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Effect of volume fiber and crack length on interlaminar fracture properties of glass fiber reinforced polyester composites (GF/PO composites)

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1. Introduction

A delamination is one of the main damage modes of two-dimensional fabrics reinforced structural composites parts [1-2]. In fact, a delamination is the result of interlaminar crack propagation. The interlaminar fracture toughness becomes one of the important indexes of the properties for the matrix [3-4]. In general, a delamination within a composite structure would be subjected to a mixture of mode I (opening), mode II (forward shear), mode III (anti-plane shear) crack driving forces [5-6]. It is more appropriate that interlaminar fracture toughness of the composites is described by critical energy release rate G_{Ic}, G_{IIc} and G_{IIIc} [5]. Mode I delamination is the lowest fracture energy mode; consequently most attention has been focused on assessing mode I delamination propagation as a measure of the damage tolerance of structural polymer composites parts. Previous literature showed characterization of mode I and II interlaminar fracture behaviors was developed using carbon fiber reinforced high performance matrixes such as epoxy resins (PEEK) [7-9].

Consequently, these testing protocols had been predominantly applied to the study of carbon fiber based materials. There were few investigations of the interlaminar fracture behaviors of other thermosetting composites which were reinforced by glass fiber. Until now, there are no studies on the interlaminar fracture behaviors of glass fiber mat reinforced polyester composites.

In this paper, mode I interlaminar fracture behaviors of the pure polyester resin and GF/PO composites by use of double cantilever beam (DCB) tests were studied and compared with that of a standard, unidirectional carbon fiber reinforced epoxy composite(CF/EP composites). The fracture area along crack propagation was analyzed by scanning electron microscope (SEM) to identify the fracture characteristics.

2. Experimental

2.1. Materials

The material used in this study is a plate made of unsaturated polyester resin and 30 layers of glass-fiber mat (V_f =30%, density 270 g/m²); fabricated by the TEN CATE ADVANCED COMPOSITE MATERIALS company.

2.2. Mode I interlaminar fracture test

Mode I interlaminar fracture tests were carried out

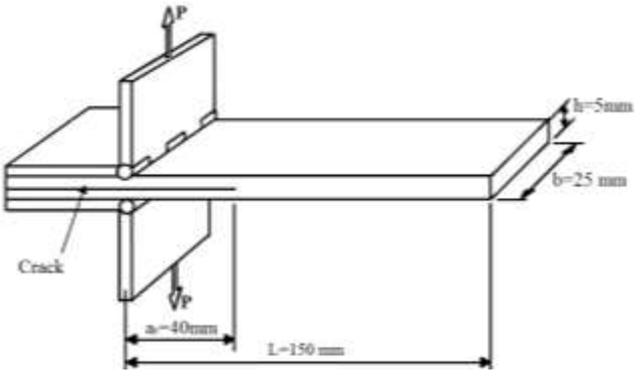

Fig. 1 Mode I DCB test

at 20°C according as ISO 15024 [10]. Force-displacement data were obtained using an Instron Universal Testing Machine operating at a crosshead speed of 0.3 mm/min. Dimensions of a DCB specimen for glass fiber based composites were shown in Fig. 1. A Polytetrafluoroethylene (PTFE) film of thickness 13 μm was inserted in the central layer at one end of the test specimens before the process, which was employed to create a initial crack from initial load. A pair of metallic hinges was glued to the loading end of the specimen in order to enable the load to be applieled (Fig. 1). Observation of the crack propagation during tests was facilitated by coating edges of the specimens with white acrylic paint and placing indicator marks along the coated edges. Marks were drawn at 5 mm intervals along edges of the specimen, extending at least 60 mm beyond the tip of the insert. Additionally, the first 10 mm and last 5mm were marked at 1 mm intervals. The crack propagation energy values were calculated using the corrected beam theory:

$$G_{IC} = \frac{3P\delta}{2b\left(a+|\Delta|\right)}\frac{F}{N}; \qquad (1)$$

$$N = 1-\left(\frac{l_2}{a}\right)^3 - \frac{9}{8}\left[1-\left(\frac{l_2}{a}\right)^2\right]\frac{\delta . l_1}{a^2} - \frac{9}{35}\left(\frac{\delta}{a}\right)^2; \qquad (2)$$

