Analysis of *Bambusa rigida* Bamboo Culms between Internodes and Nodes: Anatomical Characteristics and Physical–Mechanical Properties

Xingyan Huang Feng Li Cornelis F. De Hoop
Yongze Jiang Jiulong Xie Jinqiu Qi

Abstract

In this research, the anatomical characteristics and physical–mechanical properties of bamboo between internodes and nodes were investigated to evaluate the influence of nodes on the properties of bamboo culm. The results indicate that node sections had lower vascular bundle frequency, shorter fiber length, and wider parenchyma lumen diameters in comparison with internodes. The compressive strength parallel to grain, shear strength parallel to grain, and modulus of elasticity of bamboo culm internodes were significantly higher than those of the nodes. The basic density, volumetric shrinkage, and modulus of rupture of the former were also higher than the latter, although the difference was not significant.

Bamboo has become an important nontimber material because of its rapid growth rate, sustainability, and short maturity cycle (3 to 5 yr). Recently, bamboo is being widely used in the preparation of high-value added products such as furniture, panel, parquets, and structural composites.

Bamboo culms consist of vertically arranged parenchyma tissue, fiber tissue, and conductive tissue (including vessel and phloem). The conductive tissue is surrounded by the fiber tissue to form the vascular bundle (Grosser and Liese 1971). Bamboo culms can be regarded as a composite because the parenchyma tissues act as the matrix and the vascular bundles function as the reinforcement elements. Owing to the high strength and hollow structure, bamboo culm has a high strength-to-weight ratio. It can be comparable or even higher than steel on compressive strength and tensile strength (Gupta et al. 2015). However, because it lacks transversely arranged tissue, bamboo culm is susceptible to being split by force.

Nodes with diaphragms divide the consecutive bamboo stalk into a series of segments and two neighboring internodes sharing one node (Ding and Liese 1995). The presence of nodes not only provides branch points for the leaves of the plant but also strengthens the bamboo culm to stand upright, because nodes have a high energy absorption capacity to resist impact load, and the nodal diaphragm can also enhance the transverse strength of bamboo (Zou et al. 2016). It has been demonstrated that the nodes of bamboo have 1.87 times the toughness of the internode to hinder the interlaminar fracture of bamboo (Wang et al. 2014).

However, the node does not always have a positive effect on bamboo culm. It could accelerate the brown-rot fungi degradation by increasing the weight loss (Tomak et al. 2013). Also, the node is the most critical section for failure under tensile stresses and bending loads (Gupta et al. 2015, Taylor et al. 2015). This weakness of the nodes undermines the mechanical performance of resulting bamboo-based composites (Qi et al. 2015, Semple et al. 2015).

Although extensive publications have focused on the study of bamboo, there are still no consensus results on the effects of nodes on the bamboo culm performance. Anokye et al. (2014a) reported that the mean density in the nodal

The authors are, respectively, Assistant Professor and Graduate Student, College of Forestry, Sichuan Agric. Univ., Chengdu, Sichuan, China (14447@sicau.edu.cn, li_feng2016@126.com); Associate Professor, Louisiana Forest Products Development Center, Louisiana State Univ. Agric. Center, Baton Rouge (cdehoop@lsu.edu); and Assistant Professor, Associate Professor, and Professor, College of Forestry, Sichuan Agric. Univ., Chengdu, Sichuan, China (1728473660@qq.com, jxie6@sicau.edu.cn, qijinqiu2005@aliyun.com [corresponding author]). This paper was received for publication in June 2017. Article no. 17-00035.

