Fracture Analysis of FRP Composites Subjected To Static and Dynamic Loading

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Abstract— **The objective of this paper is to investigate the Stress Intensity Factor (SIF) for benchmark problems for static and dynamic loading in composite plates having center, edge. Further the analysis is extended to CT specimen, plate with 3-point bend, v-notch. In the static analysis SIF's are found for an isotropic material using singular and j-integral approach and it is inferred that the deviation is minimal. For the orthotropic material SIF is found out for the above specimens with Carbon /Epoxy, R Glass /epoxy, S_2 glass fabric/epoxy material properties. The Transient Dynamic analysis on the above specimens is carried out. Full method is employed to perform loading and the J-integral approach is used to find the SIF's. The detail analysis using FEA is carried out for calculating SIF for the above specimens.**

***Keywords*— Crack tip, J-integral, Stress Intensity Factor (SIF), Singularity, longitudinal and transverse modulus**

I. INTRODUCTION

The fundamental goal in production and application of composite materials is to achieve performance from the composite that is not available from the separate constituents or from other materials. The need for high performance to weight ratio structure coming from the most advanced engineering fields is the main driver of the increasing usage of composite materials for crucial application. Recent developments in industries such as aerospace industry require lightweight and stiff materials fit the bill perfectly. The materials such as fibre-reinforced plastics are widely being used as a replacement for steel in many industries.

Unlike conventional isotropic materials of steel and concrete there are no readily available design charts and guidelines to help the structural engineer when it comes to working with composites. Analytical solutions for cracked plates are very limited.

Among the available methods for calculating fracture parameters, the interaction energy integral method has emerged as a useful technique for the extraction of mixed-mode stress intensity factors. The contour integrals where derived directly from the J-integral by considering an additive composition of the existing fields with a judicious choice of known auxiliary fields. For the purpose of post processing finite element solutions, the contour integrals were typically recast as equivalent domain integrals over a finite region surrounding the crack tip [1].

The work of B.K.Thakkar and P.C.Pandey [2] reviews the progressive failure analysis of fiber-reinforced polymer composites. According to the work, various modes of failure of FRP laminae are fiber micro cracking, fiber kinking, fiber matrix debonding and matrix cracking. Matrix cracking: if the state of stress results in a pre dominant tensile stress in the direction perpendicular to the fibers, the matrix may separate out from the surface of the fibers and create a void. These voids nucleate to create a crack running parallel to the fibers. Matrix cracking affects the transfer of loads between fiber and matrix. Delamination is a mode of structural failure, which can be said to be material failure at laminate level. Delamination initiates a separation of layers in a localized manner and further propagation to peeling off of one ply from another. A continuum damage model describes mathematically the nucleation and evolution of a localized material failure zone

The need for testing such specimens is often dictated by the characteristic dimensions of the end product. A new methodology which combines experimentally determined loads and fracture time, together with a numerical model of the specimen is presented in paper [3]. Calculations are kept to a minimum by virtue of the linearity of the problem. The evolution of the stress intensity factor (SIF) is obtained by convolving the applied load with the calculated specimen response to unit impulse force. The fracture toughness is defined as the value of the SIF at fracture time. The numerical model is first tested by comparing numerical and analytical solutions of the impact-loaded beam. One point impact experiments were carried out on of commercial tungsten base heavy alloy specimens.

Aim of this paper is to provide the structural engineer with data regarding SIF and variation of stress at the crack tip using Finite Element Analysis. FEA addressing plate problem fall under two categories-one involving singularity formulations and other involving paths independent integrals approach [4].

ANSYS allows us to model orthotropic materials with specialize elements called Layered Elements. After building a model with a layered element structural analysis can be carried out. Steel and glass polymer are taken as an orthotropic materials in our present study.

