Mode II Fracture Toughness of Bamboo Scrimber with Compact Shear Specimen

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The mode II fracture toughness of bamboo scrimber was evaluated. A compact shear specimen was chosen as the specimen, while the stress intensity factor K_{IIC} was chosen as the index for the mode II fracture toughness. In total, 54 specimens containing two different grain modes and three different thicknesses were manufactured and subjected to static loading with specially designed loading clamps. The failure modes were observed, and the crack initiating loads were obtained. The stress intensity factor was calculated and analyzed. The failure of all specimens was due to brittleness and occurred instantaneously. Thus, the linear elastic fracture mechanics is applicable to the mode II fracture of bamboo scrimber. The stress intensity factor K_{IIC} was 459.9 MPa·m$^{1/2}$ for the F-L grain mode and 358.0 MPa·m$^{1/2}$ for the S-L grain mode. There was no significant difference in the stress intensity factor K_{IIC} of specimens where the thickness ranged from 10 mm to 30 mm; a specimen with a thickness of 10 mm can be used to determine the fracture toughness of the bamboo scrimber.

Keywords: Fracture toughness; Stress intensity factor; Compact shear specimen; Bamboo scrimber;

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INTRODUCTION

As the demand for sustainable buildings increases, green materials are becoming increasingly profitable and desirable around the world. Biomaterials like wood, bamboo, and rattan are promising construction materials because they are sustainable and environmentally friendly (Lakkad and Patel 1981; Amada *et al*. 1997). Compared with wood, bamboo grows faster, can be harvested in 3 to 5 years, and has a similar or higher strength-to-weight ratio than wood (Nogata and Takahashi 1995; Albermani *et al*. 2007).

Bamboo has been used as a construction material in many countries. However, the application of natural raw bamboo is limited mainly because of the high variability of its mechanical properties and diameters. The connection between raw bamboo members is difficult to design, and the safety of the raw bamboo structure is difficult to evaluate. To overcome these limitations, different types of bamboo-based composites such as bamboo plywood and laminated bamboo lumber have been developed and investigated (Xiao *et al*. 2013; Correal *et al*. 2014; Li *et al*. 2015). Bamboo scrimber is an innovative bamboo-based product that was improved by Yu and Yu (2013) and has been popularized in China. The manufacturing process of bamboo scrimber is relatively simple in comparison to other bamboo-based composites because the inner and outer layers of the bamboo do not need to be removed, and chemical treatment of the raw materials is not required, either. The bamboo scrimber has great potential to be used as a construction material due to its high manufacturing efficiency, material utilization rate, and good mechanical properties (Yu *et al*. 2014). The effect of the manufacturing process on the mechanical performance of bamboo scrimber was investigated (Yu *et al*. 2006; Zhu *et al*. 2011). To determine the design values of the mechanical properties of the bamboo scrimber, a reliability analysis was conducted (Zhong *et al*. 2014). However, the length of the bamboo scrimber was limited because of the limitation of hot press equipment, available connecting methods such as finger joints were shown to reduce the strength and stiffness of the bamboo scrimber significantly. To overcome these shortcomings, a reinforced bamboo scrimber composite (RBSC) beam was first invented by the authors, and it was generated through an intermittent cold pressing process. The bending properties of RBSC beam was investigated by experiment. When the beam was loaded to failure, cracking across the neutral plane of the beam was observed in some specimens, and the bearing capacity of the beam was much lower than the beams failed due to tension of the bamboo fiber (Zhong *et al.* 2017). Micro-cracks were introduced into the beam during the manufacturing process, the fracture mechanics may explain the cracking behavior and be used to predict the failure load of the RBSC beam.

During the manufacturing process, the bamboo culms were passed through a roller along the longitudinal grain direction to form series of linear cracks in the culms along the fiber direction. Then the fluffed culms, also called bamboo bundles, were then glued together into bamboo scrimber. Cracks may be introduced between the fibers in the bundles. To resist insects and protect itself from rain, the outer skin of bamboo is covered with a waxy layer with high silica content, and the inside of the bamboo culm is covered with a waxy layer, too. These wax coats prevent the adhesive from entering the bamboo material and cracks may also exist at the bonding interface between the two layers of bamboo bundles. Furthermore, cracks may also be introduced during service. Thus, understanding the crack resistance property of bamboo scrimber is essential.

The fracture toughness is a basic property of materials; however, compared with other mechanical properties such as tensile and compression strength, the fracture behavior of bamboo-based composites is still unclear. The fracture properties of raw bamboo of some species of different fracture modes have been investigated (Shao *et al*. 2009; Wang *et al*. 2014; Xu *et al*. 2014). The fracture characteristics of the short bamboo fibers that was reinforced polyester with different fiber to matrix ratios was investigated by Wong *et al*. (2010). However, the fracture toughness of bamboo scrimber was not determined so far.