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area was higher than that of the internode in bamboo of *Gigantochloa scortechinii*, while Poblete et al. (2009) stated that the node from *Chusquea culeou* had a lower density than the one corresponding to the internode. For the mechanical properties, the difference on compressive strength parallel to grain between node and internode was reported to vary with moisture content (Wakchaure and Kute 2012), bamboo culm height (Hamdan et al. 2009), and species. Bahari and Ahmad (2009) observed the shear strength of node was lower than that of internodes in bamboo of *G. scortechinii*, while Shao et al. (2010) found a completely reverse result in Moso bamboo (*Phyllostachys pubescens*). Shao et al. (2010) also found the node could enhance the bending strength of the bamboo culm; however, this result was opposite to the study on *G. scortechinii* (Hamdan et al. 2009). Note that tensile strength in the node is weaker than that of the internode, which agrees with the consensus (Ahmad and Kamke 2005, Shao et al. 2010, Razak et al. 2012, Wakchaure and Kute 2012). Therefore, it is necessary to expand the research on nodes to a specific bamboo species.

Bambusa rigida is one of the most abundant bamboos in southwestern China. Even though it has been used to produce bamboo-based composites, there is still a challenge to acquire a high-level quality control owing to the lack of comprehensive understanding of bamboo characteristics, especially the effect of nodes on the physical and mechanical properties. Our previous works have demonstrated that the anatomical characteristics, physical properties, and mechanical properties of *B. rigida* vary a lot with age and culm height (Huang et al. 2014a, 2014b, 2015). In this study, the anatomical characteristics, physical properties, and mechanical properties of bamboo between internodes and nodes are comparatively analyzed to provide inspiration and reference for the preparation of high-performance bamboo-based composite.

Materials and Methods

Materials

The culms of 3-year-old *B. rigida* were collected from Sichuan, China. Ten bamboo culms, having diameters at breast height from 47.21 to 50.86 mm, were cut at about 10 mm above the ground level. Thereafter, these culms were removed of branches and top parts, followed by subdividing them into three portions with eight internodes each for base, middle, and top portions. The node was located in the middle of the bamboo sample, which would be used to determine the physical–mechanical properties.

Determination of anatomical characteristics

The anatomical characteristics, such as vascular bundle frequency (VBF), fiber length (FL), and parenchyma lumen diameters (PLD) of internodes and nodes, were determined using the methods reported in our previous research (Huang et al. 2015).

Determination of physical–mechanical properties

The basic densities of internodes and nodes were carried out according to the methods outlined in ISO 22157-1:2004(E) (International Organization for Standardization 2004). The basic density was determined on the basis of ovendried weight and green volume. Oven-drying was conducted in an air-circulated oven at 103°C ± 2°C until a constant weight was acquired. The green volume of samples was determined using the water displacement method.

The mechanical properties from internodes and nodes, such as compressive strength parallel to grain (CSPG), shear strength parallel to grain (SSPG), modulus of rupture (MOR), and modulus of elasticity (MOE), were determined using a universal testing machine (Reger, RGM-4100, China), in accordance with GB/T 15780-1995 (State Bureau of Technology Supervision 1995) and ISO 22157-1:2004(E) (ISO 2004). The sampling schematics are shown in Figure 1. Sample size for the measurement of CSPG, SSPG, and bending tests were 20 mm by 20 mm by culm wall thickness, 35 mm by 20 mm by culm wall thickness, and 200 mm by 12 mm by culm wall thickness, respectively. CSPG and SSPG were measured by loading the specimen at a constant rate of 0.5 mm/min until the maximum load was reached or when failure occurred. Free span length of 150 mm and loading in the culm's wall radial direction were required for the MOR and MOE tests. The bending tests were conducted under a three-point bending device at the cross head vertical speed of 10 mm/min. Thirty replicates were carried out for each sample. The CSPG, SSPG, MOR, and MOE of bamboo culms were calculated as Equations 1 to 4.

$$\text{CSPG (MPa)} = \frac{p_{\max}}{bh} \tag{1}$$

$$\text{SSPG (MPa)} = \frac{P_{\max}}{hL} \tag{2}$$

$$\text{MOR (MPa)} = \frac{3}{2} \times \frac{p_{\max} \times l}{bh^2} \tag{3}$$

$$\text{MOE (GPa)} = \frac{1}{4} \times \frac{\Delta p \times l^3}{\Delta f \times bh^3} \tag{4}$$

where $P_{\max}$ is maximum load at which the sample fails (N), L represents length of shear surface, b represents the width (mm), h represents the depth (culm's wall thickness, mm), l is the free span (mm), and $\Delta p/\Delta f$ is the slope of the elastic zone (N/mm).

