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Tensile and flexural properties of bamboo (*Gigantochloa apus*) fiber/epoxy green composites

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Abstract. The current work deals with the tensile and flexural properties of bamboo fiber/epoxy composites. Tensile and flexural property evaluations were carried out in accordance with the ASTM D638 and ASTM D790 standards, respectively. Bamboo fiber was obtained from local bamboo by means of degumming process. The matrix being used is Eposchon general purpose Bisphenol A-epichlorohydrin epoxy resin mixed with Eposchon general purpose Polyaminoamide epoxy hardener supplied by P.T. Justus Kimiaraya. The specimens were cut from five bamboo fiber/epoxy composite panels. Five different fiber volume fractions, V_f, *i.e.* 0, 10, 20, 30 and 40 vol%, have been considered. All mechanical and physical characterization were carried out at the Mechanical Engineering laboratory, Universitas Muhammaiyah Yogyakarta. Photo macrographs of selected samples were analyzed to describe their failure modes. Physical property evaluation revealed that a slight fiber content deviation from their expected results was observed. Whilst tensile strength, modulus and strain to failure, as well as flexural strength and modulus were found to increase with the increase of fiber content up to 29.8%, maximum flexural strain to failure was being at V_f = 21.1%. Tensile specimens were mostly failed by debonding followed by fiber breakage, while flexural specimens were mostly failed by debonding followed by fiber breakage and fiber pull-out at tension sides.

Introduction

Synthetic fibers are known to take longer time to degrade in the nature after their service life. It leads to people consider natural fibers, which easier to decompose, for alternative substitution for synthetic reinforcing materials in producing composite structures and parts and household appliances. Bamboo fibers are among the potential candidates for such replacement due to its availability, low cost, and light weight yet moderately strong compared to other construction materials [1] resulting in low price material combined with high specific strength and stiffness. Van Vuure and his colleagues [2] reported that whilst specific tensile modulus and tensile strength of long bamboo fiber composites are comparable to those of GFRP composites, their specific bending stiffness is even higher than that of GFRP composites. Although a number of investigations on bamboo fiber composites have been reported [3-5], the number of research regarding tensile and flexural characterization of apus bamboo fiber/epoxy composites being reported is still limited. Bamboo can easily be found in Daerah Istimewa (Special District of) Yogyakarta and its surroundings. Some structures using composite materials are loaded in tension such as tension bars of truss structures, and flexure such as various beam structures. The current work deals with tensile and flexural property evaluation of bamboo fiber/epoxy composite.

Experimental Procedure

Bamboo fiber being used was obtained from local sources by degumming combined with mechanical process. Before being used as reinforcement, the fibers were alkaline-treated, *i.e.* submerged in 5 wt% alkaline solution for 4 hours, followed by neutralizing by submerging in water for 24 hours, in which the water was replaced every six hours, and washing them in flowing water in order to remove the alkaline residue from fiber surface. The resulted fibers were then dried at room temperature, to prevent them from surface defect, for three days. The matrix being used is Eposchon general purpose Bisphenol A epichlorohydrin epoxy resin mixed with Eposchon general purpose Polyaminoamide epoxy hardener, both were obtained from P.T. Justus Kimia Raya. The mixing ratio is 1:1 by weight as recommended by the manufacturer. Physical and mechanical characteristics of bamboo fiber and a typical cured epoxy presented in Table 1 may be utilized as references.

Table 1. Physical and mechanical characteristics of bamboo fiber and epoxy resin

Properties	Bamboo fiber	Cured epoxy
Tensile strength [MPa]	504 [6]	70 [8]
Tensile modulus [GPa]	10.1 [6]	2.25 [8]
Density [$g.cm^{-3}$]	0.91 [7]	1.2 [8]

Composite plate panels containing five different fiber contents were fabricated by press-mould process. The magnitude of pressure being applied is ~2 [MPa], and curing process took place at room temperature. The panels were post-cured at ~50°C for ~2 hours. The plates were then cut using diamond-tipped circular blade rotating at ~10000 rpm to produce tensile specimens according to the ASTM D638 [9], and flexural specimens according to ASTM D790 [10]. The gage length of tensile specimens is 33 mm, while the span and the thickness of flexural specimens are ~96 mm and ~3 mm, respectively, such that the span to depth ratio of flexural specimens is ~32. Mechanical testing was carried out at the Mechanical Engineering Department, Universitas Muhammadiyah Yogyakarta. Preliminary test suggests that end tabs for tensile specimens are not required.

