Fatigue and Fracture Properties of Laminated Bamboo Strips from *Gigantochloa scortechinii* Polyester Composites

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The fatigue and fracture properties of bamboo fiber composites made of woven layers were investigated. This study utilized a specific type of bamboo species named *Gigantochloa scortechinii* (Buluh Semantan). In these experiments, unsaturated polyester (UP) and bamboo fiber (BF) strips were prepared through a hand lay-up technique using 3-mm thick aluminum mould. The composite bamboo strips had a thickness of 1.5 mm. The strips were woven together to make a single layer. The layer was then laminated into several thicknesses. The specimens were then characterized using fatigue and fracture tests. A fatigue limit of 30 MPa and fracture toughness of 5 to 8 MPa $\sqrt{m}$ were obtained. These findings suggest that the bamboo strips, based on unsaturated polyester, provided relatively good fatigue and fracture properties and a good method of reinforcing fibers to combat fatigue and fracture failures.

Keywords: Unsaturated polyester; Bamboo strip; Gigantochloa scortechinii; Fatigue and fracture laminated composites; Mechanical testing

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INTRODUCTION

It is evident that natural fibers used for composite reinforcement are a subject of growing interest for many researchers, due to the fact that they are renewable and have excellent reinforcing properties in polymer composites (Rasiah *et al.* 2013). It was highlighted by Mohamed and Appanah (1999) that there is approximately 7.0 million tons (average 20 tons/ha) of bamboo stock in Malaysia, of which, only 6,000 tons consist of commonly used species. This bamboo stock holds an estimated value of 3 million of Malaysian Ringgit (RM), which is approximately 1 million American dollars (USD). The raw material consists of cellulose fibers embedded in a lignin matrix that is aligned along the length of the bamboo providing maximum tensile and flexural strength and rigidity in that direction (Lakkad and Patel 1981; Rao *et al.* 2010). Recent studies on bamboo (Anwar *et al.* 2009; Jiang *et al* 2012; *Liu et al.* 2012; Huang *et al* 2015; Rassiah *et al.* 2014, 2015) have been successfully and comprehensively characterized the tensile, flexural, impact, and hardness properties of bamboo composites.

The attractive features of bamboo are, specifically, its high specific strength and modulus, low density, biodegradability, recyclability, and the fact that it is a natural material. Therefore, the combination of two given materials and natural fibers produces a

stronger and more corrosion-resistant composite material. It also improves the stiffness, strength, and moisture-resistant behavior of the composite (Li *et al.* 2002; Yao and Li 2003; Van der Lugt *et al.* 2006; Obataya *et al.* 2007; Biswas and Satapathy 2010; Shao *et al.* 2010; Porras and Maronan 2012; Verma and Chariar 2012; Yeh and Lin 2012). There are also reviews on bamboo research findings (Rassiah *et al.* 2013, 2015). However, none of the available research reports on the fatigue and fracture behavior of bamboo composites. The fracture toughness of bamboo materials has been studied; however in terms of bamboo that have been made into composites, especially when it is made in a sandwich configuration, limited findings have been reported. In addition, the authors are not aware of any publications dealing with bamboo composites that used polyester or fiber glass as the matrix. Understanding the fatigue behavior and fracture toughness of these bamboo composites is vital in order to warrant a safe manufacturing environment for designing components made of bamboo composite.

The aim of this study was to characterize the fatigue and fracture properties of three different laminated bamboo strip composites of various thicknesses. The results of this research give manufacturers and engineers a sound decision on whether or not to consider bamboo composite in their selection of materials in design processes.

EXPERIMENTAL

The materials used in this study were "unsaturated polyester" (UP) as the matrix material and “bamboo fiber” (BF) in a woven form.

Unsaturated Polyester

The matrix system consisted of Reversol P-9509 unsaturated polyester (UP) supplied by the Synthomer (Malaysia) Sdn. Bhd. Company. The Reversol P-9509 had a specific gravity of 1.12 at 25 °C, a viscosity of 450 to 600 cps, a volumetric shrinkage of 8%, and an acid value of 29 to 34 mg KOH/g for the solid resin. This type of resin is a rigid, minimally reactive, and thixotropic general-purpose orthophthalic unsaturated polyester resin. This particular resin is pre-promoted for an ambient temperature cure, for which the addition of methyl ethyl ketone peroxide (MEKP) was used as the catalyst. This resin is convenient for hand lay-up applications and easy air release.