Statistical analysis

Statistical analysis was carried out using SAS (SAS Institute Inc. 2004). Analysis of variance (ANOVA) was performed to determine variance difference ($\alpha = 0.05$) among samples from internodes and nodes.

Results and Discussion

Vascular bundles

As shown in Figure 2, vascular bundles for both of internodes and nodes consisted of two metaxylem vessels and one phloem. They were surrounded by sclerenchyma sheaths and embedded in parenchyma tissue. For the nodal area, bunches of small metaxylem elements were also observed, which were branched and reunited from primary xylem. The observation was in line with the literature reported by Grosser and Liese (1971). Some vertically arranged vascular bundles in nodal areas bent radially and went across the diaphragm, resulting in the increase of nodal width compared with the internode. In general, most of the

Figure 1.—Schematic diagram of specimen selection between internodes and nodes (1) compressive strength parallel to grain, (2) shear strength parallel to grain, and (3) bending test. (Color version is available online.)

vascular bundles that passed into the diaphragm were derived from the inner part of the bamboo culm, and the other part came from the periphery (Grosser and Liese 1971). According to the three-dimensional pattern of vascular bundles in nodal areas reconstructed by Ding and Liese (1995), the vascular bundles appeared as an interwoven texture with some bundle branch intertwining around the main vascular bundles or passing into the diaphragm. As for the vascular bundle shape in the nodal area, the fiber sheath closed to intercellular space became longer in the radial direction, while the fiber sheath surrounding vessels tended to be shorter in the tangential direction (Fig. 2), which was in agreement with Grosser and Liese (1971).

The vascular bundle frequency in the node increased from 3.01/mm^2 to 5.63/mm^2 from the base to the top portion of the bamboo culm (Table 1). It was lower than that of the internode, varying from 3.32/mm^2 to 6.97/mm^2. No statistical difference on vascular bundle frequency was observed between internodes and nodes. The reduction of vascular bundle frequency at the nodal area was attributed to the enlargement of the bamboo node combined with the decrease of longitudinal vascular bundle number.

Fiber length

As can be seen in Table 1, the fiber length of the node increased from 1,362 to 1,417 μm from base to middle portion of the bamboo culm, and then decreased to 1,362 μm at the top portion. It was significantly shorter than that of the internode, varying from 1,617 to 1,848 μm. This result was supported by Poblete et al. (2009), who reported that the fiber length in node sections of *Chusquea culeou* bamboo was in the range of 1,000 to 1,080 μm, while the internodal material had an average fiber length between 1,730 and 1,780 μm.

Parenchyma lumen diameter

From base to top portion of bamboo culm, the parenchyma lumen diameter in the nodal area decreased from 30.92 to 23.98 μm, which was significantly larger than that at the internode, which was in the range of 19.07 to 23.43 μm. The increment of parenchyma lumen diameter of the bamboo node was attributed to the increase of bamboo wall thickness at the nodal area.

Basic density

Table 2 shows the difference of physical properties including basic density and volumetric shrinkage between bamboo internodes and nodes. The basic density of nodes exhibited an increasing trend from 542 to 739 kg/m^3 with increasing bamboo culm height. The internode had a higher basic density, with a minimum value of 578 kg/m^3 at the base portion and a maximum value of 808 kg/m^3 at the top portion of bamboo culm. No significant difference on basic density was found between internodes and nodes. This finding was well in agreement with the report of *G. scortechinii* (Anokye et al. 2014a). However, this result was not constant for all bamboo species; for instance, *C. culeou* and *Dendrocalamus asper* have higher density in the nodal area as compared with the internode because the node had thicker fiber cell walls and a higher proportion of fiber (Poblete et al. 2009, Srivaro and Jakranod 2016). In this present study, however, the lower basic density in the nodal area was presumably attributed to its bigger bulk with less vascular bundle in comparison with the internode.

