Original Article
J. Korean Wood Sci. Technol. 2023, 51(4): 309-319
https://doi.org/10.5658/WOOD.2023.51.4.309

Journal of the Korean Wood Science and Technology
pISSN: 1017-0715 eISSN: 2233-7180
http://www.woodj.org

Effect of Vascular Bundles and Fiber Sheaths in Nodes and Internodes of *Gigantochloa apus* Bamboo Strips on Tensile Strength

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ABSTRACT

Bamboo culm is in the form of a tube/pipe, composed of internodes which are bounded by a partition/diaphragm (node). Anatomically, bamboo is composed of vascular bundles and parenchyma ground tissue. One of the constituents of vascular bundles is fibers that are grouped to form a fiber sheath. The anatomical structure of the nodes and internodes is thought to influence the strength of bamboo strips, including tensile strength. This study aimed to determine the characteristics of vascular bundles (distribution and fiber percentage) and their effects on the density and tensile strength of *Gigantochloa apus* bamboo strips with and without nodes. The bamboo culms were divided into three parts (outer, middle, and inner) along the radial direction. The results showed that the distribution of vascular bundles and percentage of fiber sheaths decreased significantly from the outer to the inner layer. This also had a significantly decreased density and tensile strength. Furthermore, the number of vascular bundles (in the transverse plane) was greater in the internodes than in the nodes. Anatomically, the orientation of the vascular bundles at irregular nodes is observed in the radial and tangential planes, where the direction is not only in the axial direction, but also in the radial and tangential directions. This caused the tensile strength of the *G. apus* bamboo strips to be lower at the nodes than at the internodes.

Keywords: *Gigantochloa apus*, node, internode, vascular bundle, fiber sheath, tensile strength

1. INTRODUCTION

Bamboo culms can be used as substitutes for wood for various purposes, such as crafts, furniture, and building materials. Using bamboo can reduce the use of wood to preserve sustainable forests. Bamboo supports the community's economy and cannot be separated from people's lives. Bamboo is a biological product with various properties owing to variations in the bamboo culm, age, and type of bamboo (Gao *et al*., 2022; Wahab *et al*., 2010).

Morphologically, bamboo culms comprise pipe- or tube-like structures (internodes) arranged lengthwise and bounded by partitions or diaphragms (nodes). The distance between the partitions on the bamboo culm varies from base to top; it increases from the base to the middle, and then decreases toward the tips (Darwis and Iswanto, 2018; Darwis *et al.,* 2018). The partitions on

Date Received February 2, 2023, Date Revised April 27, 2023, Date Accepted June 29, 2023
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the bamboo (nodes) are where branches usually appear. In addition, the diameter of bamboo culms tends to decrease from the base to the top (Jeon *et al.,* 2018b; Maulana *et al.,* 2021a).

The use of column-shaped bamboo is limited; therefore, many culms are modified into other shapes. Various studies on bamboo and its properties include the development of bamboo strand boards (Maulana *et al*., 2021b), bamboo composites (Hwang and Oh, 2023), bamboo coloring (Lee and Lee, 2021), the termiticidal activity of bamboo vinegar against attacks by subterranean termites (Arsyad *et al*., 2020), and improvement of the properties of the fibers that make up the composite (Jain *et al.,* 2022; Oh, 2020; Setyayunita *et al*., 2022). Increased durability of wood has also been carried out through bulk furfurylation (Li *et al*., 2020) and applied to wood materials (Hadi *et al*., 2022) and bamboo impregnation (Anwar *et al*., 2009) as applied to wood materials (Sumardi *et al*., 2020). Based on this study, the fibers that makeup bamboo need to be studied further, and research on vascular bundles is the focus of this study.