Bamboo

The bamboo species used in these tests was *Gigantochloa scortechinii* (Buluh Semantan) collected from the Bukit Larang village in Melaka, Malaysia. The bamboo stalks were cut into strips using a cleaver and a handsaw. The strips were cut with a knife to a width of 1.5 mm, and then woven into a fabric (Fig. 1). The reason for using 1.5 mm width was described in another work (Rassiah *et al.* 2014). The thickness of the strip was 0.5 mm.

Specimen Preparation

The middle bamboo layers were cut and washed with water. In this case, a dry oven (MEMMERT BASIC Universal Oven- UFB 400-500) was used at 60 °C for 72 h to reduce the moisture content of the bamboo. The strips were then woven as shown in Fig. 1. The woven bamboo was subjected to a hand lay-up process, as shown in Fig. 2, to produce the sample mould. The dimensions of the mould were 120 mm × 120 mm × 3

mm. First, a scraper was used to clean the dirt inside the surface of the mould, and then, a rag was used to wipe the mould surface. The internal surfaces of the mould were then sprayed with a releasing agent (silicon) to facilitate easy removal of the bamboo. The unsaturated polyester was mixed with the methyl ethyl ketone peroxide (MEKP) catalyst at a ratio of 100:2. They were stirred together until the color of the mixture changed from light pink to pale yellow. The mixture was then poured into the mould until it covered the bottom of the mould. Then, the woven bamboo was placed slowly on the top of the lower surface to wet it. Afterwards, the mixture was poured on the top surface of the woven bamboo and brushed in one direction to ensure that it fully covered the strips. A steel plate having a weight of 10 kg was use to give pressure and hold the woven bamboo in place until the epoxy was completely harden as exhibited in Fig. 3. The UP cure time was approximately 30 min. Finally, the finished laminated bamboo composite was produced as shown in Fig. 4. Samples of thicknesses of 3 mm, 6 mm, and 9 mm were cut from the bamboo composite to study the effect of thickness on the properties of the composite.

