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Effect of Stacking Sequence on Plane Strain Fracture Toughness of Glass Fiber Reinforced Composite

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ABSTRACT

Advanced continuous polymer matrix composites offer significant enhancements in strength and fracture toughness properties as compared with their bulk and monolithic counter parts. In the present work effect of stacking sequence on mode-I plane strain fracture toughness of the glass fiber reinforced composite has been reported and discussed. Composites are prepared with orientations of fibers such as 0º, 45º and 90º. Limited topological studies have also been conducted to understand the fracture mechanism. That results thus obtained have revealed that the plane strain fracture toughness is significantly varied with fiber orientation. In particularly plane strain fracture toughness is greater in the longitudinal orientation of fibers than other orientations of fibers. Scanning electron microscopic studies revealed that higher fracture toughness in longitudinally oriented composites is due to fiber pullout of fibers and crack bridging effects.

Keywords:—*Polymer matrix composites; mode-I fracture toughness; SEM; fractographs.*

I. INTRODUCTION

Glass fiber reinforced polymer (GFRP) composites are increasingly used in many structural applications replacing metallic materials due to their low cost, high strength, high chemical resistance and excellent insulating properties. In most of these GFRP applications, fiber plays a major role in tensile load carrying capacity of a composite structure while compressive, bending, fracture behaviour, inter-laminar shear properties depend on the selection of matrix [1]. In a fiber matrix composite, matrix being the weakest component is first to fail upon such loading. Therefore, enhancement of matrix properties is desired to enhance the overall performance of fiber reinforced polymer (FRP) composites under such loading.

The reinforcing phase material may be in the form of particulates, fibers, flake or particles. The matrix phase materials are generally continuous [2, 3]. In recent years, the continuous fiber reinforced polymer matrix composites are now finding suitable materials for various application in building, electrical, automobile, and packaging sectors because of their several practical advantages like fast production cycling, ease of processing and low processing cost over traditional materials [4]. One of the major sciatic challenges for the composite researchers is the development of high strength to weight ratio structural materials supporting latest technologies and design concepts for the complex shaped structures like automotive structures, aircraft and large wind turbine blade structures [5].

However, the theories are limited to the evaluation and discussion of the reinforcement effects of K_{IC}, the plane strain fracture toughness. Glass fiber reinforced epoxy matrix composites results in an attractive combination of physical and mechanical properties which cannot be obtained by monolithic materials [6, 7]. These are widely used due to ease of availability of glass fibers and economic processing techniques adopted for production of components. Developments are still under way to tailor their properties for extreme loading conditions. The primary aim of this paper to study the Plane-strain fracture toughness (K_{IC}) of glass fiber reinforced composite in detail in order to evaluate the influence of directionality of glass fibers.

II. Experimental Details

The reinforcing material used in this study was glass fiber with 13 µm diameter. Diglycidyl ether of bisphenol-A (DGEBA) epoxy resin and diethyl toluene diamine (DETDA) hardener were used as matrix system. Unidirectional glass fibers are wound in a polymer matrix of epoxy resin mixture. The synthesis was via filament winding technique. The densification and curing process is carried out in a muffle furnace [8].

2.1 Specimen Preparation

The composite material was machined and cut into required dimensions as per the standard of ASTM D 5045-99 as shown in Figure 1. Single edge notch beam (SENB) specimens approximately of 4.5 mm thickness, 10 mm width (W) and span length of 40 mm were used to determine the fracture resistance properties.

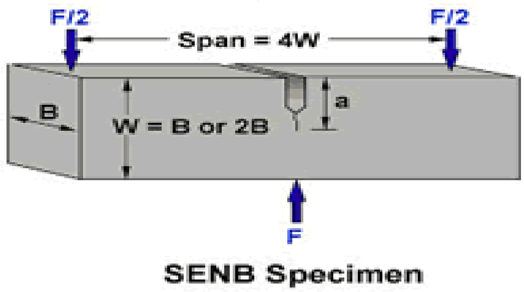

Figure 1: Three-point bend test specimen configuration

The fracture toughness in mode-I was evaluated in varying orientations of fibers such as 0º, 45º and 90º. Notches of varied crack length (a) were introduced using 150 µm thick diamond wafer blades mounted on a standard Isomet cutting machine equipped with specially designed jig to introduce straight notch. The specimen dimensions were carefully measured using Delta TM 35 x-y profile projector.

2.2 Fracture Toughness Testing

All the fracture toughness tests were conducted on a computer controlled, servo hydraulic Instron 5600R test system using a self articulating 3 point bend fixture. The tests were conducted at ambient temperature and in laboratory air atmosphere. Fracture toughness tests were carried out under ramp control speed of 10 mm/min. The loads versus crack opening displacements were recorded as per the ASTM standard D 5045 -99. All the fracture toughness tests were conducted using SENB or three-point bend specimens whose gross dimensions are given in table 1.

