Variation of Parallel-to-Grain Compression and Shearing Properties in Moso Bamboo Culm (*Phyllostachys pubescens*)

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As an abundant natural resource in Asia, bamboo is receiving increased attention as an engineering material due to its renewability and excellent strength. The parallel-to-grain compression and shearing properties of moso bamboo culm were examined. The growth characteristics (bamboo age, nodes, and location along the culm), as well as treatments for practical applications (hole punching and hoop reinforcing by hose clamp) were investigated for their influence. Mechanical tests were conducted in accordance with the ISO22157-1:2004 (2004), ISO/TR 22157-2:2004(E) (2004), and CNS GB/T 15780-1995 (1996) standards. Acceptable loading rates for the parallel-to-grain compression and shearing tests were 0.1 and 0.05 mm/s, respectively. The compressive and shearing strengths increased from the bottom to the top of the bamboo. Bamboo age and nodes exerted little influence on parallel-to-grain compressive and shearing strength. In addition, hole punches diminished the mechanical strength of the bamboo culm, while hose clamps enhanced it slightly.

Keywords: Moso bamboo; Bamboo age; Bamboo node; Hose clamps; Compression properties; Shearing properties

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INTRODUCTION

There is a strong interest in natural and renewable building materials that can be used in structural applications. Wood and bamboo are attractive engineering materials due to their renewability, easy accessibility, low energy consumption and pollution, and their high strength-to-mass ratio (Liese 1987; Simpson and TenWolde 1999; Jiang and Peng 2007; Fakoor and Rafiee 2013). As an abundant natural resource in Asia, bamboo has been used as a non-structural and structural material in many areas (Chung and Yu 2002; Albermani *et al.* 2007; Xiao *et al.* 2009; Deng *et al.* 2014a): as bamboo-based, composite-covered bamboo particleboard (Zhang *et al.* 1997), bamboo fiberboard (Matsumoto *et al.* 2001), bamboo strandboard (Sumardi *et al.* 2006), and bamboo-bundle laminated veneer lumber (Deng *et al.* 2014b,c; Chen *et al.* 2014).

Bamboo culm is a hollow and thin-walled cylinder separated by nodes (Jiang and Peng 2007), and its suitability for structural applications depends on its physical and mechanical properties (reviewed in Janssen 2000). Li (2004) investigated the bending properties of *Phyllostachys pubescens* and discussed the Young's modulus of bamboo culm. Bamboo is a biological material, like timber, and is thus subject to variability due to growing conditions and genetic factors. Ahmad and Kamke (2005) considered the variability in mechanical characteristics with respect to location along the length of the bamboo culm, nodes *versus* internodes section, and radial *versus* tangential directions. Taylor *et al*. (2015) focused on the role of bamboo nodes relative to culm stiffness and strength, and the experimental results indicated that the node could be explained as an attempt to reinforce a biologically essential feature, which would otherwise be a point of weakness when loaded in tension and bending. The mechanical properties and connecting joints of bamboo culm are suitable for a lightweight bamboo double layer grid system for construction applications (Albermani *et al.* 2007). An investigation of the effect of uniaxial and biaxial compression loadings on the circumferential-radial mechanical properties has shown that the diametric strength of bamboo evaluated by biaxial load was 2.4 to 2.5 times the uniaxial compression (Jiang *et al.* 2012).

Prefabricated houses using bamboo culms as the main load-bearing materials and thermal conductivity channels have been designed by the International Centre for Bamboo and Rattan (ICBR). The measurements of bamboo culm mechanical properties will contribute greatly to the safe design of these houses and will provide fundamental experimental data in this field of research. In the current study, the parallel-to-grain compression and shearing properties of bamboo were examined. Growth characteristics that were considered in the testing protocol included bamboo age, nodes, and location along the culm. In structural applications, bamboo culms are mostly used after some treatment, including binding by palm rope, fixing by iron nails, or reinforcement by hose clamp. Therefore, the mechanical characteristics of bamboo culm with round holes and hose clamps were also studied.