In this study, the model II fracture toughness of bamboo scrimber was obtained by compact shear specimens. The effect of thickness and grain orientation on the fracture toughness was evaluated. This work can be used as a basis to evaluate the structural performance of bamboo scrimber members.

EXPERIMENTAL

Materials

The bamboo used to manufacture the bamboo scrimber was moso bamboo (*Phyllostachys pubescens*), which was harvested from Guangde county (Anhui, China). The bamboo was aged 3 to 4 years, with an average diameter of 100 mm to 150 mm, and its thickness ranged from 12 mm to 20 mm. The commercially available phenol formaldehyde resin adhesive (PF16L510; Beijing Dynea Chemical Industry Co. Ltd (Beijing, China) with a low molecular weight was used. Its parameters were 6% to 49% of solid content, 20 to 40 mPa·s of viscosity, with a pH of 10 to 11. The adhesive was diluted with water to 7 times of its original volume before the immersion process.

For the manufacturing process, as shown in Fig. 1, a culm of bamboo was split into two halves of semicircle culms, and the inner nodes were removed. The split bamboo culms were flattened and crushed into bamboo bundles. The bundles were immersed in the resin for 15 min and dried for 8 h at 40 °C to 50 °C. The bundles were packed in a rectangular cuboid mould with one layer stacked onto one another. The stacked bundle layers were pressed at 37 MPa for 3 min and cured for 12 h at 130 °C to 140 °C. The density of the bamboo scrimber has a great influence on its mechanical properties. The chosen pressure and bamboo species resulted in a bamboo scrimber product with an average density of 1.03 g/cm^3 and a standard deviation of 0.06 g/cm^3. The bamboo scrimber beams were manufactured with dimensions of 3600 mm × 150 mm × 150 mm for this study.

The tension strength, compression strength, and shear strength parallel to grain, of the bamboo scrimber were obtained by experiments (Zhong and Wu 2017).

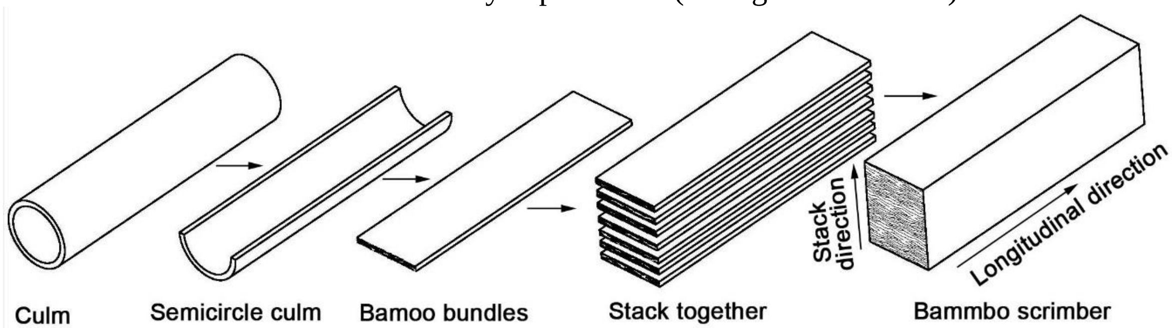

Fig. 1. Sketch of the process of bamboo scrimber

Specimens

There was not a standard procedure to determine the fracture toughness of the bamboo scrimber. Various approaches were pursued to collect the mode II fracture toughness. The compact shear specimen was suitable to test the mode II fracture toughness of wood (Cramer and Pugel 1987). Thus, the compact shear specimen was chosen to investigate the mode II fracture toughness of the bamboo scrimber. As shown in Fig. 2,