Bamboo comprises vascular bundles, with parenchymal cells as the basic tissue. Each vascular bundle of the bamboo culm consists of one or more small protoxylem vessels and two large metaxylem vessels. That is, both "protoxylem" and "metaxylem" consists of vessel elements (Liese, 1987). Vascular bundles in bamboo culms are distributed unevenly and tend to decrease in number from the outside to the inside (Darwis *et al.,* 2020; Grosser and Liese, 1971; Jeon *et al.,* 2018a). The cell arrangement characteristics in bamboo culms, such as the distribution of vascular bundles and the percentage of fiber sheaths, directly affect their physical and mechanical properties (Abdullah *et al*., 2017; Bahtiar *et al.,* 2016; Li and Shen, 2011; Li *et al.,* 2021a). According to Bahtiar *et al.* (2014), bamboo slats are a layered system in which the strength and stiffness of each layer are functions of the density of the vascular bundles. In this regard, the transformed cross-sectional method can be used as an analytical tool for estimating the strength and stiffness of bamboo slats and laminated bamboo. Furthermore, Bahtiar *et al*. (2014) showed that the ratio of the distribution of vascular bundles can be used in the transformed cross-section method as a substitute for the modulus of elasticity ratio because the theoretical results from the derived model do not differ from the empirical values.

Gigantochloa apus is a bamboo species widely found in various regions of Indonesia, especially in Java (Widjaja, 2001). The many benefits that can be obtained from bamboo make it familiar to the community. *G. apus* is still used in the form of culms, bamboo splits, or bamboo strips. This type of bamboo is used as a building material (pillars, walls, roofs, and floors), baskets, and handicrafts (Dransfield and Widjaja, 1995). Bamboo strips in the form of woven bamboo are generally used as raw materials in the handicraft industry. Bamboo splits and strips can be used as laminae in bamboo-laminated products (Galih *et al.,* 2020; Kumar and Mandal, 2022; Sumardi *et al.,* 2022; Verma and Chariar, 2012; Wang and Shao, 2020). Bamboo strips are obtained by splitting the bamboo into several parts depending on the desired width. Bamboo has good mechanical properties and can be used as a reinforcing material, such as particle boards (Iswanto *et al.,* 2022), composite boards (Cha *et al.*, 2022), ceramics (Hwang and Oh, 2023), and soil reinforcement materials (Rochim *et al.,* 2020).

Basic studies on the mechanical properties of bamboo have been conducted using columns, splits, and strips. The tensile strength of bamboo has also become the focus of many researchers because of the characteristics of the cells, which tend to be parallel to the culm axis, especially in the internodes, and the changes in the cell direction that occur in the nodes. Previous studies reported variations in the tensile strength of bamboo splits, both radially and longitudinally (Abdullah *et al*., 2017). The tensile strength of *Gigantochloa scortechinii* bamboo strips decreases radially from the outer to the inner part

(Razak *et al.,* 2012). Based on the height of the bamboo culms, the tensile strength of *Gigantochloa atter* and *G. apus* bamboo splits was highest in the middle of the culm (Rochim *et al.,* 2020). However, the tensile strength of *G. apus* bamboo strips in the radial direction has not yet been investigated. This study focused on the effects of vascular bundles and fiber sheath percentages in the nodes and internodes of *G. apus* bamboo strips on the density and tensile strength.

2. MATERIALS and METHODS

2.1. Materials

A 3-year-old Tali bamboo (*G. apus*) from Cikeruh Village, Jatinangor District, Sumedang Regency, West Java Province, Indonesia, was used in this study. The bamboo was obtained from a bamboo clump in the middle by cutting the base (first segment/internode).

2.2. Methods

2.2.1. Density and tensile strength testing

The bamboo culms with and without nodes were stripped into three parts (outer, middle, and inner), as shown in Fig. 1. The epidermis/outer and inner skin were removed from the culm. Because the wall thickness of the bamboo culms varied depending on their position in the axial direction (base to top), the size of the test samples for the density and tensile strength was modified from the BS 373:1957 standard (methods for testing small clear timber specimens). The outer, middle, and inner parts of the test samples were 300 mm (length) × 20 mm (width) × 6 mm (thickness). The tensile strength was measured using a Universal Tensile Testers-CY-6040A4 instrument (Chun Yen Testing Machines Co., LTD, Taichung city, Taiwan). The density and tensile strength tests were performed nine times.

