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Mode I interlaminar fracture property of moso bamboo (*Phyllostachys pubescens*)

Zhuo-Ping Shao · Chang-Hua Fang · Gen-Lin Tian

Abstract Bamboo is a unidirectional fiber-reinforced bio-composite. Once having cracks, the delaminating propagation is not controlled by the strength but by the interlaminar fracture toughness. In this paper, the behaviors of Mode I (crack opening mode) interlaminar fracture parallel to grain of moso bamboo (*Phyllostachys pubescens*) were studied. Based on energy theory, the Mode I interlaminar fracture toughness, G_{IC}, was measured using the double cantilever beam specimens, and the fracture surfaces were examined under scanning electron microscope. The results show that: (1) the interlaminar fracture toughness of Mode I is the basic characteristic of bamboo material. The mean value of $G_{IC} = 358$ J/m^2 (coefficient of variation $= 16.88\%$) represents the resistance arresting crack propagation. No significant difference was found for G_{IC} among the specimens located at different heights of the bamboo. (2) Due to the low G_{IC} of bamboo, the crack propagation parallel to grain developed easily. The crack was a self-similar fracture without fiber-bridging. On the fracture surfaces, smooth fibers and plane ground tissue were found at the extended area of Mode I fracture along the longitudinal direction. Under scanning electron microscope, it could be seen that the crack propagation developed along the longitudinal interface between fibers or ground tissue. It indicates that the longitudinal interface strength was weak among bamboo cells.

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Introduction

Through millions of years' evolution, bamboo has formed a particular structure in order to bear the bending load mainly caused by snow or wind. This structure contributes to its high transverse bending strength and toughness. In contrast, the anti-cleaving and anti-shearing strength along the grain of bamboo is relatively low. Therefore, bamboo often cracks along the grain direction while drying. Many studies have reported on the general mechanical properties of bamboo (Zeng et al. 1992; Ahmad and Kamke 2005; Obataya et al. 2007), but researches on fracture characteristics of bamboo are few.

The unique tissue of bamboo culm is the material basis of perfect mechanical characteristics. Various types of cells can be distinguished in bamboo. However, in view of the mechanism, bamboo cells can be classified into two groups: one is parenchymatous ground tissue, which can pass loads and take the role of a composite matrix; the other one is sclerenchymatous tissue, which is made up of bundle-sheaths. The bundle-sheaths are the main component determining mechanical characteristics of bamboo. In the entire bamboo tissue, the ground tissue accounts for about 50%, the bundle-sheaths 40%, and the rest are vessels and primary xylem (Shen 1993). Therefore, in view of macro-mechanical behavior, bamboo is a typical unidirectional long-fiber-reinforced bio-composite. It exhibits significant anisotropy in strength and stiffness corresponding to longitudinal, radial and transverse directions. The tensile strength along the longitudinal direction can be as large as 150–300 Mpa, but the transverse tensile strength and shear strength parallel to grain are fairly low. Zeng et al. (1992) reported that the tensile strength perpendicular to grain was only about 2% of the one parallel to grain. Therefore, the lateral tensile and interlaminar shear force exerted exteriorly or caused by changes in the surrounding conditions are prone to cause interlaminar fracture parallel to grain of bamboo. Then, the interlaminar cracking is controlled by the interlaminar fracture toughness rather than by the transverse strength of bamboo. Even the crack or lacuna perpendicular to grain of bamboo may easily be transformed to develop along the grain direction under loads, and thereby influencing the mechanical behavior.

In this study, based on energy theory, the Mode I interlaminar fracture toughness (G_{IC}) of bamboo was measured, and further discussion on the crack propagation behavior and mechanism are given. Moso bamboo (*Phyllostachys pubescens*) was used in the study as it is the most extensively used bamboo material in China. It covers over 2.5 million km^2 and accounts for more than 90% of total moso bamboo forest area in the world (Zhang 2003). Moso bamboo can be used as construction framework, carriage soleplate, packing board, furniture panel, etc. (Li et al. 2000).

Materials and methods

The moso bamboo (*Phyllostachs pubescens*) used in the tests was 4 years old and came from Lujiang, Anhui Province, China. The total height was about 15 m, and the diameter at breast height was 125 mm. The specimens were collected from the

internode sections located at a height between 0.6 and 6 m of the bamboo. After air-drying, the specimens were cut parallel to grain into small pieces. The moisture content of the specimens was about 11% during the experiment.

