Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **2(5),** 30-34, May **(2013)** *Res. J. Engineering Sci.*

Effect of Fiber Orientation on Mode I Crack Opening Stress Intensity of an Orthotropic Laminate

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Available online at: www.isca.in
Received 12th April 2013, revised 29th April 2013, accepted 13th May 2013

Abstract

In this paper, the influence of fiber angle on Mode I transverse crack opening stress intensity in case of (AS4/3501-6) carbon/Epoxy laminate is studied. Ten independent fiber orientations are considered and both analytical and finite element solutions are presented using macro mechanics approach of analysis of orthotropic lamina and by using ANSYS10 finite element package. It is observed that the stress intensity at the crack tip increased gradually from zero degrees to seventy degrees and showed a decline after 70 degrees. It is observed that the variations in the load carrying capacity of matrix phase around the discontinuous fibers at the crack tip for different fiber orientations influenced the stress intensity variations. The results obtained from analytical and finite element approaches showed good congruence.

Keywords: Fiber angle, stress intensity, transverse crack.

Introduction

Carbon/epoxy continuous fiber composite laminates are used as structural members due to their high strength and stiffness. Fracture of composite laminates is a serious phenomenon which needs meticulous attention. In Composite laminates, fracture crack propagation takes place through any of the three modes (Mode I, Mode II or Mode III) or through a combination of the three modes. Mode I represents the crack propagation under normal in plane loading where the crack is positioned perpendicular to the applied load. Mode II represents crack propagation due to shear type failure where the load applied is transverse to crack length. Mode III represents crack propagation due to tear type failure where the load applied is parallel to the crack length. Unlike metals, the laminate material properties in the loading direction depend on the fiber orientation and hence, the crack propagation is also influenced by fiber orientation. B.T. Astrom[1] presented various manufacturing methods like Resin transfer molding, Autoclave molding...etc in detail for polymer matrix composites. P.K.Mallick[2] gave a detailed and in depth information on materials, property characterization, testing and various methods of manufacture of fiber reinforced composites. Balaguru[3] et al, presented a new material approach for aircrafts incorporating stealth technology using coir fiber composites made out of hand layup process. Sankaran Apoorva[4] et al presented a very detailed and informative review on application of multi layered frp composites and their durability in construction and other civil applications. The semi empirical relation for transverse elastic modulus as a function of fiber volume fraction for unidirectional FRP composites was given by Halpin and Tsai[5]. Halpin[6] presented a semi empirical relation to determine the longitudinal elastic modulus of FRP composites as a function of fiber volume fraction, matrix modulus and fiber modulus. Z.Hashin[7] developed a semi empirical relation for transverse elastic modulus of FRP laminates as a function of bulk modulus and transverse shear modulus of laminate based on solid mechanics approach. O.Ishai [8] analyzed the transverse micro cracking of glass/epoxy laminate under unidirectional tensile loading. A theory based on stress tensors for predicting the failure behavior of composites under tension and compression was proposed by S.W.Tsai and E.M Wu[9]. C.T Sun[10] reviewed different failure theories and showed comparisons of theoretical predictions with experimental results for various composite material systems under different loading conditions. I.M.Daniel[11] et al analyzed the effect of material and layer stacking sequence on the stress distribution around the holes of boron/epoxy laminates. H.J.Konish and J.M.Whitney[12] presented an approximate relation for stress distribution along the in plane transverse axis of the circular hole of an orthotropic plate subjected to loading in longitudinal direction. R.J.Nuismer and J.M.Whitney[13] presented a relation to estimate the stress concentration factor for holed orthotropic plates subjected to uniaxial in plane loading based on laminate stffnesses. R.F.Karlak[14] analyzed the effect of hole size on the stress distributions in various symmetrically stacked laminates. I.M.Daniel[15] studied the failure of composite laminates due to stress concentration around the holes of various sizes and on through thickness cracks. J.Awerbuch and M.S.Madhukar[16] presented an elaborative review on various theoretical and experimental results on stress concentrations in notched composite laminates. M.Nikbakht and N.Choupani[17] investigated the crack initiation and propagation phenomenon in case of carbon/epoxy laminate using ARCAN test specimen and compared the results obtained using numerical analysis. A.B. de Moraisa[18] et al estimated the critical strain energy release rates of carbon/epoxy composites under Mode-I fracture using double cantilever beam test and incorporating modified beam theory. In the present work, the Mode I crack opening stress intensity for AS4/3501-6 carbon/epoxy laminate is studied. The laminate properties along and transverse to the loading direction for the 10 different fiber angles are found by using the transformation relations. The stress intensity around the crack tip for different fiber orientations is estimated using the R.J.Nuismer and H.J.Konish approximate relations. Using the layered shell 99 elements, the finite element analysis for the different fiber angles is carried out to determine the stress intensity around the crack tip and the results are compared with the theoretical results. A good congruence is found between the theoretical and finite element results.

