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The toughness contribution of bamboo node to the Mode I interlaminar fracture toughness of bamboo

Fuli Wang · Zhuoping Shao · Yijun Wu · Dong Wu

Abstract   Bamboo is a kind of biological composite reinforced by unidirectional long fibers. The cleavage strength along grain of bamboo internode is low; however, the existence of bamboo node can hinder the propagation of interlaminar crack to make up for the defect of weak opening mode fracture toughness along interlamination. In this article, the double cantilever beam method was applied to test the Mode I interlaminar fracture toughness of Moso bamboo internode specimens and specimens with node to study the difference of the Mode I interlaminar fracture toughness between Moso bamboo internode specimens and specimens with node. The results are shown as follows: the Mode I interlaminar fracture toughness of Moso bamboo internode specimens was $G_{IC}^{\text{Internode}} = 498$ J/m^2 (SD $= 65$ J/m^2); the Mode I interlaminar fracture toughness of Moso bamboo specimens with node was $G_{IC}^{\text{Node}} = 1{,}431$ J/m^2 (SD $= 198$ J/m^2). It can be seen that the Mode I interlaminar fracture toughness of bamboo specimens with node was higher than that of bamboo internode specimens, and the toughness contribution of node to bamboo Mode I interlaminar fracture toughness was 1.87 times. The conclusion was drawn that bamboo node can contribute a lot to hinder the interlaminar fracture of bamboo.

Introduction

Through millions of years' natural selection of the process of survival of the fittest, the fine structure of all living beings has been evolved to go through their environment. As a kind of natural biological composite reinforced by unidirectional long fibers, bamboo has a unique superior structure. The reinforcements are vascular bundles constituted by phloem cells, and the matrix is constructed by parenchyma cells. For the whole bamboo tissue, the parenchyma tissue accounts for about 50 %,

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the bundle sheaths 40 %, and the rest are vessels and primary xylem parenchyma cells (Shen 1993). It is known that bamboo has the flexibility to adapt to bending damages caused by natural forces and external forces from humans and animals, but this fine property is at the cost of the weak interface layer along the grain resulting in weak cleavage strength, tensile strength, and shear strength along the grain. However, for a whole bamboo culm to overcome this disadvantage, the excellent structure "internode + node" has formed after millions of years of evolution. The existence of node changes the damage pattern that when damage along the grain happens, the force to resist the cleavage only comes from the weak interfacial resistance. Thus, the cleavage strength along the grain is greatly improved, and this is also the perfect embodiment of function adaptability of biological material. At present, there are many studies on general mechanical properties of bamboo (Zeng et al. 1992; Ahmad and Kamke 2005; Obataya et al. 2007), but few on the fracture toughness. It is known that interlaminar fracture is easy to happen for unidirectional fibrous composites, and once crack takes place, the propagation of interlaminar crack is controlled by the interlaminar fracture toughness but not the strength of the composite (Shao et al. 2009). Then, the structural integrity is influenced, which leads to the decrease in rigidity and finally damage happens (Compston et al. 2001). In recent years, the Mode I interlaminar fracture of various composites has been studied by researchers (Wang et al. 2004; Barati and Alizadeh 2012; Khoshravan and Asgari Mehrabadi 2012), but for the Mode I interlaminar facture of bamboo, only Shao et al. (2008, 2009) proposed the crack propagation behavior and mechanism of the Mode I interlaminar fracture of Moso bamboo internode. However, no study on the Mode I interlaminar fracture of bamboo specimens with node was found by literature search. Because of the unique structure, there is a great difference between bamboo internode and node in structure, which leads to the difference in physicomechanical properties. The influence of node on general mechanical properties and transverse fracture of bamboo and the difference between bamboo internode and node in structure have been studied by Zeng et al. (1992), Shigeyasu and Sun (2001) and Shao et al. (2008, 2010). In this article, following the study "Mode I interlaminar fracture property of bamboo (*Phyllostachys pubescens*)" authored by Shao et al. (2009), based on the energy theory, the Mode I interlaminar fracture toughness difference between bamboo internode specimens and bamboo specimens with node was studied by double cantilever beam (DCB) method aiming at exploring the influence of the existence of node on bamboo Mode I interlaminar fracture.