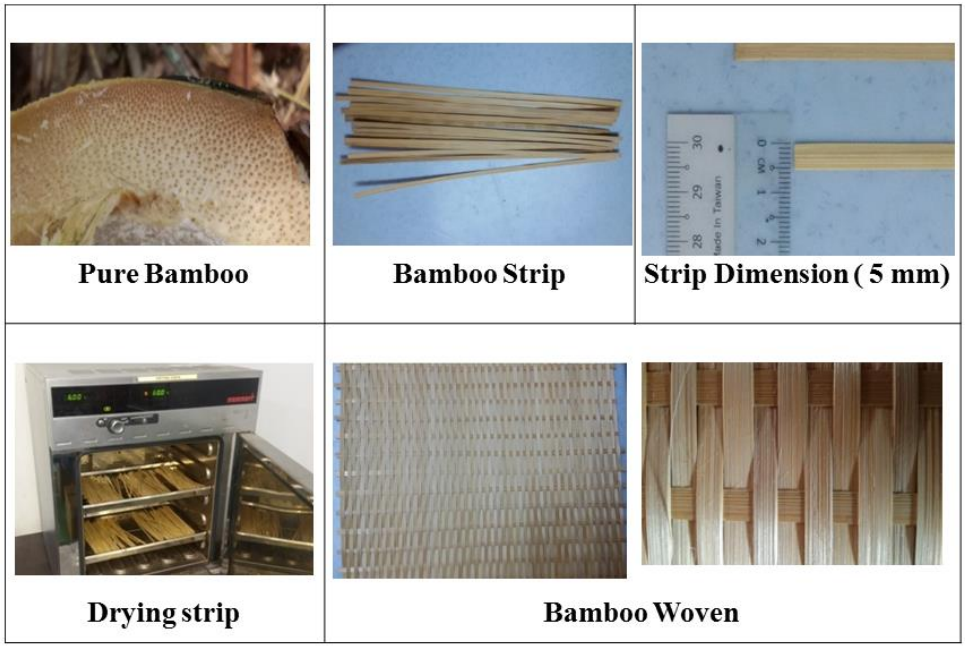

Fig. 1. Woven-fabric laminated bamboo

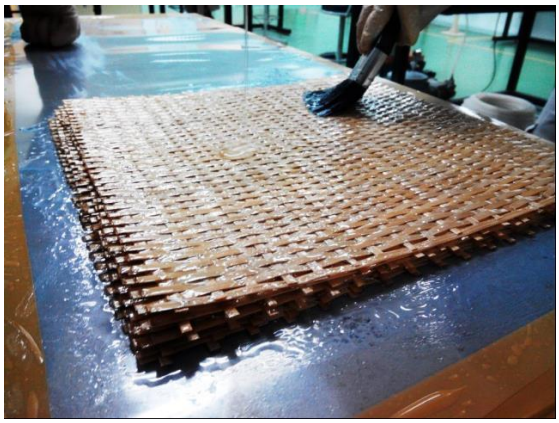

Fig. 2. The unsaturated polyester poured onto each layer of the woven bamboo

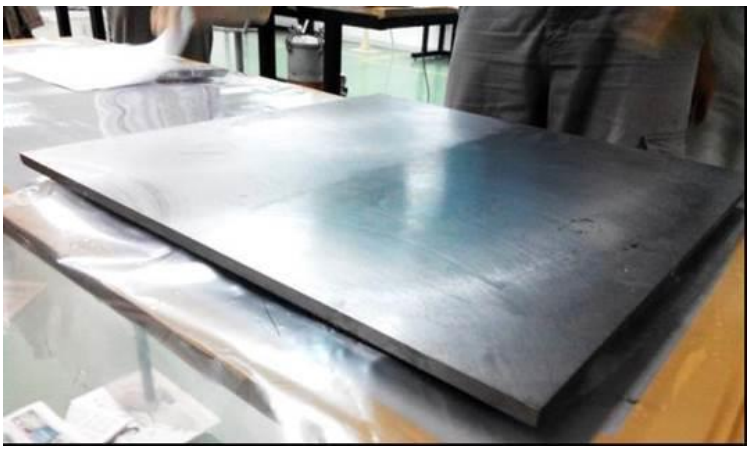

Fig. 3. A 10-kg load steel plate placed on the woven bamboo

Fig. 4. The final laminated bamboo composite

Fatigue Test

For fatigue testing, the specimens were prepared in accordance with ASTM 3039 (2008), as shown in Fig. 5. Samples were cut into rectangular cross-sections (250 mm ×17 mm × 3 mm) with a 150 mm gage length and 15 mm end tabs. The tabs (50 mm × 17 mm × 2 mm) were made from aluminum and were bonded by the epoxy resin to both ends of the specimen in order to prevent slippage and premature failure (in accordance with ASTM 3039 (2008)).

The test was conducted using a 100 kN servo hydraulic testing machine, Instron 8801 Fatigue Testing System (Instron, UK). The load ratio *R* of 0.1 and constant load amplitude with several different maximum stress levels were used. A frequency of 2 Hz was selected to avoid any hysteresis heat generated during testing. The maximum stress levels starting at 0.80 of UTS (means 80% of ultimate tensile strength) of the specimen followed by 0.60 UTS, 0.50 UTS, 0.40 UTS, 0.30 UTS, and 0.20 UTS were chosen to generate a sufficient interval of point of the S-N curve. Fatigue specimens were made to be 3 mm that requires 2 layers of woven bamboo, 6-mm specimen requires 4 layers woven bamboo, and 9-mm specimen requires 6 layers woven bamboo.

