Fracture behaviour of glass fibre-reinforced polyester composite

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Abstract: Fracture toughness and critical energy release rate of polyester-reinforced glass fibres were investigated using linear elastic fracture mechanics approach. The effect of fibre volume fraction of chopped strand mat glass fibres in the matrix on the composite properties was considered. Finite-element analysis using FRANC2D/L was adopted for further verification. The results showed a dramatic increase in the values of fracture toughness and critical energy release rate with increasing fibre content. 60% vf of glass fibres enhanced the fracture toughness and critical energy release rate properties of neat polyester by ~22-fold and 1200-fold, respectively. The numerical results showed an agreement with experimental ones.

Keywords: fibre contents, polyester composites, fracture toughness, critical energy release rate, finite-element analysis

1 INTRODUCTION

Nowadays, fibre composites are used in broad applications, particularly in the engineering and industrial areas [**1**, **2**]. The aircraft industries mainly utilize polymeric composites in secondary structures of aircrafts such as rudders, elevators, and landing gear doors [**3**, **4**]. Nevertheless, numerous materials are processed and fabricated, and thus flaws are often not completely preventable. The presence of flaws leads towards crack propagation and fracture of materials. Apart from that, brittle fracture, which causes sudden and catastrophic failures, may cause serious disasters. For instance, fracture of an aircraft's vertical stabilizer, in 2001, has led to more concern in the studies of fracture mechanics [**5**]. Hence, it is very crucial to study the behaviour of a material with flaws. To achieve this, a method for predicting failure of materials containing flaws, namely fracture mechanics, has been introduced to study the behaviour of materials with crack.

Many studies have been carried out to evaluate the strength of cracked materials with the intention of improving the mechanical performance of materials. Works have been carried out by using a double-cantilever beam, compact tension (CT), as well as compact compression to determine the critical energy release rate of carbon fibre-reinforced epoxy laminates [**6**, **7**]. Besides, the fracture toughness of graphite-reinforced epoxy laminates has been studied under room temperature and cryogenic conditions with transverse cracks on single-notch bend (SNB) specimens using four-point bending tests. It was reported that the fracture toughness does not change with specimen thickness, i.e. under cryogenic condition, the fracture toughness does not change much [**8**]. Avci *et al.* [**9**] have studied the SNB specimens of chopped strand glass fibre-reinforced sand particles-filled polyester composites using three-point bending tests and flexural strength. It was found that the fracture toughness improves when the fibre content increases. Silva *et al.* [**10**] studied sisal and coconut fibre-reinforced polyurethane composites through CT specimens and reported that the fracture toughness is not affected by the strain rate. Besides, it is found that the fracture toughness of both sisal and coconut fibre-reinforced polyurethane composites differ with different fibre surface quality. Reis [**11**] tested coconut fibre, sugar cane bagasse, and banana fibre-reinforced epoxy concrete by using three-point bending specimens. It is found that coconut and sugar cane–epoxy concretes achieve improvement in the fracture toughness but banana–epoxy concrete does not. However,

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the fracture energy of all the three types of composites shows improvement.

The current work attempts to study the fracture behaviour of glass fibre-reinforced polyester composite. In this study, polyester matrix reinforced with chopped strand mats glass fibre composites were developed with different volume fraction of fibre. Fracture toughness tests were carried out under mode I loading by using CT specimens to determine the values of fracture toughness and critical energy release rate. These experimental results were then compared with two-dimensional finite-element analysis using FRANC2D/L [**12**].

2 EXPERIMENT DETAILS

2.1 Materials

The resin selected for this study was unsaturated thermosetting polyester resin (SYNOLAC 3317AW) supplied by Jiashan Anserly Glass Fibre Company Limited Malaysia. Chopped strand mats glass fibre of E-type was supplied by the same company as well. The physical and mechanical properties of these materials are listed in Table 1. Figure 1 shows a scanning electron micrograph of glass fibre used in this study.