Material and test method

Material and devices

The material used in this test was one 4-year-old Moso bamboo (*P. pubescens*) from Huoshan, Anhui Province, China. Three adjacent internodes with two nodes (from the 12th internode to the 14th internode) collected as sample were chosen at chest height of the bamboo (Fig. 1). Before drying, the diaphragms in bamboo sample
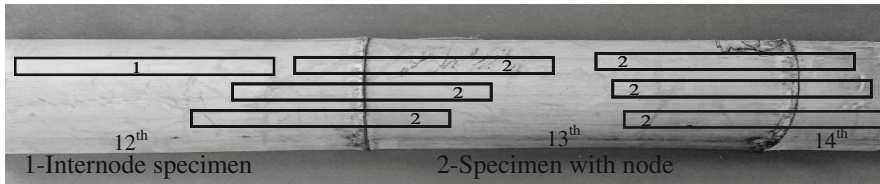
Fig. 1 Schematic diagram of specimen selection

were destroyed to make the sample ventilated during the process of drying. After forced air-drying for 7 days (60 °C) in a constant temperature humidity chamber and natural air-drying for 90 days, the sample was cut into pieces along the grain with a width of 22–25 cm.

WDW-100 computer-controlled universal mechanical testing machine was used with a test force accuracy of ±5 ‰, displacement resolution of 0.01 mm, and speed accuracy of 1 ‰. 15kN mechanical sensor, steel U hook, and steel pins, etc., were also applied.

Test method

The DCB method is always used to study the Mode I interlaminar fracture of composites. The DCB method by Triboulot et al. (1984) and Hodgkinson (2000) was used to test the fracture toughness of composites, and the finite element method was used for verification and analysis, which proved that the results by DCB method were valid. In the year 2001, the DCB method has been recommended by the American Society for Testing and Materials (ASTM) as standard measurement for Mode I interlaminar toughness of unidirectional fiber-reinforced composites (ASTM D5528 2001), and in the year 2009, Shao et al. (2009) firstly used the DCB method to test the Mode I interlaminar fracture toughness of bamboo internodes.

For DCB specimens, according to ASTM D5528 (2001), the energy release rate G of Mode I interlaminar fracture is as follows:

$$G = -\frac{1}{b} \cdot \frac{\mathrm{d}U}{\mathrm{d}a} \tag{1}$$

where U total strain energy in the test specimen, b specimen width, a delamination length. And

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

where F load, δ deflection of the load point.

C is compliance of DCB specimens namely the reciprocal of slope (k). It can be calculated by two points (δ_1, F_1), (δ_2, F_2) on the F–δ curve gained by the computer-controlled testing machine:

$$C = \frac{1}{k} = \frac{\delta_2 - \delta_1}{F_2 - F_1} \tag{3}$$

So the Mode I interlaminar fracture toughness G_{IC} is as follows:

$$G_{IC} = -\frac{1}{b} \cdot \frac{\mathrm{d}(-\frac{1}{2}F_{cr}^2 C)}{\mathrm{d}a} = \frac{F_{cr}^2}{2b} \cdot \frac{\mathrm{d}C}{\mathrm{d}a} \qquad (4)$$

Because the bamboo culm has a hollow structure separated with nodes and the length and diameter of each internode are limited, the number of specimens gained was much less than that of normal composites. In this test, the DCB specimens were collected from the 12th internode to the 14th internode, among which the internode specimens were collected from the 12th internode, 7 effective specimens (total number ≥5 recommended by ASTM D5528) were obtained, and the specimens with node were collected from the 12th–13th and 13th–14th internode, 11 effective specimens were obtained, as seen in Fig. 2. Due to ASTM Standard (2001), the dimension of the specimen was 220 × 20 × b (mm) and b was the natural thickness of the bamboo culm along the radial direction. The test room temperature was 25–27 °C, and the humidity was 60 %.

