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Evaluation of Energy Release Rate for Mode I Crack propagation in GFRP structures

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***Abstract* - Unstable propagation of a crack results in fracture due to applied stress. Fracture mechanics provides a methodology for prediction, prevention, and control of fracture in materials, components and structures subjected to static, dynamic, and sustained loads. De-lamination is considered to be the most occurring failure mode in composites, a partition of the layers that are stacked together to form laminates. Delaminations appear at stress free edges due to the difference in properties of the individual layers, at ply drops where thickness should be reduced, and at regions subjected to out-of-plane loading like bending of curved beams. An experimental analysis was performed for analyzing the energy release rate for mode I crack propagation of the DCB specimen for different volume fractions. Double Cantilever Beam Specimen was analyzed for mode I crack propagation subjected tensile load and Energy Release Rate was evaluated for different crack lengths using ANSYS 15. Virtual Crack Closure method was used to find the Energy Release Rate by considering the displacements (V) at the flagged nodes near the crack tip and then was compared with the analytical results.**

Virtual Crack Closure method showed very good agreement with the experimental results. Convergence was achieved through refinement and results were extracted for variation of SIF along the crack front. It was observed from the results that the ERR increased at a very slow rate in the beginning of the crack growth (a/w = 0.2 to a/w = 0.4). As a/w reached 0.5 there was a steep increase in the Energy Release Rate. This was purely because of the plastic zone at the crack tip getting increased. This in turn increases the resistance offered by the crack to the propagation.

Keywords - Virtual Crack Closure Technique, Energy Release Rate, Crack propagation.

I. INTRODUCTION

De-lamination is considered to be the most occurring failure mode in composites, a partition of the layers that are stacked together to form laminates. Delaminations appear at stress free edges due to the difference in properties of the individual layers, at ply drops where thickness should be reduced, and at regions subjected to out-of-plane loading like bending of curved beams. Opening mode (mode I), the sliding shear mode (mode II), and the scissoring shear mode (mode III) are the three different modes of crack propagation. The fracture toughness linked with each fracture modes must be characterized and the equivalent strain energy release rates for each mode connected with the design and loading of interest must be evaluated to predict de-lamination onset and growth.

M. Kenane et, al [1] carried out a de-lamination fatigue-crack growth experiments on unidirectional glass/epoxy laminates. Three specimen types were tested: double cantilever beam (DCB), mixed-mode bending (MMB), and end-loaded split (ELS), for mode I, mixed-mode I + II, and mode II loading, respectively. Fracture mechanics technology was applied through the principles of strain-energy release rate. The measured de-lamination growth rates were correlated with the corresponding strain-energy release rates, ΔGI, ΔGT, and ΔGII.

Shivakumar K. N .et.al [4] used virtual crack closure technique for calculating stress intensity factors for cracked three dimensional bodies.

Xie D and Biggers S. B. [5] analyzed Strain energy release rate for a moving delamination front of arbitrary shape based on the virtual crack closure technique.

Okada H [3] Three dimensional virtual crack closure-integral method (VCCM) with skewed and non-symmetric mesh arrangement at the crack front.

II. EXPERIMENTAL ANALYSIS OF DCB SPECIMEN

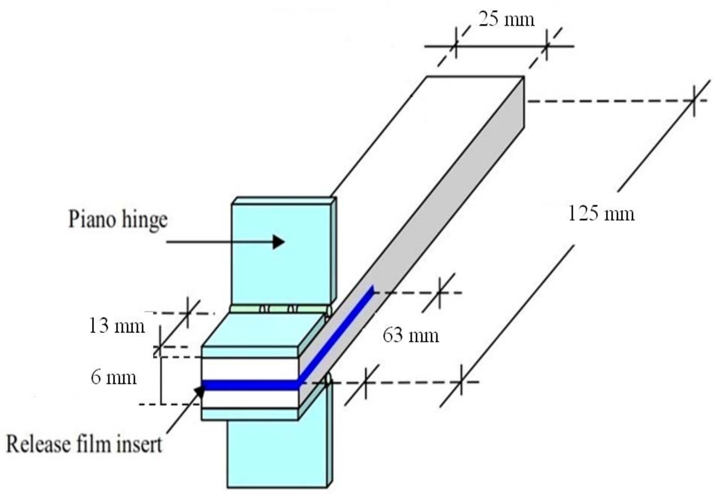

Fig.1 Standard DCB Specimen

TABLE 1. Volume Fraction combinations of fibre and matrix

Sl.No	Fibre	Epoxy Resin
1	0.4	0.6
2	0.45	0.55
3	0.5	0.5
4	0.6	0.4

The DCB specimen shown as for as ASTM standards. It consists of a rectangular, unidirectional, standardized thickness, laminated composite specimen contain a non-adhesive include at the mid-plane which serves as a delamination maker. Forces are applied to the specimen through an DCB fixture under displacement controlled loading.