2.3 Fractography

The fracture surfaces of all specimens were observed by scanning electron microscopy at several magnifications in order to study the fracture mechanisms.

III. Results and Discussion

3.1 Load Displacement Data

The load - displacement data for the all specimens are shown in the figures 2a, 2b and 2c and its details are included in Table 1. The data in figures 2a, 2b and 2c and Table 1 clearly reveals the fact that the maximum load and conditional load is significantly higher for 0° fiber oriented specimens as compared 45° and 90° fiber oriented specimens. Apart from such large variation in the magnitudes of loads for fracture, the nature of load displacement data is also too indispensable different for the 0°, 45° and 90° fiber orientation composites.

Though the load was initially found to increase linearly with the displacement for all the composites, figures 2a, 2b and 2c

Table 1: Specimen details and data for fracture toughness evaluation of the composite material in different orientation of fibers

Specimen No	Thickness, B(cm)	Width, (cm)	Crack length, a (mm)	a/W	f(a/W)	Pmax (kN)	Kmax (MPa√m)	PQ (N)	KQ (MPa√m)	Pmax/ PQ
0° Orientation of Fibers										
1	0.41	0.81	0.04	0.52	11.5	0.03	1.09	0.03	1.09	1.0
2	0.39	0.90	0.04	0.51	10.4	0.03	1.05	0.03	1.05	1.0
3	0.41	0.82	0.04	0.50	10.1	0.03	1.06	0.03	1.02	1.04
4	0.41	0.83	0.04	0.50	10.1	0.03	1.02	0.03	0.97	1.05
45° Orientation of Fibers										
1	0.51	1.06	0.05	0.47	9.80	0.01	0.23	0.01	0.23	1
2	0.51	1.18	0.06	0.52	11.3	0.01	0.27	0.01	0.26	1.05
3	0.50	1.04	0.05	0.52	11.5	0.009	0.20	0.009	0.20	1.00
4	0.50	1.01	0.05	0.49	10.5	0.01	0.21	0.01	0.20	1.05
90° Orientation of Fibers										
1	0.39	0.87	0.04	0.49	10.6	0.003	0.09	0.003	0.08	1.05

corresponding to a stage where the specimens are elastically loaded, crack extension takes place over a narrower displacement range (0-1mm) in 90º fiber orientation specimens as compared to those 0º orientation specimens (0-6 mm) and 45º orientation specimens (0-4 mm). Secondly, the crack arrest loads (the load corresponds to plateau in load displacement curves) are significantly higher and also the extent of such crack arrest displacements are higher for 0o oriented specimens. Lastly, the load drops following the attainment of Pmax is significantly steeper in case of 45º and 90º oriented specimen. All these three observations have large influence on the fracture toughness of glass fiber reinforced composite.

All the load vs. displacement curves of 0° specimens has shown a stable crack extension in all the specimens. This is because, these samples the fiber material bears the entire load and there is a minimal contribution of the matrix material. In such specimens, the crack propagation is perpendicular to the direction of fibers and it is hard to break. Whereas in the 90º and 45º specimens, it fails suddenly after reaching the maximum load because in these samples, the matrix material bears the entire load and there is minimal contribution of the fibers and the crack propagation is parallel to the direction of fibers.

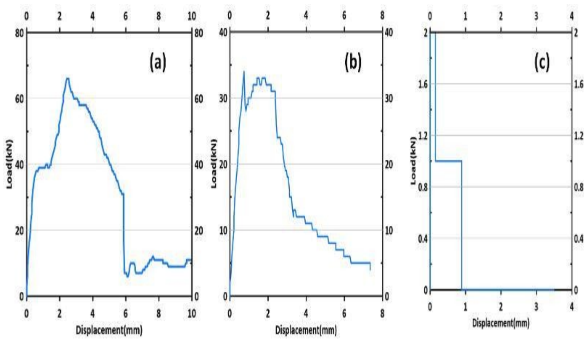

Figure 2: Load Vs. Displacement curve of composites having (a) 0º (b) 45º and (c) 90º orientation of fibers

3.2 Plane Strain Fracture Toughness (K_{Ic})

The conditional plane strain fracture toughness (K_Q) is calculated as per the procedures of ASTM standard D 5045-99, the data in Table 1 is subjected to validity so that the K_{IQ} values thus calculated are verified to be K_{IC}. The data in Table 1 shows that in all cases the values of P_{max}/P_Q are found to be <1.1 and also the thickness validity criterion B, a, w-a≥2.5 $(K_Q/\sigma_o)_2$ is found to be satisfied. Hence, the obtained results are valid and the values can be termed as K_{Ic}. The values of K_{Ic} which determined for all the composite specimens are given in Table 1. Further, though the specimens with varied a/W were tested, data corresponding to specimens with a/W values in the range of 0.45-0.55, as specified by the ASTM standard D 5045-99, were only used to arrive at K_{Ic}. The values of K_{max} and K_Q derived for each test are also listed in Table 1. The data in Table 1 shows that the material exhibits valid K_{max}/K_Q values (<1.1). In view of these observations, the K_Q values derived from specimens with a/W of 0.45 to 0.55 in all the specimens are considered to yield valid K_{Ic}.