Volumetric shrinkage

Table 2 indicates that the volumetric shrinkage of the node was slightly lower than that of the internode. The former decreased from 14.31 to 10.49 percent with the increase of bamboo culm height, and the latter was observed to decrease from 15.77 to 11.26 percent. The result

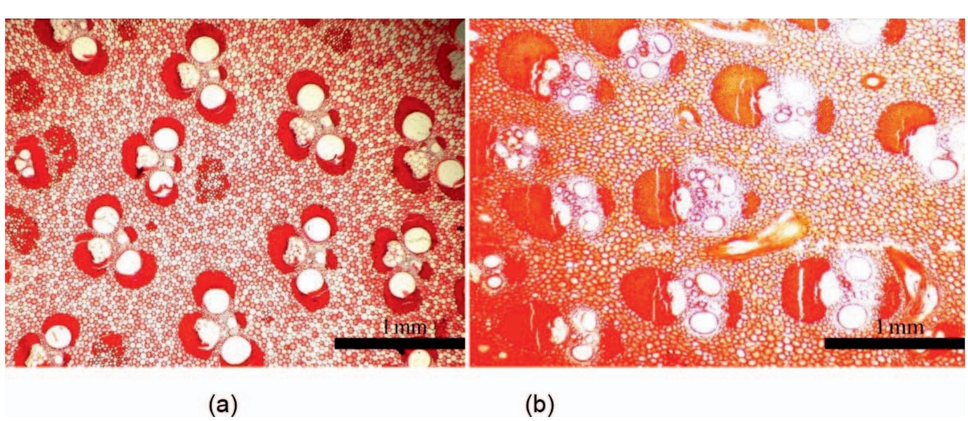

Figure 2.—Vascular bundle images of internode (a) and node (b) of Bambusa rigida. *(Color version is available online.)*

Table 1.—*Anatomical characteristics of* Bambusa rigida *between internodes and nodes at different bamboo heights.*[a]

Height	Sample	VBF (no./mm^2)	FL (μm)	PLD (μm)
Base	Internode	3.32 ± 3.22 A	1,809.90 ± 62.33 A	23.43 ± 1.82 A
	Node	3.01 ± 2.84 A	1,382.62 ± 118.63 B	30.92 ± 2.67 B
Middle	Internode	4.84 ± 4.54 A	1,848.00 ± 154.15 A	22.41 ± 1.91 A
	Node	4.42 ± 3.81 A	1,417.04 ± 124.77 B	28.70 ± 2.65 B
Top	Internode	6.97 ± 5.40 A	1,617.04 ± 167.52 A	19.07 ± 1.88 A
	Node	5.63 ± 4.92 A	1,362.16 ± 106.62 B	23.98 ± 2.23 B

[a] Values are means ± standard deviations. Values with the same letters between internode and node indicate there is no significant difference at the 0.05 probability level. VBF = vascular bundle frequency; no. = number of vascular bundles; FL = fiber length; PLD = parenchyma lumen diameter.

suggested that the volumetric shrinkage in the node was lower than in the internode, although the difference was not significant. It was in accordance with the finding by Razak et al. (2012), who had demonstrated that the volumetric shrinkage of the node (10.78%) was lower than that of the internode (14.83%). Unlike wood, bamboo does not have xylem rays in the radial direction to resist shrinkage and swelling. Nevertheless, in the nodal area, the bent vascular bundle can enhance the resistance to radial shrinkage. Razak et al. (2012) demonstrated the radial shrinkage of the node was lower than the one corresponding to the internode. Additionally, the shrinkage in the tangential direction of the node was also found to be lower than that of the internode (Ahmad and Kamke 2005, Anokye et al. 2014b).