Table 1 Physical and mechanical properties of SYNOLAC 3317AW and glass fibre [**13, 14**]

Properties	SYNOLAC 3317AW	Glass fibre
Average diameter (μm)	–	11
Tensile strength (GPa)	50	2.0
Young's modulus (GPa)	3.5	76
Elongation at break (%)	2–3	3–5
Density (Mg/m^3)	1.2–1.5	2.6

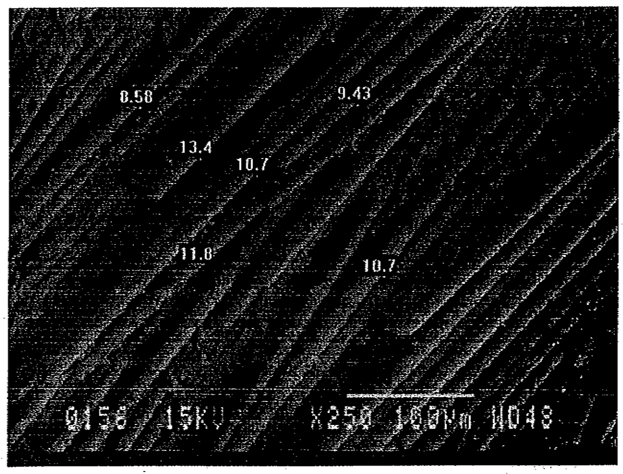

Fig. 1 A scanning electron micrograph of glass fibre

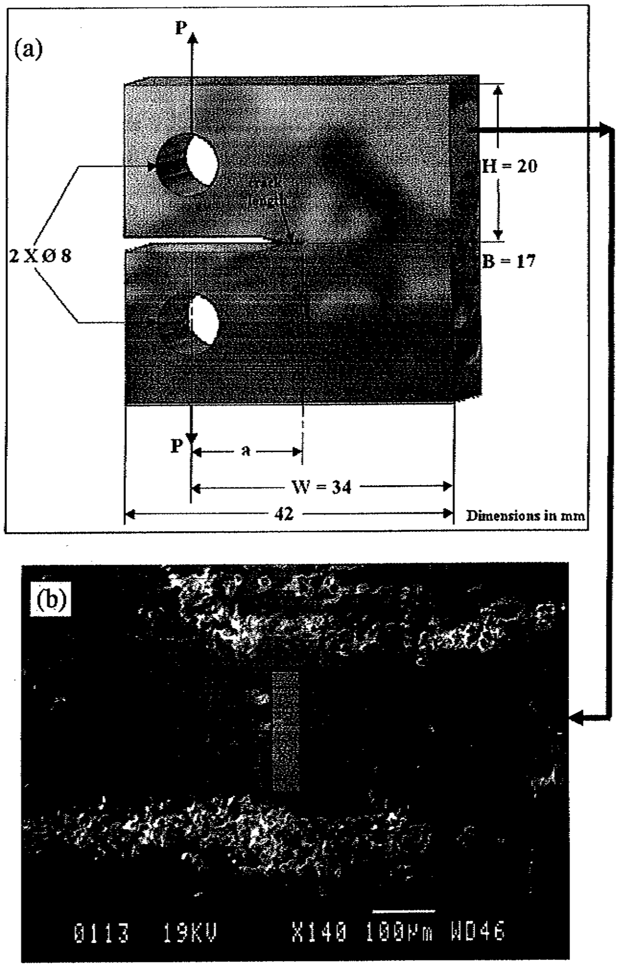

Fig. 2 (a) Dimension of the CT specimen. (b) A scanning electron micrograph showing the cross-section of the virgin surface of the GFRP composite with 48% vf

2.2 Fabrication of fracture toughness tests specimens

CT specimens with the dimensions shown in Fig. 2(a) were fabricated using hand lay-up technique. The dimensions of the specimens were determined according to ASTM D5045 [**15**]. A razor blade with a thickness of 0.1 ± 0.005 mm was inserted at the middle to initiate a precrack. Firstly, the glass fibre mats were cut according to the shape and size of the mould. The inner surfaces of the mould were coated with a thin layer of wax as a release agent. The resin was mixed with 1 per cent of methyl ethyl ketone peroxide catalyst as hardener and poured slowly into the mould. The glass fibre mats were then placed into the mould. The volume percentages of fibres were 12, 24, 36, 48, and 60. Figure 2(b) shows a scanning electron micrograph of glass fibre-reinforced polyester (GFRP) composite with 48% vf, where the distance between the layers is estimated to be 230 μm. After that, the remaining mixture was poured until the desired thickness is reached. It was then left for curing at room temperature for 24 h.