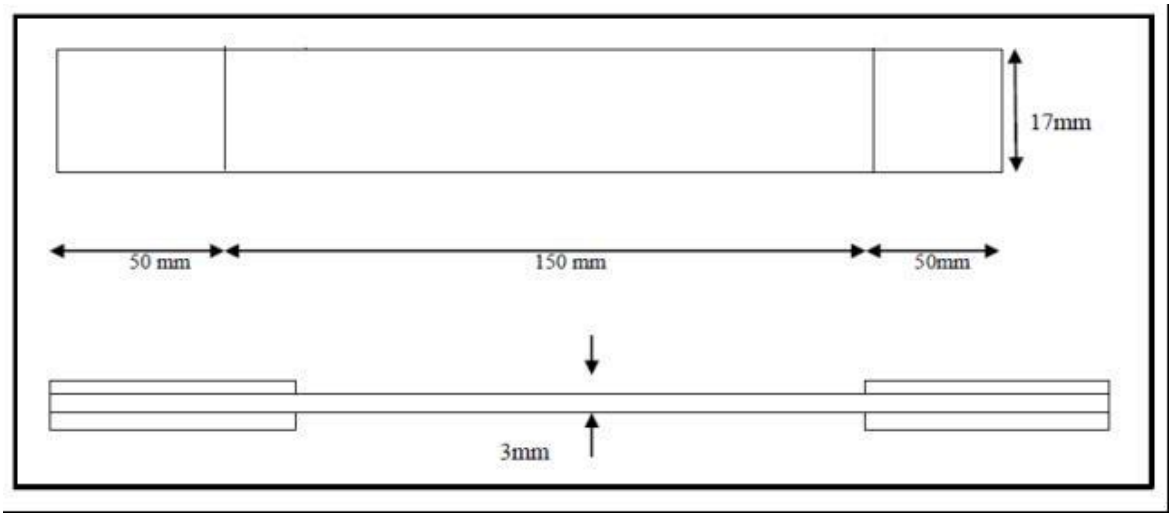

Fig. 5. Specimen geometry in accordance with ASTM D3039 (2008)

Fracture Test

A universal testing machine was used for fracture testing to analyse the compact tension testing for fracture toughness. The fracture test was carried out in accordance with ASTM D 5045 (2012). Figure 6 shows the dimensions of the test specimens (mm), using the universal testing machine type 50kN Instron, UK, Derby England, 5569A at 25 ± 2 °C ambient temperature. Specimens were made in the vertical and horizontal directions to test the effect of fiber orientation on the fracture resistance. Testing was conducted at the recommended constant speed of 10 mm/min.

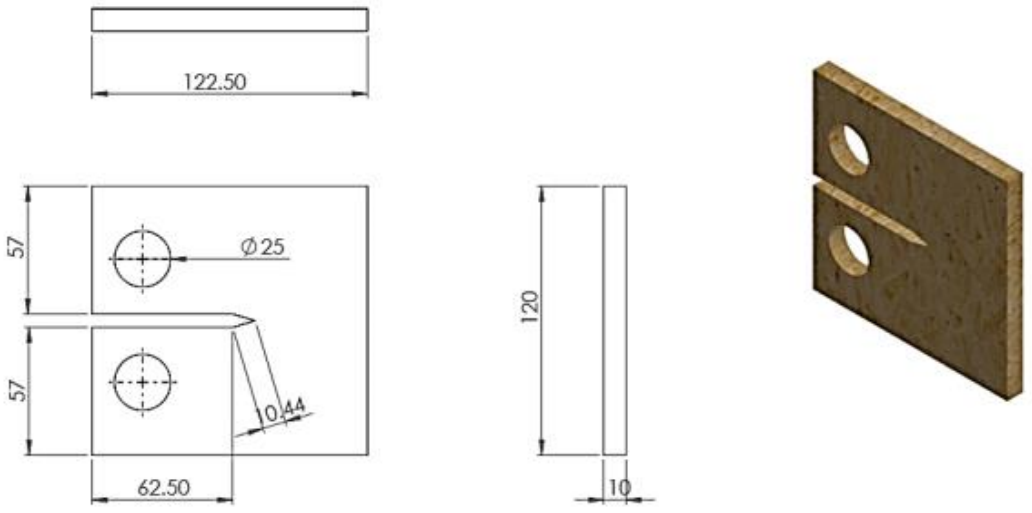

Fig. 6. Specimen geometry in accordance with ASTM D5045 (2012) all dimension in mm.

RESULTS AND DISCUSSION

Fatigue Results

The stress life (S-N) fatigue result curves are plotted in Fig. 7. Photos of some of the broken fatigue specimens are shown in Fig. 8. The exact fatigue limit is not always clearly observed during steel fatigue testing. Curves with no exact fatigue limit are also normally observed in the S-N curve of aluminum. The demarcation between the low cycle fatigue (LCF) and high cycle fatigue (HCF) of the bamboo composite is suggested to be at the knee of the curve, approximately at 1 x 10^4 cycles.