Actual volume fractions of fiber were calculated from their respective specimen cross sections by means of open source software, the *ImageJ* [11]. The magnitudes of tensile and flexural properties were calculated according to their respected adopted standards where their tensile moduli were calculated at ~0.3% strain. The magnitude of flexural strength, strain to failure, and modulus of long beam composites can be calculated using equations (1) to (3), respectively [10].

$$\sigma_f = \frac{3F_{max} \cdot S}{2wd^2}\left[1 + 6\left(\frac{D}{S}\right)^2 - 4\left(\frac{d}{S}\right)\left(\frac{D}{S}\right)\right]. \tag{1}$$

$$\varepsilon_{max} = \frac{6Dd}{S^2}. \tag{2}$$

$$E_f = \frac{S^3}{4w \cdot d^3} \times \frac{\Delta F}{\Delta D}. \tag{3}$$

where σ_f [MPa], F_{max} [N], S [mm], w [mm], d [mm] and D [mm] are the magnitude of flexural strength, magnitude of maximum applied lateral force, beam span, beam width and beam depth, respectively. And ε_{max} [$mm.mm^{-1}$], E_f [MPa] and $\Delta F/\Delta D$ [$N.mm^{-1}$] are the maximum flexural strain at the midspan of the beam, elastic modulus calculated at the initial straight line of *F-D* curve, and the slope of *F-D* curve at the initial straight line of the curve, repectively.

Table 2. Designed and actual V_f (%)

Specimen	Designed V_f				
	0	10	20	30	40
Tension	0	8,2	22,2	29,8	47,7
Flexure	0	6,7	21,1	28,9	47,3

Result and Discussion

Fiber Volume Fraction (V_f). The theoretical and actual values of V_f have been presented in Table 2. Slight deviations, either positive or negative, of actual fiber volume fractions from their respective theoretical values were observed. The increase of V_f may be attributed to resin flowing out while pressing during plate panel fabrication. In addition, although the fabrication procedure has been carried out very carefully, quite large portion of mini voids can still be observed concentrated just below the upper surface of the casted panels as can be noticed in the tensile specimen sample depicted in Fig.1. Such voids as discontinuities may affect the mechanical properties of the specimens.

