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Fracture Characterization of Plain Woven Fabric Glass-Epoxy Composites

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***Abstract*—**Delamination between layers in composite materials is a major structural failure. The delamination resistance is quantified by the critical strain energy release rate (SERR). The present investigation deals with the strain energy release rate of two woven fabric composites. Materials used are made of two types of glass fiber (360 gsm and 600 gsm) of plain weave and epoxy as matrix. The fracture behavior is studied using the mode I, double cantilever beam test and the mode II, end notched flexure test, in order to determine the energy required for the initiation and growth of an artificial crack. The delamination energy of these two materials is compared in order to study the effect of weave and reinforcement on mechanical properties. The fracture mechanism is also analyzed by means of scanning electron microscopy (SEM). It is observed that the plain weave fabric composite with lesser strand width has higher inter laminar fracture properties compared to the plain weave fabric composite with more strand width.

***Keywords*—**Glass- epoxy composites, Fracture Tests: mode I (DCB) and mode II (ENF), Delamination, Calculation of strain energy release rate, SEM Analysis

I. INTRODUCTION

ONE of the most important parameters in the application of fracture mechanics in composite structures is the strain energy release rate. Woven fabric reinforced composites are the most important and widely used forms among textile structural composites. It has been noted that delamination in a composite laminate usually occurs at the interface of different oriented plies. Fracture mechanics has found extensive applications in damage analysis of composite laminates, especially in delamination. Woven fabrics, which are attractive reinforcements, provide excellent integrity and conformability for advanced structural applications. The mode of delamination failure depends on the external loading conditions and on the intrinsic properties of fiber and resin. The interlaminar fracture behavior is one of the most important characteristics related to the overall performance of the composite system. Woven fabric composites have found widespread applications in aerospace, automobile and defence industries because of their ease of handling, low fabrication cost, and excellent mechanical properties (including damage tolerance and impact resistance)

In the present investigation characterization of the mechanical behavior of glass fiber (both 360gsm and 600 gsm) woven fabric and epoxy composite laminates has been done under two loading conditions. Double cantilever beam (DCB) and end notched flexure (ENF) to analyze toughness and failure mechanisms. Also in each mode of test two different theories have been used in order to determinate which would be the most appropriate.

II. REVIEW OF LITERATURE

The tensile fatigue behavior of plain weave and knitted fabric composites has been investigated by Pandita et al. [1]. Fatigue damage development in knitted fabric composites is quite different from that in plain-weave fabric composites. Fatigue damage in plain-weave fabric composites was initiated by transverse bundle cracking. Initial fatigue damage in knitted fabric composites was situated at the part of the curled bundle yarn that is perpendicular to the tensile loading direction. Regarding the relative residual stiffness, woven fabric composites show better fatigue resistance than knitted fabric composites. However, both woven and knitted fabric composites show comparable results in the fatigue life and the relative residual strength

Blackman and Kinloch [2] specifies a method, based upon linear-elastic fracture-mechanics (LEFM), for the determination of the fracture resistance of structural adhesive joints under an applied Mode I opening load, using the Double Cantilever Beam (DCB) and Tapered Double Cantilever Beam (TDCB) Specimens. The adhesive fracture energy GIC (also termed the critical strain energy release rate) for applied Mode I loading was calculated and a resistance-curve (R-curve, i.e. a plot of the value of the adhesive fracture energy GIC versus crack length) was plotted.

A survey of the literature and state of the art of the mechanical aspects of delamination in laminate composite structures was presented by Bolotin [3]. Surface and internal delamination of various origin, shape, and location were discussed. The origination, stability, and post critical behavior of delamination under quasi-static, cyclic, and dynamic loads were analyzed.