2.3 Fabrication of tensile tests specimens

Tensile tests were conducted to obtain Young's modulus as input to determine the critical energy release rate. Tensile specimens (Fig. 3) were fabricated according to ASTM D638 using similar procedure employed for CT specimens [16].

2.4 Experimental procedure

Fracture toughness and tensile tests were conducted using 100Q Standalone Universal Test System according to ASTM D5045 and D638, respectively, at room temperature. Crosshead speed was set to be 1.5 mm/min for both tests. The precrack for fracture toughness tests was 7 mm. Five test replicates were performed for each type of specimen and the average values were determined. Load at break and the corresponding displacement was recorded. The fracture toughness K_{IC} and critical energy release rate G_{IC} were calculated using the following equations.

The critical stress intensity factor or facture toughness is

$$K_{IC} = \frac{P}{B\sqrt{w}} f\left(\frac{a}{w}\right) \quad (1)$$

For a CT specimen, the geometry factor, $f(a/w)$, is given by

$$f\left(\frac{a}{w}\right) = \frac{2 + a/w}{(1 - a/w)^{1.5}} \left[0.866 + 4.64\left(\frac{a}{w}\right) - 13.32\left(\frac{a}{w}\right)^2 + 14.72\left(\frac{a}{w}\right)^3 - 5.6\left(\frac{a}{w}\right)^4\right] \quad (2)$$

where the relevant parameters are illustrated in Fig. 1.

For plane strain condition, the critical energy release rate is given by

$$G_{IC} = \frac{K_{IC}^2}{E}(1 - \nu^2) \quad (3)$$

in which ν is the Poisson's ratio (based on the assumption of isotropic material [10]), which is approximated as

$$\nu = 0.5\left(\frac{L}{L + \Delta L}\right) \quad (4)$$

Plane strain applies under the conditions that both neat polyester and glass fibre-reinforced composites show linear elastic material response up to peak load and satisfy the condition of

$$B > 2.5\frac{K_{IC}^2}{\sigma_{yield}^2} \quad (5)$$

which are shown later in the following results and discussion.

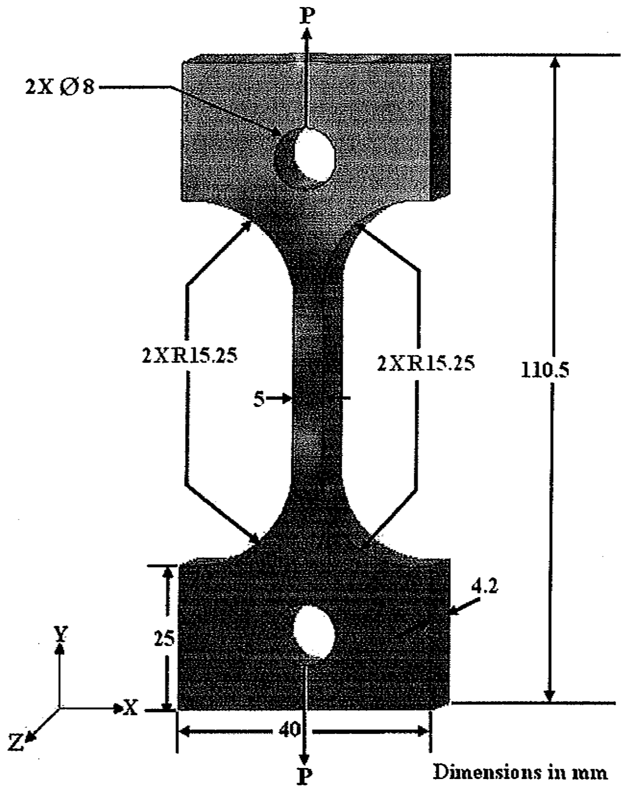

Fig. 3 Dimension of the tensile test specimen

2.5 Finite-element modelling

An open source finite-element software, FRANC2D/L, was used as a tool for the simulation of crack growth in the specimens. The material is modelled based on two-dimensional linear elastic fracture mechanics (LEFM) concepts, with the assumption that the crack propagation through the thickness is uniform [12]. The stress state is formulated within the framework of the