2.2.2. Microscopic observation

Microscopic observations of the transverse, tangential and radial sections were conducted using a Nikon Eclipse E 200 stereomicroscope (Nikon, Tokyo, Japan). The sample was first divided into the three sections with a sharp knife. The distribution of the vascular bundles was determined by counting the number of vascular bundles in an area of 1 mm^2. The percentage of fiber sheaths was calculated as the ratio of the area of the

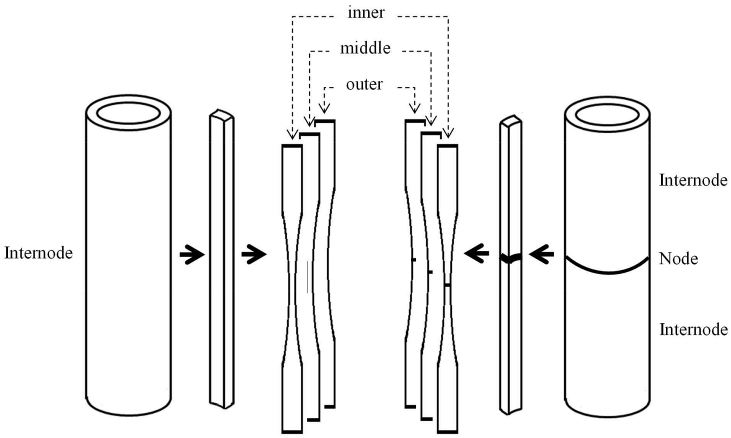

Fig. 1. Tensile strength test sample of *Gigantochloa apus*. Sampling is based on the radial direction of the bamboo strips.

fiber sheaths in each observation area (mm^2). Anatomical image data (distribution of vascular bundles and percentage of fiber sheaths) were analyzed using NIS-Elements v.4.00.00 imaging software.

2.2.3. Data analysis

A completely randomized factorial design was used to determine the effects of bamboo culms (nodes and internodes) and depth on bamboo culms (outer, middle, and inner layers). Statistical analyses were performed using IBM SPSS Statistics 19 software (IBM, Armonk, NY, USA) at $p < 0.05$. The influence of the distribution of vascular bundles and fiber sheaths on tensile strength was also analyzed by constructing a regression equation.

3. RESULTS and DISCUSSION

3.1. Distribution of vascular bundles and percentage of fiber sheaths *Gigantochloa apus* bamboo strips

The ground tissue system arises from the ground tissue meristem and consists of three simple tissues: parenchyma, collenchyma, and sclerenchyma. Bamboo culms are composed mainly of vascular bundles and parenchymal (parenchymatous) ground tissue derived from the ground tissue meristem. Similar to other monocot plants, these vascular bundles are distributed unevenly. The number and density of the vascular bundles decreased from the outer to the inner parts (Table 1). This phenomenon is also supported by the microscopic images of the bamboo cross sections shown in Figs. 2 and 3(a). According to Darwis *et al.* (2018), the varying size and shape of the vascular bundles cause variations in their distribution from the outer to the inner parts of the bamboo strips. The number of vascular bundles per unit area on the bamboo segments tended to be greater than that on the nodes in the radial direction (from the outer to the inner part). As shown in Table 1 and Fig. 2, the distribution of vascular bundles at the internodes was denser than that at the nodes of the bamboo strips.

One of the components of vascular bundles is fibers, which is important in supporting the strength of bamboo culms (Amada *et al.*, 1997). The fibers were arranged in

Table 1. The average value of the distribution of vascular bundles, percentage of fiber sheath, density, and tensile strength of *Gigantochloa apus* bamboo strips with nodes and without nodes (internode) and based on layers (outer, middle, and inner)

