Mode I Fracture Toughness of Tangential Moso Bamboo

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This paper discusses moso bamboo (*Phyllostachys pubescens*) with initial crack formation by a three-point bending (SENB) method. The corrected indentation load-displacement curve (ISO 13586-2000) and the crack opening displacement in determining the crack tip extended displacement of the specimen (ASTM E399-09) were measured using a COD gauge. Then, the load-displacement curve and the value of P_Q were found by the method of 95% stiffness correction. The results showed that the bamboo has good fracture toughness, and, in this experiment, the fracture results showed little difference; the result for fracture toughness can be up to 17.39 MPa •$m^{1/2}$. By observing the crack under the microscope and the failure mode, it was found that the crack propagation was not established in accordance with the crack opening direction; rather it extended along the fiber interface.

Key words: Fracture; COD gauge; Crack opening displacement; Fracture toughness

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INTRODUCTION

Bamboo is an important part of the forest resources in China and is a typical, natural, functional graded material (FGM) and composite material (Wegst and Ashby 2004) with a hierarchical structure. At the same time, bamboo is a typical unidirectional long-fiber reinforced bio-composite (Shao *et al.* 2009). It has been used as a structural material at construction sites in China, India, and other countries because it is a strong, tough, and low-cost material (Amada and Untao 2001). The mechanical properties of bamboo are topics of interest directing recent research and are an important foundation for the use of bamboo processing. Fracture toughness is one of the basic properties of materials. Wood fracture toughness has been discussed and studied for various kinds of fracture mechanisms (Vincent 1990). Fracture toughness K_{IC}, and strain energy release rate G have been measured for various woods (Jeronimidis 1980; Bodig and Jayne 1993; Sato *et al.* 1995), but the fracture properties of bamboo have received little attention.

This paper presents the mode I fracture toughness of tangential moso bamboo (*Phyllostachys pubescens*) and discusses the results obtained based on tangential data. However, there is no standard K_{IC} for bamboo. It is necessary to refer to the standards for other materials, such as plastic (ISO13586 2000) and metal (ASTM E399). The ISO standard 13586-2000 concerns plastic. Because the plastic is a viscoelastic material, the specimen may appear indented during testing; however the specimen may subsequently recover, correcting the indentation. Bamboo is a composite material and is porous.

During testing, the specimen may also appear indented, and such deformation may have a big influence on the results. Therefore, bamboo specimens should also be corrected for such effects. The measured displacement should be corrected for the indentation of the loading pins, compression of the test specimen, and the machine compliance to properly determine the stiffness *S* of the specimen at crack growth initiation. ASTM E399-09 is for the testing of metal, and it uses a COD gauge to measure the crack opening displacement.

EXPERIMENTAL

Materials

Four-year-old moso bamboo (*Phyllostachys pubescens*) was obtained from Huangshan Anhui province in China. The total height was about 15.6 m, and the diameter at breast height was 128 mm. The specimen was collected from the internode sections located at a height between 1.5 and 4 m. Then, the specimen was cut parallel to the grain into small pieces. The moisture content of the specimen was about 7 to 8%, and the average density was 0.68 g/cm^3.

Sample Preparation

The specimen was processed in a processing factory, and then the bamboo node was removed. After that, the bamboo was split into pieces longitudinally. Referring to the standards, the bamboo was processed into standard three-point bend specimens. The dimensions of specimens were 8 mm, 16 mm, and 120 mm in the radial (R), tangential (T), and longitudinal (L) direction, respectively. In other words, the normal size of the specimen was as follows: $L \times W \times H = 120 \times 16 \times 8$ mm. In the middle of the specimen, lengthwise, a sharp notch of size *a* was machined. A small band was used to saw a mechanical cut, and then a tip was placed on the crack tip. The depth of the groove can be selected according to the actual conditions; accordingly, a notch two-thirds of the width of the specimen was formed. The relationship between *a* and *W* is $a = 0.45\sim0.55W$. Figure 1 is a schematic diagram of the sample dimensions.

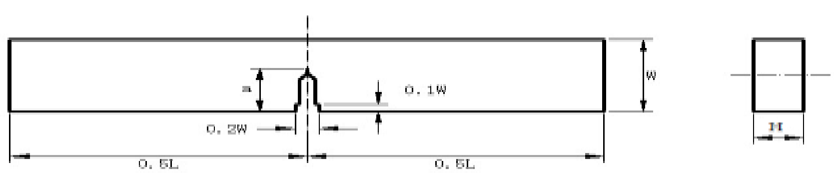

Fig. 1. Schematic diagram of the sample dimensions with the notch

where *W* is the width, *H* is the thickness, *L* is the overall length, and *a* is the crack length.