A record of the apply force opposed to center roller displacement is obtained using an x-y recorder or equivalent real-time plotting device.

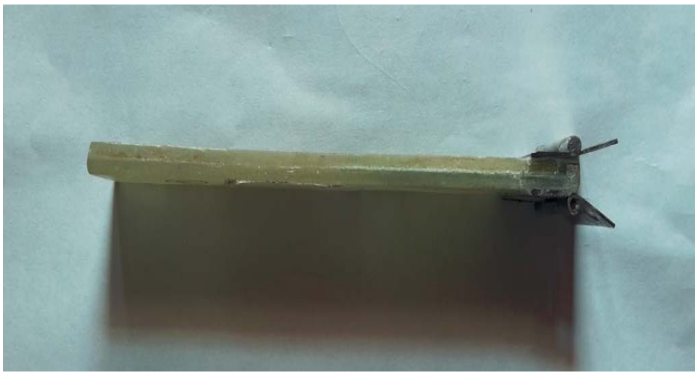

Fig.2 Fabricated Standard DCB Specimen

It can be obtained and stored digitally. The mode I inter-laminar fracture toughness, G_{IC}, is obtained by using the compliance calibration (CC) method.

Fig.3 Experimental Testing

III. Virtual Crack Closure Technique

Numerical analysis of energy release rate in Double Cantilever Beam specimen made of Glass-Epoxy composite was done using Virtual Crack Closure Technique to study the behavior of G with respect to change in volume of fiber and matrix content in the composite having unidirectional fiber orientation.

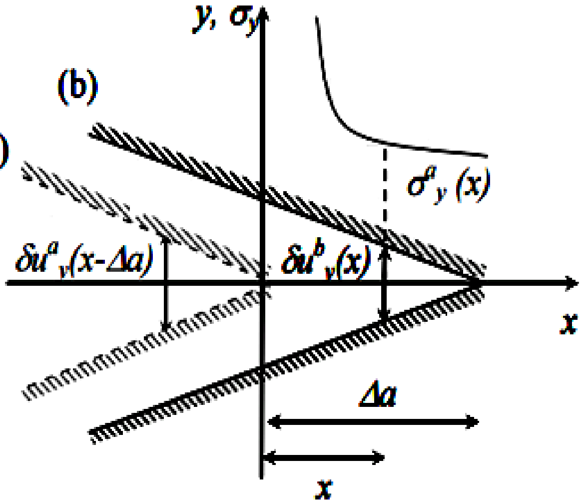

Fig 4. Virtual crack closure technique: schematization of the two configurations before (a) and after the crack extension (b) [1]

Work W required to close the crack is evaluated by considering the stress field at the crack tip for a crack of length a and displacements in the configuration with the crack front appropriately extended from a to a+Δa (Figure 4). The expression of the work W evaluated according to Virtual Crack Closure Technique is given by Eq. (1).

$$W=\frac{1}{2}\left[\int_0^{\Delta a}\sigma_{yy}^{(a)}(x)\,\delta u_y^{(b)}(x)\,dx+\int_0^{\Delta a}\sigma_{yx}^{(a)}(x)\,\delta u_x^{(b)}(x)\,dx+\int_0^{\Delta a}\sigma_{yz}^{(a)}(x)\,\delta u_z^{(b)}(x)\,dx\right] \quad \text{---------} \quad (1)$$

Equation 1 shows the work done to close the crack [2] and the stress displacement distribution to the crack displacement shown above.