II. ELEMENT DESCRIPTION USED IN ANALYSIS

1. *PLANE82-2D, 8-node structural solid:* It provides more accurate results for mixed (quadrilateral-triangular) meshes and can tolerate irregular shapes without as much loss of accuracy. The 8-node elements id defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element may be used as a plane element or as an axisymmetry element. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

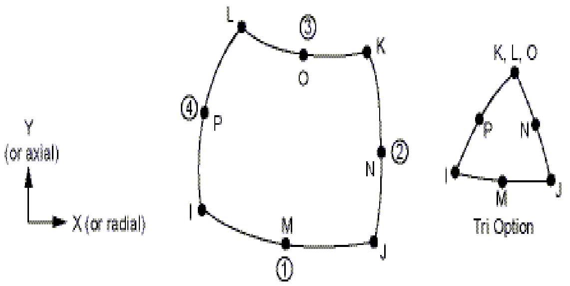

Figure 1: PLANE82 Geometry

2. *SHELL99-Linear layered structural shell:*

This is an 8-node, 3-D shell element can be used for layered applications of a structural shell model. It is designed to model thin to moderately thick plate and shell structures with aside-to-thickness ratio of roughly 10 or more . it allows up to 250 layers. The element has six degrees of freedom at each node; translations in the nodal x,y and z directions and rotations about the nodal x,y, and z-axes.

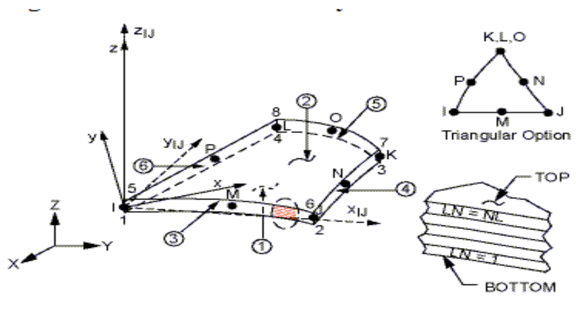

Figure 2: SHELL99 Geometry

LN= Layer number NL= Total number of layers

III. FRACTURE ANALYSIS OF CRACKS USING FEA

For case study-I, Plane 82 element is used for modelling of plate under plane stress conditions as per given dimensions. For case study –II, SHELL 99 element is used varying the number of layers. The element near crack tip were meshed with crack tip elements by shifting mid side node to 1/4th distance. The meshed models are solved by applying tensile load and symmetric boundary conditions. Then the J-integrals are completed.

Material properties

For isotropic plate E=48.3 GPa, υ=0.3.

For orthotropic plates:

Table 1: Orthotropic Plates

Properties	R-glass	S-glass	Carbon/epoxy
E_x	48GPa	22.925GPa	70 GPa
E_y	12.4 GPa	22.925GPa	25 GPa
E_z	12.4 GPa	12.4 GPa	25 GPa
Vxy	0.32	0.12	0.32
Vyz	0.28	0.2	0.25
Vzx	0.28	0.2	0.25
Gxy	6.6 GPa	4.7 GPa	15 GPa
Gyz	4.14 GPa	4.2 GPa	12 GPa
Gzx	4.14 GPa	4.2 GPa	15 GPa
Density	2 gm/cm^3	1.8gm/cm^3	2 gm/cm^3

IV. CALCULATION OF FRACTURE PARAMETERS

For finding SIF first define a crack tip and crack path around the tip. The first node on the path should be the crack-tip node. For a half-crack model, two additional nodes are required, both along the crack face. For a full-crack model, where both crack faces are included, four additional nodes are requires: two along one crack face and two along the other path along crack face.