Section	Radial segment	Distribution of vascular bundles (Σ number of VB/mm^2)	Percentage of fiber sheaths (%)	Density (g/cm^3)	Tensile strength (kg/cm^2)
Internode	Outer	8.33 ± 1.00^a	51.83 ± 5.41^a	0.85 ± 0.04^a	$3,284.14 \pm 476.30^a$
	Middle	4.89 ± 0.93^b	44.71 ± 5.47^b	0.73 ± 0.05^b	$2,622.45 \pm 179.34^b$
	Inner	4.22 ± 0.97^b	37.51 ± 6.24^c	0.62 ± 0.04^c	$1,626.85 \pm 421.03^c$
	Average	5.81 ± 2.06^A	44.68 ± 8.11^A	0.73 ± 0.10^A	$2,511.15 \pm 784.89^A$
Node	Outer	8.11 ± 0.78^a	44.11 ± 4.16^b	0.82 ± 0.03^a	$1,777.68 \pm 196.86^c$
	Middle	3.44 ± 0.53^c	31.93 ± 3.42^d	0.60 ± 0.05^c	875.83 ± 116.59^d
	Inner	2.56 ± 0.53^d	23.12 ± 1.84^e	0.45 ± 0.03^d	258.28 ± 118.24^e
	Average	4.70 ± 2.55^B	33.05 ± 9.32^B	0.62 ± 0.16^B	970.60 ± 654.97^B

Statistical groupings of vertical and horizontal segments are shown in capital and lowercase letters, respectively.
[A,B,a–e] Mean values with different letters in the same column are significantly different at $p < 0.05$.