σyy [a]= Normal stress in y-direction

σyx [a]= Shear stress in yx plane

σyz [a]= Shear stress in yz plane

δux [b]= Displacement in x-direction

δuy [b]= Displacement in y-direction

δuz [b]= Displacement in z-direction

In Eq. (1) the apex (a) and (b) are evaluated in configuration (a) and (b) of Figure 1 respectively giving the crack tip status, before and after the crack propagation. The evaluation of the Strain Energy Release Rate can be simplified by adopting an alternative approach: the one step Virtual Crack Closure Technique (VCCT). In VCCT it is assumed that an infinitesimal crack extension has minimal effects on the crack front hence both stress and displacement can be evaluated within the same configuration by considering only one analysis. By adopting this technique, the expression of the work W required to close the crack becomes as in Eq. (2).

$$w = \frac{1}{2}\left[\int_0^{\Delta a}\sigma_{yy}^{(a)}(x)\delta u_y^{(b)}(x-\Delta a)dx + \int_0^{\Delta a}\sigma_{yx}^{(a)}(x)\delta u_x^{(b)}(x-\Delta a)dx + \int_0^{\Delta a}\sigma_{yz}^{(a)}(x)\delta u_z^{(b)}(x-\Delta a)dx\right] \quad \text{-------------- (2)}$$

Equation 2 shows the modified work done to close the crack considering both stress field and the displacement [2]

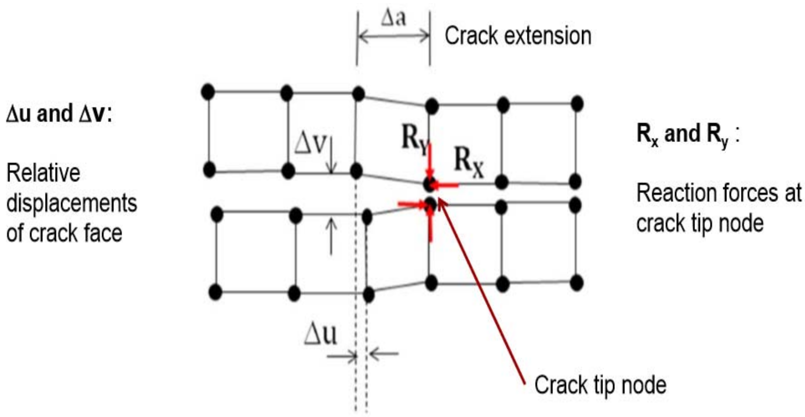

Fig 5. Nodal displacements at the crack tip

IV. Numerical Evaluation of Energy Release Rate

Double Cantilever Beam specimen (DCB) was simulated for mode I crack propagation using ANSYS V15 and Energy Release Rate was evaluated along the crack front and for different crack lengths.

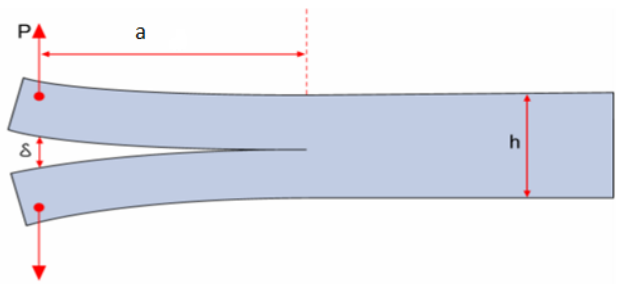

Figure 6. Double Cantilever Beam specimen (DCB)

Dimensions of the DCB specimen were taken as per ASTM standards shown in Figure 6.

Analytical solution for the DCB specimen was calculated for mode I crack propagation for different crack lengths from equation (7) [K R Y Simha 2001]

h = Width in mm

δ = Crack mouth opening displacement in mm

P = Load in N

a = Crack length in mm

$$G = \lim_{\Delta a \to 0} \frac{W}{\Delta a} \quad \text{-------} \quad (3)$$

Where W is the work done on the crack faces. From equation (4), it can be seen that for homogenous crack problem mode I can be directly calculated using the square root of the mode I energy release rate.

The properties of the Glass/Epoxy material are calculated using rules of mixtures. Preconditioned Conjugate Gradient (PCG) solver was used for the analysis of SIF. This solver starts with element matrix formulation. Instead of factoring the global matrix, PCG solvers assemble the full global stiffness matrix and calculate the DOF solution by iterating to convergence.

V. Results and Discussions

The load versus deflection curve is obtained in the digital recorder of the universal testing machine.. The results obtained are compared with each other to find the fiber volume fraction at which possesses high inter-laminar fracture toughness. As the glass fiber reinforced polymer is a brittle material the load V/S curve drop vertically after the peak load.

A. *Experimental results for different volume fraction of fiber*

Energy Release Rate was evaluated for opening mode of crack using Finite element method and Virtual Crack Closure method along the crack front and for different crack lengths. The Energy Release rate was calculated for volume fractions 0.4, 0.5 and 0.6.