Methodology

Theoretical Approach: The properties related to AS4/3501-6 carbon/epoxy laminate are as shown in table 1.

Table-1
Mechanical properties of Laminate

Elastic Modulus (E_1)	177.325 (Gpa)
Elastic Modulus (E_2)	10.413 (Gpa)
Shear Modulus (G_{12})	7.980 (Gpa)
Major Poisson's Ratio (Θ_{12})	0.2375
Minor Poisson's Ratio (Θ_{21})	0.01394

The properties of the composite lamina parallel and perpendicular to the loading direction (parallel and perpendicular to the plate geometrical axes) for different fiber orientations are obtained using the following transformation relations.

$$\frac{1}{E_x}=\frac{\cos^2\theta}{E_1}\left(\cos^2\theta-\sin^2\theta\upsilon_{12}\right)+\frac{\sin^2\theta}{E_2}\left(\sin^2\theta-\cos^2\theta\upsilon_{21}\right)+\frac{\cos^2\theta\sin^2\theta}{G_{12}} \quad (1)$$

$$\frac{1}{E_y}=\frac{\sin^2\theta}{E_1}\left(\sin^2\theta-\cos^2\theta\upsilon_{12}\right)+\frac{\cos^2\theta}{E_2}\left(\cos^2\theta-\sin^2\theta\upsilon_{21}\right)+\frac{\cos^2\theta\sin^2\theta}{G_{12}} \quad (2)$$

$$\frac{1}{G_{xy}}=\frac{4\cos^2\theta\sin^2\theta}{E_1}\left(1+\upsilon_{12}\right)+\frac{4\cos^2\theta\sin^2\theta}{E_2}\left(1+\upsilon_{21}\right)+\frac{\left(\cos^2\theta-\sin^2\theta\right)^2}{G_{12}} \quad (3)$$

$$\frac{\upsilon_{xy}}{E_x}=\frac{\upsilon_{yx}}{E_y}=\frac{\cos^2\theta}{E_1}\left(\cos^2\theta\upsilon_{12}-\sin^2\theta\right)+\frac{\sin^2\theta}{E_2}\left(\sin^2\theta\upsilon_{21}-\cos^2\theta\right)+\frac{\cos^2\theta\sin^2\theta}{G_{12}} \quad (4)$$

The stress concentration around the crack tip of the laminate due to the applied far field unidirectional uniform stress along the longitudinal axis of the plate geometry for different fiber orientations is estimated using the H.J.Konish relation and Whitney-Nuismer equation as given below.

$$\sigma_{\max}=\sigma\left(1+\frac{1}{2}\rho^{-2}+\frac{3}{2}\rho^{-4}-\left(\frac{k-3}{2}\right)\left(5\rho^{-6}-7\rho^{-8}\right)\right) \quad (5)$$

$\sigma_{\max}$ is the max stress intensity around the crack tip vicinity.

σ is the far field uniform stress applied along the geometric longitudinal axis of plate.

$\rho=\frac{y}{a}$ (Ratio of distance along the in plane transverse axis of crack tip to crack length)

Where k is the stress concentration factor given by Whitney-Nuismer equation as shown

$$k=1+\sqrt{\left(\frac{2}{A_{yy}}\left(\sqrt{A_{xx}A_{yy}}-A_{xy}+\left(\frac{A_{xx}A_{yy}-A_{xy}^2}{A_{ss}}\right)\right)\right)} \quad (6)$$

Where A_{xx}, A_{yy}, A_{xy} and A_{ss} are the in plane extension stiffness components and are expressed as:

$$A_{xx}=\sum_{k=1}^{n}\left(Q_{xx}\right)_k\left(Z_k-Z_{k-1}\right) \quad (7)$$

$$A_{yy}=\sum_{k=1}^{n}\left(Q_{yy}\right)_k\left(Z_k-Z_{k-1}\right) \quad (8)$$

$$A_{xy}=\sum_{k=1}^{n}\left(Q_{xy}\right)_k\left(Z_k-Z_{k-1}\right) \quad (9)$$

$$A_{ss}=\sum_{k=1}^{n}\left(Q_{ss}\right)_k\left(Z_k-Z_{k-1}\right) \quad (10)$$