It is worth noting that the 3 mm-thick specimen exhibited the highest fatigue limit of 30 MPa, compared with the 6-mm and 9 mm-thick specimens, which had fatigue limits of 20 MPa and 19 MPa, respectively. In another work by Shah *et al.* (2013) the S-N curves of different plant fiber/yarn polyester composites showed similar trends. However, a high-tech bamboo/epoxy composite made from Chinese Moso bamboo is reported to reach a 80 MPa fatigue limit (Platts 2014).

In the composite, the transition region could have a slight influence on the fatigue data. The transition region is normally can be related to the types of damage that the composite experiences.

It is commonly known that the mechanism of a composite failure involves several stages before the failures take place including matrix cracking, fiber breakage, delamination, and fiber-matrix debonding. In this experiment, the maximum stress of 0.4 from UTS level is presented as the transition point. It is indicated that at or below this point, the specimens could still have cycled without having any significant damage in the early life.

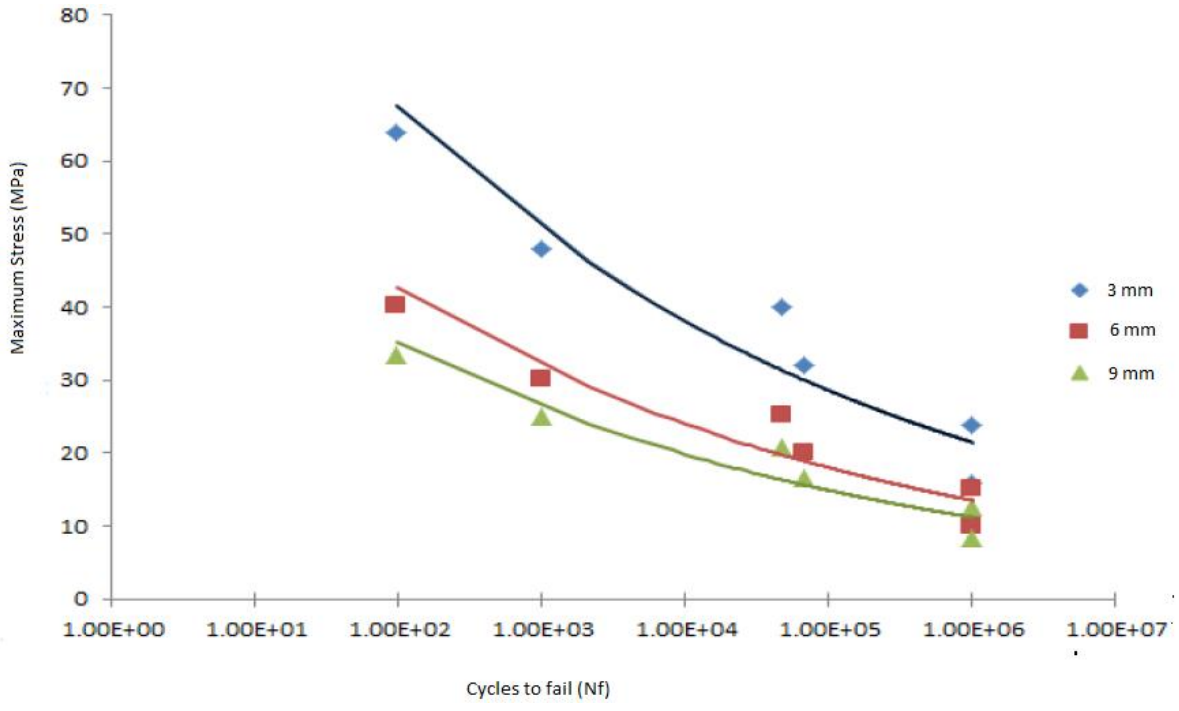

Fig. 7. S-N curves of the bamboo laminated composite of different thicknesses

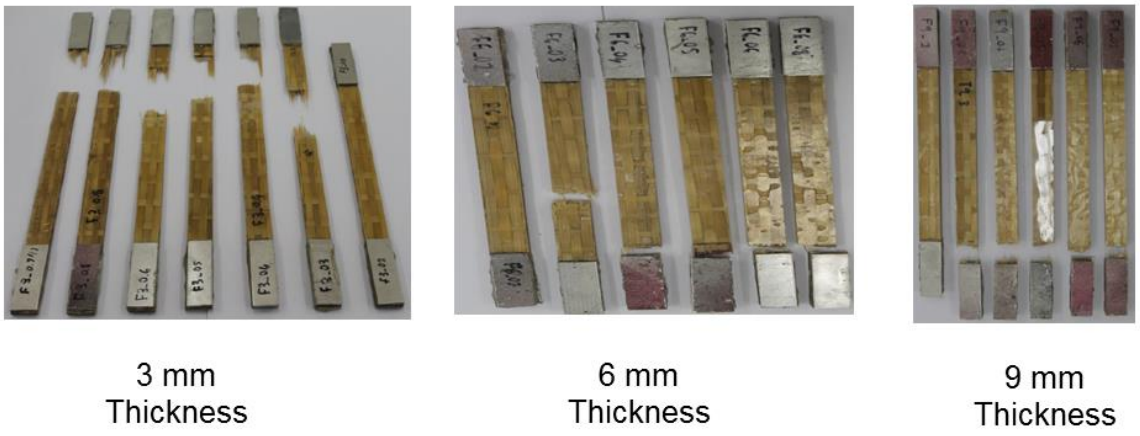

Fig. 8. Some of the fatigue broken specimens of the bamboo composite