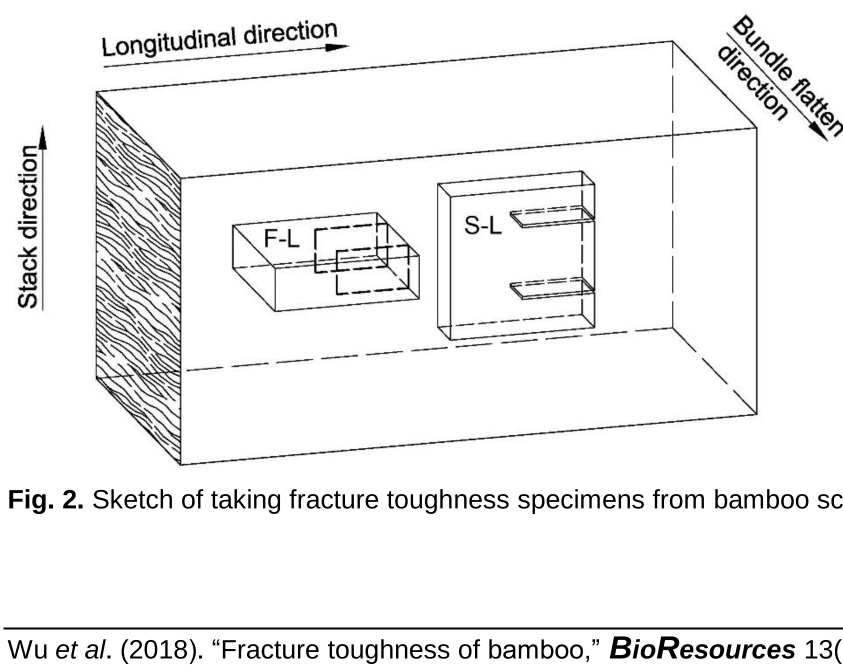

Fig. 2. Sketch of taking fracture toughness specimens from bamboo scrimber beam

two types of specimens with different grain modes were cut from the bamboo scrimber beams, *i.e.* the F-L and S-L specimen. The specimens were named using a two letter code, the first letter designating the direction normal to the crack plane, and the second letter the expected direction of crack propagation. Letter "L" represented the longitudinal direction of the bamboo scrimber, "S" represented the stack direction and "F" represented the bundle flatten direction. As shown in Fig. 3, the different grain modes can be clearly observed on the end surface of the specimen.

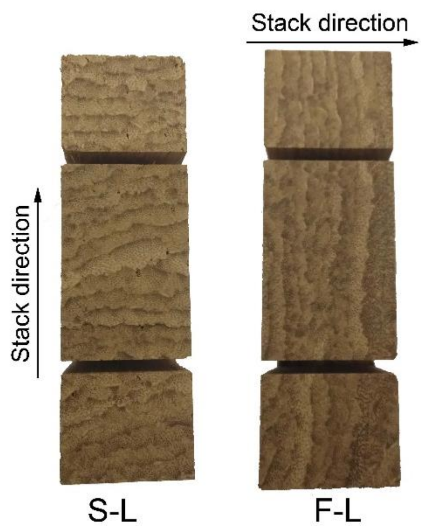

Fig. 3. Photo of the grain mode of the fracture toughness specimens

Figure 4 shows that the dimensions of the compact shear specimen were 100 mm × 100 mm × *t*, where *t* was set to 10 mm, 20 mm, and 30 mm to investigate the effect of the thickness on the fracture toughness. There were two 50 mm long gaps cut along the longitudinal direction, a slit of approximately 3 mm long was inserted at the end of each gap using a razor blade that was 0.28 mm thick. There were 10 specimens for each thickness and grain mode, and a total of 60 specimens were manufactured.

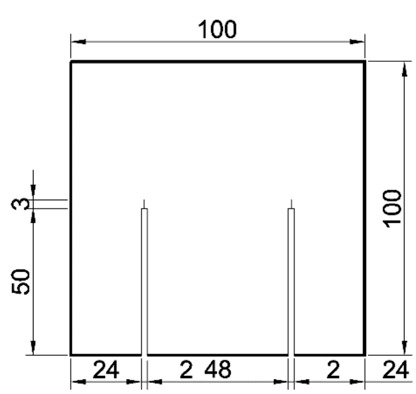

Fig. 4. Shape and dimensions of the fracture toughness specimen

Test Procedure

Figure 5 shows the mode II toughness test with a specimen under loading. The test was conducted using a 10 kN universal test system (Instron Corporation, Massachusetts, USA). Special bearing and loading clamps were designed to fulfill the testing requirement.

The load was applied to the two tines through a compressive force. The lower bearing seats can also be used to support the unforked parts of the specimen, with the compressive load applied to the middle fork of the specimen, *i.e.*, placing the specimen shown in Fig. 5 upside down. However, the latter loading scheme induced tension perpendicular to the grain crack in the specimen. Thus, the loading scheme in Fig. 5 was chosen. A crosshead speed of 0.5 mm/min was chosen based on the work of Liu (2009). The tests were performed at room temperature (approximately 20 °C). There were nine replicates performed for each condition.

Fig. 5. Photo of a specimen under testing

RESULTS AND DISCUSSION

Failure Mode

Failure generally occurred at one crack (slit) tip of the specimen instantaneously and catastrophically, however, the other crack remained intact, as shown in Fig. 6. There were differences between the crack surfaces in the specimens in the S-L and F-L groups. The crack surface of the specimens in the F-L group was coarser than the specimens in the S-L group.

