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Estimation on tensile elastic properties of engineered bamboo boards with image information

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ABSTRACT

Engineered bamboo boards, which are made of glued bamboo strips, can be used as sustainable construction materials with high performance by terms of high strength-to-density ratio, excellent thermal insulation performance, and easy-to-manufacture. The strength of the bamboo strip is mainly determined by its fiber content. Thus, by terms of micromechanics definition, the bamboo fiber bundle element can be modeled as a representative volume element (RVE). This paper proposed a simple approach to evaluate the tensile elastic properties of engineered bamboo (EB) panel through the image information of bamboo strips. According to the image analysis of the bamboo strip section in different parts of bamboo culm, the distribution of the RVE along the thickness can be established. Mechanical properties of bamboo strips were tested, and the relationship between properties and RVE content of bamboo strips was estimated. Based on the model in composite mechanics, the tensile elastic properties of the engineered bamboo panel were predicted.

1. INTRODUCTION

Engineered bamboo (EB) boards can be used as a sustainable construction material with high-performance by terms of high strength-to-density ratio, good thermal insulation performance, and easy-to-manufacture. Meanwhile, compared with conventional metal construction materials and composite materials, smaller carbon footprint and better degradability are noticed for engineered bamboo products. In the recent 20 years, this material has been successfully used for residential buildings, bridges, and wind blades. A fast and accurate method to estimate the mechanical properties of engineered bamboo products is the prerequisite for the vast application of

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this environmentally friendly material in the engineering field. Bamboo fiber bundles are the primary sources of its strength, as well as that the specific distribution of it along the section of bamboo columns creates its hierarchical structure, which is naturally optimized. As shown in Fig. 1, the mesoscopic structure of bamboo fiber bundles indicates that the bamboo fiber bundles are embedded in a matrix of parenchyma cells, thus it reasonable to be described as a natural fiber-reinforced composite material. In terms of micromechanics definition, the bamboo fiber bundle element can be modeled as a representative volume element (RVE). In these models, the bamboo fiber is the reinforced fiber, with the volume V_f. The parenchyma is the matrix, with the volume V_m. The volume fraction of the fiber is calculated as $c_f = V_f /(Vf + V_m)$. Based on this geometric information, along with the elastic parameters of bamboo fibers and parenchyma matrix, the mechanical properties of EB can be estimated based on the micromechanics equations or finite element models.

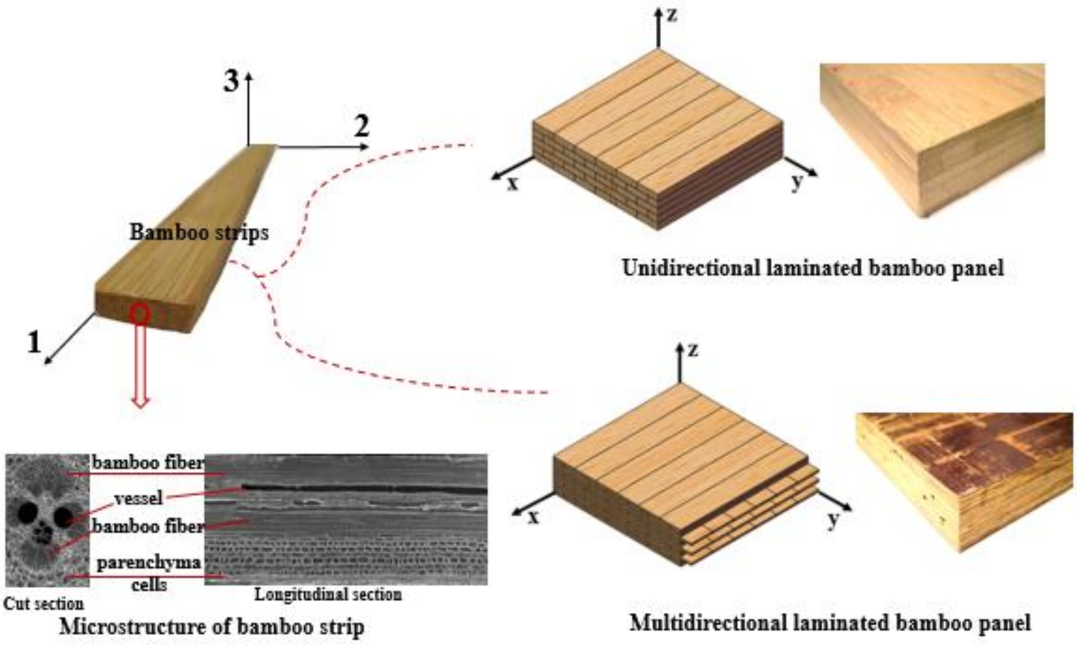
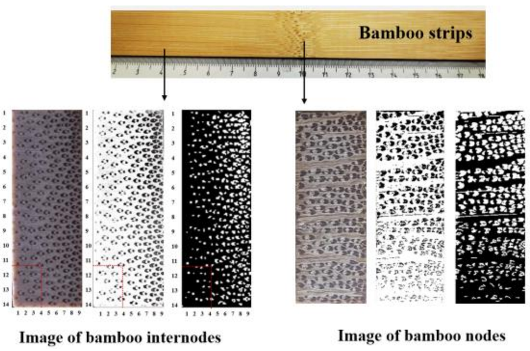