Naik and Reddy [4] performed an experimental analysis of laminated composite plates under transverse loading and drilling of composites. Interlaminar critical strain energy release rate properties in mode I, mode II, mixed mode I/II and mode III have been evaluated for two types of plain weave fabric E-glass/epoxy laminates. The double cantilever beam test and the end notch flexure test have been used for mode I and mode II loading. The mixed mode bending test and split cantilever beam test have been used for mixed mode I/II and mode III loading. It is observed that the plain weave fabric composite with lesser strand width has higher Interlaminar fracture properties compared to the plain weave fabric composite with more strand width. Further, crack length versus crack growth resistance plots have been presented for mode III loading. In general, it is observed that total fracture resistance is significantly higher than the critical strain energy release rate.

A mixed mode specimen was proposed by Sørensen et al. [5] for fracture mechanics characterization of adhesive joints, laminates and multilayers. The specimen was a double cantilever beam specimen loaded with uneven bending moments at the two free beams.

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By varying the ratio between the two applied moments, the full mode mixity range from pure mode I to pure mode II was generated for the same specimen geometry. The specimen allowed stable crack growth. In case of large scale crack bridging, mixed mode cohesive laws were obtained by a J integral based approach. As a preliminary example, fracture of adhesive joints between two glass-fibre laminates was studied. The mixed mode fracture resistance increased with increasing crack length due to fibre cross over bridging, eventually reaching a steady-state level (R-curve behaviour). The steady-state fracture toughness level increased with increasing tangential crack opening displacement. Cohesive stresses were determined by a J integral approach. The deducted shear stress was found to be relative high (≈ 20 MPa) in comparison with the normal stress (≈ 1 MPa).

The research work carried out by Zenasni et al. [6] deals with the strain energy release rate of three woven fabric reinforced thermoplastic composites. The interlaminar fracture behavior was studied using the mode I, double cantilever beam test and the mode II, end notched flexure test, in order to determine the energy required for the initiation and growth of an artificial crack. The materials used were made of two types of glass fiber weave (2/2 Twill, 8H Satin) and a carbon fiber (8H Satin). The matrix was polyetherimide. The delamination energy of these two materials was compared in order to study the effect of weave and reinforcement on mechanical properties. The fracture mechanism was also analyzed by means of scanning electron microscopy.

Mode I and Mode III fracture properties of silk fibre/polyester composites have been studied by Zulkifli et al [7] Tests for mode I interlaminar fracture was carried out using double cantilever beam specimens (DCB) testing method and mode III fracture behaviour was determined using trouser tearing test method. The multi-layer woven fabric silk fibre/polyester composites were produced by vacuum bagging method in an autoclave. Sample for mode I were prepared with increasing layers of silk of between 8 and 14 layers in thermoset polyester while sample for mode III consisted of a single layer silk fibre reinforced polyester resin. For mode I interlaminar fracture using double cantilever beam specimens (DCB) testing method, it was found that the interlaminar fracture toughness, G of the composite increases as the number of silk layers increases. Stable crack propagation was observed during the tests and the crack propagation areas showed all the fibres were bare with no matrix covering them as were seen at 100x and 500x magnification using Scanning Electron Microscopy. Failure occurred at the fibre-matrix interface with no fibre bridging observed between the two fracture surfaces. The smooth clean surface of the silk fibres was the result of weak interfacial debonding. The results give the indication of the effect of the layers because the thicknesses of all the specimens were same. For the mode III tearing test, the effect of the autoclave processing time has been studied. It shows that longer processing time will improve the tearing strength of the silk fibre/polyester composites. However, the addition of matrix to the silk fibre reduced the tearing strength of the silk fibre/polyester composites.

The results give the indication of the effect of the layers and processing time on the mode I and mode III fracture properties. Due consideration on the high costs of silk fibre and processing time if more layers of silk are required in order to improve fracture toughness properties of these composites.