For 40% fiber volume fraction of the GFRP composite, Longitudinal young's modulus, E1=36.2GPa.

The load vs. displacement arc recorded for the period of fracture toughness test for 0.4 Fibre Volume Fraction shown in the figure below

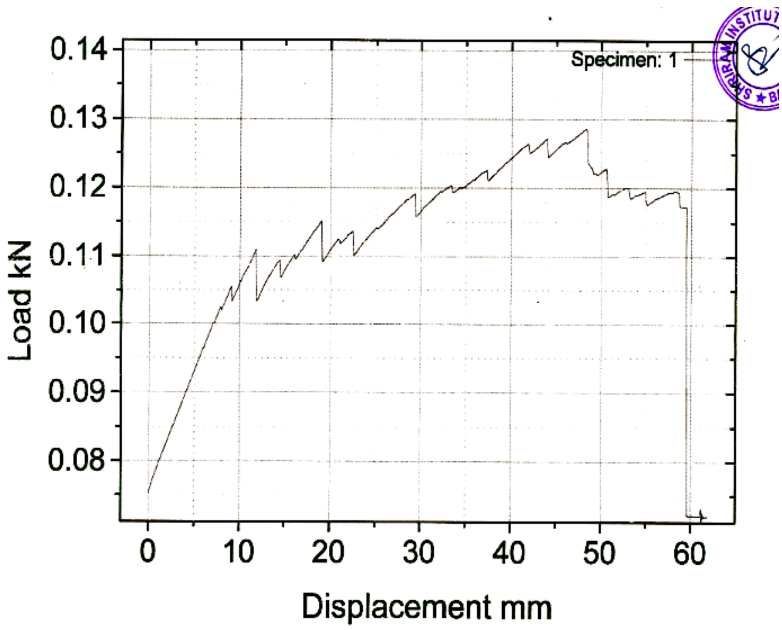

Fig 7. Nodal displacements v/s load

The maximum load obtained in the recorder is 0.086KN at the displacement of 48.01 mm.

$$G_I = \frac{nP\delta}{2ba}$$

$$G_{IC} = \frac{Pma^3}{E_{11}h^2b^2} \quad \text{----------} \quad (4)$$

Equations 4 shows the Energy release rate equation considering critical crack length for critical load. Using the above equation it was found that 54.62 J/m2 Energy Release Rate got released when the delamination occurred.

For 45% fiber volume fraction of the GFRP composite, Longitudinal young's modulus, E1=40.35GPa, from table 5.3.

The load against displacement curve recorded in the fracture toughness test is as shown in the figure 8.

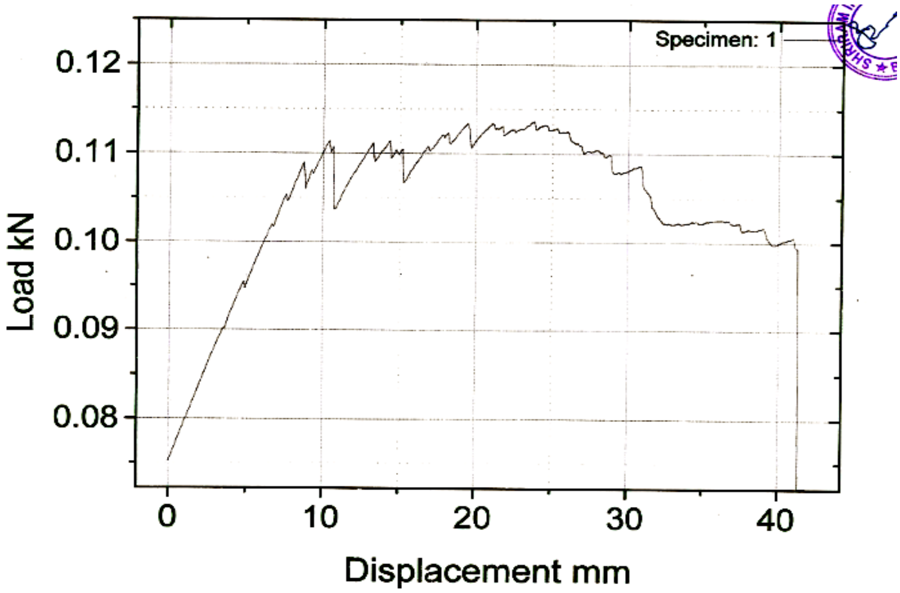

Fig 8. Nodal displacements v/s load

The maximum load obtained in the recorder is 0.102KN at the displacement of 23.833 mm. Using the equation it was found that 57.64 J/m2 Energy Release Rate got released when the delamination occurred.