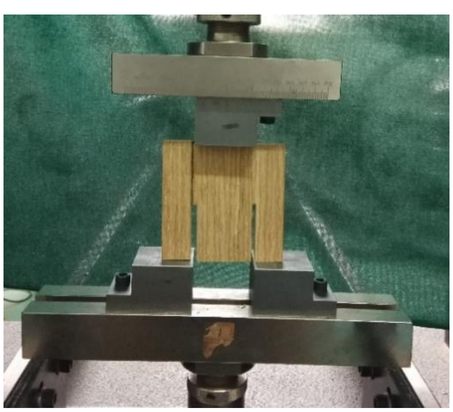

Fig. 6. Photo of a specimen under testing

Some of the failure surfaces of specimens in the S-L group propagated along the bonding interface between each layer in the bundle, which made the green outer layer of the bamboo exposed after the specimen cracked, as shown in Fig. 7. This phenomenon might be caused by less bonding strength between the outer green layers with other bundles than the bonding strength between fibers in the same layer of bundles.

Figure 8 shows a typical load-crosshead displacement curve of the specimen, the relationship between the load and crosshead displacement was generally linear before failure. However, when the load reached the failure load, it dropped sharply and instantly. The failure load can be measured in the load-crosshead displacement curve and was taken as the load initiating cracking of the specimen.

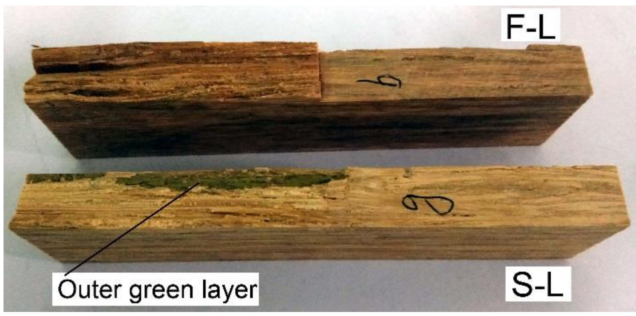

Fig. 7. Comparison of the failure surfaces between two types of specimens

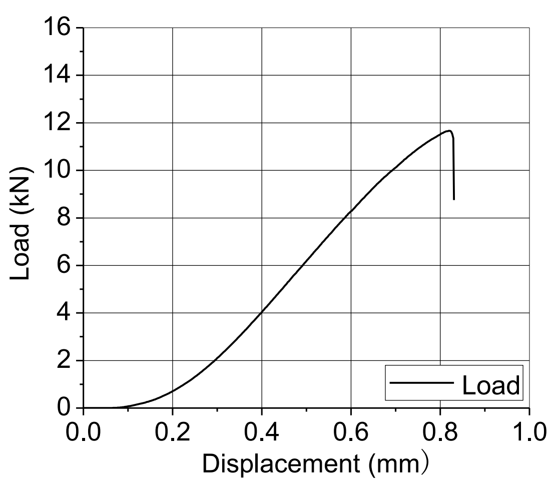

Fig. 8. Typical load-crosshead displacement curve of a mode II fracture specimen

Test Results

The stress intensity factor K is used in fracture mechanics to predict the stress intensity near the tip of a crack caused by a remote load or residual stresses. It is theoretically constant for the linear elastic brittle materials, where the yield at the crack tip is rather small. In this work, the stress intensity factor for the mode II fracture, $K_{IIC,}$ which was used to represent the fracture toughness of bamboo scrimber was determined using Eq. 1 derived by Dixon and Strannigan (1972),

$$K_{IIC} = \frac{5.11 P_Q}{2BW} (\pi a)^{1/2} \tag{1}$$

where P_Q is the load when the crack initiated, B is the thickness of the specimen, W is the height of the specimen, and a is the length of the initial crack. The calculated stress intensity factor K_{IIC} for all specimens are listed in Table 1; the average, standard deviation, and coefficient of variation for each condition was also calculated.