According to Marat-Mendes and Freitas [8] delamination is an important mode of failure on laminated composite materials and the characterization of this failure mode is a subject of research. Mode I, mode II, mode III and mixed-mode I+II fracture toughness were obtained using the double cantilever beam test (mode I), the end notch flexure test (mode II), the original and the modified edge crack torsion test (mode III) and the mixed-mode bending test (mixed-mode I+II) respectively. Fracture surfaces obtained during mode III interlaminar fracture toughness of glass/epoxy composites have been also studied using the original and the modified edge crack torsion test geometry. Results were compared with delaminating surfaces obtained during tests of mode I, mode II and mixed-mode I+II. In the original ECT test the hackle marks appears only in the side of the loading pin. In the modified ECT test the hackle marks appears in both sides of the sample and slightly less well defined and smoother fracture features in the middle of the sample.

There has been significant increase in use of glass fibre reinforced composites as structural materials in naval mine countermeasure surface ships. Sea mines when detonated emit underwater shock waves, which could impart severe loading to naval ship structure; there are attempts to model the response of a ship structure to this loading by Singla and Chawla [9]. For the model to be accurate & useful, material property data were determined experimentally by taking different weight percentage of glass fibers (E-300, mat form) with epoxy resin & comparison was made with fly ash reinforced composite. Specimens in the form of cube of size 10x10x10 (mm's) were used & results were presented.

III. SCOPE

i. An attempt to develop two composites by using same matrix(epoxy) and the fiber(glass) of same weave pattern(plain) but having different gsm (360 gsm & 600 gsm).
ii. Fracture characterization by Mode I and Mode II tests to calculate crack propagation energy (GIC).
iii. In each test, calculation of crack propagation energy (GIC) by both Corrected Beam theory (CBT) and Berry's method (BM).
iv. Comparing the different values of crack propagation energy (GIC) by the two theories in two methods.
v. Studying the scanning electron micrographs for the two composites with different magnifications.
vi. Selection of the better composite out of the two types under above testing conditions.

IV. THEORETICAL ANALYSIS

Mode I Interlaminar Test. For the mode I test, DCB specimen geometry has been used (Fig. 1). Crack propagation energy values or the critical values of the energy of the delamination, GIC have been calculated using the corrected beam theory

$$G_{IC}=\frac{3p\delta}{2B(a+|\Delta|)} \tag{1}$$

Where P is the force, **δ** is the displacement of the notch lip, a crack length, and B 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. This factor **Δ** was obtained by drawing one-third power compliance against crack length (C1/3−a). In addition, the experimental compliance calibration or Berry's method was employed. In this case

$$G_{IC}=\frac{np\delta}{2Ba} \tag{2}$$

Where n is the slope of the plot log C-log a(C=Kan). The values of the crack propagation energy, GIC, for the three composite materials are presented by using the corrected beam and Berry's theories. It has seen that the corrected beam theory provided more conservative values.

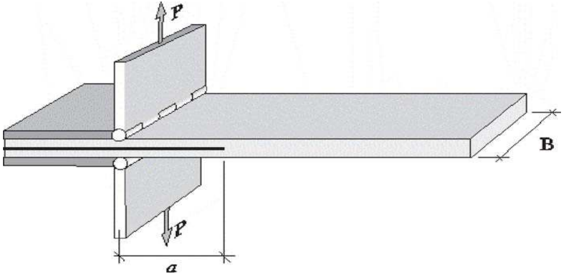

Fig. 1 Mode I, DCB Test

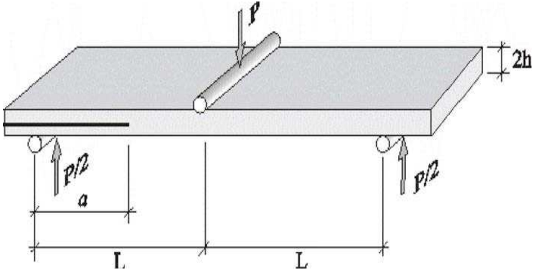

Fig. 2 Mode II, ENF Test

Mode II Interlaminar Test. For the mode II test, ENF specimen geometry has been used (Fig. 2). The specimen was loaded in a standard three-point bending fixture at a crosshead speed of 0.5 mm/min. The delamination energy GIIC has been calculated at the characteristic points according to the corrected beam theory