For 50% fiber volume fraction of the GFRP composite, Longitudinal young's modulus, E1=44.5GPa, from table 5.3.

The load v displacement curve record in the fracture toughness test is as in the figure 9.

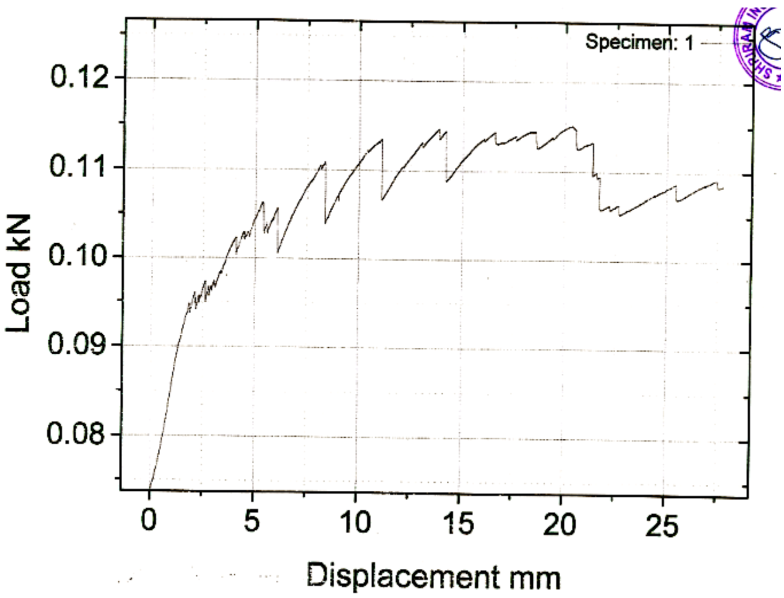

Fig 9. Nodal displacements v/s load

The maximum load obtained in the recorder is 0.096KN at the displacement of 20.339 mm. Using the equation it was found that 48.64 J/m2 Energy Release Rate got released when the delamination occurred. For 60% fiber volume fraction of the GFRP composite, Longitudinal young's modulus, E_1=44.5GPa, from table 5.3.

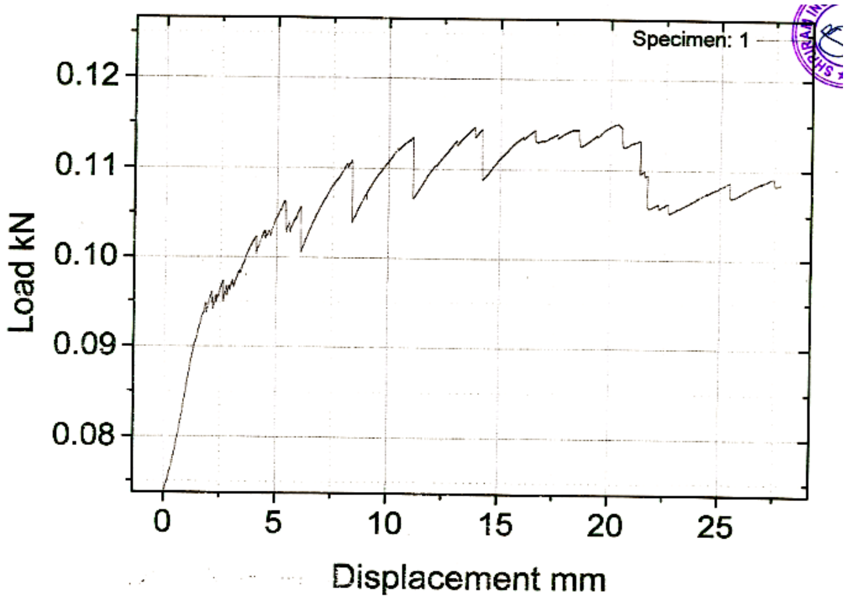

Fig 10. Nodal displacements v/s load

The load v/s displacement curve record in the fracture toughness test is as shown in the figure. The highest load obtained in the recorder is 0.080KN at the displacement of 9.167 mm. Using the equation it was found that 34.21 J/m2 Energy Release Rate got released when the delamination occurred.