The Mode I interlaminar fracture toughness, i.e. the critical value of energy release rate, G_{IC}, for delamination growth of composite material is often measured by symmetric bending tests using double cantilever beam (DCB) specimen and calculated with the compliance of the specimen (Hodgkinson 2000). Triboulot et al. (1984) measured wood fracture toughness for TL-crack opening mode using DCB method, and compared it with finite element analysis (FEA). The results tallied well with each other. Now, the DCB method has been recommended by American Society for Testing and Materials (ASTM) as standard measurement for Mode I interlaminar toughness of unidirectional fiber-reinforced composites (ASTM D 5528 2001).

For DCB specimen shown in Fig. 1 under opening loads (Fig. 2), the strain energy U and its release rate G_{IC} can be calculated as follows:

$$U = \frac{1}{2}F\delta = \frac{1}{2}F^2C \tag{1}$$

$$G_{IC} = \frac{\partial U}{\partial A} = \frac{F_{cr}^2}{2b}\frac{\partial C}{\partial a} \tag{2}$$

where δ is load point deflection, $C = \delta/F$ the compliance of DCB specimen. Therefore, it is only necessary to measure the differential increase in compliance (∂C) depending on the differential increase in crack length (∂a), and then the G_{IC} can be calculated by Eq. 2.

The bamboo DCB specimens were taken from three different heights of the culm, i.e., Section 7 (height of 1.3 m), Section 14 (height of 3 m) and Section 19 (height of 5 m), respectively. Five or six DCB specimens per internode section were prepared according to ASTM (ASTM D 5528 2001). The dimensions of the specimens are shown in Fig. 1. Generally, the initial crack of the wood specimen was first cut by a band saw and then extended by a razor blade (Yoshihara and Ohta 2000; Reiterer and Tschegg 2002). In our case, the initial crack of bamboo specimen was cleaved by knife along the middle-line of the specimen parallel to grain in order to simulate a naturally sharp crack. The range of initial crack length (α_0) was
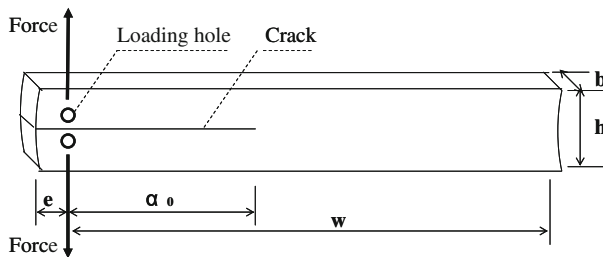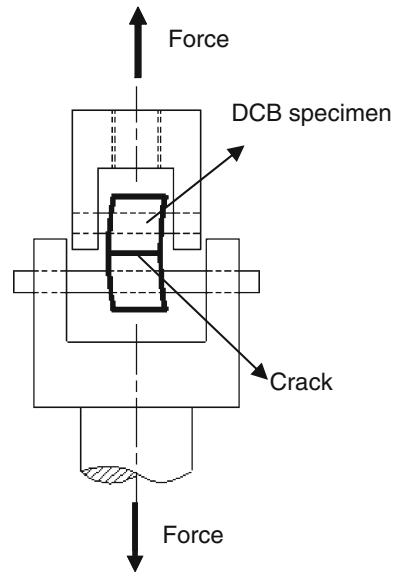

Fig. 1 Sketch of double cantilever beam (DCB) specimen. $w = 200$ mm (longitudinal direction); $e = 20$ mm; $h = 20$ mm (tangential direction); $b = 8$–10 mm (natural thickness, radial direction); diameter of loading hole = 5 mm; $\alpha_0 = 40$–50 mm

Fig. 2 Sketch of U hook for testing

controlled within 40–50 mm. The crack was produced in the longitudinal–radial plane, which is the so-called TL system (T = tangential and L = longitudinal) where the first letter indicates the direction normal to the crack propagation plane and the second determines the direction of crack propagation.