The pre-crack: to simulate a naturally sharp crack, the crack was cleaved along the middle level parallel to the grain by a knife as seen in Fig. 3. For bamboo internode specimen, the length of the initial crack was controlled about 40 mm from the centre of the loading holes; for bamboo specimen with node, the initial crack tip was controlled 2 mm from node to insure that the crack would spread through the node by one-off test. When the initial crack was cleaved and before the knife was pulled out, a red dyeing reagent that had been prepared in advance was used to dye the crack tip in order to obtain accurate initial crack length.

The DCB specimen was connected with a steel U hook by a steel pin loaded by the computer-controlled testing machine with a crosshead speed between 1 and 4 mm/min. For bamboo internode specimens, single specimen with multi-point method was used, that is, for one single internode specimen, during loading, crack propagated and the corresponding applied load versus load point deflection (F–δ) curve was recorded by a computer. Once the load (F) went down, the load machine stopped, and the crack tip at both the inner part (a_{1inner}) and the outer part (a_{1outer}) of
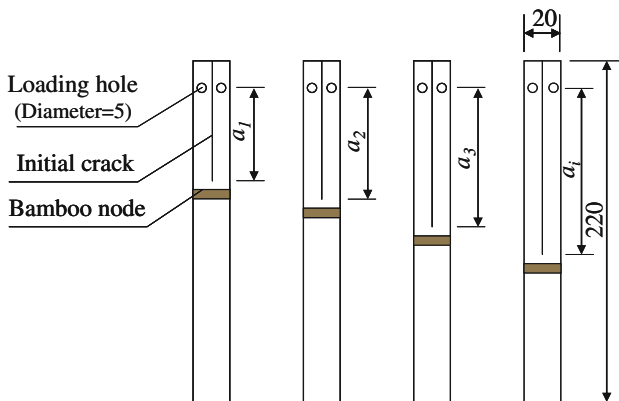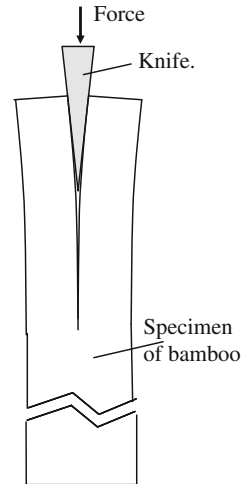

Fig. 2 Schematic diagram of Mode I interlaminar fracture specimens with node (unit mm)

Fig. 3 Schematic diagram of crack cleaving

the internode specimen was marked taking the average length of a_{1inner} and a_{1outer} as the corresponding crack length a_1. Then, it was unloaded and reloaded and the same procedure was repeated until complete fracture appeared so the corresponding crack length a_2, a_3, $a_4…a_n$ was obtained. The loading speed was lifted with increasing length of crack (Hodgkinson 2000); for bamboo specimens with node, multi-specimen with single-point method was used, that is, on one single specimen with node, load was applied only once and the crack length a was obtained by averaging the a_{inner} and a_{outer} correspondingly. For different specimens, the loading speed was lifted properly with increasing length between node and the center of loading holes. The curve of load–load point deflection (F–δ) was automatically recorded by a computer during the test. The typical F–δ curve of one internode specimen is shown in Fig. 4, and the crack length of each curve from test point a_1 to test point a_{29} was 43.80, 46.75, 49.10, 50.65, 53.10, 55.30, 56.50, 59.10, 61.80, 64.50, 67.55, 74.65, 76.65, 79.80, 84.95, 89.40, 94.00, 97.50, 101.35, 112.20, 115.85, 122.05, 129.55, 133.60, 138.00, and 141.70 (unit mm), respectively, and for the internode specimen, 29 test points were collected; the F–δ curves of all specimens with node are shown in Fig. 5, and the corresponding crack length was 45.00, 51.00, 62.50, 63.65, 70.30, 80.00, 80.75, 103.50, 117.50, 133.60, and 136.25 (unit mm), respectively. From the two figures, it could be seen that in the initial loading, the F–δ curve kept linear until the specimen started crazing. Once crazing, the bearing capacity of the specimen decreased sharply and then the crack rapidly propagated along the grain. The maximum load F_{max} of the F–δ curve was determined as the critical load F_{cr}.