To better understand the failure, the broken samples were observed by a scanning electron microscope (SEM) ZEISS Merlin manufactured in Germany to observe the fractographic surface of the specimen after failure occurred. Most researchers have registered that fracture fractography of a specimen may be related to the stiffness degradation and fatigue damage accumulation. Unlike metallic materials, composite materials have one or more damage mechanisms. According to one report (Harris 2003), composite materials were found to be inhomogeneous and anisotropic. They tend to accumulate damage in a general rather than a localized fashion, and failure does not always occur by the propagation of a single macroscopic crack. The damage mechanisms, including fiber breakage and matrix cracking, debonding, transverse-ply cracking, and delamination, occur sometimes independently and sometimes interactively. The predominance of one failure over another may be strongly affected by both the material properties and the testing conditions.

Figure 9 shows the SEM images of the 0.6 UTS bamboo fiber composite. There are several types of failure observed in the images, included matrix cracking, fiber breakage, and failure at a void.

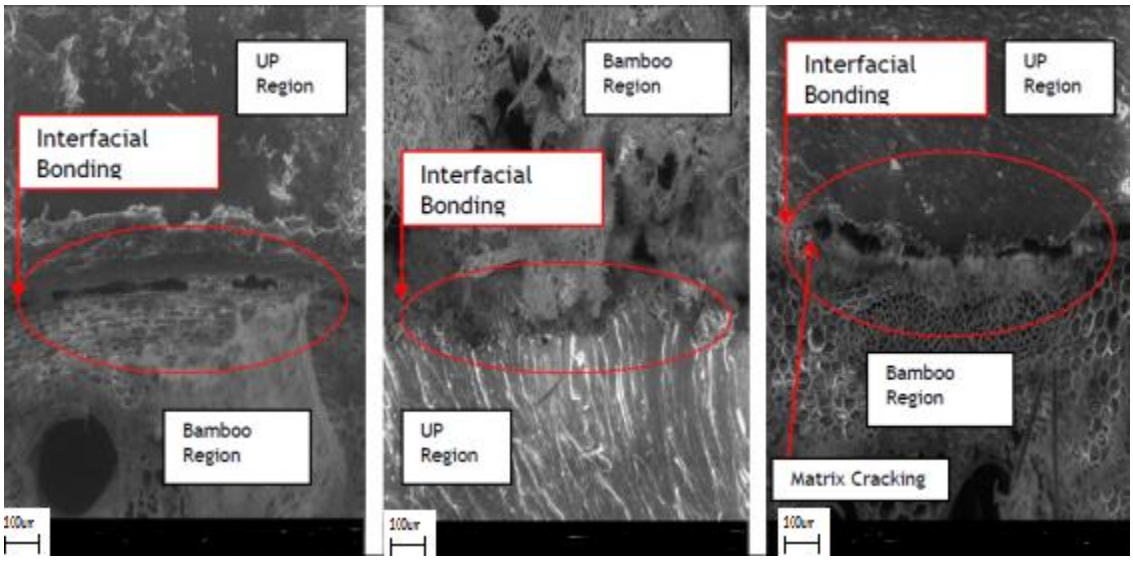

Fig. 9. SEM images of the fatigue bamboo broken specimen with 0.6 UTS of stress applied