Tests were performed on a computer-controlled testing machine. The test room temperature was 18°C, and the humidity was 60%. The DCB specimen was connected with steel U hook by steel pin (Fig. 2) with a crosshead speed between 1 and 5 mm/min. At the beginning of the test, a low crosshead speed was used, while the cantilever beams were short in order to facilitate identifying the initial movement of the delamination. The crosshead speed was increased when the cantilever beams were relatively long (Hodgkinson 2000; ASTM D 5528 2001). A curve of the applied load versus opening displacement (F–δ) was automatically recorded by a computer during the test. From start loading to maximum load F_{max}, the F–δ curve remained linear until the specimen started crazing. Once crazing, the bearing capacity of the specimen decreased sharply and the crack propagation parallel to grain was unstable. The top point of F–δ curve represented the critical point of rapid cracking and F_{max} was taken as the critical load value F_{cr}. After the load went down, the test machine was stopped immediately and the recorded data was stored. The crack tips were marked on both sides of the specimen by means of optical microscope. Then, the specimen was unloaded and reloaded and the same procedure was repeated until the specimen was fractured completely. The specimen was taken from the test machine and the crack length after each increment of delamination crack growth was measured. As the resistance arresting crack propagation of the outer layer is lower than that of the inner layer of bamboo, the delamination crack lengths on each side were unequal and the crack of the outer layer was 5–6 mm longer than that of the inner layer. Thus, the average crack length of two sides was taken as the actual crack length.
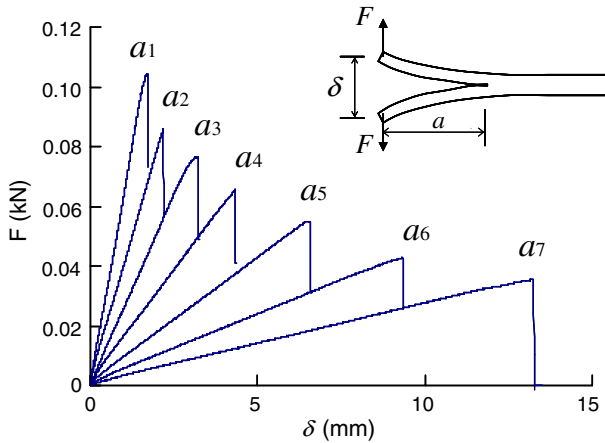
Fig. 3 Typical F–δ curve of DCB specimen. $a1 = 45$ mm, $a2 = 60$ mm, $a3 = 72$ mm, $a4 = 89$ mm, $a5 = 114$ mm, $a6 = 141$ mm and $a7 = 173$ mm are crack lengths

F–δ curves corresponding to different crack lengths obtained from one of the DCB specimens of this study are shown in Fig. 3, which shows the typical F–δ curve of DCB specimen. With increasing crack length, the slope of the linear part of F–δ curve decreased. The reciprocal of the slope is the corresponding compliance (C_i) of the DCB specimen with a certain crack length (α_i). The relationship between C and α of this specimen is shown in Fig. 4. A power law relationship between C and α could be obtained as follows:

$$C = qa^m \tag{3}$$

where q and m are the fitting coefficients of the compliance curve of the DCB specimen. The values of index m calculated in this study ranged from 2.1 to 3. The coefficients of determination (R^2) were all above 0.98.

Mode I fracture toughness, G_{IC}, was calculated by Eq. 2. The arithmetic mean values of toughness of one specimen $\bar{x}$ and one group of specimens $\overline{X}$ were calculated respectively as:

$$\bar{x} = \frac{1}{k} \sum_{i=1}^{k} (G_{IC})_i \tag{4}$$

$$\overline{X} = \frac{1}{n} \sum_{j=1}^{n} \bar{x}_j \tag{5}$$

where k is the amount of measured points of one specimen and n the amount of the specimens in one group.

Results and discussion

The total mean value and standard deviation of G_{IC} in this study were 358.08 ± 61.18 J/m^2 (Table 1). The variance analysis of G_{IC} in different sections,

$$C = 0.0016a^{2.3814}$$
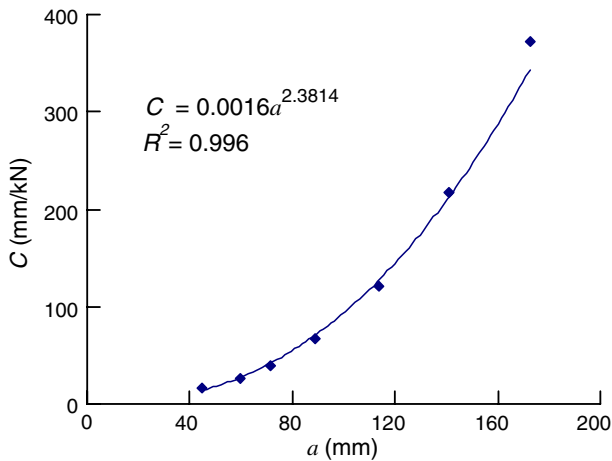$$R^2 = 0.996$$

Fig. 4 Relationship between compliance (C) and crack length (a)