$$F = 1-\frac{3}{10}\left(\frac{\delta}{a}\right)^2 - \frac{2}{3}\left(\frac{\delta - l_1}{a^2}\right), \qquad (3)$$

where P is the load, δ is the displacement of the notch lip, the crack length and b is the specimen width. The corrected beam theory requires the determination of a correction factor Δ, which takes into account crack tip rotation and shear deformation. a is the total crack length ($a = a_0+\Delta a$) (Δa is crack propagation length and a_0 is measured along the curved coordinate scale fixed to the specimen, as described by Fig. 2), N is a correction factor for the stiffening caused by the metallic hinge (described by Eq. (2)) [l_1 is the distance from the center of the loading pin to the midplane of the specimen; l_2 is the distance from the loading pin center to its edge of the load metallic hinge], F is a correction factor for large displacements described by Eq. (3).

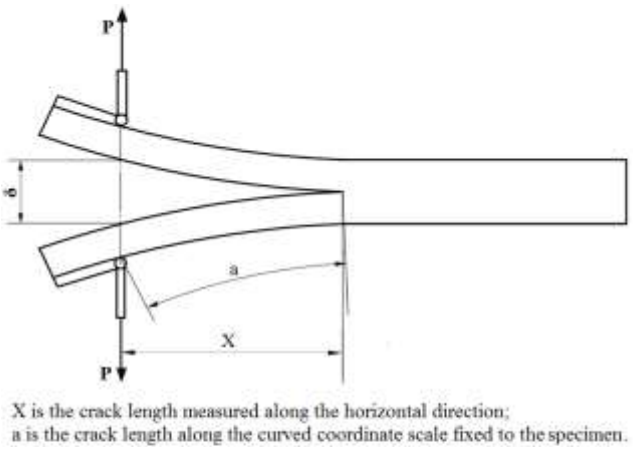

Fig. 2 The DCB specimen under the load

3. Results and discussion

3.1. Effect of V_f (the volume of fiber) on the interlaminar fracture properties

Typical mode I interlaminar fracture data were shown in Figs. 3 and 4. Fig. 3 showed the force-displacement plots for GF/PO composites and CF/EP composites [11]. The displacement of the GF/PO composite was much greater than that of CF/EP composite, which showed the high flexibility of the specimen and the need to account and correct for large displacement, F (described by Eq. (3)).

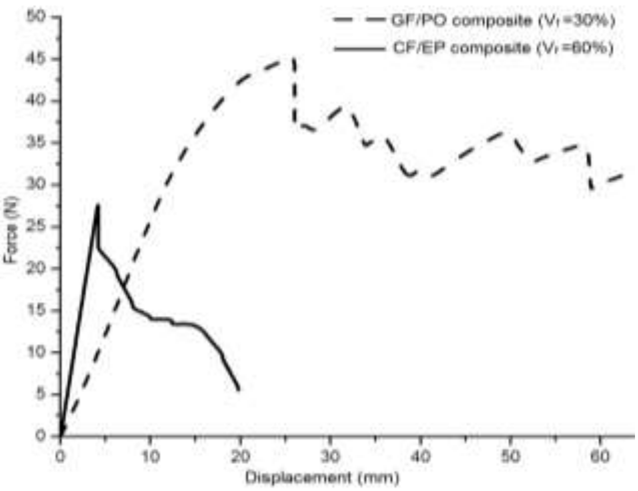

Fig. 3 Load displacement curve

The force-displacement plot of CF/EP composite was linear prior to crack initiation, after which the force dropped as the crack propagates. The sudden drop in force immediately after crack propagation was typical of brittle materials. Crack propagation in this type of composite was relatively stable. In contrast, the plot of GF/PO composites exhibited distinct curvature prior to initiation, which occurred at a much greater displacement. Crack propagation was unstable and there was evident repeated crack initiation and crack arrest. The force-displacement plots reflected the difference in toughness of the pure polyester resin compared with that of the epoxy resin.