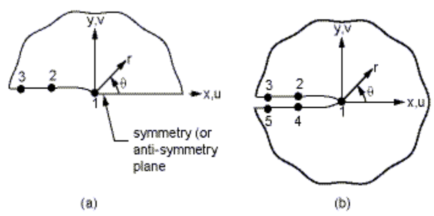

Figure 3: path along the crack face

J-Integral is one of the most widely accepted parameters for elastic-plastic fracture mechanics. The J-Integral is defined as follows:

Where W is the strain energy density, T is the kinematic energy density, σ represents the stresses, u is the displacement vector, and Γ is the contour over which the integration is carried out. For a crack in a linear elastic material, the J-Integral represents the energy-release rate

V. RESULTS & DISCUSSIONS

Case-1: Isotrophic Material

Static analysis:

Table 2: SIF's for isotropic plate under static loading

Approach	J –Integral	Singular
SIF	`26.29	37.528

Case-2 composite material:

Static analysis:

Layers / **a/b ratio**	**SIF, N-mm-3/2**			
	0.2	0.4	0.6	0.8
2	7.0892	12.8333	20.1301	30.8745
4	4.8577	9.6751	14.5123	22.2153
6	5.12	10.1272	15.4309	23.4259
8	4.8577	9.6751	14.5123	22.2153

Evaluation of stress intensity factor (SIF) in composite plate with centre line crack.

Table 3: SIF'S for different layers by varying a/b ratios of R-glass material

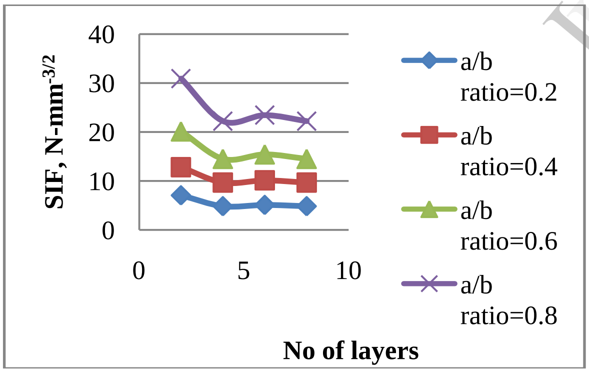

Figure 4: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table 3 it is observed that by increasing the (a/b) ratio, the SIF is increasing. This is due to the crack propagation; material separation and energy release rate is high as the crack grows. However the variation of SIF with respect to number of layers is not linear. It is observed that the SIF for the plate with 4 and 8 layers is same and for plate with 2 layers SIF is very high as compared to all other layers. Due to symmetry lay up and when the crack is parallel to fibre direction the SIF is more and when it is in transverse direction the SIF is less.

Table 4: SIF'S for different layers by varying a/b ratios of S-glass material

Layers / a/b ratio	SIF , N-mm-3/2			
	0.2	0.4	0.6	0.8
2	4.4728	9.0672	13.6758	22.1776
4	4.4728	9.0672	13.6758	22.1776
6	4.4730	9.0675	13.6764	22.1785
8	4.4728	9.0672	13.6758	22.1776

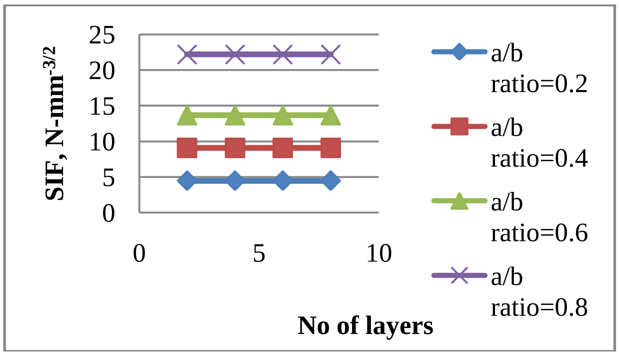

Figure 5: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table 4 it is observed that by increasing the (a/b) ratio, the SIF is increasing. This is due to the crack propagation, material separation and energy release is high as the crack grows. However the variation of SIF with respect to number of layers is almost constant because the transverse modulus effect is neglected.