Table 1 Statistical analysis of Mode I interlaminar fracture toughness (G_{IC}) for different sections of the bamboo

Section	Location (height, m)	Number of samples	Number of measurements	Mean G_{IC} (N mm^2)	Standard deviation	Coefficient of variation (%)
7	1.3	6	41	371.17	52.39	14.44
14	3.4	6	52	351.55	64.20	18.02
19	5.1	5	41	367.96	64.07	18.02
Total		17	134	358.08	61.18	16.88

i.e., at different heights, is shown in Table 2 and no significant difference was found among different heights.

In general, along the longitudinal direction, bamboo density increases from the bottom to the top (Ma and Ma 1997). In this study, the mean air-dry densities of the samples located at Section 7 (height of 1.3 m), Section 14 (height of 3 m) and Section 19 (height of 5 m) were 0.636, 0.712 and 0.729 g/cm^3, respectively. The increased density could be explained by the increased bundle-sheath proportion as from the bottom to the top of bamboo the culm diameter decreased, but the amount of bundle-sheath varied little. Density is always important to characterize the property of cellular materials. However, for Mode I interlaminar fracture toughness (G_{IC}) of bamboo, no significant difference was found among different heights, i.e., among different densities. This may be explained because the resistance arresting crack propagation was governed by the properties of the interface between bamboo cells or cell walls. Similarly, along the radial direction, bamboo density increased from the inner to the outer part due to the increasing bundle-sheath proportion. Accordingly, mechanical strength should increase from the inner to the outer part. Whereas, as mentioned above in the section "Materials and methods", during the tests it was found that the delamination crack lengths on each side of the samples

Table 2 Variance analysis of Mode I interlaminar fracture toughness (G_{IC}) for different sections of the bamboo

Sources of variation	SS	df	MS	F value	$F_{0.05}$	Significance
Between	1,414.9	2	707.5	0.1914	3.0653	Not significant
Within	484,189.1	131	3,696.1			
Sum	485,604	133				
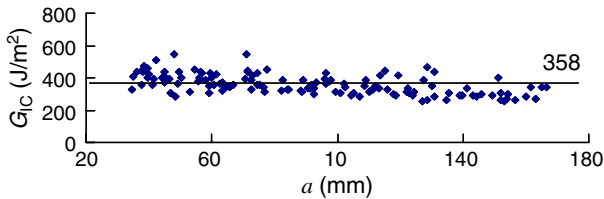
Fig. 5 Relationship between G_{IC} and a

were unequal and the crack of the outer layer was slightly longer than that of the inner layer. It indicates that the resistance arresting crack propagation of the outer layer was slightly lower than that of the inner layer. As the ground tissue absorbs more energy than the bundle-sheath due to its higher flexibility during the crack propagating, higher proportion of bundle-sheath and less and incomplete continuous ground tissue in the outer layer caused lower interlaminar strength. This further confirms that the resistance arresting crack propagation was controlled by the interlaminar strength between fibers or ground tissue.

Figure 5 shows the relationship between Mode I interlaminar fracture toughness (G_{IC}) and crack length (a). The value of G_{IC} decreased slightly as the crack length increased, which is similar to the results found on polymer matrix composites (Yu and Jiao 1996). This could be mainly due to the non-linear phenomenon caused by large deflection of double cantilever beam, i.e., so-called geometry-non-linearity, as crack increases. Therefore, for materials with low-flexural modulus or high interlaminar fracture toughness, in order to minimize the error caused by the geometry-non-linearity, the thickness (h) of the specimens should meet the following criteria (Eq. 9) recommended by American Society of Testing Materials (ASTM D5528 2001), to ensure the linearity of the response of load versus displacement.