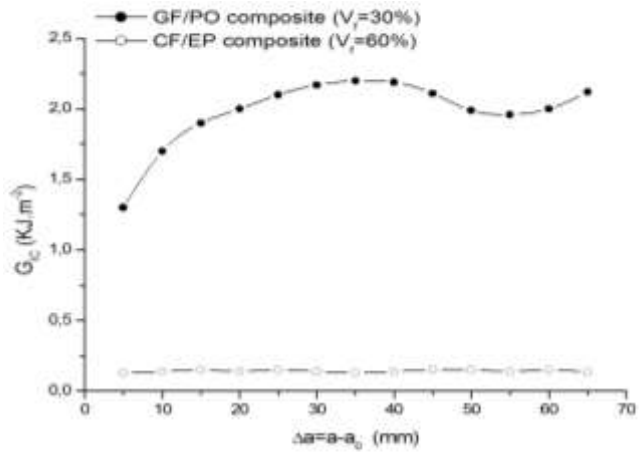

Fig. 4 *R-curves* derived from force displacement curves of FG/PO composites and CF/EP

Mode I force-displacement plots were used to form delamination-resistance curves (*R-curves*) in Fig. 4, which showed the delamination resistance with delamination length (crack propagation length Δa). Fig. 4 showed that G_{Ic} varied significantly during crack propagation, with values lying between the upper and lower bounds with a variation in G_{Ic} of 1.0 KJ/m^2, corresponding to crack initiation and crack arrest [12]. In contrast, the *R-curve* for CF/EP composite was relatively flat and a single propagation value can be obtained, which also showed crack propagation in this type of the composite was relatively stable.

Values of G_{Ic} determined from Mode I interlaminar tests were summarized in Table. Values of G_{Ic} for GF/PO composites were significantly higher than that for the pure polyster resin, which were explained by the additional force required to fracture fiber bridging in GF/PO composites, also described by Moura and Morais, et al [13, 14]. In contrast, CF/EP composite was produced using individually stacked plies of unidirectional CF pre-impregnated with the epoxy resin and had little interlaminar fiber bridging. Consequently, during DCB test, fiber bridging can be negligible and crack propagation along the midplane was relatively smooth, which was in accordance with.

To demonstrate the occurrence of fiber bridging, comparative DCB tests were carried out using a hybrid composite, in which two plies of unidirectional continuous fiber were incorporated into the central ply to displace the corresponding plies of GF/PO composites, also employed by Morais, et al [14]. The total number of glass fiber plies for the hybrid composite was the same as that for GF/PO composites (V_f is 30%).The central two unidirectional plies can significantly reduce interlaminar fiber penetration and eliminate fiber bridging during crack propagation. *R-curves* for GF/PO composites (V_f is 30%) and the hybrid composite were shown in Fig. 5. There was markedly less variation in G_{Ic} with crack length for the hybrid composite, the value of G_{Ic} for the hybrid composite was about 0.7 KJ/m^2, which was similar to that of the pure polyster resin in Table 1. It can be seen that the value of fracture toughness G_{Ic} was slightly improved with the increase of the volume of fiber V_f. Additionally, the value of fracture toughness G_{Ic} was affected by the types of weave, fiber orientation, the types of the matrix, the thermal treatment and so forth [15].

Table

Values of G_{IC} for the pure polyester resin, GF/PO composites and CF/EP composite

Material	V_f , %	G_{IC}, KJ/m^2
The pure polyester PP resin	0	0.65
GF/PO 1	11.5	1.1~2.15
GF/PO 2	23.2	1.2~2.1
GF/PO 3	30	1.3~2.2
GF/PO 4	37.7	1.5~2.3
CF/EP	60	0.15