After the test was finished, the specimens with node were cleaved to measure initial crack length: at the front end of the dyeing area, five points were marked from the outer bamboo wall to the inner bamboo wall uniformly, and the distance between each point and the center of loading holes was measured. Finally, the average length of the five points was gained as the initial crack length (Fig. 6).
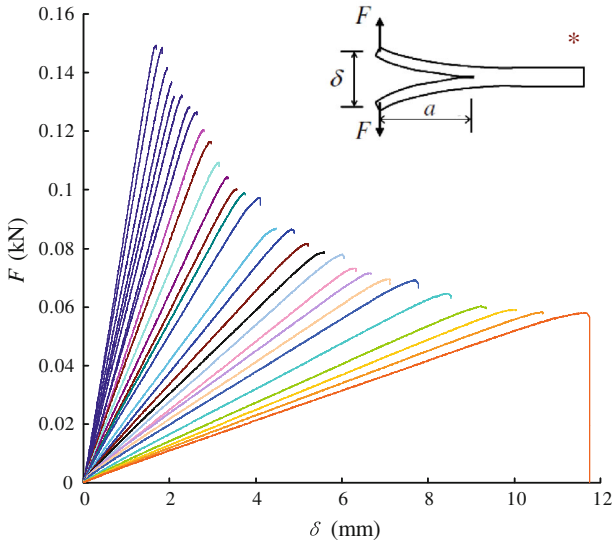
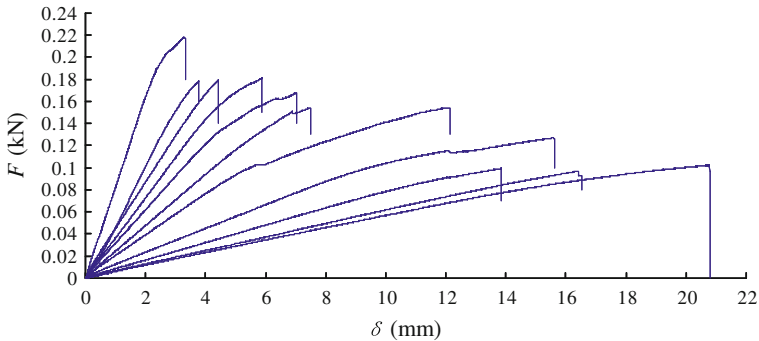**Fig. 4** Typical Mode I interlaminar fracture F–δ curve of one internode specimen

Fig. 5 Mode I interlaminar fracture F–δ curves of all specimens with node

From the typical F–δ curve of DCB specimen, it could be seen that 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 (a_i). According to the compliance method, a power law relationship between C and a can be obtained as follows:

$$C = qa^m \tag{5}$$

where q and m are the fitting coefficients of the compliance curve of the DCB specimen.

Fig. 6 Measurement of the
initial crack length of specimen
with node
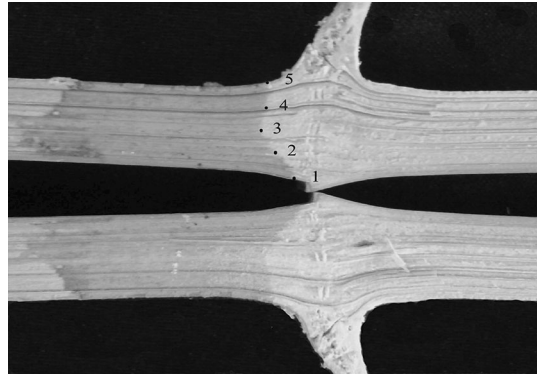
Results and analysis

