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Tensile and interfacial properties of unidirectional flax/glass fiber reinforced hybrid composites

Yongli Zhang, Yan Li *, Hao Ma, Tao Yu

School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, PR China

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ABSTRACT

This paper studied the mechanical behaviors of unidirectional flax and glass fiber reinforced hybrid composites with the aim of investigation on the hybrid effects of the composites made by natural and synthetic fibers. The tensile properties of the hybrid composites were improved with the increasing of glass fiber content. A modified model for calculating the tensile strength was given based on the hybrid effect of tensile failure strain. The stacking sequence was shown to obviously influence the tensile strength and tensile failure strain, but not the tensile modulus. The fracture toughness and interlaminar shear strength of the hybrid composites were even higher than those of glass fiber reinforced composites due to the excellent hybrid performance of the hybrid interface. These macro-scale results have been correlated with the twist flax yarn structure, rough surface of flax fiber and fiber bridging between flax fiber layers and glass fiber layers.

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1. Introduction

In recent years, the usage of natural fibers as a replacement for synthetic fibers such as carbon and glass fibers in composite materials has gained interest among researchers throughout the world. Extensive studies on natural fibers, such as sisal [1], jute [2,3] and flax [4,5], showed natural fibers has the potential to be an effective reinforcement for composite materials. The renewed interest of natural fibers over synthetic fibers was that they are abundant in nature and are also renewable raw materials. The usage of natural fibers also provided a healthier working condition than that of glass fibers [6]. Furthermore, natural fibers offer good thermal properties and excellent acoustic performance. These advantages made natural fibers gain applications in automotive, packaging and construction industries [7]. However, the products made from natural fiber composite were still limited to the non-structure or sub-structure applications, for example, the interiors of cars due to their relatively poor mechanical properties [8]. Different approaches have been attempted to increase the mechanical properties of natural fiber reinforced composites, such as chemical or physical modifications of the matrix, fibers or both of the components. Mohanty et al. [9] found that alkali treatment increased the bending strength of jute/biopol composites by 30%. Xie et al. [10] reviewed the influence of silane coupling agents used for natural fiber/polymer composites. Besides, hybridizing the natural fibers with a stronger synthetic fiber could significantly improve the strength and stiffness of the natural fiber reinforced composites [11]. Earlier works done on the natural fiber/glass fiber hybrid composites basically focused on the short fibers [12]. Nayak et al. [13] proved that hybridization with short glass fiber, the storage modulus of short bamboo fiber reinforced polypropylene composites could be improved. Velmurugan and Manikandan [14] reported addition of glass fiber to palmyra fiber in the matrix could increase the mechanical properties and decrease the moisture absorption of the composites.

The comparison on the mechanical properties of different natural fibers and E-glass fiber was shown in Table 1. It was seen that flax fibers possess superior mechanical properties over other natural fibers. The tensile properties and elongation at break of natural fibers are all lower than those of E-glass fiber. However, the density of natural fibers are almost 1/2 of that of glass fiber. Therefore, hybridizing flax fibers with glass fibers might yield a material with interesting properties (lighter in weight, higher in strength and modulus and greener than synthetic materials) and the new hybrid effect might be revealed from the point of views of properties matches of the component fibers and the structure characteristics of natural fiber yarns.

In this work, unidirectional flax fibers and glass fibers were selected to make the hybrid composite laminates so that the hybrid effects could be revealed more easily. The mechanical properties, such as tensile, interlaminar shear and interlaminar fracture toughness properties of the hybrid composite laminates, were studied. The influence of hybrid ratio and stacking sequence were

* Corresponding author. Address: School of Aerospace Engineering and Applied Mechanics, Tongji University, 1239 Siping Road, Shanghai 200092, China. Tel.: +86 021 65985919; fax: +86 021 65983950.

E-mail address: liyan@tongji.edu.cn (Y. Li).

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Table 1
Mechanical properties of natural fibers and glass fiber [12,15].

Fibers	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Flax	1.2	800–1500	60–80	1.2–1.6
Hemp	1.48	550–900	70	1.6
Sisal	1.33	600–700	38	2–3
Jute	1.46	400–800	10–30	1.8
E-glass	2.5	2000–3500	70	2.5

investigated and the hybrid mechanisms were revealed with the aid of the Scanning Electronic Microscopy (SEM) observations.

2. Materials and experimental

2.1. Materials

The unidirectional flax fabric was supplied by Belgium Lone Company, which had a density of 1.20–1.25 g/cm^3 and aerial weight of 200 g/m^2. The unidirectional glass fabric was supplied by Zhejiang Mengtai Composites Company, which also had an aerial weight of 200 g/m^2. Phenolic resin was supplied by the Institute of Chemistry, Chinese Academy of Sciences.