EXPERIMENTAL

Material Preparation

Four-year-old and six-year-old moso bamboo (*Phyllostachys pubescens*) was grown in Zixi, Jiangxi Province, China. Bamboo culms with a DBH (diameter at breast height) of no less than 100 mm were first cut into bamboo tubes of 9 m lengths. Specimens were obtained from the bottom (B, 3 m), middle (M, 3 m), and top (T, 3 m) part of each tube and stored in a conditioning chamber (23 ± 2 °C and 50 ± 5% relative humidity) until an EMC (equilibrium moisture content) of 8% to 12% was achieved.

Methods and Measurement

The mechanical property tests were conducted in accordance with ISO 22157-1:2004 (2004), ISO/TR 22157-2:2004(E) (2004), and CNS GB/T 15780-1995 (1996). Experiments were performed with respect to bamboo age (four and six years old), location along the length of the bamboo culm (B, M, and T), nodes *versus* internodes section (six-year old culm), the diameter of round holes (six and ten mm), and the number of reinforcing hose clamps (one and two). Five specimens were prepared for each group.

Parallel-to-Grain Compression Test

Compression tests parallel to the axis were conducted such that the end planes of the specimen were kept at right angles to the length of the specimen, and the length was equal to the outer diameter. The specimen was set at an initial load of not more than 1 kN so that the center of the movable head was vertically above the center of the cross-section of the specimen. The load was applied at a constant rate of 0.01 or 0.1 mm/s. The final reading of the maximum load was recorded when the specimen failed.

The maximum compressive stress was determined by Eq. 1,

$$\sigma_{ult} = \frac{F_{ult}}{A} \tag{1}$$

where σ_{ult} is the ultimate compressive stress (MPa), F_{ult} is the maximum load at which the specimen fails (N), and A is the cross-sectional area (mm^2). A was calculated using Eq. 2,

$$(\pi/4) \times [D^2 - (D - 2t)^2] \tag{2}$$

where D and t are the means of the outer diameter and the wall thickness of the specimen.

Parallel-to-Grain Shearing Test

The tests were carried out in a compression machine where the specimen was supported at the lower end over two quarters, opposite one another, and loaded at the upper end over the two quarters that were not supported. The conditions were the same as the compression tests, except that the load was applied at a constant rate of 0.01 or 0.05 mm/s. The final reading of the maximum load when the specimen failed, as well as the number of areas that failed, were recorded. The ultimate shear strength was calculated using Eq. 3,

$$\tau_{ult} = \frac{F_{ult}}{\sum(t \times L)} \tag{3}$$

where τ_{ult} is the ultimate shear strength (MPa), F_{ult} is the maximum load at which the specimen fails (N), and $\sum(t \times L)$ is the sum of the four products of t and L.

Mechanical Testing for Bamboo Culm with Round Holes and Hose Clamps

Because limited quantities of raw materials were available, different parts of bamboo culms were employed for mechanical testing. To investigate the effect of round holes on parallel-to-grain compression and shearing properties, the top (T) part of six-year-old bamboo culms was drilled with centered holes of 6 mm or 10 mm diameter. For tests with hose clamps, the middle (M) part of six-year-old bamboo culms was reinforced with one and two hose clamps, and the tightening torque was 3 N·m for each hose clamp. The rest of the experimental operation was performed as discussed above.