Test Method

The calibration of the test system should be performed as follows: The rollers of the three-point-bending rig are moved together to reduce even further the small flexing of the unnotched test specimen under load. In this way, the corrected load-displacement curve is constructed. At a corresponding load, the displacement taken from the correction curve is subtracted from the displacement in the actual fracture test with a notched test specimen (Fig. 2). ASTM E399-09, the standard test for metal, uses a COD gauge to measure the crack opening displacement, as shown in Fig. 3. When determining the value of P_Q (the load at crack growth initiation), one uses the stiffness secant. In other words, the obtained experimental results are used when drawing the load-displacement curve. When the stiffness is reduced by 5%, the point of intersection between the tangent and curve is P_Q. After determining P_Q, the value of K_{IC} is calculated according to the formula. K_{IC} is the value of the stress intensity factor when the crack under load actually starts to enlarge under a plane-strain loading condition around the crack tip. According to two standards (ISO 13586-2000 and ASTM E399), the experiments were conducted separately using an INSTRON 5582 device. During the experiments, an appropriate load was applied to the notched SENB specimen, so that the crack tip was loaded in mode I, causing crack extension (Fig. 2).

Fig. 2. SENB testing according to ISO 13586-2000 and ASTM E399-09

The test results, *i.e.*, the downward and strain 1 displacement, were automatically recorded by load and displacement sensors and simultaneously recorded. The loading was uniform. The loading speed was about 2 mm/min. This ensured that the specimen was destroyed in 60 to 90 s.

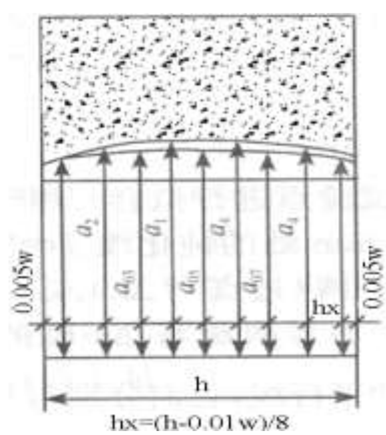

Fig. 3. Measurement of pre-crack length *a*

Measurements of Pre-Crack length *a*

For the SENB test specimen, the pre-crack length was the crack length up to the tip of the initial crack, measured from the notched face, expressed in meters. The specimen pre-crack size, *a*, was measured after fracture. After loading, the crack front was drawn and then the pre-crack length along the crack leading edge (Fig. 3) was measured at nine equal intervals. The average of the measurements was calculated (Cheng and Zhao 2006). Finally, the pre-crack size, *a*, was obtained.

RESULTS AND DISCUSSION

The method and the processing of the two standards were the same. The trends of the two curves were largely consistent. Before the initial crack appeared, the initial load-displacement curves were approximately linear. The zero-point tangent was drawn to the curve in Fig. 4 to determine the initial stiffness *S*. When the stiffness was reduced by 5%, a further line could be drawn accordingly. The maximum of the load-displacement curve fell within these two lines, and the point of intersection was P_Q. That is, the method to determine the load at crack growth initiation (P_Q) was the same.

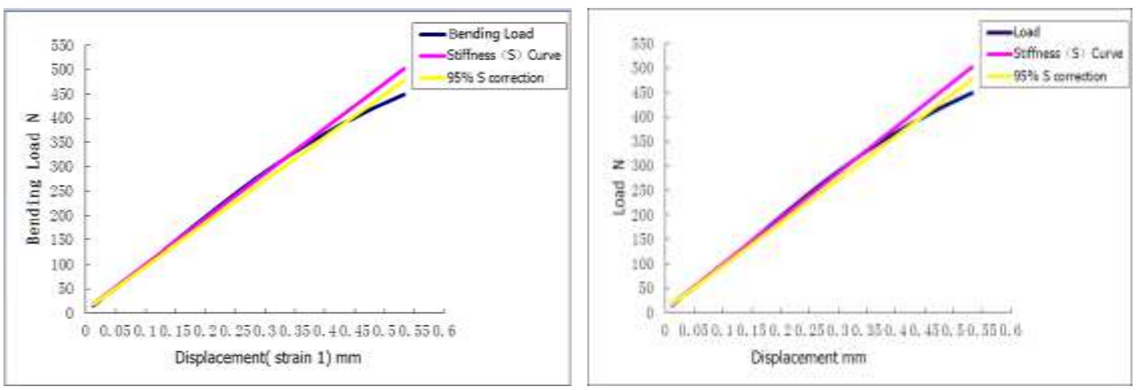

Fig. 4. Stiffness method to determine the initial crack load

Provisional K_{IC} Result

The critical stress intensity factor K_{IC} was calculated from the load P_Q at crack growth initiation and the original crack length *a* as follows,