Table 5: SIF'S for different layers by varying a/b ratios of carbon /epoxy material

Layers / a/b ratio	SIF , N-mm-3/2			
	0.2	0.4	0.6	0.8
2	6.6811	11.4237	17.5825	26.7372
4	5.38	9.4828	14.0852	22.1491
6	5.5616	9.8354	14.7751	23.016
8	5.38	9.4828	14.0852	22.1491

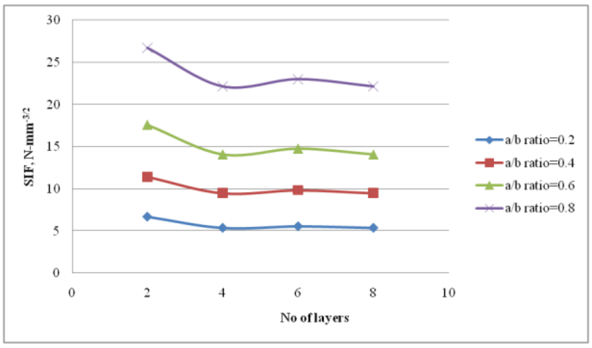

Figure 6: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table 5 It is observed that by increasing the a/b ratio, the SIF is increasing. This is due to the crack propagation; material separation and energy release rate is high as the crack grows. However the variation of SIF with respect to number of layers is not linear. It is observed that the SIF for the plate with 4 and 8 layers is same and for plate with 2 layers SIF is very high as compared to all other layers. Due to symmetry lay up and when the crack is parallel to fiber direction the SIF is more and when it is in transverse direction the SIF is less.

The SIF is high in R-glass as compared to S-glass and Carbon composite due to longitudinal and transverse modulus influence. In carbon composite, Ey=Ez , Hence its SIF is less than R-glass.

Evaluation of stress intensity factor (SIF) in composite plate with edge crack

Table 6: SIF'S for different layers by varying a/b ratios of R-glass material

Layers / a/b ratio	SIF , N-mm$^{-3/2}$			
	0.2	0.4	0.6	0.8
2	12.9616	27.7766	62.9939	206.5355
4	10.3766	22.7027	53.4329	176.0265
6	10.8965	24.4534	56.889	187.9538
8	10.3766	22.7027	53.4329	176.0265

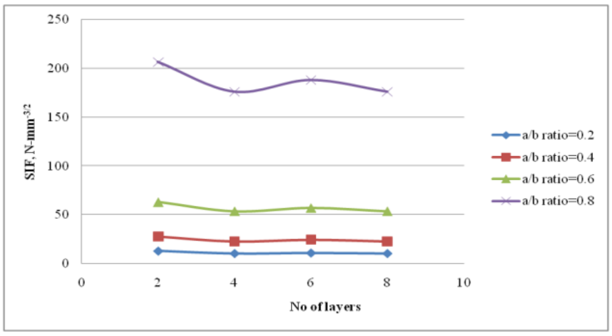

Figure 7: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table 6 It is observed that by increasing the (a/b) ratio, the SIF is increasing. This is due to the crack propagation, material separation and energy release rate is high as the crack grows. However the variation of SIF with respect to number of layers is not linear. It is observed that the SIF for the plate with 4 and 8 layers is same due to the symmetry lay up of even distribution. The SIF is higher at less number of layers and gradually decreases while increasing the number of layers symmetrically in odd numbers.

Table 7: SIF'S for different layers by varying a/b ratios of S-glass material

Layers / a/b ratio	SIF , N-mm$^{-3/2}$			
	0.2	0.4	0.6	0.8
2	9.7147	21.2567	50.6355	166.2591
4	9.7147	21.2567	50.6355	166.2591
6	9.7151	21.2576	50.6375	166.2658
8	9.7147	21.2567	50.6355	166.2591

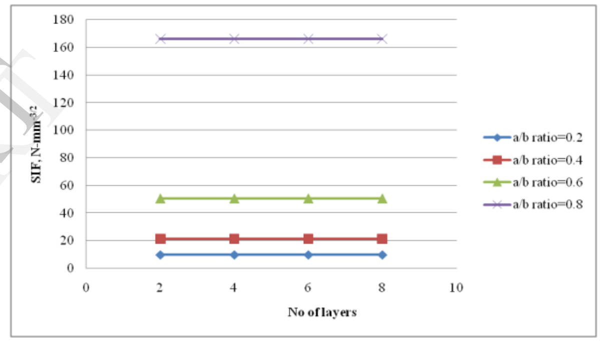

Figure 8: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table-7 It is observed that by increasing the a/b ratio, the SIF is increasing. This is due to the crack propagation, material separation and energy release rate is high as the crack grows. However the variation of SIF with respect to number of layers is almost constant because the transverse modulus effect is neglected.