Where Q_{xx}, Q_{yy}, Q_{xy} and Q_{ss} are the in plane stffnesses with reference to the geometrical axes of the lamina under consideration. k=1 to n denotes the number of layers and Z_k , Z_{k-1} are the layer thicknesses measured from the mid plane of the laminate. For the present problem, since there is only a single layer, $Z_{k-1}=0$, Z_k represents one half of the layer thickness and the number of layers n=1. The stffnesses along the plate geometrical axes are obtained by transforming the stffnesses along the material (fiber) directions using the following transformation equations.

$$Q_{xx}=Q_{11}\cos^4\theta+Q_{22}\sin^4\theta+2\left(Q_{12}+2Q_{66}\right)\sin^2\theta\cos^2\theta \quad (11)$$

$$Q_{yy}=Q_{11}\sin^4\theta+Q_{22}\cos^4\theta+2\left(Q_{12}+2Q_{66}\right)\sin^2\theta\cos^2\theta \quad (12)$$

$$Q_{xy}=\left(Q_{11}+Q_{22}-4Q_{66}\right)\sin^2\theta\cos^2\theta+Q_{12}\left(\cos^4\theta+\sin^4\theta\right) \quad (13)$$

$$Q_{ss}=\left(Q_{11}+Q_{22}-2Q_{12}-2Q_{66}\right)\sin^2\theta\cos^2\theta+Q_{66}\left(\cos^4\theta+\sin^4\theta\right) \quad (14)$$

The stffnesses along the material (fiber) direction are expressed in terms of lamina properties as shown:

$$Q_{11}=\frac{E_1}{1-\upsilon_{12}\upsilon_{21}} \quad (15)$$

$$Q_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}} \quad (16)$$

$$Q_{12} = \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}} \quad (17)$$

$$Q_{66} = G_{12} \quad (18)$$

The maximum stress intensity around the crack tip vicinity given by equation 5is estimated for different fiber orientations using equations 6 to 18.

Finite Element approach: The plate geometry considered has the dimensions (Length=200mm, Width=100mm and thickness=15mm). It is modeled as a three layered composite laminate having transversely placed crack (Perpendicular to plate length) with a crack length of 20 mm. The Shell99 layered element available in the ANSYS10 element library are used to model the plate as well as the crack vicinity. The shell99 element coordinate system is initially reoriented in such a way that the shell99 element normals are parallel to the Z-axis of the global Cartesian coordinate system. The plate is modeled in such a way that the length of the plate is parallel to the reference y-axis of ANSYS coordinate system. The plate is modeled with a global element size of 3.5 mm for all the sides of the plate and with densely concentrated elements having skewed midside nodes around the crack tip. The plate is loaded by arresting all the degrees of freedom along the bottom edge of the plate and by applying a uniform pressure intensity of 10Mpa on the top edge. Figure 1 shows the finite element model of the plate with densely populated skewed elements around the crack tip vicinity.

Results and Discussion

The maximum stress intensity around the crack tip for different fiber orientations obtained from theory and finite element analysis are tabulated in table 2.

The stress intensity distribution around the crack tip for zero degree fiber orientation is shown in figure 2 and variation of stress intensity around the crack vicinity with fiber angle is shown in figure 3.