B. *Numerical results in ANSYS software for different volume fraction of fiber*

Numerical method is carried out in ANSYS software using Virtual Crack Closure Technique (VCCT). In VCCT the strain energy release rate of each crack front node is can be obtained directly. From the literature survey it is found that the best numerical technique that can be used for fracture analysis is VCCT.

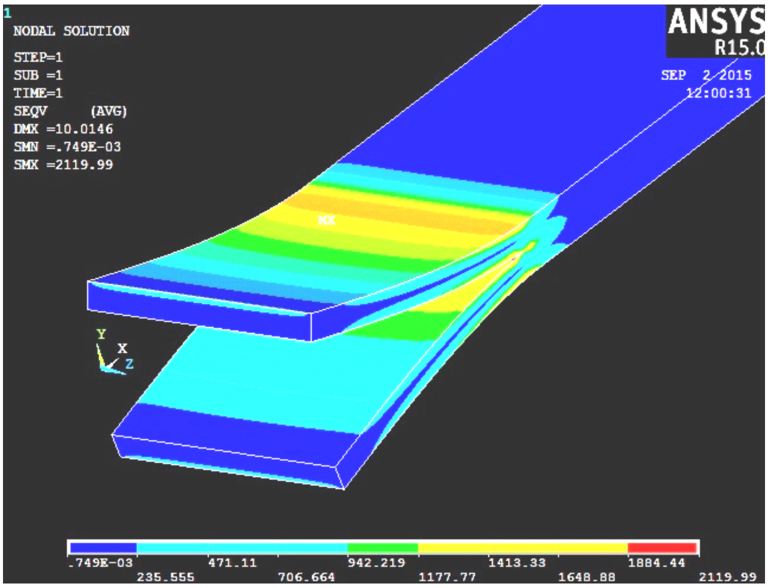

Fig 11. Stress at the crack tip for 0.5 fiber volume Fraction

Figure 4 shows the stress condition and plastic zone size at the crack tip. G evaluation for fiber volume fraction 0.4, 0.5 and 0.6 is considered for the study in variation of SERR of the composite de-lamination using Virtual Crack Closure Technique. Variation of SERR along the crack front has been observed for details on effective magnitude of SERR along the crack front.