The composite exhibits a significantly higher fracture toughness value in the 0_o fiber orientation with an absolute value of K_{Ic} 1.03 MPa√m is more than 15 times higher than the value obtained for the 90º fiber orientation composite (0.08 MPa√m) and 5 times higher than the value obtained for the 45º fiber orientation composite (0.22 MPa√m). Such large variation in the fracture toughness in the test direction in these glass fiber reinforced composites are directly attributed to uni-directional weaving of the glass fiber, which essentially results in gross fracture toughness anisotropy.

IV. Fractography

The fracture surfaces were studied by using SEM in order to evaluate the fracture mechanism in mode-I loading. The crack propagation and breakage of fibers is clearly shown in figure 3. Glass fibers were observed some degree of pull-out during the fracture. While they were pull-out, they bridge the surfaces which were undergoing cleavage there by increasing the energy for fracture.

Diameter of glass fibers in the as received form was around 13 µm, while the present image showing slightly higher diameter i.e., 15.05 µm. This clearly reveals that better bonding between epoxy matrix and glass fibers (Figure 3). Figure 4 also shows some degree of pull-out of fibers and breakage of fibers. SEM image also shows good bonding between epoxy matrix and glass fibers. In 0º orientation fiber composite specimen crack propagation perpendicular to fiber orientation where as in 90º orientation specimen (Figure 4b) crack propagation is parallel to fibers.

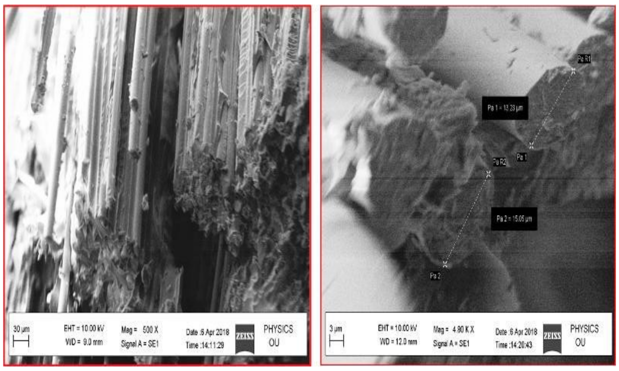

Figure 3: SEM micrographs of Mode-I fracture surface for composite (0^o orientation fibers)

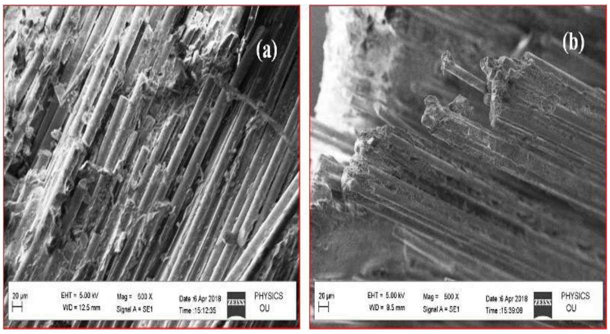

Figure 4: SEM micrographs of Mode-I fracture surface for composite (a) 45^o and 90^o orientation of fibers

V. Conclusions

The glass fiber reinforced epoxy matrix composite material has been comprehensively evaluated for its mode-I fracture toughness in three different orientation of fibers. The important conclusions drawn from this study are:

1. All the composite laminates i.e., with 0º, 45º & 90º fiber orientation were prepared successfully by using filament winding technique. There is no breakage or disturbance in the orientation of fibers even after various heat treatment cycles during preparation of composite.

2. The tests are conducted to quantify the effect of directionality on the fracture toughness properties.

   i) The fracture toughness is significantly greater for 0º fiber as compared to 90º fiber orientation composite laminates.

   ii) This is due to the fact that in 0º fiber orientation specimen the crack propagation is arrested by fibers during fracture process.

   iii) In 90º fiber orientation composite there is a minimum contribution of fibers during fracture process.

3. The SEM fractographs clearly reveals that there is good bondability between the glass fiber and epoxy matrix.

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