2.2. Fabrication of composite laminates

The composite laminates were manufactured by compression molding. The curing pressure was 1.8 MPa for obtaining the least amount of voids in the composites. The curing temperature was 140 °C for 1 h to get 100% curing of the resin. Six types of unidirectional hybrid composites with different hybrid ratios shown in Table 2 were made to investigate the effect of hybrid ratio on the tensile properties of the composites which included one flax fiber reinforced polymer composite (FFRP), 4 types of flax/glass fiber reinforced hybrid polymer composites (HFRP) and one glass fiber reinforced polymer composite (GFRP). The fiber volume fractions of flax and glass in the composites were varying while the total fiber volume fractions of the composites were kept the same which were around 67%. Another three types of hybrid composites were made to investigate the influence of stacking sequences on the tensile properties of the hybrid composites shown in Table 3. The total fiber volume fraction and fiber volume fractions for each component fibers were all the same (total fiber: 67%; flax fiber: 35%; glass fiber: 32%).

3. Experimental

Tensile properties of the composites were measured based on ASTM D3039 and the test speed was 3 mm/min. The nominal dimensions of the specimens were 15 mm × 1 mm × 250 mm. Short beam shear tests were performed based on ASTM D2344 to measure the interlaminar shear strength of the composites. The test speed was 1 mm/min and the span-to-depth ratio was 4:1. The sizes of the specimens were 12 mm × 6 mm × 32 mm. Mode I interlaminar fracture toughness were measured according to ASTM D5528-01 with the test speed of 2 mm/min. All the mechanical tests were carried out by a universal mechanical testing machine, CSS-44010, manufactured by Changchun Testing Machine Institute, China. In each case, five specimens were tested to obtain the average values. The micro-structures and the failure modes of the composites were observed with a SEM (PHILIPS XL30 FEG). The surfaces were coated with gold before observation.

Table 2
Hybrid composite laminates with different hybrid ratios.

Designation	Volume fraction ratio (flax/glass)	Ply number ratio (flax/glass)	Stacking sequence
FFRP	100/0	10/0	○○○○○○○○○○
2G8F	86/14	8/2	●○○○○○○○○●
4G6F	69/31	6/4	●○○●○○●○○●
6G4F	50/50	4/6	●○●○●●○●○●
8G2F	27/73	2/8	●●●○●●○●●●
GFRP	0/100	0/10	●●●●●●●●●●

● GFRP ply; ○, FFRP ply.

Table 3
Hybrid composites with different stacking sequences.

Designation	Stacking sequence
GF	●○●○●○●○○●○●○●○●
GGFF	●●○○●●○○○○●●○○●●
GGGGFFFF	●●●●○○○○○○○○●●●●

● GFRP ply; ○, FFRP ply.

4. Results and discussion

4.1. Tensile behaviors and properties of flax/glass fiber reinforced hybrid composites

4.1.1. Tensile behaviors and properties of the hybrid composites with different hybrid ratios

The tensile modulus of unidirectional flax/glass fiber reinforced hybrid composites, shown in Fig. 1a, increased with the increasing of the relative volume fraction of glass fibers. The theoretical values predicted by the Rule of Mixture (ROM) were also shown in the same figure. It can be seen that ROM prediction values essentially agreed with the experimental values as expected since there was strain compatibility throughout the hybrid composites for measuring the modulus (i.e., initial elastic deformation) and glass fibers acted as an improvement in resulting in better stiffness for the hybrid composites [16].

The effect of hybrid ratio on the tensile strength of flax/glass fiber reinforced hybrid composites was shown in Fig. 1b. The tensile strength increased with the increasing of the relative volume content of glass fibers. However, the tensile strength of the HFRP did not obey to the ROM since the fibers with low elongation were expected to break when the failure strain was reached [12,17]. The stress–strain curves of the FFRP, GFRP and HFRP, shown in Fig. 2a, indicated that FFRP possessed lower strength and smaller tensile failure elongation compared to those of GFRP. Therefore the tensile behavior of the hybrid composites could be divided into two types due to the differences in failure elongation of flax fiber and glass fiber, shown in Eq. (1) [18]. If the volume fraction of flax fibers in the hybrid composites was high, the hybrid composites would fail when the tensile strain reached the failure elongation of FFRP. However, if the volume fraction of glass fibers in the hybrid composites was high, the FFRP phase would also fail at first. But the hybrid composites would still keep their integrity until the failure of the GFRP phase occurred due to the bigger failure elongation of glass fiber.

$$\sigma_{HT} = \begin{cases} (1 - V_m)(\sigma_f V_f + \varepsilon_f E_g V_g); & V_g \le V_{crit} \\ (1 - V_m)\sigma_g V_g; & V_g \ge V_{crit} \end{cases} \quad (1)$$

where σ_{HT} was the tensile strength of the HFRP. σ_g, E_g and V_g were the tensile strength, tensile modulus and relative volume fractions of glass fiber. ε_f, σ_f and V_f are the tensile failure strain, tensile strength and relative volume fractions of flax fiber. V_m and V_{crit} were

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