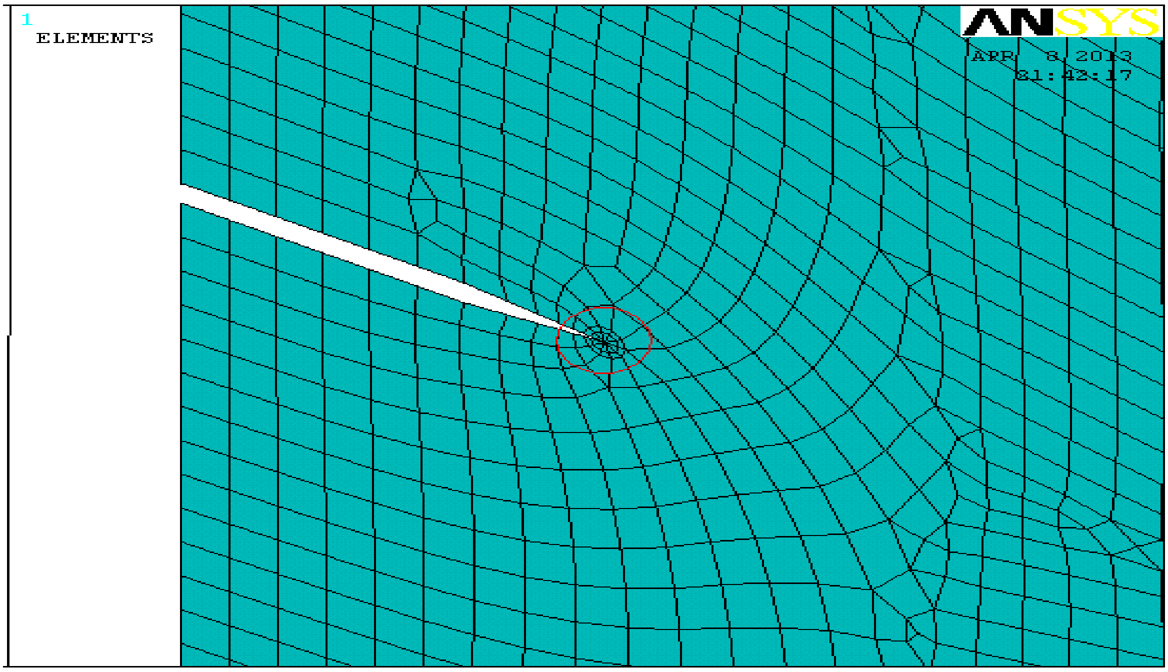

Figure-1
Meshed plate with dense skewed elements around the crack tip

Table-2
Max stress intensity around the crack tip for different fiber angles

Max Stress (Mpa)	**Angle in Degrees**									
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Theory	14.851	15.122	16.985	17.452	18.394	19.027	19.687	20.021	18.988	17.012
Ansys	13.042	13.355	14.257	15.551	16.771	17.22	17.29	17.372	16.55	15.694