$$G_{IIC}=\frac{9P^2a^2}{16B^2\,E\,h^3} \tag{3}$$

The value of E is the modulus measured during the compliance calibration for a=0. It is calculated as

$$E=\frac{L^3}{4BCh^3} \tag{4}$$

In this mode, according to the experimental compliance calibration method

$$G_{IIC}=\frac{3mP^2a^2}{2B} \tag{5}$$

After the fracture tests, the specimens are broken open. The distances from the marks made during the calibration load cycles to the tip of the inserted film are measured and the mean of the values at the edges and the centre of the specimen are plotted against the corresponding compliances. A least square linear regression is then carried out, of the form

$$C = C_0 + ma^3 \tag{6}$$

The value of the crack length can thus be obtained; m being the slope of the curve C= f (a3) and C0 the value of C at the origin. The different values of m for the three materials have been calculated from the graphs. The values of the delamination energy calculated by the experimental calibration method are more or less similar to those obtained using the corrected beam theory.

V. EXPERIMENTAL INVESTIGATIONS

E-Glass fiber plain woven fabric (both 360 gsm-Type-I and 600 gsm-Type-II) are cut into size 175mm×90mm. Epoxy (CY 230 of Hindistan Ciba Geigy) is mixed with hardener (HY-951) in the ratio 1:10. The composite was prepared by hand moulding process by adding glass fabric and epoxy resin alternatively. The composite consists of six layers of fibric and seven layers of epoxy resin. In the middle of the composite an aluminium foil was inserted to give the initial crack. The weight ratio of fibric and epoxy was 1:2. The thickness of the adhesive bondline was carefully controlled. Then under the application of pressure , the material was kept for approximately 24 hours for curing. When fully cured, any excess adhesive was removed by means of cutter carefully. Specimens have been prepared with dimensions of 164mm×20mm×5mm and weighing 23grams.

1) *Specimen for Mode I (DCB) Test:* Metal clamps have been provided at both the sides of those pieces of composite parallel to the foil inserted by using hardener (Fig. 3). Four specimens were prepared by using 360 gsm fiber (Type I specimen) and two for 600 gsm fiber (Type II specimen).
2) *Specimen for Mode II (ENF) Test*: Out of those six pieces of composite specimens two specimens have been used for Type II test without end connections.

Fig. 3 Specimens for both DCB Test and ENF Test

Fig. 4 Experimental set up for DCB Test

Fig. 5 Experimental setup for ENF Test

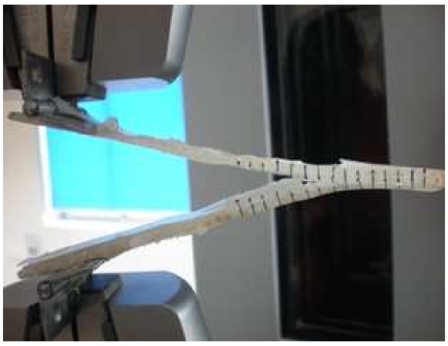

Fig. 6 Fracture in DCB test

Delamination in composites can occur due to tensile stress (mode I), in-plane shear stress (mode II), and out-of-plane tearing stress (mode III). In both the tests (DCB & ENF), INSTRON Universal Testing Machine (Fig. 4) has been used to record the load-deflection curves for calculating fracture toughness. Fig.5 shows the specimen under ENF test and Fig.6 the progress of fracture in the machine. Specimens have been designed by referring ASTM standards [10]. In this experiment both the DCB and ENF specimens have been designed for measuring the resistance to delamination under mode I and mode II loading respectively. The out put data have been recorded and graphs have been plotted as required.