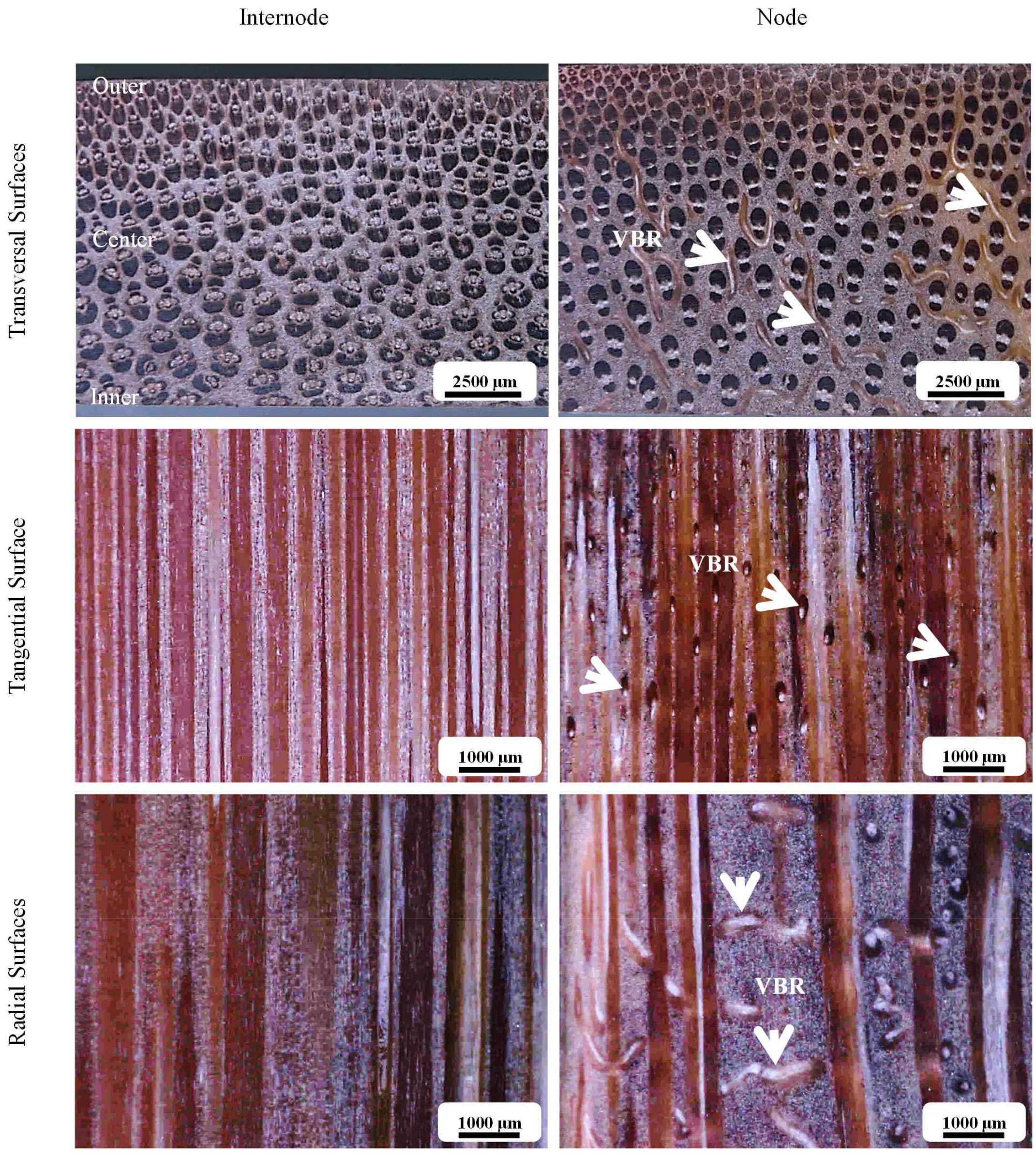

Fig. 2. Transverse, tangential, and radial sections of the internodes and nodes of *Gigantochloa apus* at 10× magnification. VBR: vascular bundle radially.

groups to form a fiber sheath. The proportion of fibers was also unevenly arranged when viewed from the cross-section of the bamboo (Kenneth and Uzodinma, 2021; Li *et al*., 2021b). A decrease in the percentage of fiber sheath was clearly visible from the outer layer to the inner layer of the culm [Table 1 and Fig. 3(b)]. The dense distribution of vascular bundles in the outer part causes the proportion of fiber sheets to be greater than

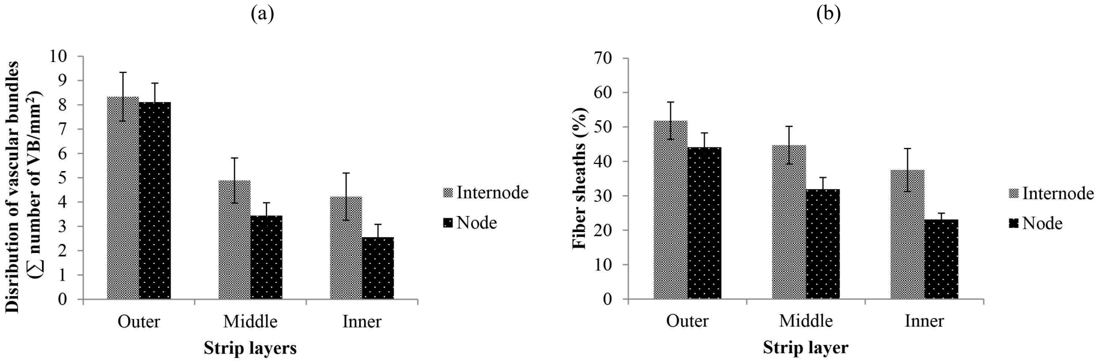

Fig. 3. Distribution of vascular bundles (a) and percentage of fiber sheaths (b) of *Gigantochloa apus* bamboo strips at nodes and internodes in the outer, middle, and inner layers.

that in the middle or inner parts of the bamboo strips.

3.2. Density of the *Gigantochloa apus* bamboo strips

The density of *G. apus* bamboo strips in the internode and node sections varied from the outer to the inner layer (Fig. 4). The density of the bamboo strips decreased from the outer to the inner layer. The density of bamboo in the internode section tended to be greater than that in the node section. The density is directly proportional to the distribution of vascular bundles and the percentage of fiber sheath area in the bamboo, as shown in Table 1 and Fig. 5. The greater the percentage of vascular bundles and fiber sheath area, the higher the density of *G. apus* bamboo strips. Based on the results of Anwar *et al.* (2005), the density of *G. scortechinii* bamboo is also influenced by the two components of its anatomical structure. Furthermore, according to Abdullah *et al.* (2017), the macrostructure of the culm and the fiber content of vascular bundles affect the density of bamboo.