Table 8: SIF'S for different layers by varying a/b ratios of carbon /epoxy material

Layers / a/b ratio	SIF , N-mm$^{-3/2}$			
	0.2	0.4	0.6	0.8
2	13.1761	30.6753	66.0074	219.79
4	10.8237	23.5611	52.7597	174.364
6	11.2033	24.895	55.3584	183.4079
8	10.8237	23.5611	52.7597	174.364

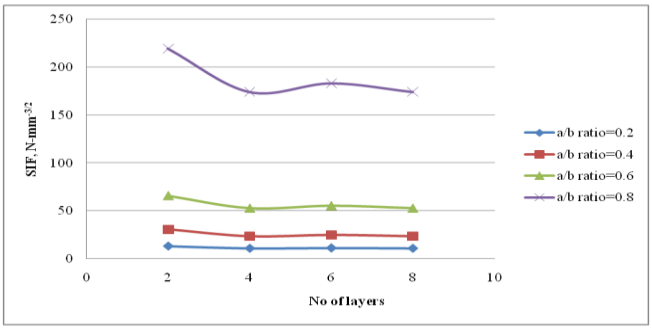

Figure 9: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table-8 It is observed that by increasing the a/b ratio, the SIF is increasing. This is due to the crack propagation, material separation and energy release rate is high as the crack grows. However the variation of SIF with respect to number of layers is not linear. It is observed that the SIF for the plate with 4 and 8 layers is same due to the symmetry lay up of even distribution. The SIF is higher at less number of layers and gradually decreases while increasing the number of layers symmetrically in odd numbers.

The SIF is high in R-glass as compared to S-glass and Carbon composite due to longitudinal and transverse modulus influence. In carbon composite, Ey=Ez, hence its SIF is less than R-glass.

Evaluation of stress intensity factor (SIF) in composite plate with 3-point bend.

Table 9: SIF for different layers and different materials

S.NO	SIF , N-mm-3/2			
	Layers	R-Glass	S-Glass	Carbon
1	2	196.7223	94.8953	153.4209
2	4	183.8553	94.8953	154.4226
3	6	170.1841	94.8983	143.1733
4	8	183.8553	94.8953	154.4226

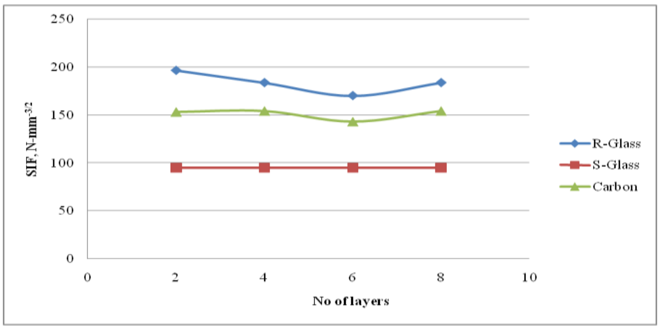

Figure 10: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table-9 it is observed that the variation of SIF with respect to number of layers is not linear for the plates with R-glass and Carbon /Epoxy materials. It is also observed that the SIF for these plates with 4 and 8 layers is same. The variation of SIF with respect to the number of layers for the S-Glass plate is almost minimal.

The SIF is high in R-glass as compared to S-glass and Carbon composite due to longitudinal and transverse modulus influence. In carbon composite, Ey=Ez ,hence its SIF is less than R-glass.