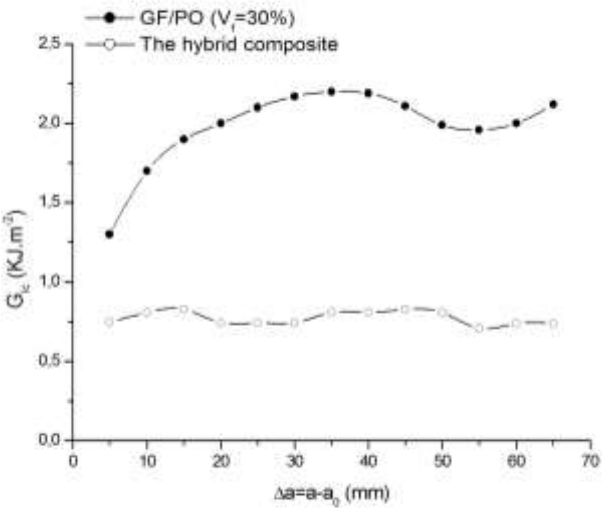

Fig. 5 Comparative *R-curves* of FG/PO composite and the hybrid composite

3.2. Effect of initial crack length on the interlaminar fracture properties

In mode I interlaminar fracture tests, different initial crack lengths a_0 were used in different literatures. We also found that a_0 affected values of G_{Ic} in the experiments. Fig. 6 showed effects of a_0 on values of G_{Ic}. When a_0 was

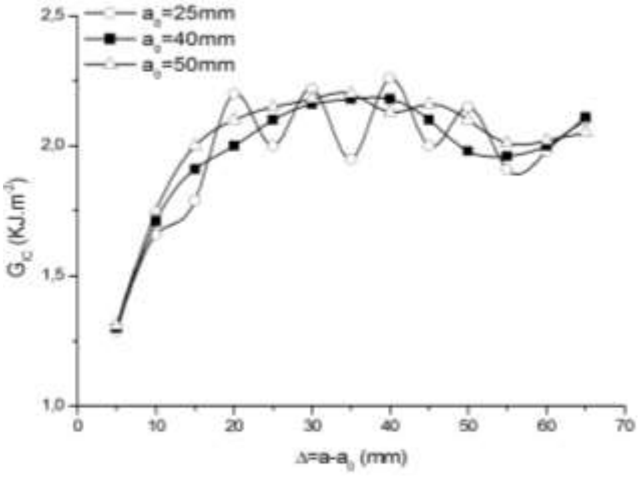

Fig. 6 Typical *R-curves* of different initial crack length a_0

25 mm, values of G_{Ic} varied markedly and were much dispersed. As a_0 increased, the degree of dispersing was reduced, which was in accordance with Jiao and Todo [16, 17]. Because the inserted film would influence the resin flow and form the rich area in the resin. Values of G_{Ic} determined in this area may be invalid. Therefore, the initial crack length may not be too long. When a_0 was 40 mm, values of G_{Ic} showed little variation. Therefore, 40 mm was chosen as initial crack length in this study.

3.3. Fractography

After mode I interlaminar fracture tests, the fracture areas of GF/PO composites were analyzed by SEM to identify the fracture characteristics and to verify the deformation behaviour predicted from the modelling. Figs. 7 and 8 were SEM photographs of the fracture areas when the distance of crack propagation length $\Delta a = a - a_0$ was about 45 mm. It showed the surface of the fiber was not bare and clean, which indicated good interface bonding between the fiber and the matrix. The crack propagation can be transferred from the matrix to the interface between the fiber and the matrix. So the crack propagated along the interface between the fiber and the matrix, and finally was transferred to the fiber through the good interface [18-21]. In general, the fiber can endure high applied load, therefore the fiber based composites can achieve high mechanical properties. Cook-Gordon Damage Theory mentioned values of G_{Ic} for thermosetting materials would be mainly decided by the interface between the fiber and the matrix [3, 11]. As a result, GF/PO composites can achieve high mechanical properties because of good interface bonding.