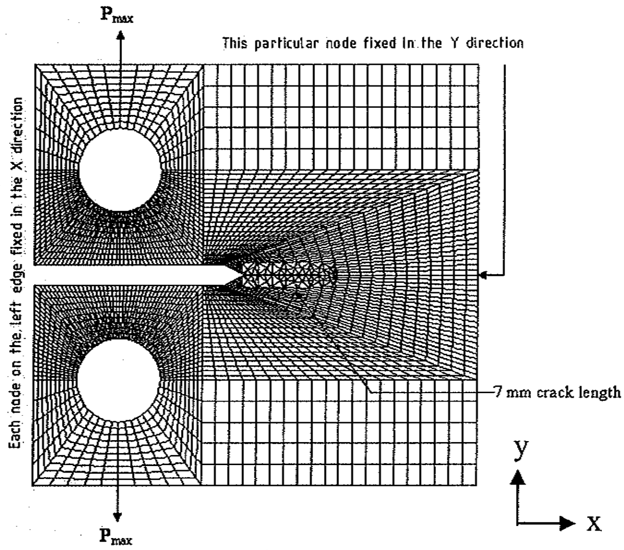

Fig. 4 Finite-element model

theory of elasticity, and the fracture process is governed by the stress intensity factors. The finite-element model, shown in Fig. 4, was discretized by using bilinear four-side elements. The Young's modulus values were determined experimentally and used as input data. The load was applied at both holes, which is similar to the experimental loading. The corresponding magnitude is the load at break, which is also determined experimentally. As for boundary conditions, each node on the left edge was fixed in the x-direction to allow deformation in the y-direction only. Besides, one particular node at the middle of the right edge was fixed in the y-direction to prevent the model from separating infinitely upon fracture.

3 RESULTS AND DISCUSSION

3.1 Tensile properties

The stress–strain diagrams of the selected materials are shown in Fig. 5. Stress is calculated based on the nominal area. The curves for neat polyester and fibre-reinforced polyester exhibited a brittle behaviour, in which no plastic deformation could be observed. A linear increase of stress with increasing applied displacement until the attainment of maximum stress was followed by a single and abrupt stress drop-off. Yield strength and strain at break increased as the fibre volume percentage was increased due to a relatively high strength and less brittleness behaviour possessed by glass fibres. The highest yield strength obtained is approximately 325 MPa, or almost 680 per cent improvement compared to neat polyester, which is only about 50 MPa. As for the strain at break, it improves for almost 170 per cent when compared between neat polyester and GFRP with 60% vf of fibre. This shows that the ability of polyester to withstand load and elongation is improved with fibre reinforcement. From equation (4), it can be observed that an increment in elongation decreases Poisson's ratio, which also indicates the ability to be compressed.