$$h \geq 8.28\sqrt[3]{G_{IC}a^2/E_{ll}} \qquad (6)$$

where E_{ll} is the modulus of elasticity of the specimen in the fiber direction and in this study this value was replaced by the elastic modulus measured on each section of the bamboo by means of a bending test according to the National Standard of China (National Technical Monitoring Bureau 1995). The specimen dimension in this study met the above condition of Eq. 6. Therefore, although the value of G_{IC} measured on DCB specimen was affected to a certain extent by the crack length, the statistical results show that the change of G_{IC} due to the different crack lengths was
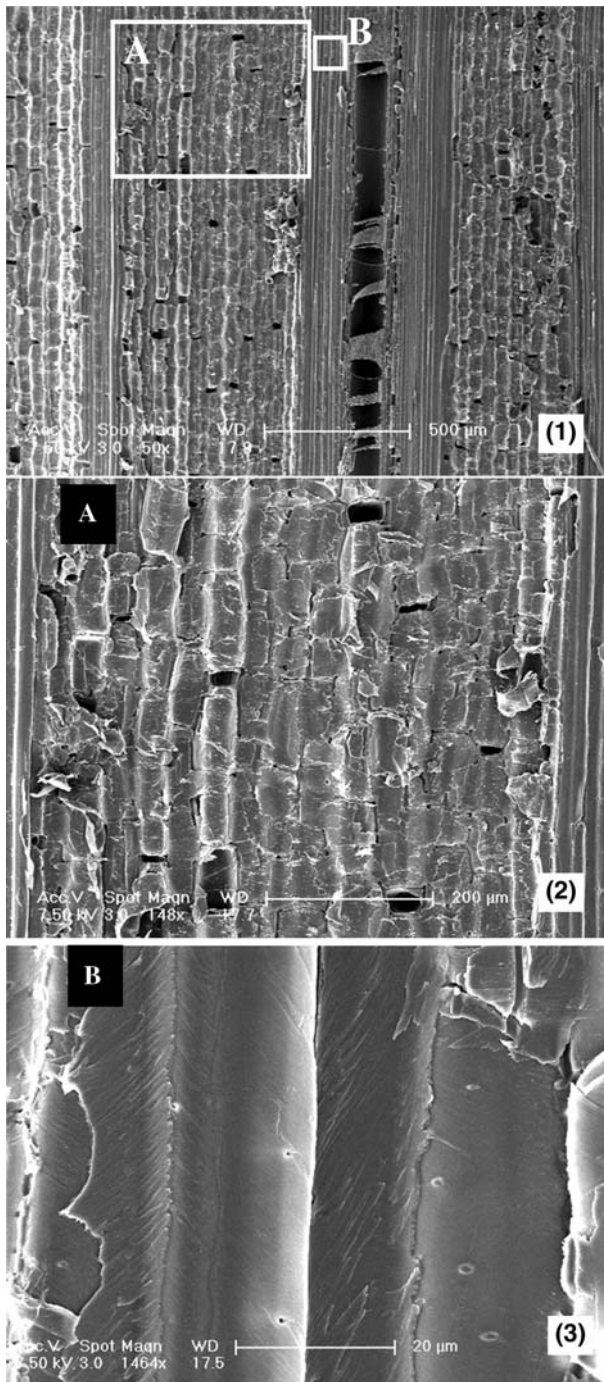
Fig. 6 (**1**) Image of Mode I interlaminar fracture surface of bamboo obtained by scanning electron microscope; (**2**) 148× magnification image of zone *A* in (**1**); (**3**) 1,464× magnification image of zone *B* in (**1**)

not significant in this study. Thereby, the interlaminar fracture toughness of Mode I, G_{IC}, can be regarded as a basic characteristic of bamboo material representing the resistance arresting crack propagation.

Figure 6 shows the micrographs of Mode I interlaminar fracture surface obtained by scanning electron microscope. It can be seen from Fig. 6(1) that in the Mode I crack expanding-area, there are the characteristics of smooth fiber and a matrix (ground tissue) neatly parallel to the stem axis. Fig. 6(2) shows the parenchyma tissue of zone A in Fig. 6(1) after $148\times$ magnification. Viewed from interlaminar fracture surface, the contour of the ground tissue generally maintains integrity. The surface is smooth or with few slice-debris. Occasionally tearing and stripping of the whole cell wall happened. This indicates that the crack propagation among ground-tissues develops along the middle lamella or the primary cell wall. Figure 6(3) shows the fibers of zone B in Fig. 6(1) after $1464\times$ magnification. It shows the integrity of bamboo fiber and the smooth interlaminar fracture surface only with a few traces of slight tearing in the middle lamella or primary cell wall. No tearing or stripping was found on the secondary cell wall. It indicates that the Mode I crack among the bamboo fibers develops through the interface between fibers, which means that the interlaminar strength of bamboo is weak.