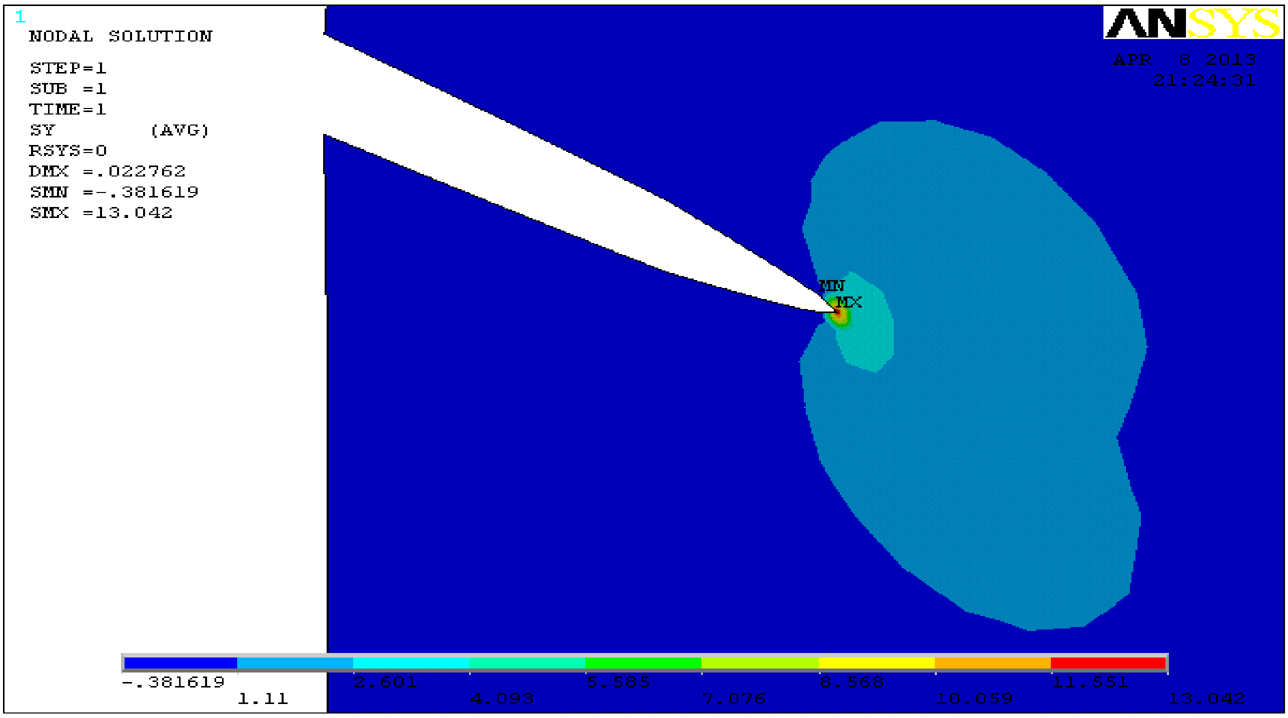

Figure-2
Stress intensity at the crack tip for zero degree fiber orientation

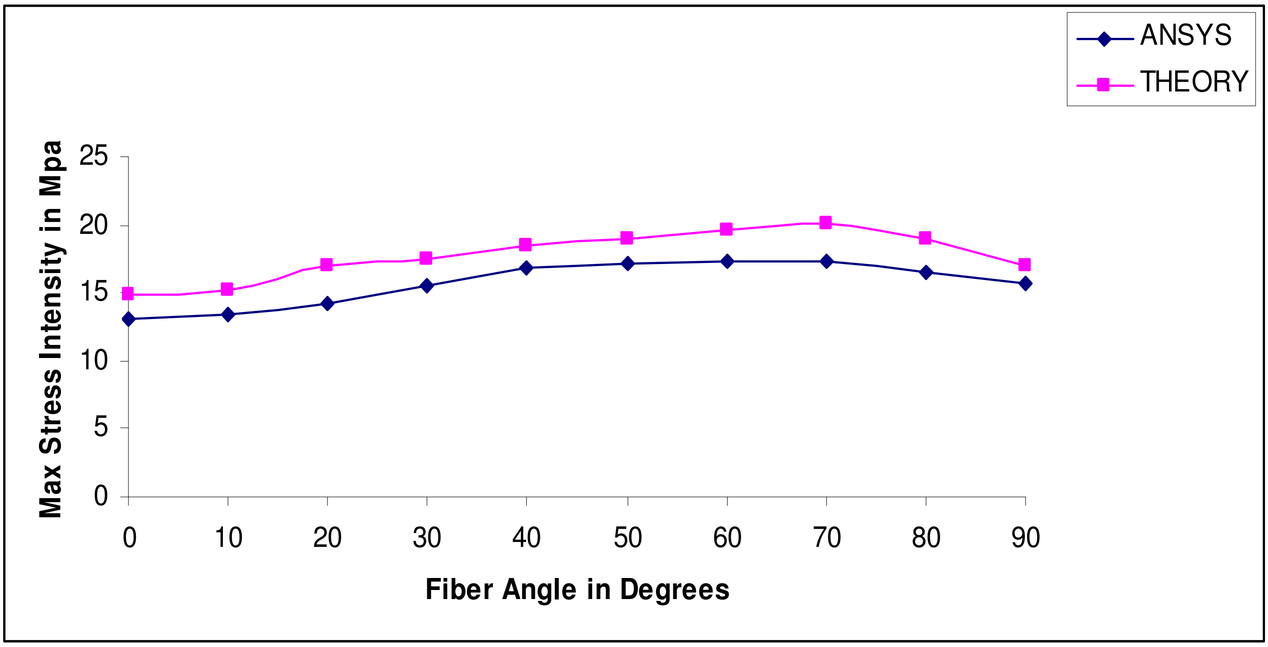

Figure-3
Stress intensity variation with fiber orientation.

Figure-3 shows the variation of stress intensity around the crack tip for different fiber orientations. It is observed that the stress intensity is maximum around 45 to 70 degrees and showed a decline later on. From zero degrees to 20degrees, the fibers are more or less approximately parallel to the crack front. The number of discontinuous fibers at the crack front are very less and the major portion of the load is taken up by the matrix phase. This results in low stress intensity distribution around the crack tip. From 40 to 70 degrees, there is high probability of slippage of fibers due to induced shear stresses apart from the normal tensile stresses at fiber matrix interface. This results in high stress intensity around the crack tip. From 70 degrees to 90 degrees, the number of continuous fibers sharing the far field uniformly applied pressure intensity also increases resulting in reduction of stress intensity around the crack tip.

Conclusion

In the present work, the influence of fiber angle, on the stress intensity concentration around the crack tip of carbon / epoxy orthotropic laminate is analyzed using theoretical and finite element approaches. The results obtained from both the approaches showed that the combined influence of shear stresses at fiber matrix interface and the fiber discontinuity around the crack tip influenced the Mode I crack propagation stress intensity for fiber orientations around 40 to 70 degrees.

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