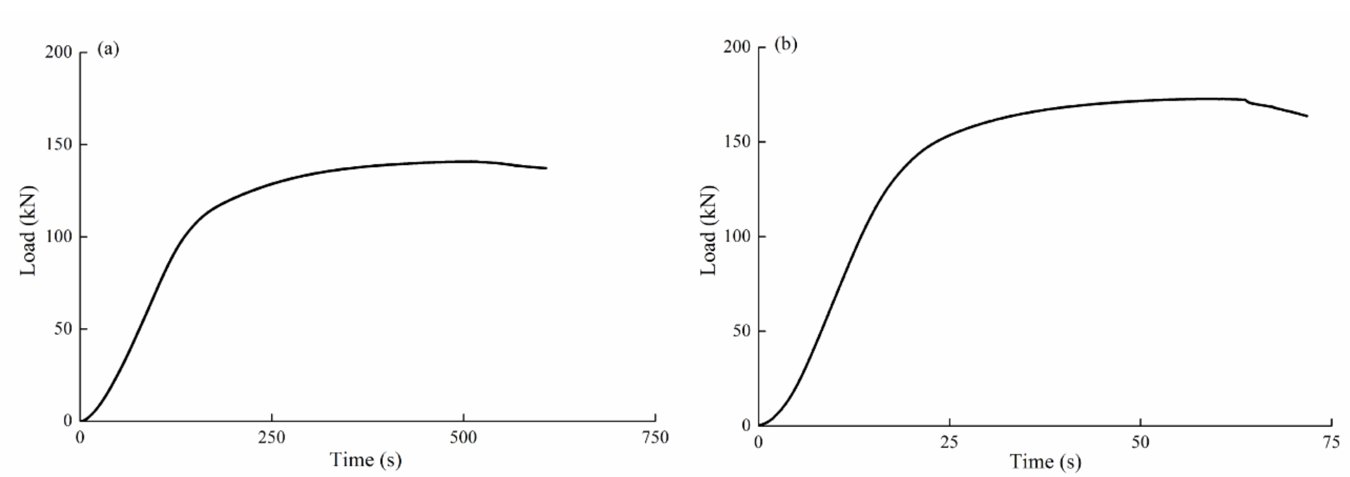


Fig. 1. Load-time relation curve for compression loading of (a) 0.01 mm/s and (b) 0.1 mm/s

RESULTS AND DISCUSSION

Variation in Parallel-to-Grain Compression Properties in Bamboo Culm

Determination of loading rate

The load-time relation curves for two different loading rates are shown in Fig. 1. While the specimen failed at approximately 600 s with a loading rate of 0.01 mm/s, 0.1 mm/s loading caused failure at 60 ± 30 s, with a slightly higher observed fracture load. These results were in accord with the destructive testing requirements of CNS GB/T 15780-1995 (1996) and reveal that the loading rate exerted little influence on the variation trend of load *vs.* time. To improve testing efficiency and decrease the effect of an overlong yield stage on compression strength, the 0.1 mm/s loading rate was used in subsequent parallel-to-grain compression test.

Parallel-to-grain compression properties for different bamboo ages and culm locations

The mean values of the parallel-to-grain compressive strength were 48.5, 55.2, and 60.2 MPa for the bottom (B), middle (M), and top (T) parts of four-year-old bamboo culms, respectively, and 48.0, 54.9, and 61.9 MPa for the B, M, and T of six-year-old culms, respectively (Table 1). There was little difference in the parallel-to-grain compressive strength between four-year-old and six-year-old culms. The average compressive failure load of six-year-old moso bamboo was larger than that of four-year-old bamboo in all three positions. However, in terms of mean compression strength, the value was larger in four-year-old bamboo for part B and M, and the opposite was true for part T. This result was probably related to the combined influence of macrostructure and cross-sectional area as the bamboo age changed.

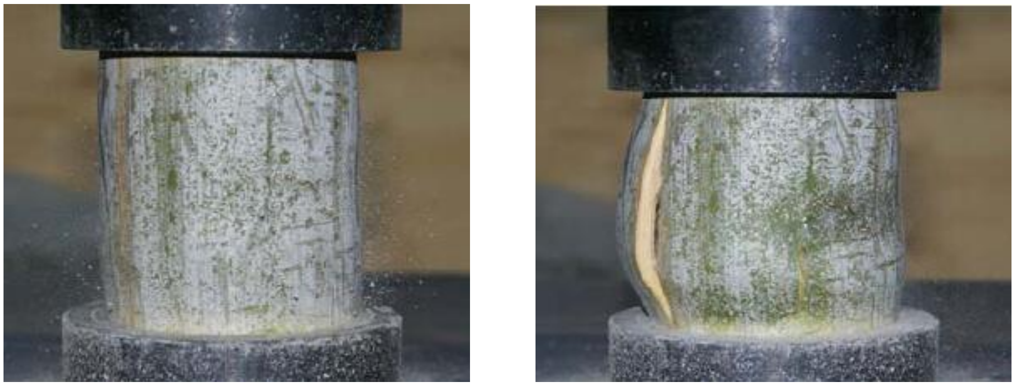
Regardless of bamboo age, the failure load decreased from part B to T, whereas the compressive strength increased. One possible explanation is that the bamboo culm had a diminishing outer diameter and wall thickness (loading area) from part B to T, leading to decreased failure load. Alternatively, the density of the vascular bundles increased from the bottom up, whereas the bore diameter of the vessel decreased, giving rise to the maximal compression strength at the top of the bamboo culm (Jiang and Peng 2007).