Fig. 1 The microscopic structure of engineered bamboo products

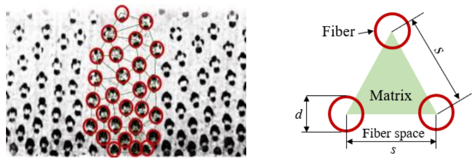
The final aim of this research is to develop a fast and practical method to estimate the mechanical properties of commercially available engineered bamboo boards, which can be further laminated for GluBam or cross-laminated bamboo (CLB) structures. The bamboo fiber packing geometry of bamboo strips used for EB boards is studied firstly; experimental research on bamboo strips used for 30 mm EB boards was carried out. Mechanical properties of tensile strength f_{tx} and tensile modulus E_{tx} were obtained. Before the tests, the image information of the sections of test specimens are recorded, and a MATLAB program is used to calculate the geometrical parameters of bamboo strips.

2.IMAGE INFORMATION ON BAMBOO FIBER PACKING GEOMETRY

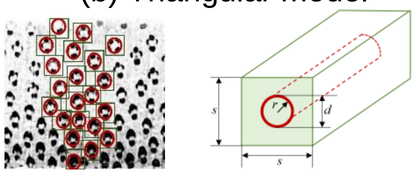
Three types of bamboo strips are studied in this research, with average cut sections of 5.4/6.4/7.0 mm × 21.5 mm. The average length of bamboo strips is 2110±1.83 mm. The images of bamboo strips' sections are randomly collected at the random length of the strips between two nodes, in order to fit the real production process adapted in the factory, as shown in Fig. 2(a). The average internode length is 22.29 mm, with a stand deviation of 4.28 mm for all strips. The binary image is created with the MATLAB program, the white part of the rightmost images, as shown in Fig. 2(a) is calculated as the area of fibers on a section. The nodes of the bamboo are typically the weakest part of bamboo strips under longitudinal tension tests, the cells are longitudinally oriented, and no radial cells exist, as shown in Fig.2 (a). Thus, only strips between nodes, which are modeled as unidirectional fiber-reinforced composites, are considered in this research for experimental researches.

