Intra-Laminar Fracture Toughness of Glass Fiber Reinforced Polymer By Using Theory, Experimentation and FEA

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Abstract. Fiber reinforced polymer (FRP) composites are widely use in aerospace, marine, auto-mobile and civil engineering applications because of their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance and potentially high durability. The purpose of this research is to experimentally investigate the mechanical and fracture properties of glass-fiber reinforced polyester composite material, 450 g/m^2 randomly distributed glass-fiber mat also known as woven strand mat with polyester resin as a matrix. The samples have been produced by the conventional hand layup process and the specimens were prepared as per the ASTM standards. The tensile test was performed on the composite specimens using Universal testing machine (UTM) which are used for the finite element simulation of composite Layered fracture model. The mechanical properties were evaluated from the stress vs. strain curve obtained from the test result. Later, fracture tests were performed on the CT specimen. In case of CT specimen the load vs. Displacement plot obtained from the experimental results was used to determine the fracture properties of the composite. The failure load of CT specimen using FEA is simulated which gives the Stress intensity factor by using FEA. Good agreement between the FEA and experimental results was observed.

Keywords Fiber reinforced Polymer, Stress intensity Factor,FEA

1. Introduction

The modernization in material science and development of high strength to weight ratios composite materials capture the eye of industrial, Medical, Defence and Space application. Excessive use of composite leads to the research in the field of failure and fracture of composite material

The Intra-laminar and Intra-Laminar Fractures are two basic failures found in laminated composite material. If the crack is present in between two laminates of composite material that failure is called as Inter-laminar failure, most commonly it is known De-lamination [1, 2, 3]. Intra-laminar fracture in Mode I is also known as trans-laminar fracture, Trans-laminar fracture is characterized by a crack which passes through the laminates across fibers which has not been addressed to a great degree. Extensive research was carried out to determine failure criterias of inter-laminar fracture of FRP by using theoretical and experimental Techniques.For mode I failure of inter-laminar composite, double-cantilever beam test [4, 5] is used and for mode II end-notched flexure test [6] while for mixed-mode bending test. The matrix cracking or a crack apparently running parallel to fibers (Intra-laminar) through the thickness is also one of the

problems encountered in fiber reinforced polymer composite. Extensive research work carried on inter-laminar fracture has led to the development and standardization of inter-laminar fracture toughness testing on various Modes. Parhizgar et.al [7] showed that intra-laminar fracture toughness depends on orientation, the value of K_{IC} being twice for $/90^0$) oriented fibers than $(0^0$ oriented fibers, even though the failure is due to matrix cracking. They observed that the mode of failure is by self-similar crack breaking the fiber for cross ply laminate. Pinho et. al [8] have found that the Mode I intra-laminar critical energy release rate for through the thickness crack growth was very similar to the inter-laminar toughness in unidirectional laminates, so inter-laminar critical energy release rate can be a good approximation for intra-laminar energy release rate. Intra laminar fracture in composite are not being researched, but the recent history shows the attention towards the failure of composite due to This type of failure although there are not any specific test were developed. But some of the researchers are using ASTM D 5045 [9] method for testing of intra-laminar Failure. Jose et.al [10] investigated intra-laminar fracture toughness on carbon / epoxy with 0^0, 90^0 fibers oriented and cross-ply (0^0 /90^0) laminates. This research has been carried out to find out the theoretical results of mode 1 fracture stress intensity factor which are obtained by using experimental testing on Compact test specimen. Also the results are compared to the analytical results with experimental. Intra-laminar (transverse) fracture of graphite and epoxy laminates using Compact test and 3 Point bend specimens are investigated by Garg [11] also studied the influence of width, thickness of the specimen. His result shows that that K_{IC} is independent of geometry and thickness of the specimen.

In this paper,stress intensity factor of woven strand glass fiber reinforced polyester laminates for Mode I failure is measured by experiments on CT specimen. The Stress intensity factor is validated with Finite element analysis .The mechanical properties required for the Finite element analysis is calculated with help of anlytical equation and tensile test results.

2. Fracture Mechanics Applied To FRP Composites

The Fracture mechanics is not only applicable to metals, but also can be studied in polymers, glass and ceramics which are brittle materials. As composites were made up of ductile as well as brittle material it can fail in both ways. There are several fracture modes encountered in composites such as de-lamination or inter-laminar fracture, matrix cracking or intra-laminar fracture, matrix-fiber de-bonding, fiber breaking, fiber pull-out, etc. In the fiber reinforced polymer composite, the matrix is likely to fail due to tearing as it absorbs energy while the high strength fibers fails due to brittle cleavage. The fracture prediction of composite are unpredictable, but mostly composite materials failed due to de-bonding of matrix layer in between the laminates.