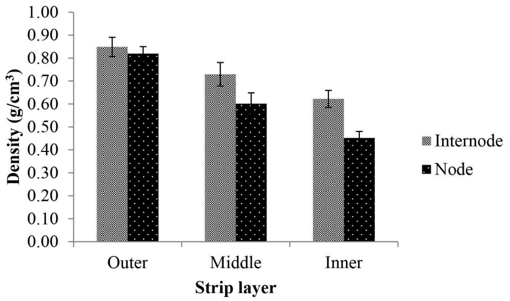

Fig. 4. Density of *Gigantochloa apus* bamboo strips (outer, middle, and inner layers) at internode and node.

3.3. Tensile strength of *Gigantochloa apus* bamboo strips

The tensile strength of *G. apus* bamboo strips varied in the radial direction. The tensile strength of the bamboo strips decreased from the outer to the inner layer (Fig. 6). The distribution of vascular bundles and the percentage of the fiber sheath area in the bamboo strips were positively correlated with their tensile strength, as shown in Fig. 7. The greater the number of vascular bundles and percentage of fiber sheath area, the higher the tensile strength of *G. apus* bamboo strips. This was also proven by Liu *et al.* (2014) in the tensile strength testing of Moso bamboo (*Phyllostachys pubescens* Mazei ex H. de Lebaie) and Wang *et al.* (2014) on *Dendrocalamus latiflorus* Munro bamboo, where the proportion of fibers in the vascular bundles had a large effect on

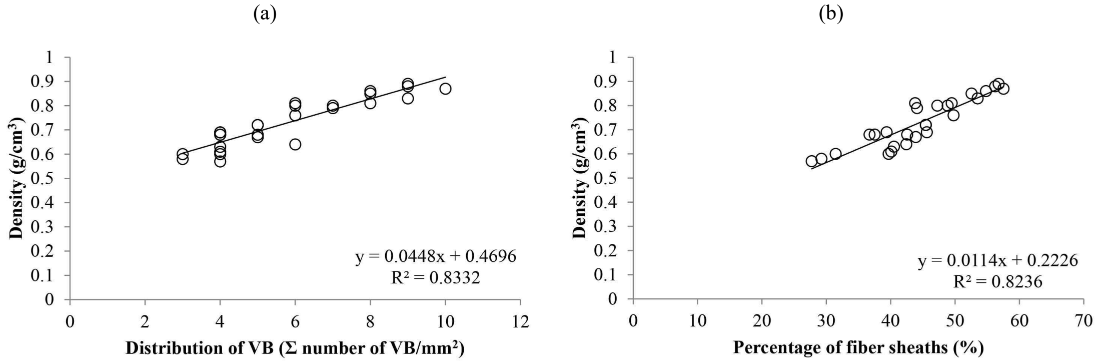

Fig. 5. The relationship between the distribution of vascular bundles (a) and the percentage of fiber sheaths (b) and the density of *Gigantochloa apus* bamboo strips.

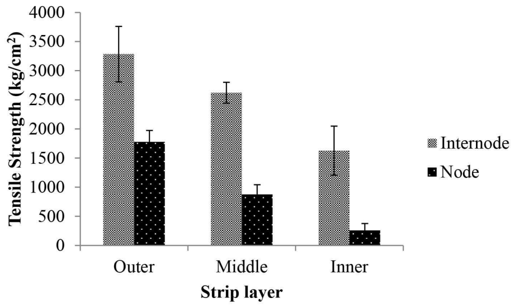

Fig. 6. Tensile strength of *Gigantochloa apus* bamboo strips (outer, middle, and inner layers) at internodes and nodes.

tensile strength. Fiber cells play an important role in determining the mechanical properties of wood. The proportion of fibers in an individual vascular bundle plays an important role in its tensile strength (Osorio *et al.*, 2018). According to Li and Shen (2011) and Shang *et al.* (2021), the tensile strength of individual vascular bundles is the highest in the outer layers of the bamboo culm and tends to decrease toward the inner part. This was due to the higher proportion of the fiber sheath area in the outer vascular bundles compared to that in the inner part.

As shown in Fig. 2, the distribution of vascular bundles at the nodes was lower than that at the internodes. In addition, the orientation of cells in the bamboo internodes is parallel to the axis of the culm (axial), whereas, in the bamboo nodes, the vascular bundles are arranged in an axial or radial direction (Huang *et al.,* 2015; Wang and Shao, 2020). Both these differences impact the tensile strength, where the tensile strength of bamboo in the internode section tends to be greater than that of the node section (Liu *et al.,* 2021). This was evidenced by the damage that occurred during the tensile test where the bamboo strips contained nodes, and the damage that occurred in the nodes (Fig. 8).