Table 1. Compressive Properties of Bamboo at Different Ages and Locations Along the Culm

Bamboo Age (years)	Location Along the Culm	Density (kg/m^3) [Mean ± SD]	Failure Load (kN) [Mean ± SD]	Compressive Strength (MPa) [Mean ± SD]
4	B	655 ± 31	176.3 ± 28.1	48.5 ± 3.7
4	M	711 ± 37	115.2 ± 21.3	55.2 ± 4.6
4	T	741 ± 42	88.5 ± 20.1	60.2 ± 4.3
6	B	683 ± 44	159.0 ± 21.0	48.0 ± 3.6
6	M	734 ± 44	111.7 ± 9.1	54.9 ± 3.6
6	T	799 ± 53	80.3 ± 9.6	62.0 ± 3.6

B, bottom; M, middle; T, top

In terms of bamboo age and location along the culm, the variation in parallel-to-grain compression properties in culms was similar to that of bamboo chips (Li 2009). The mean parallel-to-grain compression strength of bamboo chips ranged from 69.1 to 83.0 MPa, which is greater than that of bamboo culm. While bamboo culm suffered both compression failure and bending failure (Fig. 2), the bamboo chips experienced only compression failure.



(a) (b)

Fig. 2. Bamboo culm (a) before and (b) after compressive failure

Table 2. Compressive Properties of Node and Internode Sections along the Culm of Six-Year-Old Moso Bamboo

Node or Internode	Location Along the Culm	Failure Load (kN) [Mean ± SD]	Compressive Strength (MPa) [Mean ± SD]
Internode	B	159.0 ± 21.0	48.0 ± 3.6
Internode	M	111.7 ± 9.1	54.9 ± 3.6
Internode	T	80.3 ± 9.6	62.0 ± 3.6
Node	B	165.0 ± 10.2	48.6 ± 2.9
Node	M	111.2 ± 10.3	53.9 ± 3.4
Node	T	84.1 ± 12.7	62.2 ± 4.2

B, bottom; M, middle; T, top

Parallel-to-grain compression properties for nodes and internodes

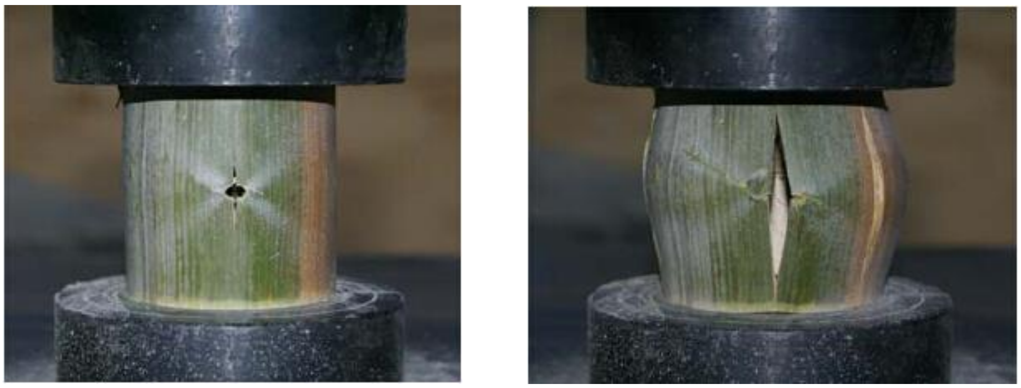
Table 2 displays the parallel-to-grain compressive properties of node and internode sections along the culm of six-year-old moso bamboo. The mean value of longitudinal compressive strength in the internode section was 48.0, 54.9, and 61.9 MPa in the bottom, middle, and top parts, while those values were 48.6, 53.9, and 62.2 MPa in the node section.

Bamboo nodes had no evident influence on parallel-to-grain compressive strength. Vascular bundles have a strictly axial arrangement in the internode, while irregular crisscrossing is observed in the neighboring nodes (Jiang and Peng 2007; Wang *et al.* 2013). The moso bamboo node consists of a nodal ridge, sheath scar, and diaphragm (Jiang and Zhenhua 2007), the synthetic action of which leads to the enlargement of the cross-sectional area. Thus, compressive strength may decrease at the cross-sectional area of the node. In other words, it is likely that bamboo nodes exert a negative effect on the longitudinal compression strength.