$$f\left(\frac{a}{W}\right) = 6\sqrt{\left(\frac{a}{W}\right)}\frac{1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left[2.15-3.93\frac{a}{W}+2.7\left(\frac{a}{W}\right)^2\right]}{\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

$$K_{IC} = f\left(\frac{a}{W}\right)\frac{P_Q}{H\sqrt{W}} \quad \text{(According to ISO13586-2000)} \tag{1}$$

$$f\left(\frac{a}{W}\right) = 3\sqrt{\left(\frac{a}{W}\right)}\frac{1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left[2.15-3.93\frac{a}{W}+2.7\left(\frac{a}{W}\right)^2\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

$$K_{IC} = f\left(\frac{a}{W}\right)\frac{P_Q S}{HW^{3/2}} \quad \text{(According to ASTM E399-09)} \tag{2}$$

where H is the thickness, W is the width, a is the crack length, P_Q is the load at crack growth initiation, S is the span between rollers ($S = 4W$), and $f\ (a/W)$ is the geometry calibration factor, which depends on the crack length a ($0.45 \leqslant W \leqslant 0.55$).

According to Fig. 4, when the load was between 300 and 400 N, the initial crack appeared. In Table 2, ISO 13586-2000 results are compared with uncorrected ones; the results from ISO 13586 were lower than for the uncorrected ones. The indentation may affect the results, so indentation correction was necessary. At the same time, ISO 13586-2000 results were compared with those from ASTM E399-09, and the average K_{IC} were 16.05 MPa•m$^{1/2}$ and 15.80 MPa•m$^{1/2}$, respectively (the uncorrected average K_{IC} was 16.76 MPa•m$^{1/2}$). The two standard results were generally consistent. Although the results of the two standards showed only slight differences, ASTM E399-2000 is much easier to perform than ISO13586, so we chose ASTM E399-2000. For a single bamboo specimen, the data were relatively stable.

Table 1. K_{IC} Value of the Specimen Initial Fracture

NO.	E399 / MPa •m$^{1/2}$	ISO13586 /MPa •m$^{1/2}$	Uncorrected /MPa •m$^{1/2}$
1	14.79	14.60	14.79
2	16.73	17.0	18.16
3	14.88	15.63	16.11
4	16.91	15.29	16.28
5	15.56	15.29	16.78
6	17.39	16.78	17.94
7	16.11	15.38	16.11
8	15.58	15.58	17.04
9	16.50	16.62	17.43
Average	16.05	15.80	16.76
Standard deviation	0.91	0.81	1.07
Coefficient of variation/%	5.67	5.13	6.38

From Fig. 5, when the ratio of the crack length a to the specimen width W fluctuated within 0.45 to 0.55, K_{IC} also showed little fluctuation, so the results of K_{IC} were effective as long as the ratio was between 0.45 and 0.55.

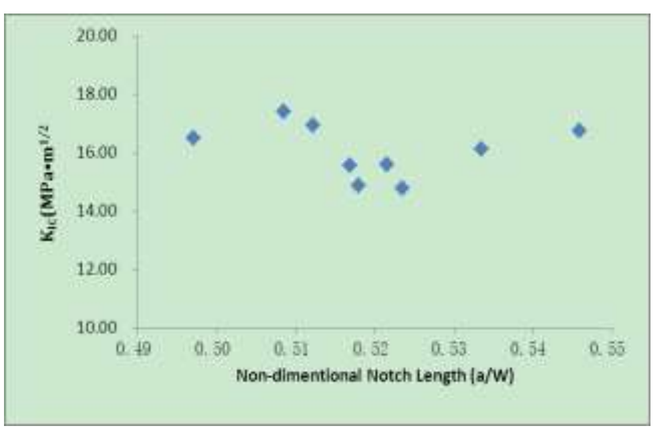

Fig. 5. The relationship between K_{IC} and *(a/W)*

Fracture Failure Mode of the Bamboo Specimen

Figure 6 shows micrographs of the Mode I fracture surface obtained from a scanning electron microscope. Viewed from the fracture surface (1 and 2), after the destruction of the specimen, as it continued to expand, there was no propagation of the initial crack, but instead there was a tearing crack. The outer and inner layers presented different failure modes. For one specimen, compared with the outer layer, the inner layer has less bamboo fiber and it tears easily. At the same time, the inner layer has more bamboo fiber. The crack did not extend along the pre-crack direction, but along the fiber direction. Figure 6(3) shows that there were high stress concentrations at the interface in the mode I crack tip area that expanded rapidly, revealing the tearing state.