2.1. Woven strand mat

Fiberglass woven strand mat Fiberglass woven strand mat is a woven fiberglass reinforcement consisting of uniformly distributed fiberglass strands held together with a powder or emulsion. Woven Mat is produced by the uniform distribution of rovings of glass fiber like cloth material in a uniform bonded mat. Woven strand mat has unidirectional physical properties. It has excellent wetting and durability, high tensile strength, and allows easy removal of trapped air-bubbles. The products are widely used for all kinds of FRP composites products such as internal covering of auto-mobile parts, FRP boat hulls, sanitary wares, chemical corrosion resistant pipe, storage tank, building materials, furniture, electrical parts and insulated glue joint etc.
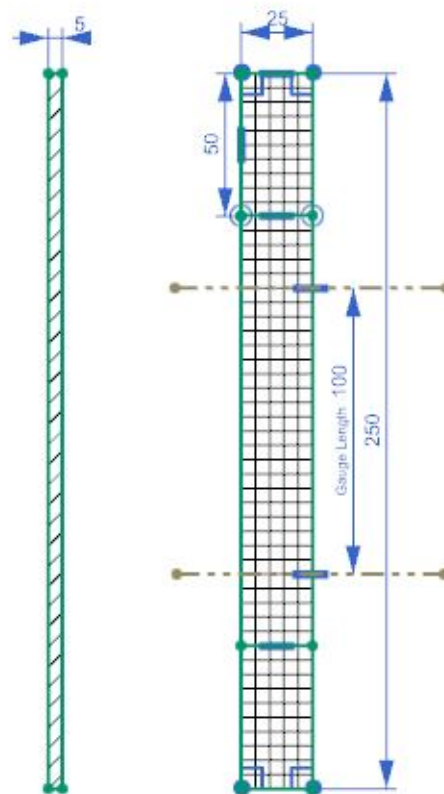
- A woven strand matt are stored on 76 mm internal diameter cardboard tubes.
- A rectangular polyethylene sheet of 27 × 27 cm is used for the first and the last layer of composite structures.

3. Material

In the present study, we have used Polyester as thermosetting plastic which is in the form of liquid at room temperature and glass fiber as reinforcement material. The hand lay-up process is used for preparing FRP sheets for polyester and glass fibers. Methyl ethyl ketone peroxide is used as inhibitor and cobalt octane is used as an accelerator during processing of FRP sheets. To prepare a sheet of required size, we have used the volume fraction approach. The required amount of an individual material is taken as per the standard calculation for hand lay-up process.

3.1. Preparation of Specimen

The experimental testing of any composite materials is a cumbersome job because its specimen preparation takes time. It is, however an essential process and can be somewhat simplified by the testing of simple structures. To find mechanical properties of glass fiber reinforce polyester resin we have prepared a tensile test specimen. The tensile specimen was prepared as per the ASTM D3039 standard. Figure 1 shows the configuration of the tensile specimen. The tensile specimen was glued with the emery sheet at the end so that proper gripping can be achieved during the testing.

Figure 1. Tensile Specimen specification.

The specimens were prepared from the laminates as per the ASTM standard for Compact test specimen. The specimen was cut using the shearing machine, followed by grinding and

filling the surface to get a good finish and accurate dimensions. After the surface is finished, a layer of resin is applied to the finished surface to avoid the moisture absorption. The crack was created using the carpentry hacksaw using a blade of thickness 0.5 mm.The Figure 2 shows the configuration of the Compact test specimen used for evaluation of K_{IC} for intra-laminar fracture in composites. The assumed value of W is W = 50 mm.Based on this value of W the specimen dimensions were calculated.
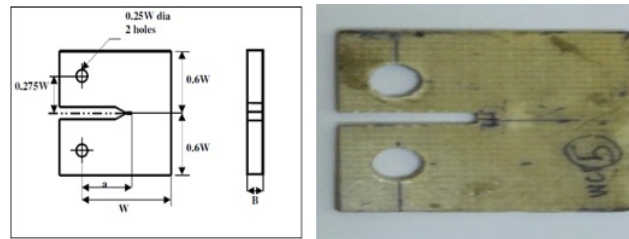

Figure 2. Compact test specimen Configuration.