Reliability analysis of data

In this test, the fitting coefficient q ranged from 0.0007 to 0.0017, the fitting coefficient m from 2.34 to 2.52, and the regression coefficients R^2 were all above 0.98. The fitting curve of a and C of one internode specimen is shown in Fig. 7. To analyze the reliability of the data, the data analysis software SPSS was used. According to SPSS, *Linear Model* was chosen to perform the linear regression analysis. So after taking logarithm of formula (5), it met the linear model, as follows:

$$\lg C = \lg q + m \lg a \tag{6}$$

The linear regression analysis result of lg$a$ and lg$C$ of the corresponding internode specimen is shown in Table 1. The C and a fitting curve of all specimens with node is shown in Fig. 8. And the corresponding linear regression analysis result of lg$a$ and lg$C$ is shown in Table 2. It can be seen from the Table that lg$C$ has a remarkable correlation to lg$a$ and the data are reliable.
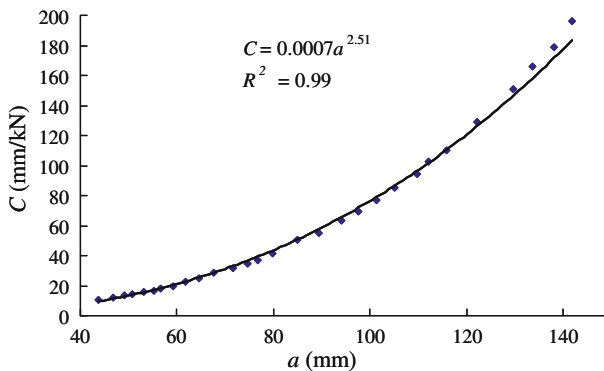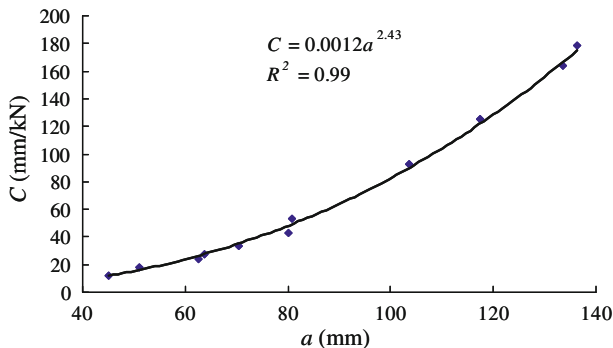

Fig. 7 *Fitted curve* of test curve compliance and crack length of one internode specimen

Table 1 Corresponding linear regression analysis result of lg*a* and lg*C* of one internode specimen

Model	Sum of squares	df	Mean square	F	Sig.
Regression	4.31	1	4.31	15,185.931	0.000
Residual	0.008	27	0.000		
Total	4.317	28			

Predictors: (constant), *lga*; dependent variable: *lgC*

$$C = 0.0012a^{2.43}$$
$$R^2 = 0.99$$

Fig. 8 *Fitted curve* of test curve compliance and crack length of all specimens with node

Results and discussion

According to Formula (4), by DCB method, the Mode I interlaminar fracture toughness of internode specimens is listed in Table 3 and the Mode I interlaminar fracture toughness of specimens with node in Table 4. From the information above, the average Mode I interlaminar fracture toughness of internode specimens was 498 J/m^2 (SD = 65 J/m^2) with coefficient of variation of 12.9 %; the average Mode I interlaminar fracture toughness of specimens with node was 1,431 J/m^2 (SD = 198 J/m^2) with coefficient of variation of 13.8 %. The conclusion was drawn that the Mode I interlaminar fracture toughness of bamboo specimens with node was much higher than that of bamboo internode specimens.

The relationship between crack length (*a*) and Mode I interlaminar fracture toughness (G_{IC}) of both internode specimens and specimens with node is shown in Fig. 9, from which it is obvious that the Mode I interlaminar fracture toughness of

Table 2 Corresponding linear regression analysis result of lg*a* and lg*C* of all specimens with node

Model	Sum of squares	df	Mean square	F	Sig.
Regression	1.58	1	1.58	1,573.66	0.000
Residual	0.009	9	0.001		
Total	1.589	10			

Predictors: (constant), *lga*; dependent variable: *lgC*

Table 3 Descriptive statistics of the Mode I interlaminar fracture toughness of all internode specimens