The fabrication of this specimen using the hand lay-up technique seems to not have been fully efficient, as voids or trapped gasses are observed. Vacuum infusion is a popular technique that would be better suited for future experiments. Interfacial debonding of the matrix composite began with an initial crack after certain cyclic loading and then propagated until the specimen experienced complete failure. In some circumstances, the defects crack likely existed before the specimen was subjected to the fatigue load. On the other hand, fatigue damage cracks also occurred, which included crack propagation, coalescing, and accumulating after undergoing several fatigue cycles. In this study, the defect distribution was not examined, so therefore it is hard to quantify the intensity of the defect and its relation with damage.

Fracture Results

Images of the compact tension (CT) bamboo specimens are shown in Fig. 10. To investigate the effect that the bamboo fiber orientation had on the fracture toughness, specimens with horizontal and vertical fiber orientations were made, as shown in Fig. 11. It is worth noting that the specimen with vertical orientation showed greater resistance to crack propagation compared with horizontal orientation, as shown in Figs. 12 and 13.

Fig. 10. CT specimen of the bamboo composite

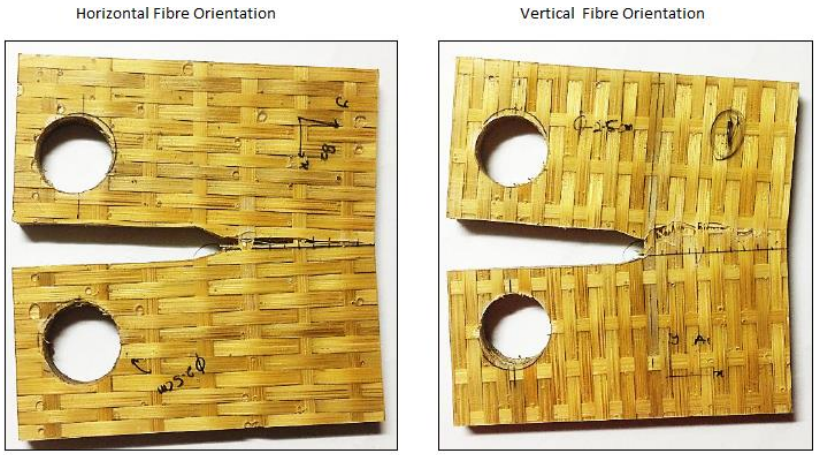

Fig. 11. Two different fiber orientations of the CT specimen

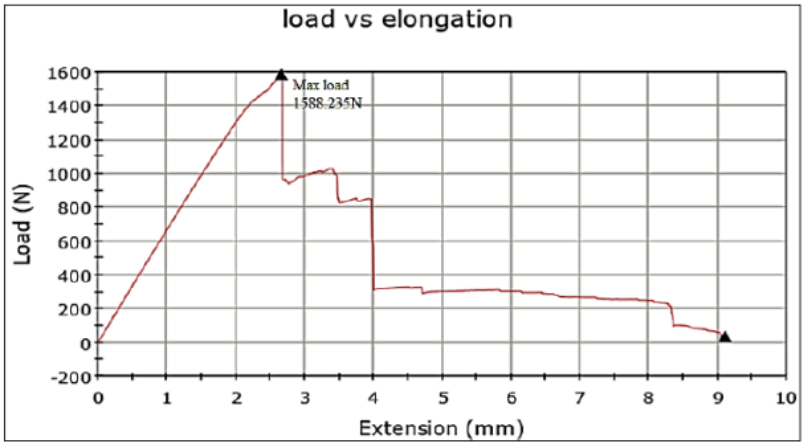

Fig. 12. Load *vs* Elongation crack resistance curve of the horizontal orientation specimen