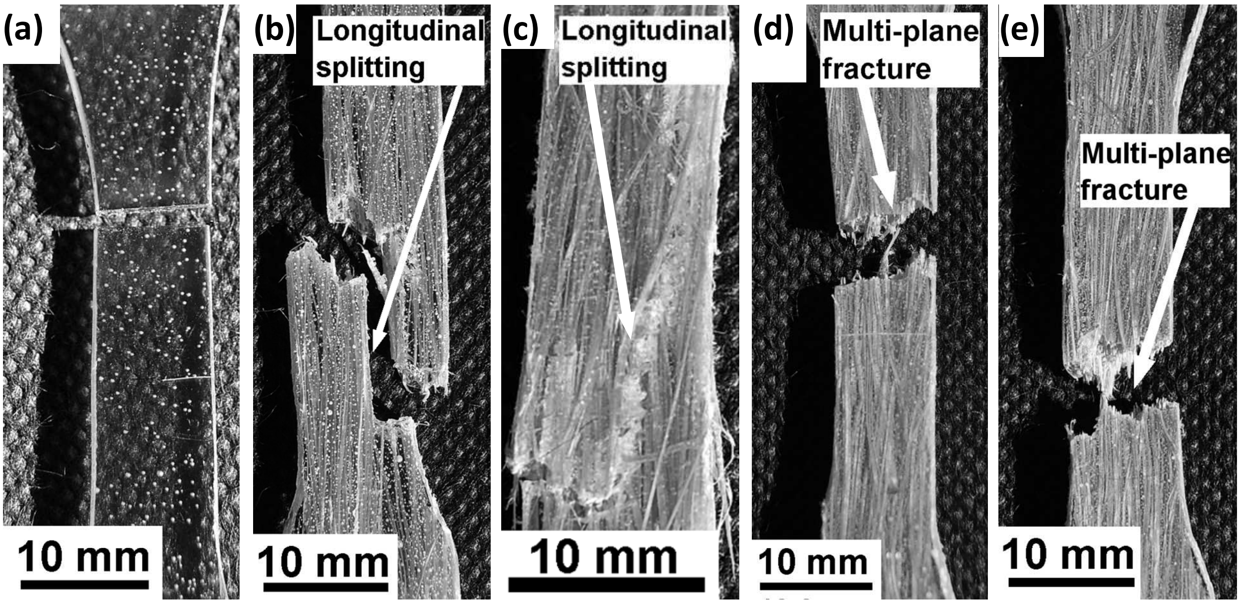

Fig. 1. Representative tensile specimen showing mini voids (clear dots) and failure modes. (a) V_f = 0% with single-plane fracture, (b) V_f ~ 8.2% with longitudinal splitting, (c) V_f ~ 22.2% with longitudinal splitting, (d) V_f ~ 29.8% with multi-plane fracture, (e) V_f ~ 47.7% with multi-plane fracture.

Tensile Properties (σ_t, ε_t and E_t). Representative fractured tensile specimens have been presented in Fig. 1. It can be observed in Fig. 1 that there is failure mode shift from single-plane fracture at V_f = 0% to longitudinal splitting as reported by Lee *et al.* [12] for GFRP composites at low V_f (8.2% and 22.2%), then to multi-plane fracture at higher V_f (29.8% and 47.7%). Generally speaking, most tensile specimens failed due to interface debonding followed by fiber breakage leading to specimen failure. The plot of V_f on one hand versus σ_t, ε_t and E_t on the other hand have been presented in Fig. 2. It shows that all σ_t, ε_t and E_t

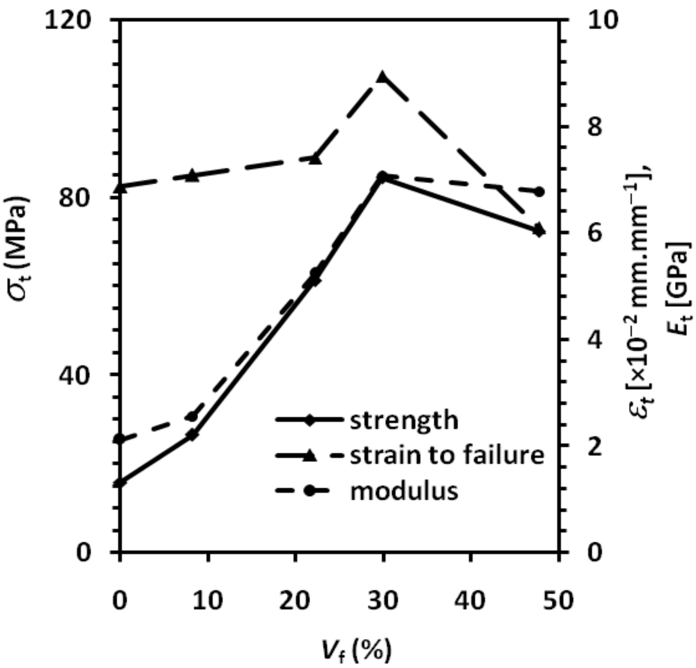

Fig. 2. Effect of fiber content on tensile properties

increase with the increase of V_f up to ~30%. Their values are 84.5 [MPa], 0.090 [mm.mm^{-1}], and 7.1 [GPa], respectively. The tensile strength and tensile modulus being obtained are comparable to those reported by Trujillo *et al.* [13], for bamboo fiber/epoxy composites at almost the same fiber