VI. Results And Discussion

By calculating the value of **Δ** from the graph (Fig.7) and putting in Equation-1, the value of GIC has been calculated. Finding out the value of 'n' from graph (Fig.8) and putting in Equation-2, the value of GIC has been calculated by Berry's method. In mode II test, by calculating the value of E from Equation-4 and putting in Equation-3, the value of GIIC has been calculated by CBT (Corrected Beam Theory). The value of m has been found out from the graph (Fig.9), and then putting in Equation-5, GIIC has been calculated by Berry's method or experimental compliance method. All these values of GIC and GIIC were for type I specimen. Similarly same equations have been used to calculate the values of GIC and GIIC for the type II specimen by referring the corresponding graphs (Fig.10 to Fig.12). Scanning electron micrographs have been shown in Fig.13 and 14 to generate ideas about fracture of specimens.

A. *Curves for specimen type-I*

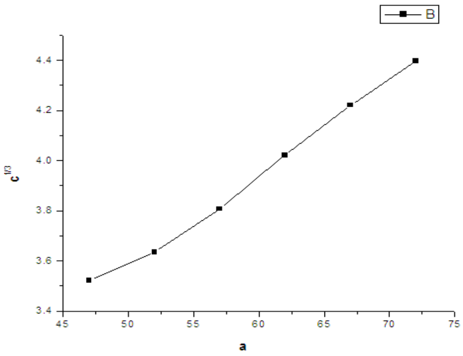

Fig. 7 Curve for correction factor, **Δ**

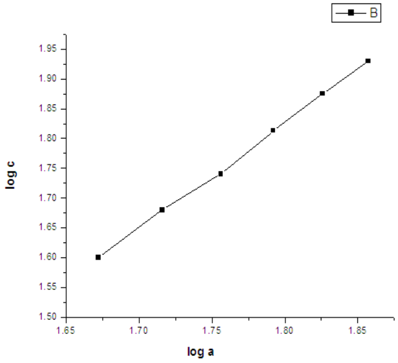

Fig. 8 Curve for slope of logc vs log a, 'n'

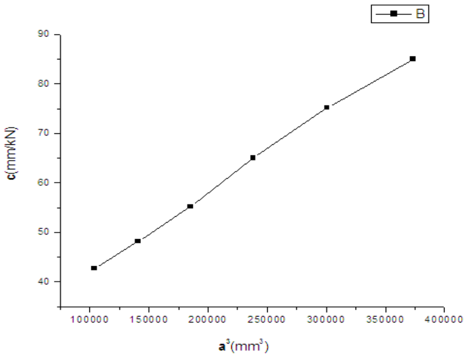

Fig. 9 Curve for specimen geometry factor, 'm'

B. Curves for specimen type-II

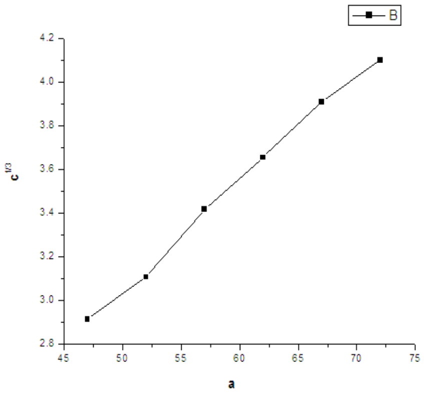

Fig. 10 Curve for correction factor, **Δ**

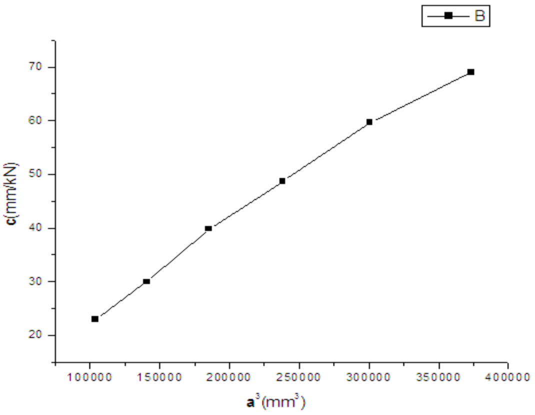

Fig. 11 Curve for slope of logc vs log a, ‘n’