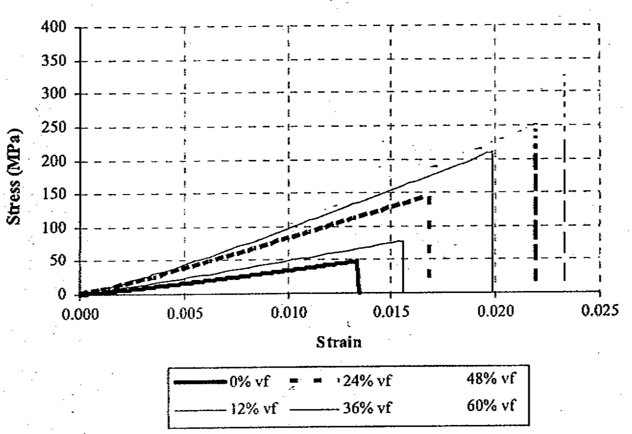

Fig. 5 Stress–strain curves of neat polyester and GFRP

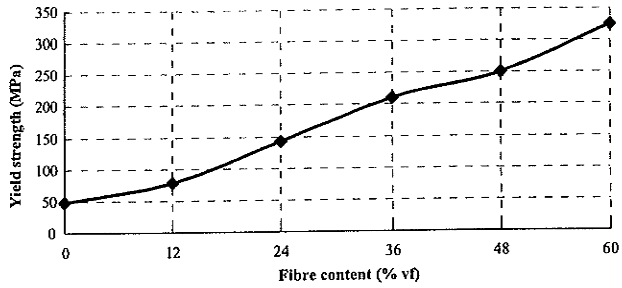

Fig. 6 Yield strength of different fibre content

Young's modulus also increased with the increment of fibre volume percentage, as shown in Fig. 6. Maximum improvement of ~380 per cent is observed when the polymer was reinforced with 60% vf of glass fibre, where the value increased from 3.5 GPa for neat polyester to 13.9 GPa. This reflects that the composite is stiffer with fibre reinforcement.

3.2 Fracture toughness behaviour

Figure 7 shows the load–displacement curves of CT specimens. It is observed that the load–displacement curves are linear for all specimens. This validates the LEFM approach in which considerable non-linearity is not exhibited. Catastrophic fracture occurs for neat polyester once the maximum load is reached. On the other hand, a different behaviour is observed for GFRP specimens where a linear behaviour is observed initially and after certain displacements, the curves began to fluctuate. No apparent abruption or catastrophic fracture is noted. The observation is same for different number of fibre volume percentages. The first load drop-off, which is believed to be matrix cracking, is accompanied by a sequence of increments and decrements on load. This is due to the presence of fibres that prevent rapid propagation of brittle cracks.

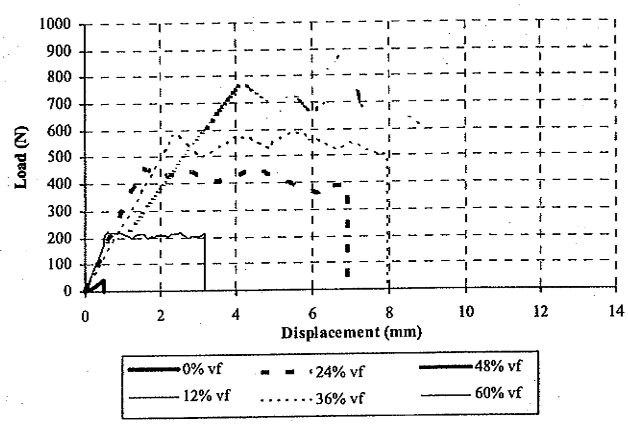

Fig. 7 Load–displacement curves of neat polyester and GFRP

Therefore, glass fibres serve as a barrier to crack propagation [17]. Besides, it can be observed that when the number of fibre volume percentages increases, the peak load also increases. The polyester matrix binds the fibres together and acts as the medium by which an externally applied load is transmitted and distributed to the fibres. During crack propagation, a part of the applied load is transferred from the polyester matrix to the fibres. Only a small proportion of an applied load is sustained by the polyester matrix [16]. Apart from that, the values of displacement at fracture also increases with increasing glass fibre content. Again, this proves that glass fibre helps in reducing the brittleness of polyester matrix.

Besides, it is observed that the stiffness of CT specimens dropped as the fibre content increased, which is in contrast to tensile specimens. This could be due to the pre-existing crack on CT specimens that weaken the ability to resist deformation. It is also reported in the work of Avci *et al.* [9], where the stiffness of the notched specimen was significantly decreased compared to that of the unnotched specimen. In GFRP composite, the stiffness of glass fibre ($E = 76$ GPa) dominates over the stiffness of polyester ($E = 3.5$ GPa). Higher fibre content indicates a higher amount of fibre being cracked, and hence the stiffness is further weakened.