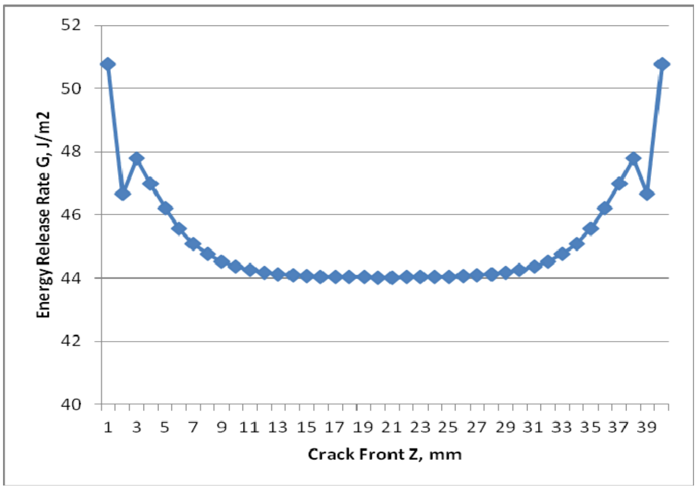

Fig 12. Variation of G along the crack front for Volume fraction 0.4

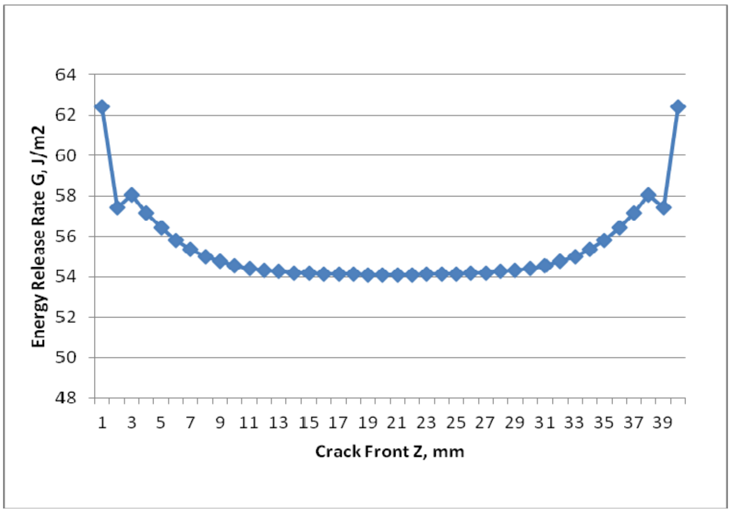

Fig 13. Variation of G along the crack front for Volume fraction 0.5

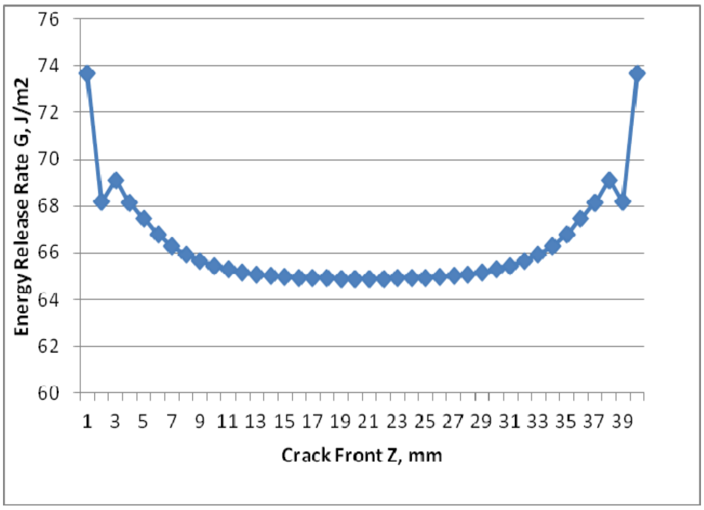

Fig 14. Variation of G along the crack front for Volume fraction 0.6

G_I was analyzed for different crack lengths by using equations for volume fraction 0.4, 0.5 and 0.6. Solutions obtained from VCCT as shown in figures 5, 6 and 7.

Around 51 J/m2 energy is dissipated at the free surface as the crack moves along the plane for the volume fraction 0.4 and 63 J/m2 energy is dissipated at the free surface as the crack moves along the plane for the given volume fraction 0.5.

Maximum of 74 J/m2 energy dissipation was observed for the volume fraction 0.6.

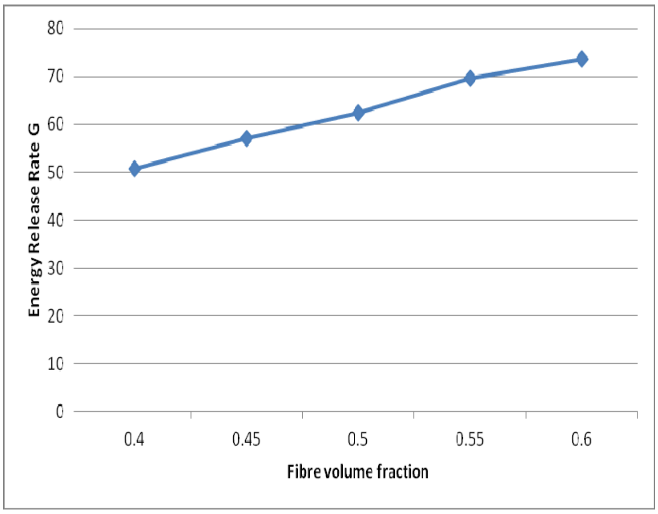

Fig 15. Variation of Energy Release Rate for different volume fractions

Figure 8 shows the variation of energy release rate for different volume fractions. As the fibre content increases the energy release rate is also increasing which clearly specifies that the as the brittleness of the glass epoxy composite increases the resistance to the crack propagation also decreases.

Hence it clearly indicates that fibre volume fraction 0.4 yields high resistance to crack propagation due to high ductility at the crack tip.

VI. Conclusions

An extensive analysis for Mode I has been performed in order to study the pattern of Energy Release Rate variation with respect to change in fiber volume through numerical methodology. The study was performed for 00 orientation of glass fiber having 9 elastic constants. It is observed that the strain energy released increases as the composition of the glass fiber increases and corresponding stress increases. Lower composition of glass fiber in the GFRP composite laminate is desirable for resistance of crack propagation.

The results obtained so far are quite satisfactory. VCCT gave more accurate results as a result mesh convergence.

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