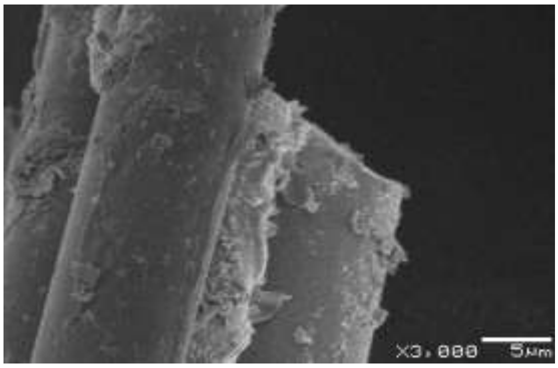

Fig. 7 SEM photograph of the fracture area in the region of Δa is about 45 mm (×3000)

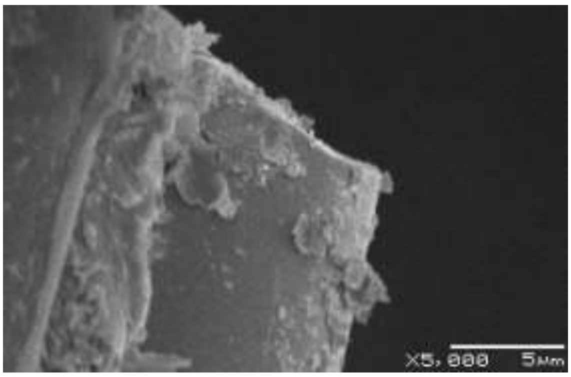

Fig. 8 SEM photograph of the fracture area in the region of Δa is about 45 mm (×5000)

4. Conclusions

Mode I interlaminar fracture behaviors by use of DCB tests were studied. G_{Ic} varied significantly during crack propagation. The occurrence of fiber bridging led to significant variation of G_{Ic} (1.1~2.3 $KJ.m^{-2}$) of GF/PO composites and higher G_{Ic} than that of the pure polyster resin (0.65 $KJ.m^{-2}$). When initial crack length was 40mm, G_{Ic} showed little variation. Crack propagation can be transferred from the matrix to the interface between the fiber and the matrix, finally to the fiber, which indicated good interface bonding in GF/PO composites.

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N. Mahmoudi

PLUOŠTO TŪRIO IR ĮTRUKIMO ILGIO ĮTAKA STIKLO PLUOŠTO SUSTIPRINTO POLIESTERO KOMPOZITU TARPSLUOKSNINIAM LŪŽIUI (GF/PO KOMPOZITAI)

R e z i u m ė

Dvisluoksnės gembės (DCB) bandiniai yra naudojami stiklo-pluoštu sustiprinto poliestero kompozito kritinės energijos išlaisvinimo greičio (G_{Ic}) I modos matavimams (GF/PO kompozitai). Parodyta, kad G_{Ic} kinta žymiai susidarant plyšiui. GF/PO kompozitų G_{Ic} yra didesnis nei gryno poliestero (PP) dervos dėl papildomos jėgos reikalingos perlaužti pluošto tiltelį GF/PO kompozituose. Palyginamieji dvisluoksnės gembės bandymai atlikti tikslu pademonstruoti pluošto jungiamosios grandies atvejį. G_{Ic} kito ženkliai ir buvo labai išsklaidytas, kas turėjo sukelti mažus pokyčius, kai pradinis plyšio dydis buvo 40 mm. Lūžimo charakteristikos buvo ištirtos skanuojančiu elektroniniu mikroskopu.

N. Mahmoudi

EFFECT OF VOLUME FIBER AND CRACK LENGTH ON INTERLAMINAR FRACTURE PROPERTIES OF GLASS FIBER REINFORCED POLYESTER COMPOSITES (GF/PO COMPOSITES)

S u m m a r y

Double-cantilever beam (DCB) specimens are widely used to measure the mode I critical-energy release rate G_{Ic} of glass-fiber reinforced polyester composites (GF/PO composites).

It showed G_{Ic} varied significantly during crack propagation. G_{Ic} of GF/PO composites are higher than that of the pure polyester (PP) resin because of the additional force required to fracture fiber bridging in GF/PO composites. Comparative DCB tests were carried out to demonstrate the occurrence of fiber bridging. G_{Ic} varied markedly and were much dispersed, which would induce little variation when initial crack length was 40 mm. The fracture characteristics were analyzed by scanning electron microscope.

Keywords: Mode I (DCB), glass-fiber, fracture.

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