Parallel-to-grain compression properties for punched and reinforced culms

The presence of round holes diminished the parallel-to-grain compressive strength of the bamboo culm (Table 3). The mean compressive strength decreased by 9.5% for the 6-mm hole and 11.1% for the 10-mm hole. The bore diameter of the hole made little difference in parallel-to-grain compression properties. As it neared the failure load, the bamboo culm began to crack along the grain direction at the round holes, as Fig. 3 illustrates.

The parallel-to-grain compression properties for reinforced bamboo culms are shown in Table 4. Hose clamps slightly enhanced the mean compression strength of the bamboo culm. The mean compressive strength increased by 1.6% or 2.5%, respectively, when one or two hose clamps were used. The hose clamps were not destroyed during the test (Fig. 4).



(a) (b)

Fig. 3. Bamboo culm with round holes (a) before and (b) after compressive failure

(a) (b)

Fig. 4. Bamboo culm with hose clamps (a) before and (b) after compressive failure

Table 3. Parallel-to-Grain Compressive Properties of Culm with Round Holes

Hole Diameter (mm)	Failure Load (kN) [Mean ± SD]	Compressive Strength (MPa) [Mean ± SD]
Negative Control	80.3 ± 9.6	62.0 ± 3.6
6	74.2 ± 9.8	56.1 ± 3.6
10	73.0 ± 8.1	55.1 ± 2.6

Table 4. Parallel-to-Grain Compressive Properties of Culm with Hose Clamps

Number of Hose Clamps	Failure Load (kN) [Mean ± SD]	Compressive Strength (MPa) [Mean ± SD]
Negative Control	111.7 ± 9.1	54.9 ± 3.6
1	107.3 ± 15.0	55.8 ± 5.4
2	114.9 ± 19.0	56.3 ± 2.5

Variation in Parallel-to-Grain Shearing Properties in Bamboo Culm

Determination of loading rate

The load-time curves of bamboo culms were calculated for shearing tests with two different loading rates (Fig. 5). The specimen failed after nearly 250 s with a loading rate of 0.01 mm/s and after 60 ± 30 s for the 0.05 mm/s loading condition, which was in agreement with CNS GB/T 15780-1995 (1996). The loading rate had little influence on the fracture load. Therefore, the loading rate of 0.05 mm/s was used for subsequent parallel-to-grain shearing tests.

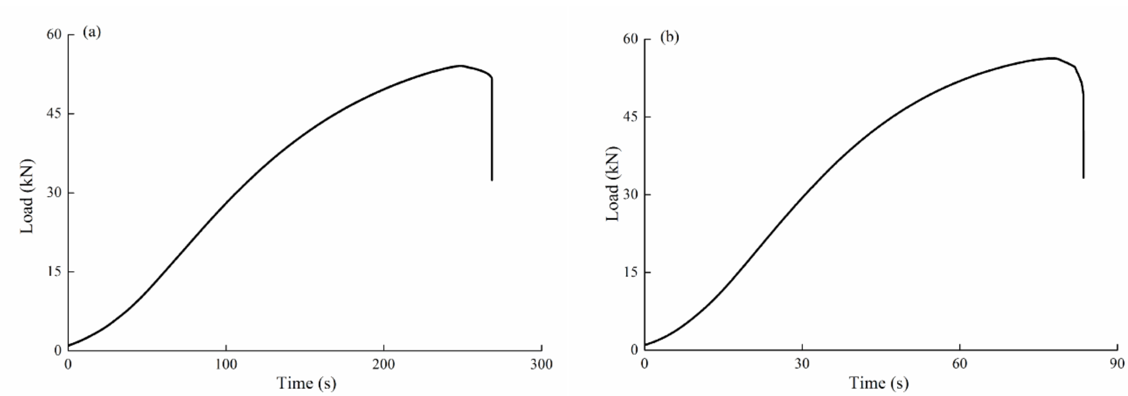
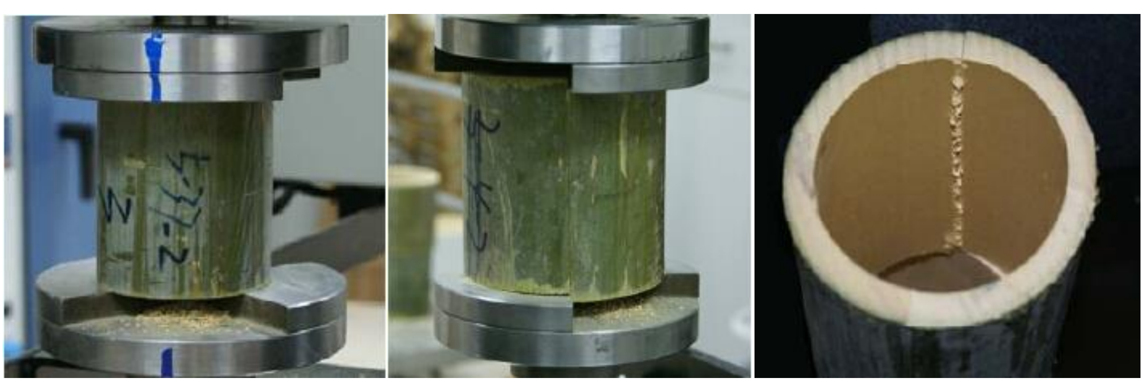