Specimen no.	Number of test points	$G_{IC}^{Internode}$ (J/m^2)	Standard deviation	Coefficient of variation (%)
1	7	523	56	10.7
2	11	538	71	13.1
3	14	509	58	11.4
4	19	547	82	14.9
5	29	475	43	9.0
6	19	473	59	12.5
7	18	470	38	8.1

Table 4 Mode I interlaminar fracture toughness of all specimens with node

Specimen no.	a (mm)	b (mm)	Fmax (kN)	C (mm/kN)	dc/da	G_{IC}^{Node} (J/m^2)
1	45.00	11.20	0.217	12.096	0.661	1,396
2	51.00	11.10	0.178	17.983	0.79	1,128
3	62.50	11.20	0.179	23.91	1.056	1,518
4	63.65	11.05	0.181	27.377	1.084	1,614
5	70.30	11.00	0.168	33.068	1.249	1,599
6	80.00	10.85	0.155	42.976	1.501	1,653
7	80.75	11.30	0.154	53.436	1.521	1,603
8	103.50	11.80	0.126	92.945	2.167	1,462
9	117.50	11.60	0.099	125.44	2.596	1,105
10	133.60	12.00	0.097	164.18	3.118	1,223
11	136.25	11.60	0.102	178.65	3.206	1,445
Average						1,431

a initial crack length; *b* natural thickness of bamboo wall; F_{max} was determined as the critical load F_{cr}

bamboo specimens with node is much higher than that of bamboo internode specimens. The Mode I interlaminar fracture toughness of bamboo internode specimens decreased slightly with increasing crack length, which could be mainly due to the nonlinear phenomenon caused by large deflection of DCB, i.e., so-called geometry nonlinearity, as crack increases (Yu and Jiao 1996); however, there was no obvious trend for the Mode I interlaminar fracture toughness of specimens with node, which may result from the small amount of specimens.

From the results above, it can be concluded that the Mode I interlaminar fracture toughness of bamboo specimens with node is much higher than that of bamboo internode specimens, which was mainly caused by the difference in structure between bamboo internode and node (Table 5). The bamboo internode wall consists of the outer wall, the middle of wall, and the inner wall, and the distribution density of vascular bundles from the outer to the inner decreased gradually; on the contrary, the proportion of ground tissue increased gradually, and in the inner wall, there is
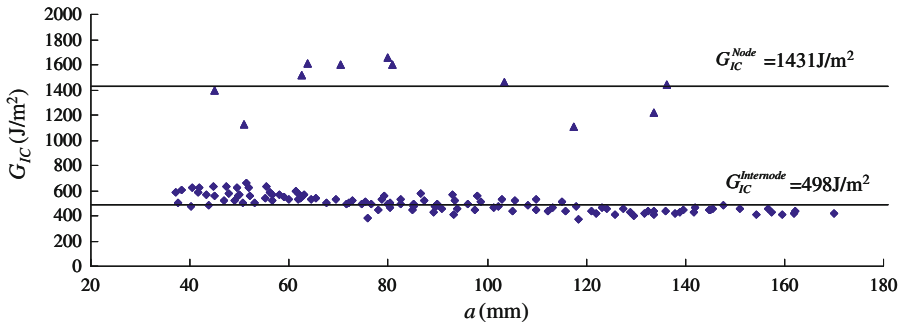
Fig. 9 Relationship between a and G_{IC} of both internode specimens and specimens with node

Table 5 Statistics analysis of all test points of internode specimens and specimens with node

Specimen	Number of all test points	G_{IC} (mean) (J/m²)	Standard deviation (J/m²)	Coefficient of variation (%)
Internode	117	498	65	12.9
With node	11	1,431	198	13.8

only few vascular bundles. It is known that the cells of bamboo internode are strictly axially arranged and there is no transverse ray cell (Fig. 10). The node of Moso bamboo consists of nodal ridge, sheath scar, and diaphragm (Jiang and Peng 2007), which strengthen the bamboo culm to stand upright and also play the role of transporting water transversely. When vascular bundles pass through node from internode, they bend inordinately except for the outmost vascular bundle that breaks off at where sheath scar falls off. Among bending of the vascular bundles, some bend slightly outwards or inwards in node, but when they have passed through, they recover straight in internode; the other vascular bundles change their direction in node: the vascular bundles close to the inner wall trend to the outer wall and the vascular bundles close to the outer wall trend to the inner wall oppositely; meanwhile, there are some vascular bundles entering into the diaphragm circuitously, which incline procumbent circumferentially or interweave together through diaphragm to the opposite wall. The bent vascular bundles are generally thickened in node; thus, the thickness of the bamboo wall at node is thicker than that at internode. As seen in Fig. 11 (Jiang and Peng 2007), the reconstruction 3D structure graph of bamboo node reflects the structure feature of vascular bundles vividly.