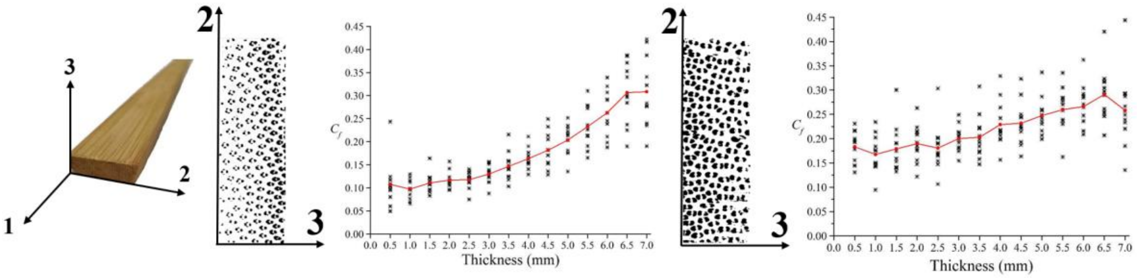


(a) Section image of bamboo strips and nodes



(b) Triangular model


(c) Voronoi cell model



Bamboo strips **Bamboo nodes**

(d) Distribution of bamboo fibers

Fig. 2 Image information of bamboo strip's section and RVE model

A fundamental aspect of the micromechanical analysis is the characterization of the relative volume or weight contents of the various constituent materials. Simplified geometric RVE models are suggested for the fast modeling of composite materials. As shown in Fig. 2(b), the triangular array is usually used for the representative area elements (RAE) for the idealized fiber-packing geometries. Two geometric parameters are measured to identify the characteristics of RAE, which are fiber center-to-center spacing s, and the fiber diameter d, respectively. Another RVE model is the Voronoi cell model, as shown in Fig. 2(c), which can be approximated by the nearest square section. Such a model can be more useful for the biomaterials with random fiber packing geometry, and the Weibull distribution found to adequately characterize the probability density function for the Voronoi cell size. Such image information-based models are the basement for the precise finite element modeling of composite materials. The bamboo fiber volume fraction c_f increases from the inner side of the bamboo strips (0.05-0.15) to the outer wall (0.15-0.45), as shown in Fig. 2(d) at a spacing of 0.5 mm in the thickness direction. The value of c_f is around 0.2 at the location of bamboo nodes; meanwhile, no hierarchical distribution is noticed of it.

3. TENSION TEST OF BAMBOO STRIPS

3.1 Test method

Tensile test method suggested in ISO 13061 (ISO 13061-6 2014) is used herein to evaluate longitudinal modulus of bamboo strips E_{tx} and tensile strength f_{tx}. The details of the specimens were illustrated, as shown in Fig. 3(a). Two steel plates were used during the cutting of test samples from bamboo strips to ensure the geometrical precise of specimens. Strain gauges were attached in the middle of the specimens, which is called as effective region herein. Before testing, all oven-dry specimens in this research were conditioned in a humidity chamber with humidity of 60 ± 5% RH and temperature of 20 ± 2 ℃ for more than 48 hrs. The measured moisture content (MC) of the specimen was about 9.0 ± 0.5%. The width b and thickness t of specimens in the effective region were measured three times before the loading and used for the calculation of corresponding elastic parameters. The bamboo fiber volume fraction c_f of tensile specimens were measured and analyzed before the loading test, as shown in Fig. 3(c), only the area corresponding to the effective region was used to calculate the c_f values of specimens.

(a) Test specimens (b) Loading jigs (c) Area for fiber volume fraction calculation

Fig. 3 Bamboo strip specimens and loading jigs

Twenty specimens were tested for each group. The elastic modulus along the fiber direction E_x is calculated as:

$$E_x = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{1}$$

where $\Delta\sigma$ is the difference in applied tensile stress between two strain points between 1000 με and 3000 με in this research, in MPa. And $\Delta\varepsilon$ is the measured difference strain between the two points.

The longitudinal tensile strength f_{tx} is calculated as:

$$f_{tx} = \frac{P_{\max}}{A} \tag{2}$$

where $P_{\max}$ is the measured maximum forced before failure, in N. A is the measured average cross-sectional area of the effective region, in mm^2.

The Poisson's Ratio ν_{12} is calculated as:

$$\nu_{12} = \frac{-\Delta\varepsilon_1}{\Delta\varepsilon_2} \tag{3}$$

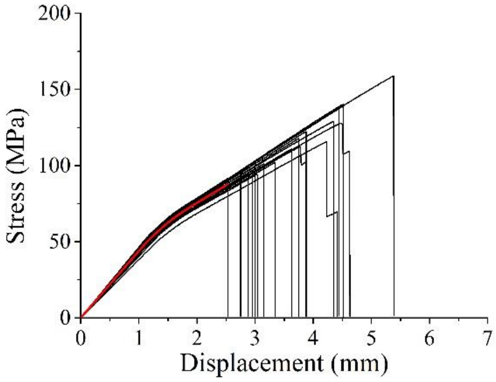
where $\Delta\varepsilon_1$ is the difference in lateral strain between the two longitudinal strain points around 1000με and 3000 με. $\Delta\varepsilon_2$ is the differences between the two measured transverse strain points.