4. Experimental Investigation

Empirical relation obtained from woven matt laminates

Empirical relation obtained from woven matt laminates [12] As we know $\sigma_m=$ Maximum tensile stress obtained during a tensile test for matrix material, i.e. polyester 8 MPa

$E_m=$ Youngs modulus of the matrix material i.e. for polyester = 1.2 GPa

$\sigma_m=$The maximum tensile stress of glass fiber =2300 Mpa

$E_m=$ Youngs modulus of the glass fiber =70 GPA

$\sigma_c=$ Maximum tensile stress of composite

$E_c=$ Youngs modulus of the composite

$E_l=$ Youngs modulus of the composite in longitudinal direction

$E_t=$ Youngs modulus of the composite in transverse direction

l = Length of the fiber =5 mm

D = Diameter of fiber = 100 μ m

$V_f=$ Volume fraction of fiber =0. 25

V_m A =Volume fraction of the matrix=0. 75

HALPIN-TSAI prediction Modulus equations

$$E_l = E_m \frac{(1 + ((2 \times l/\mathrm{d})\eta l \times Vf)}{(1 - \eta l \times Vf)} \tag{1}$$

$$\eta_l = \left(\frac{Ef}{Em}\right) - 1)/((\left(\frac{Ef}{Em}\right) + \left(2 \times \left(\frac{l}{d}\right)\right) \tag{2}$$

$$\mathrm{E}t = Em \times \frac{(1 + 2 \times (\eta t) \times (Vf))}{(1 - \eta t \times Vf)} \tag{3}$$

$$\eta t = \frac{\left(\frac{Ef}{Em}\right) - 2}{\left(\frac{Ef}{Em}\right) + 2} \tag{4}$$

$$E_c = \frac{3}{8} \times El + \frac{5}{8} \times Et \tag{5}$$

$$G_c = \frac{1}{8} \times El + \frac{1}{4} \times Et \qquad (6)$$

$$\sigma c = \sigma f \times \frac{1}{8} \times Vf + \sigma m \times Vm \qquad (7)$$

4.1. Testing procedure of FRP laminates

The tests were conducted on the UTM (Universal Testing Machine) giving a constant strain rate of 1mm/min. Five specimens were tested and the resulting Load vs. Displacement curves were obtained. For the tensile test the specimen was loaded in tension until a drop in the load was observed. In case of fracture test the specimens were loaded until an unstable crack growth was seen and the load started dropping down. The Mechanical and Fracture properties are measured with help of experimental testing. The Fracture Load P_s measured when the pop up noise comes at the time of crack initiation .The results are compared to theoretical values. Fracture loads P_s, obtained from the tests are used to determine K_{IC} values as a measure of fracture toughness by using the following data.

$$K_{IC} = \frac{Ps \times f(\frac{a}{w})}{B \times W^{1/2}} \qquad (8)$$

$$f\left(\frac{a}{w}\right) = \frac{(2 + \frac{a}{w})}{(1 - (\frac{a}{w}))^{1.5}} \times (0.886 + 4.64 \times \left(\frac{a}{w}\right) - 13.32 \times (\frac{a}{w})^2 + 14.27 \times \left(\frac{a}{w}\right)^3 - 5.6 \times \left(\frac{a}{w}\right)^4 \qquad (9)$$

where "B" is the thickness. "w" is the width. "a/w" is the aspect ratio of the Compact test specimen and

In case of fracture test of Compact test specimens, the specimens were loaded to pop up noise will be heard from the same while testing on UTM at a speed of 0.2mm/min. Figure 3 shows the actual pictorial view of the same. The specimen buckled during the testing of the first specimen owing to the stiffness of the woven matt FRP hence for the testing of remaining specimens, anti-buckling plates are used as shown in Figure 4

Figure 3. Crack propagation in Compact test specimen without anti-buckling plate .

Figure 4. Crack propagation in Compact test specimen with anti-buckling plate .