Table 1. K_{IIC} Value of the Bamboo Scrimber

	K_{IIC} (MPa·m$^{1/2}$)			K_{IIC} (MPa·m$^{1/2}$)		
	F-L			S-L		
	t = 10 mm	t = 20 mm	t = 30 mm	t = 10 mm	t = 20 mm	t = 30 mm
1	592.16	449.88	458.14	384.48	343.41	322.91
2	386.49	492.94	422.34	366.61	375.26	308.08
3	454.51	488.56	432.00	227.32	387.03	328.73
4	454.77	459.08	444.22	386.56	452.14	351.71
5	429.82	550.01	478.06	315.33	386.50	277.68
6	467.63	447.98	471.43	348.86	372.57	361.64
7	490.44	461.97	444.17	424.48	334.51	291.33
8	427.64	461.71	404.72	337.96	363.42	345.00
9	447.30	421.39	477.76	465.08	448.09	358.88
Average	461.19	470.39	448.09	361.85	384.77	327.33
Standard Deviation	57.03	36.70	25.64	67.76	41.06	30.07
Coefficient of Variation (%)	0.12	0.08	0.06	0.19	0.11	0.09

Table 1 shows that for specimens whose fracture surfaces normal were along the bundle flatten direction, *i.e.*, the F-L group, the average value of K_{IIC} was 459.9 MPa·m$^{1/2}$. The value for the specimens fracture surfaces normal were along the stack direction was 358.0 MPa·m$^{1/2}$, *i.e.*, the value of K_{IIC} of the F-L grain mode was generally 28.5% larger than the S-L grain mode. A possible reason for this result could be the bonding interface strength was weakened by the wax coat in the outer layer of the bamboo. The fracture toughness of the F-L mode was more uniform with a smaller coefficient of variation than the F-L grain mode.

The fracture toughness of raw bamboo was at the same level with wood. For example, the K_{IIC} of the Chinese northeast larch was approximately 141.2 MPa·m$^{1/2}$ (Liu 2009). Thus, the stress intensity factor of the bamboo scrimber was higher than the wood and raw bamboo, which means that the fracture toughness of bamboo was improved by the manufacturing technology. This result was similar to the trend of other mechanical properties like the compression strength (Zhong *et al*. 2014).

The average and standard deviation for each condition are plotted in Fig. 9, to decide whether there were any statistically significant differences between the means of each condition. The one-way analysis of variance was conducted for each thickness in one grain mode and between the two grain modes. There was no significant difference between each thickness in the same grain mode. Thus, all specimens ranged from 10 mm to 30 mm, were in a plane strain state, and could be used as a specimen to test the mode II fracture toughness for the bamboo scrimber. However, the K_{IIC} of specimens in the S-L and F-L modes were significantly different at the 0.05 level. Because the fracture toughness of the F-L grain mode was larger, when used as beams, it is recommended to place the bundle stack direction of the beam parallel to the horizontal plane to avoid cracks in the beam.

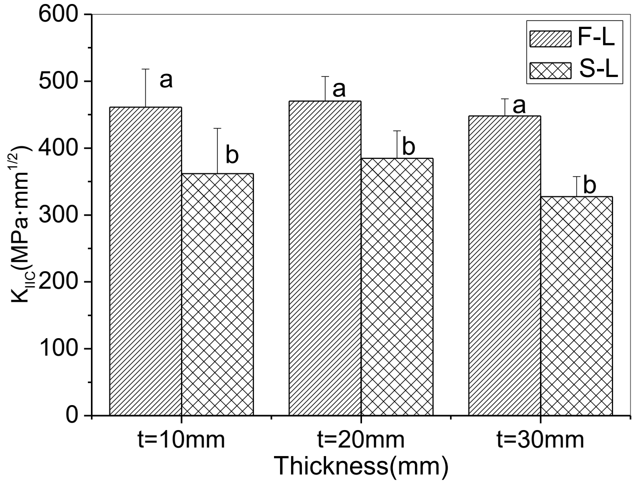

Fig. 9. K_{IIC} for different thickness and grain mode

CONCLUSIONS

1. The aim of this work was to determine the mode II fracture toughness, *i.e.*, the stress intensity factor K_{IIC} for bamboo scrimber. The effect of the grain mode and thickness on the fracture properties were evaluated based on the work of this research.
2. The average value of stress intensity factor K_{IIC} for F-L grain mode of bamboo scrimber was 459.9 MPa·m$^{1/2}$, and the average value of K_{IIC} for S-L grain mode was 358.0 MPa·m$^{1/2}$. It is recommended to place the bundle stack direction of the beam parallel to the horizontal plane to avoid cracks in the beam.
3. There was no significant difference for the stress intensity factor K_{IIC} of specimens ranged from 10 mm to 30 mm. Thus, for convenience and economical reasons, 10 mm specimens can be used to determine the Mode II fracture toughness of the bamboo scrimber.
4. The failure of both the S-L and F-L groups were instantaneous, which means that the plastic strain in the crack tip before failure was small. Thus, the linear elastic fracture mechanics is applicable to the mode II fracture of bamboo scrimber.

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