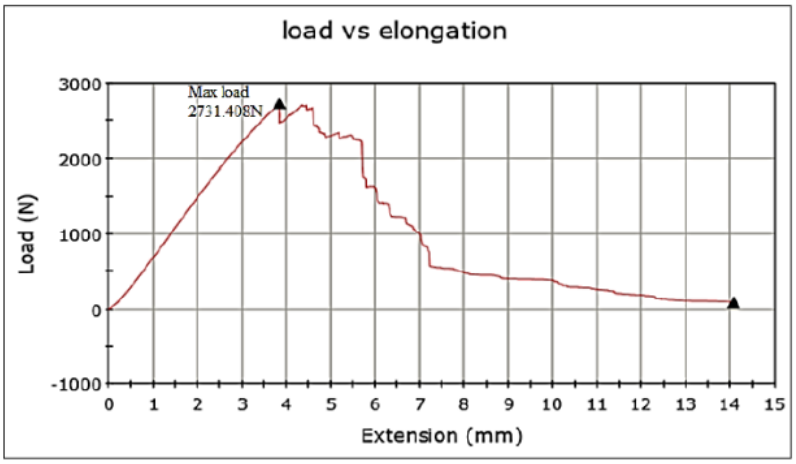

Fig. 13. Load *vs* Elongation crack resistance curve of the vertical orientation specimen

The maximum load obtained in fracture toughness testing was used to calculate the fracture toughness, *Kic*, of the bamboo composite. Measurements from 10 test samples resulted in average *Kic* values of 4.84 MPa $\sqrt{m}$ ± 0.05 and 8.33 MPa $\sqrt{m}$ ± 0.05 for the horizontal and vertical fiber orientations, respectively. In terms of crack propagation direction, in the case of horizontal orientation, the crack propagation path was parallel to the fiber orientation with a little incline. However, the crack path for the vertical orientation samples had an incline in the vertical direction. It is clear that the composite ripped apart more easily in the direction of fiber orientation. In the horizontal case, the notch was placed inside the bamboo strips, whilst for the vertical case it was placed in between the two strips. It is suggested that these two factors explain the different toughness values obtained. It takes less strength (or load) to separate the fibers from each other than that required to break the fibers apart. Amada and Untao (2001) reported that bamboo itself has an average fracture toughness, *Kic*, of 56.80 MPa$\sqrt{m}$ ± 0.05. However, the cited authors did not perform the test on a bamboo composite, but rather on bamboo raw materials only. The reported value was slightly higher than that with aluminum and steel alloy. Therefore, the fracture resistance of bamboo itself cannot be compared with that of the bamboo composites.

To get a bigger picture on the bamboo composite performance in terms of fracture resistance, Table 1 tabulates a comparison of *Kic* values of various other composites and materials. As expected, the *Kic* of metal shows that metal has a much greater fracture toughness than that of natural fiber composites. However, among composites, the bamboo-laminated composite has a higher fracture resistance compared with that of a hybrid glass matrix composite. It should be noted though, that some carbon fiber/epoxy composites might have higher fracture toughness, which are not shown in the table.

Table 1. Comparison of *Kic* Values of the Bamboo Composite with Other Materials

Material Type	Material	Kic MPa $\sqrt{m}$
Metals	Steel Alloy (4340)	50
	Titanium Alloy	44-66
	Aluminium	14-28
	Aluminium Alloy (7075)	24
Composites	Laminated natural bamboo composite	4-8
	Nylon	4.34
	Hybrid Glass matix composites	2.6-6.64
	Polycarbonate	3.6
Ceramics	Mullite-Fibre Composites	
	Soda-lime glass	0.7-0.8
	Concrete	0.2-1.4

CONCLUSIONS

1. The fracture toughness of the laminated bamboo composite was found to be 4.847 MPa√ for the horizontal fibre orientation specimen and 8.334 MPa√ for the vertical fibre orientation.
2. There was no exact fatigue limit for the bamboo composite. The fatigue strength of the composite at 30 MPa registered the highest with 1 x 10^6 cycles. The 3-mm thickness provided best fatigue resistance.
3. The bamboo composites studied in this work provided relatively good fatigue and fracture resistance as compared with other composites.

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