5. Finite element Analysis

The finite element model is prepared as per the dimension required for the Compact test specimen. Material properties required for the FE analysis are taken from the theoretical HALPIN TSAI calculations. Orthogonal properties for the model is taken as follows, $E_1 =$5.76 GPA, $E_2 = E_3 =$ 1.905GPa, $G_{13} = G_{13} =$2.005 GPa , $\mu_{13} = \mu_{12} =$ 0.3, and $G_{23} = \frac{0.5E_2}{1+v_{23}} =$ 0.68GPa , where the Poisson's ratio in the isotropic cross-sectional plane is taken as $\mu_{23} =$ 0.4. The ANSYS composite structure modelling is used to create the laminated cross section of GFRP considering woven strand mat. The 2D FE Model with meshing Shell181 element is as shown in Figure 5 The Model was solved by applying boundary condition on to the Compact test specimen, making one hole fixed and force is applied to the other hole. The Model solved differently until the maximum stress obtained is equal to the failure stress GFRP composite material which gives us the Failure load of FEA model. This failure load is used in Eq. 8 to determine the Stress intensity factor of mode I.
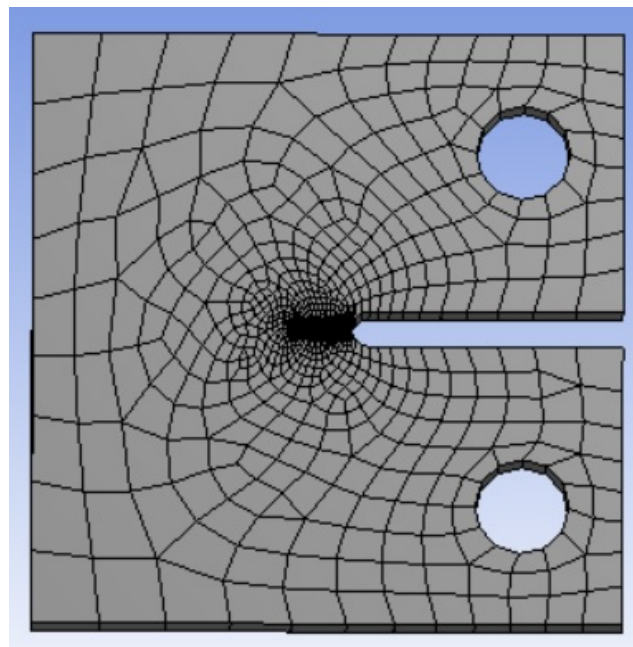

Figure 5. FE mesh Model.

6. Results and discussion
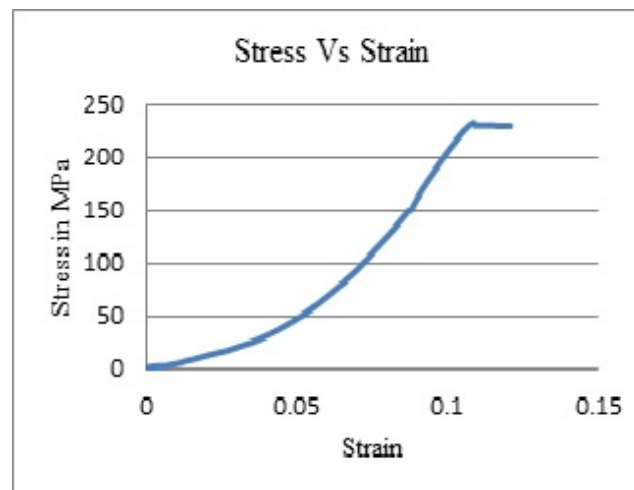
6.1. Tensile Test Result

Mechanical properties of glass fiber reinforced polyester obtained by using HALPIN-TSAI equation which is given in Appendix A. Table 1 shows the mechanical properties of GFRP after analytical results which has been calculated from HALPIN-TSAI Equations (Eq. 1-7).

The test was performed on the UTM at a constant strain rate to maintain uniformity of the test. Tensile testing of specimen is carried up to the ultimate failure of GFRP. Using the data obtained from the UTM the mechanical and fracture properties of the laminates were calculated. The tensile test was performed on five woven matt specimens The mean value maximum stress of composite structure after the experimentation is found out to be 212.8 MPa and the mean value of Youngs modulus to be 3.808 GPa with a standard deviation of 0.43 .The difference between the experimental and analytical results are due to the assumption taken into consideration analytical calculatio. Table No 2 infers the mechanical properties obtained for each specimen

Table 1. Mechanical Properties Obtained After Analytical Result IN GPa.

Property Description	Experimental	Theoretical Values
E_c	5.76 GPa	3.808 GPa
σ_c	228.76 MPa	212.8 MPa

after tensile testing. The mechanical properties obtained after theoretical and experimental Calculation given in Table No 2 to show good agreement. The stress strain relationship of Glass fiber reinforced polymer for a specimen number 1 can be visualized in Figure 6.

Figure 6. The Variation of Stress against strain for tensile specimen.