3.2 Test results

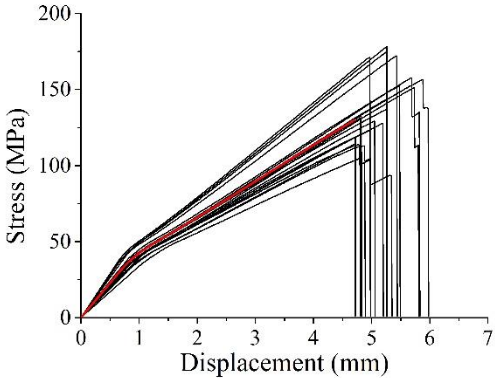
Three different failure modes were noticed during the test, as shown in Fig. 4. The percentage of withdrawal failure is increasing with the increase of the thickness of bamboo strips. The stress-displacement curves obtained for the strips with three different thickness are given in Fig. 5, and the mechanical properties calculated from test results are shown in Table 1.

(a) Tension failure (b) Shear failure (c) Withdrawal failure

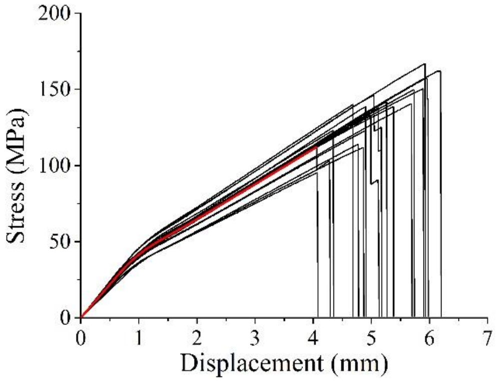
Fig. 4 Failure modes of bamboo strips



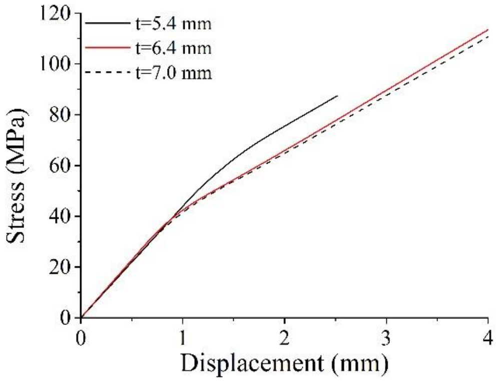
(a) 5.4 mm strips



(b) 6.4 mm strips



(c) 7.0 mm strips



(d) all strips

Fig. 5 Stress-displacement curves of bamboo strips under tensile test

Table 1 test results of bamboo strips under tensile test

Property	Thickness (mm)	*n*	Value （MPa）	St. D (MPa)
Elastic modulus E_x	5.4	18	7277.42	1249.74
	6.4	17	8770.89	1120.85
	7.0	16	8722.52	1397.12
	all	51	8228.61	1422.11
Tensile strength f_{tx}	5.4	19	115.19	19.29
	6.4	20	139.95	22.41
	7.0	19	136.22	17.73
	all	58	130.62	22.46
Poisson's Ratio ν_{12}	5.4	18	0.36	0.10
	6.4	17	0.42	0.09
	7.0	16	0.41	0.09
	all	51	0.40	0.10

4. MODULUS & STRENGTH PREDICTION BASED ON IMAGE ANALYSIS

4.1 Micromechanical model

Elastic tensile modulus along the fiber direction E_{xt} can be estimated with the so-called rule of mixtures (ROM) method or iso-strain model, as expressed in Eq. 4.

$$1.25E_{xt} = E_{f1}c_f + E_{mt}c_m = E_{f1}c_f + E_{mt}(1-c_f)$$
$$c_f + c_m = 1 \tag{4}$$

where E_{f1} is the longitudinal modulus of the fiber sheath, which is assigned to be 55 GPa in this research, as reported by Shang et al. (Shang 2015). c_f is the volume fraction of the fiber as mentioned above, and it is measured based on the image information, as shown in Fig. 2(d). E_{mt} is the longitudinal tensile modulus of the parenchyma cells, which is about 1.7 GPa, as reported by An (An 2013). c_m is the volume fraction of the matrix. Factor 1.25 is used herein due to the voids (vessels) are not considered in Eq. 4.