Compressive strength parallel to grain

The average values for CSPG, SSPG, MOR, and MOE of the bamboo culms between nodes and internodes are presented in Table 3. The CSPG in the nodal area increased from 48.16 to 54.12 MPa, and a statistically greater value for internode was found to increase from 71.93 to 89.13 MPa with increasing bamboo height. Accordingly, the higher CSPG at the top portion was attributed to the higher basic density, which was ascribed to the higher vascular bundle frequency (Huang et al. 2014a, 2014b). The lower CSPG in the nodal area was attributable to the lower vascular bundle frequency in comparison with the internode, as shown in Table 1. The difference of CSPG between internodes and nodes varied with bamboo species, bamboo culm height, and moisture content of the sample. For instance, a higher CSPG in the nodal area over internode was observed in Maso bamboo (Shao et al. 2010, Deng et al. 2016). This result was the opposite of our finding, because they found the fiber proportion in the node was higher than that of the internode (Shao et al. 2010). For *G. scortechinii*, the CSPG of the node at the base portion was higher than the internode, while the trend was inversed at the middle and top portion of the bamboo culm (Hamdan et al. 2009). The CSPG for the nodes that were seasoned 1 month was slightly greater than that of the internodes. However, this tendency would be reversed with prolonging the seasoning period. This result was ascribed to the difference of moisture content variation rate with the seasoning time (Wakchaure and Kute 2012).

Table 2.—*Physical properties of* Bambusa rigida *between internodes and nodes at different bamboo heights.*[a]

Height	Sample	BD (kg/m^3)	VS (%)
Base	Internode	578 ± 29 A	15.77 ± 1.83 A
	Node	542 ± 22 A	14.31 ± 0.97 A
Middle	Internode	693 ± 34 A	14.64 ± 0.30 A
	Node	611 ± 33 A	12.18 ± 1.02 A
Top	Internode	808 ± 57 A	11.26 ± 1.58 A
	Node	739 ± 23 A	10.49 ± 0.85 A

[a] Values are means ± standard deviations. Values with the same letters between internode and node indicate there is no significant difference at the 0.05 probability level. BD = basic density; VS = volumetric shrinkage.

Shear strength parallel to grain

From Table 3, the SSPG value for the node increased from 5.49 to 6.62 MPa with increasing bamboo height, which was significantly lower than that of the internode, which ranged from 10.46 to 13.07 MPa. A similar result was observed in work on *D. asper* (Srivaro and Jakranod 2016). The increase on SSPG with increasing bamboo height was ascribed to the increasing vascular bundle frequency (Huang et al. 2014a, 2014b). Similarly, the node had a lower vascular bundle frequency compared with the internode, which would contribute to decreasing the SSPG. Moreover, the significant increase on parenchyma lumen diameter in the node area probably undermined the SSPG because the parenchyma is weaker than fiber and will always be the initial failure point (Grosser and Liese 1971).

MOR and MOE

The MOR of nodes increased from 153.26 to 205.56 MPa, and the MOE increased from 11.46 to 13.21 GPa from the base to the top portion. These values were lower than those of internodes in that the MOR and MOE were in the range of 186.61 to 221.13 MPa and 15.50 to 18.35 GPa, respectively. A significant difference in MOE was observed between internodes and nodes. This result suggested that the node has a negative effect on the bending strength. It was supported by the findings of *G. scortechinii*, *Dendrocalamus strictus*, and *D. asper* (Ahmad and Kamke 2005, Hamdan et al. 2009, Srivaro and Jakranod 2016). The bottom surface (inner side of bamboo culm) of the bending test sample actually was bearing to the tensile force. Generally, the tensile strength of the node was noticeably lower than that of the internode (Razak et al. 2012). According to the literature, the tensile strength has a direct positive relationship with fiber length (Omobowale and Ogedengbe 2008). The irregular fibers in the nodal area were significantly shorter than those of the internode. Therefore, it was reasonable that the node has lower tensile strength compared with the internode (Abd. Latif et al. 1993). Hence, the decrease of tensile strength in the node could lead to the decrease of bending strength.