Table 2. Mechanical Properties Obtained After Experimental Results

Specimen No	Maximum load kN	Maximum Deflection (mm)	Maximum tensile Stress (MPa)	Maximum Strain	Youngs modulus GPa
1	23.29	14.5	232.9	0.12	4.104
2	17.595	11.12	175.95	0.092	3.45
3	19.31	11.8	193.5	0.098	3.259
4	23.05	13.34	230.5	0.1111	4.279
5	23.095	13.34	230.95	0.1178	3.948

Mechanical properties of glass fiber reinforcement polyester obtained after analytical and experimental study show only 4.42 percent errors in values of maximum normal stress

6.2. Fracture test Results
In case of Compact test specimen it can be inferred from the Figure 7 that the maximum load taken up by the specimen was observed to be in the range of 1.5 to 2 kN. This change in the load values can be attributed as a consequence of defects present in the specimen resulting.
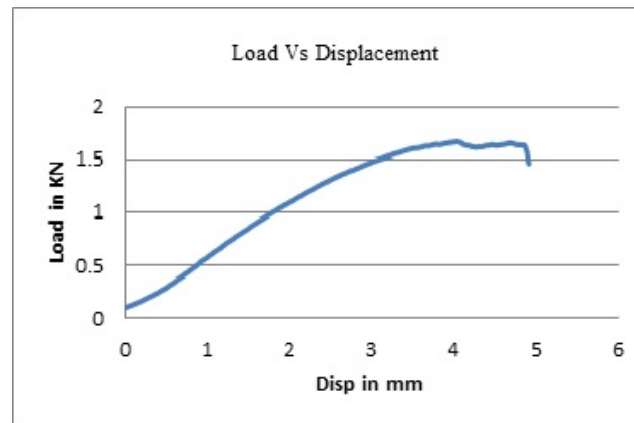

Figure 7. . The Variation of Load against deformation of Compact test specimen

Table 3. Mechanical Properties Obtained After Analytical Result IN GPa.

Specimen No	Peak Load in kN	K_{IC} in MPa $\sqrt{m}$
1	1.605	16.84
2	1.505	15.79
3	1.54	16.16
4	2.005	21.049
5	1.66	17.47

The critical stress intensity factor of five specimens for GFRP is tabulated in the Table. Mean value of K_{IC} is 17.46 MPa $\sqrt{m}$, standard deviation is 1.788

6.3. FE Results
FE simulations gives the stress distributions on the Layered structure of composite materials. The stress distribution shows the stress intensity in one surface is different than the other surface because of the woven strand mat. Stress distribution at the failure load is as shown in Figure 8. Failure load obtained after FE simulation is 2 kN. Stress intensity factor is calculated by using Eq.8 is 20.99 MPa $\sqrt{m}$.

7. Conclusion
This research focussed on the study of mechanical and fracture properties of GFRP composites manufactured by hand lay-up process. The hand lay-up technique is used predominantly because its ability to fabricate very large, complex parts with a quick initial start-up. Additional benefits of the process are simple equipment and tooling that are relatively less expensive.
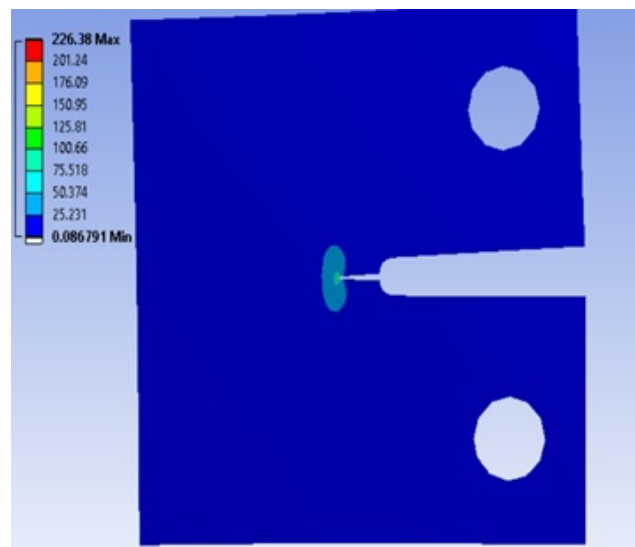
Figure 8. . Stress Distribution of GFRP at failure Load

- Analysis of the testing results obtained for the tension and the Compact test specimens demonstrated good mechanical properties. The results obtained after experimentation were in close approximation to the theoretical values.

- It was also observed that the modes of fracture in case of tensile and compact test specimen were in accordance with the theoretically predicted modes of failure.

- The FE simulation of intra-laminar GFRP composites gives us the stress intensity factor within the limits from which we can infer that FE models can be used to predict the fracture mechanical properties for mode I fracture mechanics.

- These properties can further be enhanced by following a standard manufacturing process so that the defects can be eliminated. Another important observation was made with respect to the amount in percent weight of glass fibers and resin to be used to get optimum properties. However the addition of inhibitors and catalyst also plays a major role in determining the laminate properties.

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