The analysis of composite strength is more complicated than the analysis of elastic behavior, as the strength values depend on the various failure modes that can occur in engineered bamboo products. For longitudinal tension strength f_{tx}, it is governed by the failure strain of fiber and matrix, as well as the fiber volume fraction c_f. For engineered bamboo products, the failure strain of parenchyma cells ε_m (3.16%) is larger than that of bamboo fibers ε_{f1} (2.04%) (Shang 2015), as well as the value of c_f is between 10% and 25% as measured in this research. The equation to estimate the longitudinal tensile strength is given in Eq. 6 based on such preconditions.

$$1.25 f_{tx} = f_{f1}c_f + f_{mf1}(1-c_f)$$
$$f_{mf1} = E_{mt}\varepsilon_{f1} = E_{mt}\frac{f_{f1}}{E_{f1}} \tag{5}$$

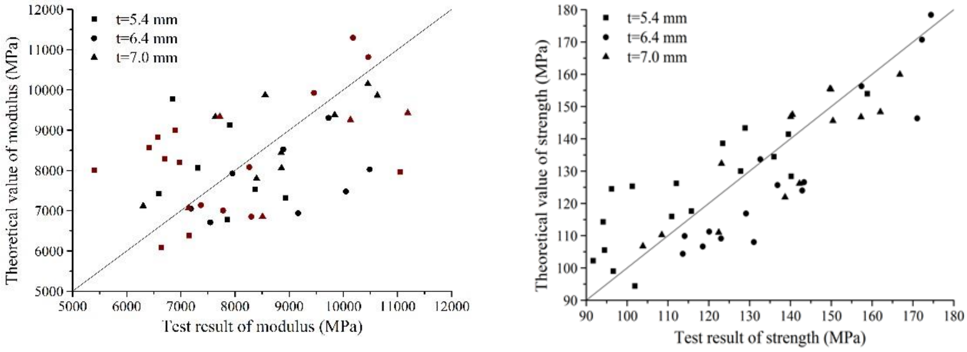
where f_{f1} is the tensile strength of bamboo fiber sheath, which is assigned to be 729 MPa in this research (An 2013). Factor 1.25 is used herein due to the voids (vessels) are not considered in Eq. 5.

4.2 Test results and theoretical values

The comparison between the test and theoretical tensile mechanical values of bamboo strips are given in Fig. 6. Different with the conventional understanding on unidirectional reinforced composite materials, the estimation on tensile strength values gains relatively more accurate results than the estimation on modulus values. It may be due to the hierarchical structure of bamboo as shown in Fig. 2(d). Meanwhile, the bending of the tension specimens is inevitable due to the inherent uneven distribution of bamboo fibers on the tensile sections. The percent bending in specimen B_y can be evaluated as Eq. 6.

$$B_y = \frac{|\varepsilon_f - \varepsilon_b|}{|\varepsilon_f + \varepsilon_b|} \tag{6}$$

where ε_f is the strain from the front stain gauges, ε_b is the strain from the back strain gauges. The measure B_y values can reach up to 25% according to the tests in this research.



(a) E_x (b) f_{tx}

Fig. 6 Test and theoretical tensile mechanical values of bamboo strips

The tensile elastic values E_{tx} calculated based on the strain values measured by strain gauges attached to the surface of bamboo strips with higher density of bamboo fibers are denoted as wine red color, as shown in Fig. 6(a).

5. CONCLUSION

Three groups of bamboo strips with different thickness were experimental studied in this research. According to the image analysis of the bamboo strip, the distribution of fibers in the section of bamboo strip and bamboo node along the thickness were obtained and analyzed. Tension tests of bamboo strips were conducted, and the elastic modulus, tension strength and Poisson's ratio were calculated. Based on the theoretical model of composite mechanics, the tensile modulus and strength of bamboo strips were estimated in accordance with the volume fraction of fibers.

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