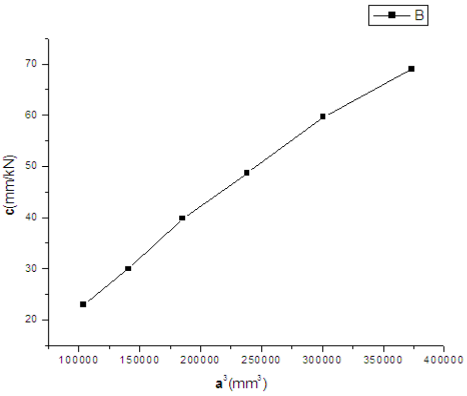

Fig.12 Curve for specimen geometry factor, ‘m’

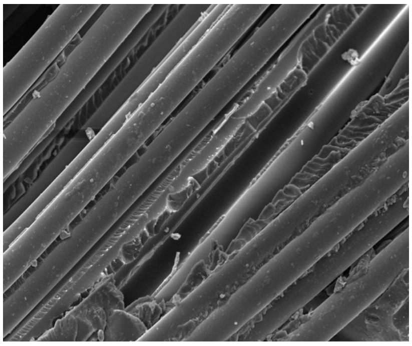

Fig. 13 Micrograph of type I specimen [10µm, WD- 15.5, Mag-1.00 KX]

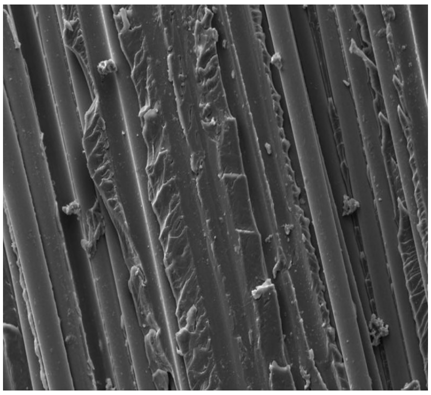

Fig. 14 Micrograph of type II specimen [10µm, WD-16.5, Mag-1.00KX]

In mode I, the theories have been used out of which the corrected beam theory have provided more conservative values of GIC than Berry’s theory. The value of GIC for the type II composite material is more in composition to the type I composite material. Hence the type II composite has more resistance than type I composite. As matrix is same (epoxy) and fibre is different in both the composites, it may be concluded that 600gsm glass fibre has more resistance.

In mode II also corrected beam theory has provided more conservative values of GIIC in both the cases of composites. The value of GIIC for the type II composite is more than the other type of composites. In this mode, the material that has presented the highest resistance to the delamination is 600gsm glass fibre. Micrograph for type I specimen has been presented in Fig.13 and for type II specimen, in Fig.14 with the magnification mentioned below the figure. In general, the damage is more important in mode II than in mode I. The results obtained from calculations are well corroborated by the micrographs.

VII. CONCLUSIONS

A. General Conclusions

It is observed that the plain weave fabric composite with lesser strand width has higher interlaminar fracture properties compared to the plain weave fabric composite with more strand width.

B. Specific Conclusions

- 600 GSM glass fibre is more resistant to fracture than 360 GSM glass fibre when used as a fibre with the same matrix (epoxy) in composites.
- The results are in good agreement with results obtained by earlier researchers Naik and Reddy [4].

C. Future scope

The following work may be taken up in future

- Mode III, mode I+II and mode II+III tests are to be conducted for both the composites.

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- Different composites are to be designed by taking glass fiber of twill weave and satin weave with the same matrix.
- The values of G_{IC} and G_{IIC} for the above mentioned composites are to be compared.
- Fracture characterizations are to be analyzed by using finite element analysis and are to be compared with the experimental investigations

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