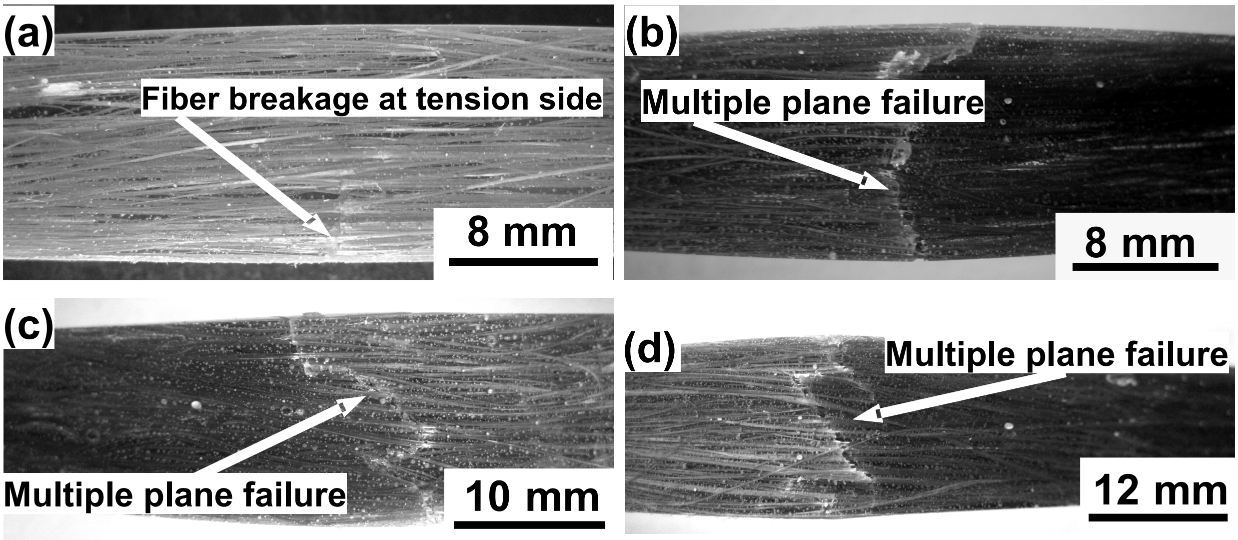

Fig. 3. Representative flexural specimens showing mini voids (white dots) and failure modes. (a) V_f = 6.7% with failure initiated at tension side, (b) V_f ~21.1% with multiple-plane failure, (c) V_f ~ 28.9% with multiple-plane failure, (d) V_f ~ 47.3% with multiple-plane failure.

content. An additional increase of V_f up to 47.7% resulted in slight decrease in tensile strength and modulus, and significant decrease in tensile strain.

Flexural Properties (σ_f, ε_f and E_f). After being tested, a number of representative fractured specimens were photographed using digital camera, and the results have been presented in Fig. 3. It can be observed in Fig. 3(a) that, unlike high strength synthetic fiber composites, failure was initiated at tension side. It can be said that most flexural specimens failed due to fiber breakage. The plot of V_f on one hand versus σ_f, ε_f and E_f on the other hand have been presented in Fig. 4. It shows that whilst σ_f, and E_f increase with the increase of V_f, ε_t decreases. Maximum values for σ_f, E_f and ε_t were found being 74.6 [MPa] at V_f = 47.3%, 3.19 [GPa] at V_f = 47.3% and 0.07 [mm.mm^{-1}] at V_f = 21.1%, respectively. These three values are very much higher in comparison with their respective values for randomly oriented chopped straw fiber/polyester composites reported by Dong and Davies [14]. This result may be attributed to the fiber orientation which is unidirectional, and the flexural strength of bamboo fiber being higher than that of sugar palm fiber [1].

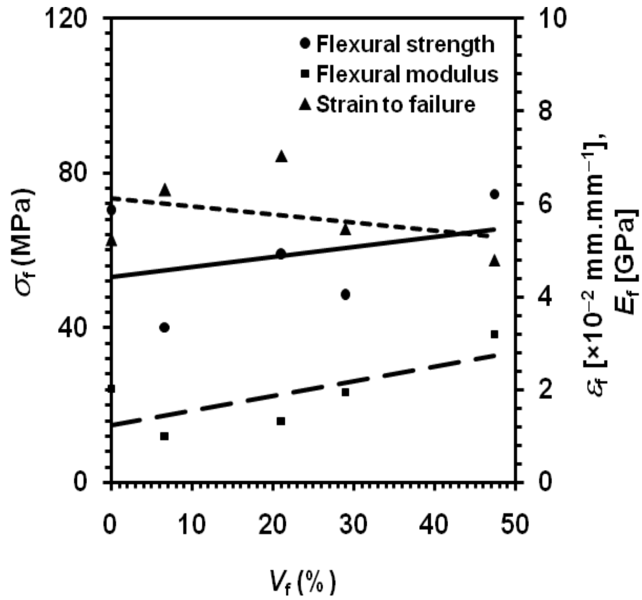

Fig. 4. Effect of fiber volume fraction on flexural properties

Conclusion

Tensile strength (σ_t), strain to failure (ε_t) and modulus (E_t) were found to increase with the increase of fiber content up to V_f = 29.8%, followed by a slight decrease at V_f = 47.7%. Most specimens failed due to longitudinal splitting followed by fiber breakage. Apart from strain-to-failure, flexural strength and flexural mudulus tend to increase with the increase of fiber content. Unlike high strength synthetic fibers, flexural failure were found being initiated at the tension face.

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