Fig. 5. Load-time relation curve for shearing with loading rates of (a) 0.01 mm/s or (b) 0.05 mm/s

Parallel-to-grain shearing properties for different bamboo ages and culm locations

Shearing properties were investigated with respect to bamboo age and location along the culm (Table 5, Fig. 6). The mean values of the parallel-to-grain shearing strength were 11.9, 14.0, and 15.4 MPa for the bottom, middle, and top parts of four-year-old bamboo culms, while the values were 11.8, 13.2, and 15.3 MPa for those of six-year-old bamboo.

The failure load decreased from part B to T, and the shearing strength increased irrespective of bamboo age. This variation was consistent with the compressive properties of bamboo culm. In addition, there was little difference in the shearing strength of four-year-old and six-year-old moso bamboo.



(a) (b) (c)

Fig. 6. Bamboo culm (a) before and (b) after, (c) shear failure

Table 5. Shearing Properties with Respect to Bamboo Age and Culm Location

Bamboo Age (years)	Location Along the Culm	Failure Load (kN) [Mean ± SD]	Shearing Strength (MPa) [Mean ± SD]
4	B	57.7 ± 7.7	11.9 ± 0.9
4	M	39.8 ± 6.5	14.0 ± 0.7
4	T	31.2 ± 5.0	15.4 ± 0.9
6	B	56.2 ± 7.8	11.8 ± 0.8
6	M	38.8 ± 3.3	13.2 ± 1.6
6	T	29.6 ± 4.1	15.3 ± 1.2

B, bottom; M, middle; T, top

Table 6. Shearing Properties of Node and Internode Sections along the Culm of Six-Year-Old Moso Bamboo

Node or Internode	Location Along the Culm	Failure Load (kN) [Mean ± SD]	Shearing Strength (MPa) [Mean ± SD]
Internode	B	56.2 ± 7.8	11.8 ± 0.8
Internode	M	38.8 ± 3.3	13.2 ± 1.6
Internode	T	29.6 ± 4.1	15.3 ± 1.2
Node	B	60.2 ± 5.9	12.4 ± 1.1
Node	M	39.9 ± 3.2	13.5 ± 0.9
Node	T	30.1 ± 3.7	15.9 ± 1.4

B, bottom; M, middle; T, top

Parallel-to-grain shearing properties for node and internode sections

The shearing properties of six-year-old culm samples with and without nodes were examined (Table 6). The mean values of longitudinal shearing strength in the internode section were 11.8, 13.2, and 15.3 MPa for the bottom, middle, and top parts, while the values were 12.4, 13.5, and 15.9 MPa in the node section. Samples with nodes exhibited slightly larger than average shearing strength and failure load compared with those without nodes. Similar phenomena have been observed in studies where the bamboo node hindered interlaminar fractures and had a reinforcing effect on the longitudinal shearing strength (Shao *et al.* 2010; Wang *et al.* 2013), while the opposite was found by Taylor *et al*. (2015).

Parallel-to-grain shearing properties for punched and reinforced culms

The parallel-to-grain shearing properties for the hole-punched culms are presented in Table 7 and Fig. 7. Holes had a negative effect on shearing strength, resulting in a reduction of the mean shearing strength by 9.6% for the 6-mm hole and 21.0% for the 10-mm hole. When load was applied, cracks were initiated at the round holes.