It is known that the strength of cell body biomaterial depends on the thickness of the cell wall; however, the Mode I interlaminar fracture resistance of bamboo is determined by the interface property between cells and wall layers. For bamboo internode, the resistance comes from the interface resistance between ground tissue and ground tissue, ground tissue and vascular bundle, vascular bundles and vascular bundles; for bamboo node, the resistance not only comes from the interface
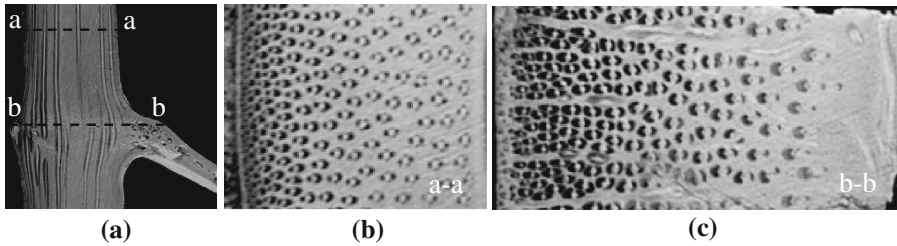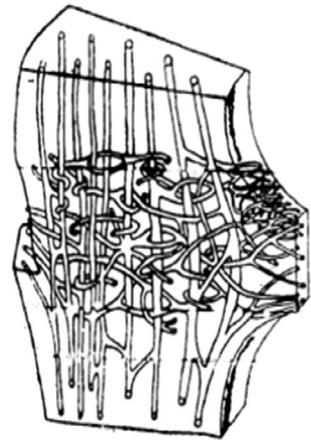
Fig. 10 Structure of internode and node: **a** bamboo *diametral plane*, **b** *cross section* of bamboo internode, **c** *cross section* of bamboo node

Fig. 11 *Reconstruction graph* of bamboo node 3D structure (Jiang and Peng 2007)

resistance between ground tissue and ground tissue, ground tissue and vascular bundle, vascular bundles and vascular bundles but also from the contribution of the fracture of transverse vascular bundles. As seen in Fig. 10, from the radial section of bamboo node, the transverse vascular bundles distribute sporadically and then gradually densely thickened from the outer wall to diaphragm; meanwhile, some vascular bundles distribute dispersedly in tangential direction and it can be seen that once Mode I interlaminar fracture appears in node, crack has to go through these transverse fibers to propagate continually; thus, the force to resist crack propagation increases, then more energy is needed for the crack to propagate.

Conclusion

In this article, the DCB method was applied to test the Mode I interlaminar fracture toughness of Moso bamboo internode specimens and specimens with node to study the difference of the Mode I interlaminar fracture toughness between Moso bamboo internode specimens and specimens with node. The results are shown as follows: the Mode I interlaminar fracture toughness of Moso bamboo internode specimens was

$G_{IC}^{Internode} = 498$ J/m^2 (SD $= 65$ J/m^2); the Mode I interlaminar fracture toughness of Moso bamboo specimens with node was $G_{IC}^{Node} = 1,431$ J/m^2 (SD $= 198$ J/m^2). It can be seen that the Mode I interlaminar fracture toughness of bamboo specimens with node was 1.87 times higher than that of bamboo internode specimens. The conclusion was drawn that bamboo node can contribute a lot to hinder the interlaminar fracture of bamboo. By analyzing the fracture mechanism, it was the unique structure of node that caused the difference in Mode I interlaminar fracture toughness between internode specimens and specimens with node.

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