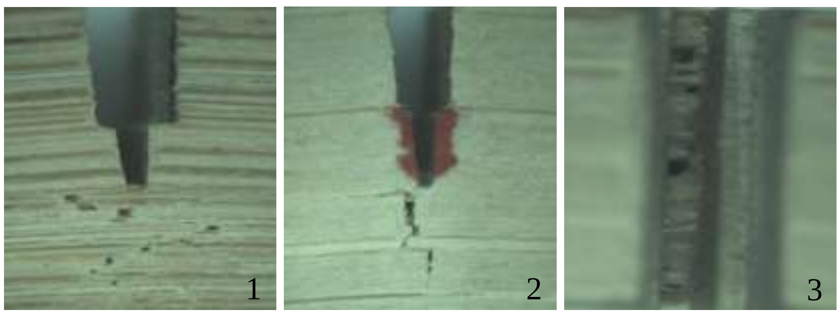

Fig. 6. Failure mode of bamboo specimen

CONCLUSIONS

1. Mode I fracture toughness K_{IC} is a basic characteristic of bamboo material. In this study, the mean K_{IC} determined by ISO 13586-2000 and ASTM E399-09 was 16.05 MPa •$m^{1/2}$ and 15.80 MPa •$m^{1/2}$, respectively, and the maximum fracture toughness reached 17.39 MPa •$m^{1/2}$.
2. The ASTM E399-09 standard avoids correcting the porous material indentation. It is much easier to carry out than the ISO13586-2000 standard and is a more suitable method of bamboo fracture toughness.
3. The distribution of K_{IC} agrees well with the ratio of *a/W*. That means for this study, when the ratio of *a/W* is between 0.45 and 0.55, there is little change in the fracture toughness, so the results of K_{IC} are effective as long as the ratio is between 0.45 and 0.55.

ACKNOWLEDGMENTS

The authors are grateful for the financial support of the Agricultural Science and Technology Achievements Transformation Fund (2012GB24320594). The constructive comments from the anonymous reviewers are also greatly appreciated.

REFERENCES CITED

Amada, S., and Untao, S. (2001). "Fracture properties of bamboo," *Composites Part B-Engineering* 32(5), 449-457.

ASTM E399-09. *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{IC} of Metallic Materials*.

Bodig, J., and Jayne, B. A. (1993). *Mechanics of Wood and Wood Composites*, Krieger, Malabar, FL.

Cheng, J., and Zhao, S. S. (2006). *Fracture Mechanics*, Science Press, Beijing.

ISO 13586-2000. *Plastics — Determination of Fracture Toughness (G_{IC} and K_{IC}) — Linear Elastic Fracture Mechanics (LEFM) Approach*.

Jeronimidis, G. (1980). "The fracture-behavior of wood and the relations between toughness and morphology," *Proceedings of the Royal Society Series B-Biological Sciences* 208(1173), 447-460.

Sato, K., Honda, T., Ando, K., Kubo, T., and Fushitani, M. (1995). "Fracture toughness and acoustic emission characteristics of sugi (*Cryptomeria japonica*)," *Research Bulletin of the University Forests, Tokyo University of Agriculture and Technology* 33, 19-26.

Shao, Z. P., Fang, C. H., and Tian, G. L. (2009). "Mode I interlaminar fracture property of moso bamboo (*Phyllostachys pubescens*)," *Wood Science and Technology* 43(5-6), 527-536.

Vincent, J. F. V. (1990). "Fracture properties of plants," *Advances in Botanical Research Incorporating Advances in Plant Pathology* 17, 235-287.

Wegst, U. G. K., and Ashby, M. F. (2004). "The mechanical efficiency of natural materials," *Philosophical Magazine* 84(21), 2167-2181.

Article submitted: November 15, 2013; Peer review completed: January 24, 2014; Revised version accepted: February 12, 2014; Published: February 19, 2014.