The values of K_{IC} were obtained by using equations (1) and (2). P is the corresponding peak load for each type of composites, whereas B, a, and w are geometrical properties stated in Fig. 2(b). The results are shown in Fig. 8. It is obvious that the fracture toughness increased as the fibre content increased, due to the increment in the peak load, P, while the other geometrical parameters remained the same. Increment in the fracture toughness also increased the critical energy release rate, as can

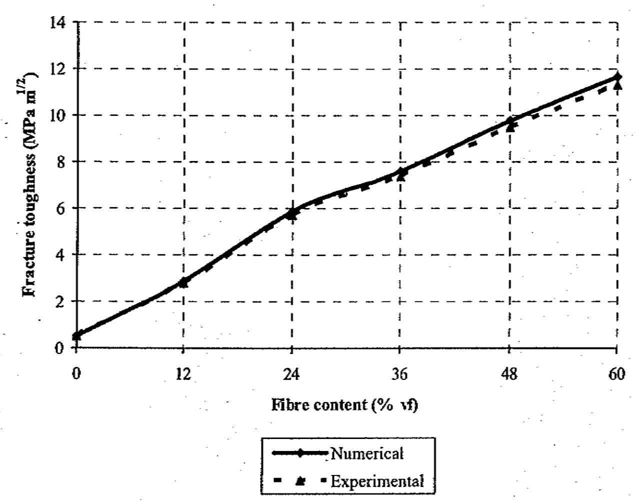

Fig. 8 Comparison of the fracture toughness between experimental and numerical results

Table 2 Verification of specimen thickness for plane strain condition

Volume fraction (%)	Thickness B (mm)	$2.5\frac{K_{IC}^2}{\sigma_{yield}^2}$ (mm)
0	16	0.29
12	16	3.17
24	16	4.00
36	16	3.08
48	16	3.58
60	16	3.03

be observed from equation (3). Although the Poisson's ratio was decreased, the increment in the fracture toughness dominates over the decrement of the Poisson's ratio. With 60% vf of glass fibre, the fracture toughness improved by about 22-fold, whereas the critical energy release rate improved by approximately 1200-fold compared to neat polyester. This reflects that the ability of the material to resist fracture is improved or the amount of energy needed for crack growth is increased when glass fibre is used as reinforcement.

To further verify that plane strain condition applied according to equation (5), calculations were carried out and tabulated in Table 2. The results show that thickness of neat polyester and all types of composites are sufficient for plane strain condition.

3.3 Finite-element modelling

Figure 9 shows the stress contours of the simulated model. The stresses are in the y-direction and the unit of the scale is in N/mm^2. It can be observed that the highest stress is concentrated at the crack tip, which is indicated by a red patch. Hence, it is predicted that a crack will start to propagate from that particular region. This is identical to experimental observation where crack propagation is initiated at the crack