Table 7. Parallel-to-Grain Shearing Properties of Culm with Round Holes

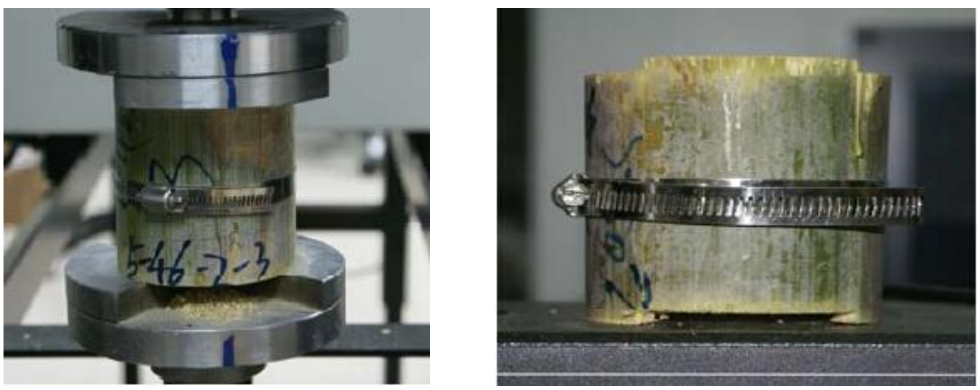
Hole Diameter (mm)	Failure Load (kN) [Mean ± SD]	Shearing Strength (MPa) [Mean ± SD]
Negative Control	30.1 ± 3.7	15.9 ± 1.4
6	26.5 ± 2.9	14.3 ± 1.1
10	24.1 ± 3.4	12.5 ± 1.1

Table 8. Parallel-to-Grain Shearing Properties of Culm with Hose Clamps

Number of Hose Clamps	Failure Load (kN) [Mean ± SD]	Shearing Strength (MPa) [Mean ± SD]
Negative Control	39.9 ± 3.2	13.5 ± 0.9
1	39.6 ± 4.3	13.9 ± 1.2
2	41.7 ± 5.1	14.4 ± 1.3

(a) (b)

Fig. 7. Bamboo culm with round holes (a) before and (b) after shear failure



(a) (b)

Fig. 8. Bamboo culm with hose clamps (a) before and (b) after shear failure

The parallel-to-grain shearing properties of the reinforced bamboo culms are displayed in Table 8 and Fig. 8. The mean shearing strength of bamboo culm increased by 3.1% and 7.2% with one and two hose clamps, respectively. Taken together, these data suggest that hose clamps placed at the location where defects exist or initiate readily could lead to higher safety performance.

CONCLUSIONS

1. The loading rate slightly affected the parallel-to-grain compression and shearing properties of bamboo culms. The specimens exhibited a longer yield stage when being loaded in the ISO 22157-1:2004(E) (2004) and ISO/TR 22157-2:2004(E) (2004) tests than in the CNS GB/T 15780-1995 (1996) test. To increase testing efficiency, the

loading rate was determined in line with the destructive testing requirements of GB/T 15780-1995.

2. There was little change in the parallel-to-grain compressive strength between four-year-old and six-year-old culms, nor was there a dramatic change in shearing strength. Regardless of bamboo age, the failure load decreased from bottom to top, whereas the compressive and shearing strength increased. In addition, the bamboo node provided unremarkable reinforcement of mechanical strength.
3. Punching holes or reinforcing the bamboo with hose clamps affected the failure behavior of bamboo culms when bearing load. Holes diminished the parallel-to-grain compressive and shearing strength, while hose clamps slightly enhanced mechanical strength. Thus, placement of a hose clamp at the location where defects exist or initiate readily may lead to higher safety performance.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the Fundamental Research Funds for the International Centre for Bamboo and Rattan (1632016001), entitled "The investigation of circumferential-laminated processing and performance evaluation of bamboo fiber reinforced filament-wound pipe". The constructive comments from the anonymous reviewers are also greatly appreciated.

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Article submitted: October 5, 2015; Peer review completed: December 2, 2015; Revised version received and accepted: December 14, 2015; Published: January 6, 2016.
DOI: 10.15376/biores.11.1.1784-1795