Bamboo is a kind of high anisotropic biomaterial with most of its tissues arranged along the longitudinal direction and conglutinated together by the non-cellulose component. This unique structure causes low interface strength. However, it is just because of the weak interface strength that bamboo has high toughness in the transverse direction, which makes bamboo adapt to bending load caused by snow or wind. This could be explained by the toughening mechanism due to weak interface, which was first described by Cook et al. (1964) and has been widely used in designing composite material.

Conclusion

Bamboo is a typical unidirectional long-fiber reinforced bio-composite. In this paper, the behaviors of Mode I (crack opening mode) interlaminar fracture parallel to grain of moso bamboo (*Phyllostachys pubescens*) were studied using the double cantilever beam (DCB) specimens. From this study the following conclusions are drawn:

- Mode I interlaminar fracture toughness, G_{IC}, is a basic characteristic of bamboo material, which represents the resistance arresting crack propagation of Mode I interlaminar fracture parallel to grain. In this study, the mean G_{IC} was 358.08 J/m^2 (coefficient of variation = 16.88%) and no significant difference was found for G_{IC} among the specimens located at different heights of the bamboo.
- Due to the low G_{IC} of bamboo, the crack propagation parallel to grain developed easily. The crack was a self-similar fracture without fiber-bridging. On the fracture surfaces, smooth fibers and plane ground tissue were found on the extended area of Model I fracture along the longitudinal direction. Under scanning electron microscope, it could be seen that the crack propagation

developed along the longitudinal interface between fibers or ground tissue. It indicates that the longitudinal interface strength was weak among bamboo cells.

References

Ahmad M, Kamke FA (2005) Analysis of Calcutta bamboo for structural composite materials: physical and mechanical properties. Wood Sci Technol 39(6):448–459

American Society of Testing Materials (ASTM) (2001) Standard test method for Mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites. Annual book of ASTM standards. Philadelphia, PA, D 5528-01

Cook J, Gordon JE, Evans CC, Marsh DM (1964) A mechanism for the control of crack propagation in all-brittle systems. Proc R Soc 282A:508–520

Hodgkinson JM (2000) Mechanical testing of advanced fibre composites. Woodhead Publishing and CRC Press, Cambridge

Li Q, Hua XQ, Yu XW, Fu QT (2000) Development of artificial bamboo board and its research direction in China. J Zhejiang For Sci Technol 20(3):79–85 (in Chinese)

Ma LF, Ma NX (1997) Study on variation in bamboo wood properties of *Phyllostachys heterocycla* var. pubescens. Sci Silvae Sin 33(4):357–364 (in Chinese)

National Technical Monitoring Bureau (1995) National standard GB/T 15780–1995: testing methods for physical and mechanical properties of wood. China Standard Press, Beijing

Obataya E, Kitin P, Yamauchi H (2007) Bending characteristics of bamboo (*Phyllostachys pubescens*) with respect to its fiber–foam composite structure. Wood Sci Technol 41:385–400

Reiterer A, Tschegg S (2002) The influence of moisture content on the mode I fracture behaviour of sprucewood. J Mater Sci 37:4487–4491

Shen ZQ (1993) Wood science. Forest Publishing Company of China, Beijing

Triboulot P, Jodin P, Pluvinage G (1984) Validity of fracture mechanics concept applied to wood by finite element calculation. Wood Sci Technol 18(6):448–459

Yoshihara H, Ohta M (2000) Measurement of Mode II fracture toughness of wood by the end-notched flexure test. J Wood Sci 46:273–278

Yu ZC, Jiao GQ (1996) The size effects of crack in DCB test of composite materials. J Aeronaut Mater 16(4):46–53 (in Chinese)

Zeng QY, Li SH, Bao XR (1992) Effect of bamboo nodal on mechanical properties of bamboo wood. Sci Silvae Sin 28(3):247–252 (in Chinese)

Zhang QS (2003) Attaching importance to science and innovation in the processing and utilization of bamboo timber in China. J Zhejiang For Coll 20(1):1–4 (in Chinese)