The failure type after bending tests showed remarkable differences between internodes and nodes (Fig. 3). For the

Table 3.—Mechanical properties of Bambusa rigida *between internodes and nodes at different bamboo heights.*[a]

Height	Sample	CSPG (MPa)	SSPG (MPa)	MOR (MPa)	MOE (GPa)
Base	Internode	71.93 ± 7.04 A	10.46 ± 0.51 A	186.61 ± 14.30 A	15.50 ± 1.09 A
	Node	48.16 ± 0.76 B	5.49 ± 0.45 B	153.26 ± 13.37 A	11.46 ± 1.20 B
Middle	Internode	81.52 ± 2.57 A	12.42 ± 0.97 A	216.13 ± 2.73 A	17.70 ± 1.19 A
	Node	50.84 ± 0.93 B	5.70 ± 0.70 B	204.01 ± 1.73 A	12.34 ± 1.70 B
Top	Internode	89.13 ± 5.00 A	13.07 ± 1.31 A	221.13 ± 5.68 A	18.35 ± 1.16 A
	Node	54.12 ± 0.89 B	6.62 ± 0.95 B	205.56 ± 4.29 A	13.21 ± 1.00 B

[a] Values are means ± standard deviations. Values with the same letters between internode and node indicate there is no significant difference at the 0.05 probability level. CSPG = compressive strength parallel to grain; SSPG = shear strength parallel to grain; MOR = modulus of rupture; MOE = modulus of elasticity.

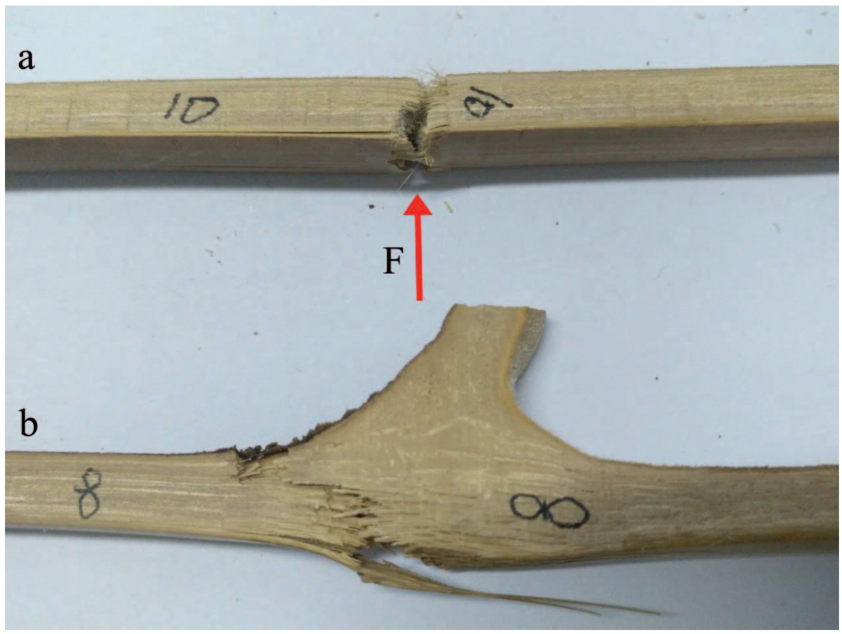

Figure 3.—Failure types of bending test between internode (a) and node (b). (Color version is available online.)

internode sample, the fracture presented a distinct transverse plane, whereas the fracture of the node showed an irregular failure pattern. This could be due to the discontinuity of vascular bundles as they cross the node area of the bamboo culm.

Conclusions

The bamboo node had a lower vascular bundle frequency, shorter fiber length, and a wider parenchyma lumen diameter than those of the internode. They were the contributing factors for the lower physical and mechanical properties of the node as compared with the internode. The radially bent vascular bundles that crossed the diaphragm decreased the volumetric shrinkage of the node. The existence of the node weakened the strength of the bamboo culm. Hence, the staggered arrangement of bamboo culm between nodes and internodes is recommended to optimize the structure of bamboo-based composites.

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