Evaluation of stress intensity factor (SIF) in CT specimen

Table 10: SIF for different layers and different materials

S.NO	SIF , N-mm-3/2			
	Layers	R-Glass	S-Glass	Carbon
1	2	14.3631	4.8929	12.6748
2	4	3.5936	4.8929	6.2458
3	6	5.8188	4.8893	7.663
4	8	3.5936	4.8929	6.2458

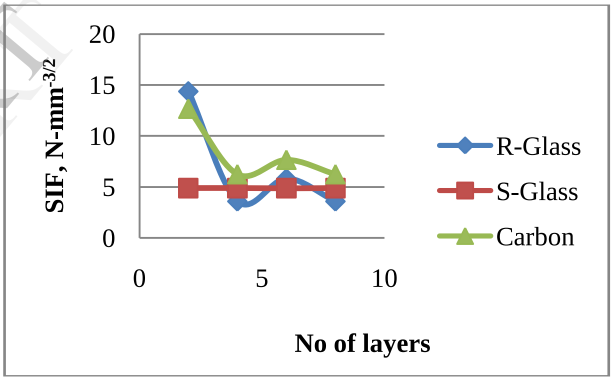

Figure 11: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table-10 it is observed that the variation of SIF with respect to number of layers is not linear for the plates with R-glass and Carbon /Epoxy materials. It is also observed that the SIF for these plates with 4 and 8 layers is same. The variation of SIF with respect to the number of layers for the S-Glass UD/Epoxy plate is almost minimal.
The SIF is high in R-glass as compared to S-glass and Carbon composite due to longitudinal and transverse modulus influence. In carbon composite, Ey=Ez ,hence its SIF is less than R-glass.

Evaluation of stress intensity factor (SIF) in composite plate with V-notch

Table 11: SIF for different layers and different materials

S.NO	SIF , N-mm$^{-3/2}$			
	Layers	R-Glass	S-Glass	Carbon
1	2	15.5864	8.7347	6.9341
2	4	16.5136	8.7347	4.8469
3	6	17.5849	8.7350	4.2871
4	8	16.5136	8.7347	4.8469

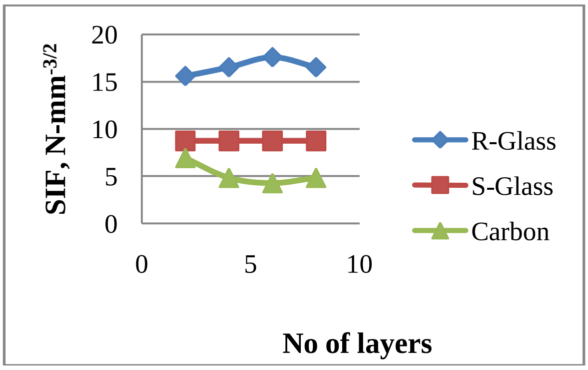

Figure 12: Variation of Stress Intensity Factor (SIF) with increasing number of layers

From table-11 It is observed that the variation of SIF with respect to number of layers is not linear for the plates with R-glass and Carbon /Epoxy materials. It is also observed that the SIF for these plates with 4 and 8 layers is same. The variation of SIF with respect to the number of layers for the S-Glass plate is almost minimal.

The SIF is high in R-glass as compared to S-glass and Carbon composite due to longitudinal and transverse modulus influence. In carbon composite, Ey=Ez ,hence its SIF is less than R-glass.

VI. CONCLUSIONS

Singular finite element approach is used for calculating SIF's for plate made up of isotropic material and J-Integral approach is used for calculating SIF for both the plates made up of isotropic and orthotropic materials. Stress induced in the composite material plates are found to be much lesser than isotropic material plates due to fibre reinforcements at different angles. Further the crack growth is obstructed by the fibre orientation. The SIF in R-glass plates is high as compared to S-glass fabric/epoxy and Carbon /epoxy is due to longitudinal and transverse modulus influence. The SIF in S-glass is almost constant because the transverse modulus effect is being neglected. The SIF for all specimens subjected to dynamic loading is found to be nearly double when compared to static loading.

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