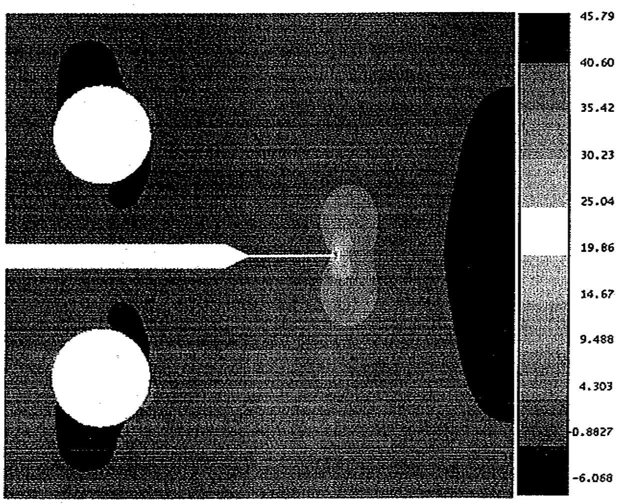

Fig. 9 Stress distributions of a CT specimen

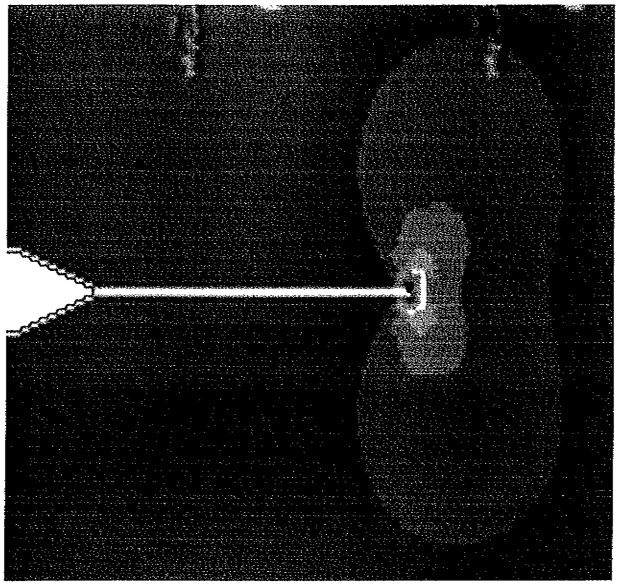

Fig. 10 Plastic zone of the simulated CT specimen

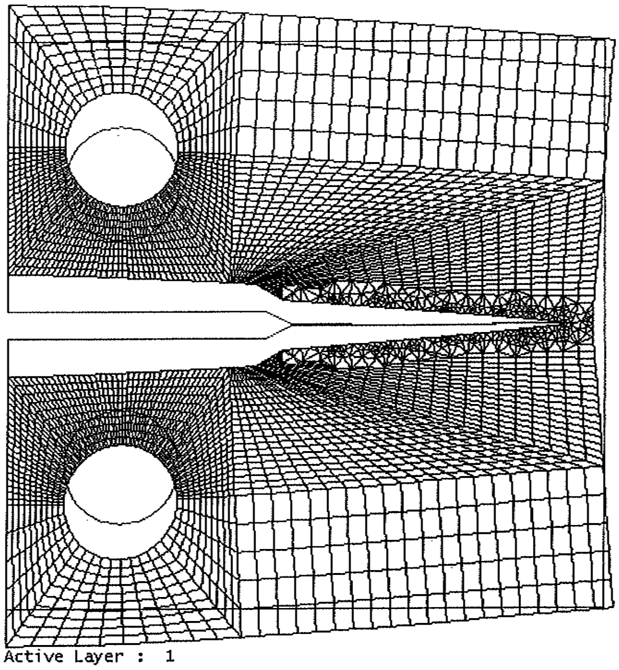

Fig. 11 Simulated crack propagation

tip. FRANC2D/L calculates the fracture toughness by using modified crack closure techniques [**12**]. Computation is first carried out to calculate the energy release rate and then the fracture toughness is calculated from equation (5) [**18**]. Besides, the plastic zone size is relatively small, and a thinner roll of material is observed for the plastic zone shape [**19**], which again satisfies plane strain condition. If a relatively large plastic zone occurs, plane strain condition is invalidated and elastic–plastic fracture mechanics has to be considered. An enlarged view of the plastic zone is shown in Fig. 10. Since the crack is observed to propagate in the horizontal direction experimentally without any crack deflection, similar crack propagation path was modelled, and hence the crack propagation as shown in Fig. 11 can be observed.

3.4 Comparison of the results from experiments and simulations

The values of fracture toughness for composites with different fibre content obtained experimentally and numerically are shown in Fig. 8. It can be seen that the results obtained from both agree with each other, where the increasing fibre content will improve the fracture toughness. The variation of results obtained from experiments and simulation is comparatively small, where an error of less than 4 per cent was generated for each fibre content. Therefore, the results obtained from experiments and simulations are believed to be valid.

4 CONCLUSIONS

In this study, the effects of chopped strand mats glass fibre content on the mechanical properties of polyester composites were investigated. Tensile and fracture toughness tests were performed on neat polyester and GFRP composites with fibre volume percentages that ranged from 12 to 60% vf, with an interval of 12% vf. Based on the findings, it can be concluded that the application of LEFM approach is valid throughout the study. Besides, the yield strength, strain at break, Young's modulus, fracture toughness, and critical energy release rate are improved with the reinforcement of fibre. As the fibre content increases, the values of each parameter increase as well. The highest values correspond to the highest amount of fibre content, which is 60% vf of fibres. With such amount of fibre content, the yield strength is improved up to 700 and 170 per cent improvement is observed for the strain at break. As for Young's modulus, almost 400 per cent increment is achieved. Besides, the fracture toughness has improved 22-fold, whereas the critical energy release rate shows an improvement of 1200-fold. Also, the numerical results agree with experimental results with similar trends and an acceptable variation of error below 4 per cent. Most importantly, sudden and catastrophic failure of specimens is significantly reduced with reinforced fibres. Hence, GFRP is proven to be a better material for crack resistance.

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