Table 1 shows the correlation between the tensile strength of bamboo strips and the percentage of fiber sheath as a ratio, with values of 63.36 (outer layer), 58.65 (middle part), and 43.37 (inner layer) for the internode and 40.30 (outer layer), 27.43 (middle part), and 11.17 (inner layer). The ratio of the tensile strength to the percentage of the fiber sheath decreased from the outer layer to the inner layer. This shows that the percentage of fiber sheaths affects the tensile strength of the bamboo strips.

4. CONCLUSIONS

The distribution of vascular bundles and fiber sheath percentages in the internodes and nodes of *G. apus*

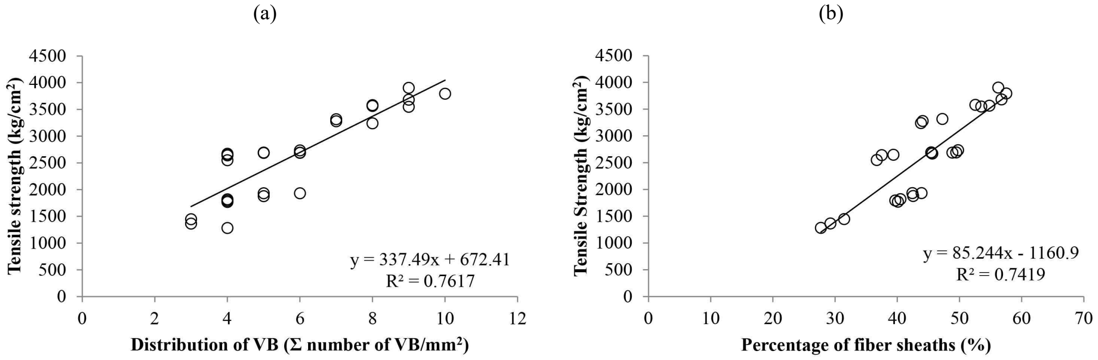

Fig. 7. The relationship between the distribution of vascular bundles (a) and the percentage of fiber sheaths (b) and the tensile strength of *Gigantochloa apus* strips.

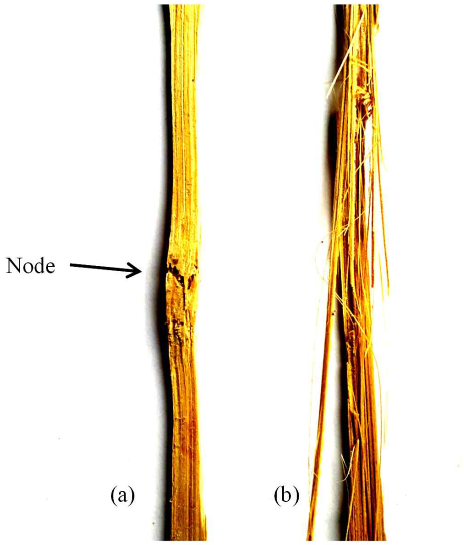

Fig. 8. Differences in damage to bamboo strips with nodes (a) and without nodes (b) during a tensile test. In bamboo strips with nodes, the nodes are damaged, whereas, in bamboo strips without nodes (internodes), all parts are damaged.

bamboo varied in the radial direction. This affected the density and tensile strength of *G. apus* bamboo strips. The distribution of vascular bundles and percentage of fiber sheaths were positively correlated with the density and tensile strength of the bamboo strips. The orientation of the vascular bundles influenced the tensile strength of *G. apus* bamboo strips at the internodes and nodes. The radial orientation of the vascular bundles at the nodes of the bamboo strips caused the tensile strength to be lower than that of the internodes of the bamboo strips.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENT

I would like to thank the Institut Teknologi Bandung for financial support of the research via the Research, Community Service and Innovation Program (P3MI-ITB 2018).

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