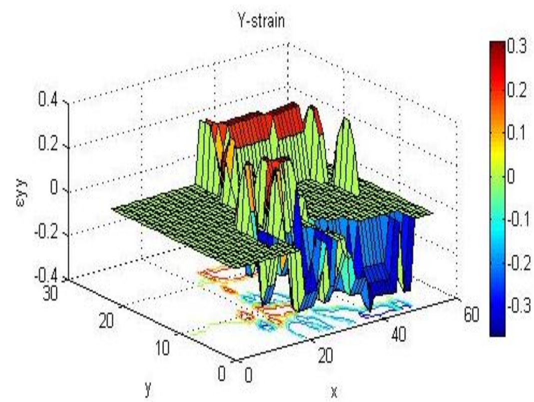
Fig. 5. The effect of node on the radial-circumferential strength under biaxial loading

Strain Field Characterization by DSCM

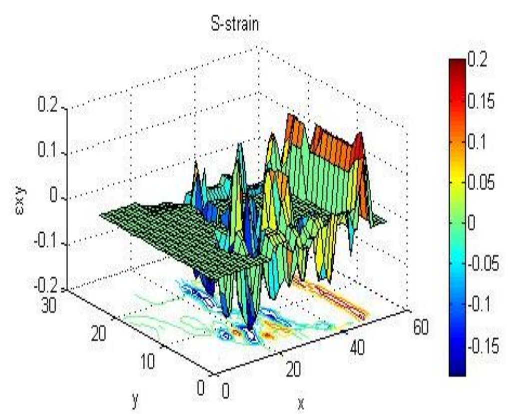
The strain concentration illustrated in Fig. 6b is an important and serious sign that is likely to result in lowered effectiveness under biaxial compression loading. The value of Y-strain located in the inner surface of bamboo was positive, which matches the direction for the strain field calculation. This indicates that the inner side was subjected to compressive stress. The value of Y-strain near the outside surface of bamboo was negative, which is in the opposite direction of the coordinate. This clearly indicates that the outsider surface of bamboo was subjected to tensile stress. The maximum normal tensile stress in the circumferential direction was located in the outside surface of the 45° direction. These analyses above provided by DSCM successfully predicted and demonstrated the source of micro-cracks under biaxial compression loading.



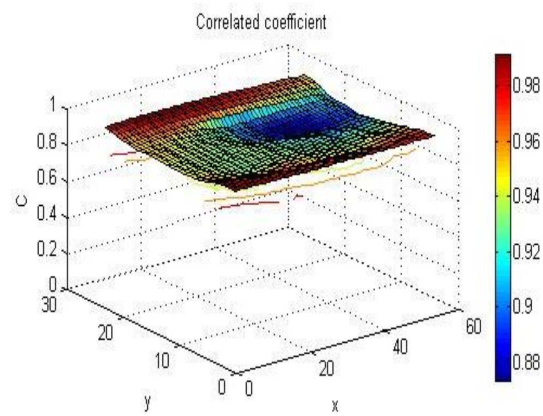
(a) Strain field in X-direction



(b) Strain field in Y-direction



(c) Shearing Strain-field



(d) Correlated Coefficient

Fig. 6. The information of strain field under biaxial compression load between 0~300 N

Effects of Environmental Treatments

The uniaxial and biaxial compression properties for bamboo rings subjected to different environmental treatments are summarized in Table 1. It can be seen in Table 1 that environmental treatments have an obvious effect on the mechanical properties of bamboo. The main trend for biaxial performance was $\sigma_{IV} > \sigma_{III} > \sigma_{II} > \sigma_I$, and it was the same for the uniaixal test. Generally, the lower the treated temperature, the higher the value of compression strength. In comparison with type I, the strength of the type II, III, and IV-treated bamboo increased 21.54%, 51.62%, and 58.76% in the uniaxial test and 34.00%, 39.09%, and 59.23% for biaxial compression, respectively. The statistical analysis revealed that the effect of environmental treatments on the strength increase rate was significant at a 95% confidence level ($P<0.05$). Specimens treated according to type I may have shrinkage stress induced during the air-drying process. The shrinkage stress will be released when the moisture penetrates into the bamboo for type II treatment. Therefore, after constant temperature and relative humidity treatment, the dimensional stability and strength in circumference of bamboo improved compared with air-dried bamboo.

Table 1. The Effect of Different Environmental Treatments on the Radial Mechanical Properties of Bamboo Ring Under Uniaxial and Biaxial Compression

Type	Treated Temperature (°C)	Moisture Content (%)	Density (g/cm^3)	Uniaxial Strength σ (N /mm)	Biaxial strength (N/mm)		Uniaxial Strength Increase Rate W_1 (%)	Biaxial Strength Increase Rate W_2 (%)
					σ_X	σ_Y		
I	24 to 28	8.89	0.62	16.14	41.52	41.65	0	0
II	22	15.74	0.62	19.61	55.80	55.65	21.54	34.00
III	- 2	15.95	0.62	24.46	58.30	57.38	51.62	39.09
IV	- 80	15.93	0.62	25.61	66.31	66.13	58.76	59.23

NOTE: W_1=100%*(σ_i- σ_I) /σ_I , W_2=100%*((σ_{Xi}- σ_{XI})/ σ_{XI} + (σ_{Yi}- σ_{XI})/ σ_{YI}) /2, where i=I,II,III, and IV.

Specimens treated according to types III and IV reflected a higher strength compared with type II. The increase after relatively low and ultra-low temperature treatments was probably due to the status change of bound water along with the improvement of stiffness. Bamboo is a naturally occurring composite material, consisting of cellulose fibers and hemi-cellulose imbedded in a lignin matrix. These long and thin macromolecular chains can undergo relative motion between chains. The minimum unit of the chains possessing independent moving ability was defined as a segmer (Guan and Zhang 2006). Segmers with a large number of polar hydroxyl groups will become frozen as the temperature falls below the point of glass transition. Bamboo was likely to be transformed into a rigid, glassy state. Therefore, the strength of bamboo increased for the relative low and ultra-low temperature treatments.

CONCLUSIONS

1. A novel 3D composite material analysis system to test bamboo circumferential-radial properties under uniaxial and biaxial loads was presented. The results indicated that biaxial compression corresponds to a higher strength but a lower breaking time, compared to uniaxial tension. The node provides a positive effect on the transverse strength and stability for bamboo.

2. Strain fields characterized by using DSCM are capable of predicting signs of collapse during the biaxial compression process. The maximum tensile stress at the 45° circumferential direction between the X and Y axial was located in the outside surface of bamboo.
3. Environmental treatments have a significant effect on the mechanical properties of bamboo ring for uniaxial and biaxial compression tests. The lower the treated temperature, the higher the obtained compression strength.

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