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EFFECT OF STACKING SEQUENCE ON NOTCH STRENGTH IN LAMINATES

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ABSTRACT

In the present work data is presented for three different stacking sequences of a 10-ply and 16-ply laminates comprised of unidirectional and angled plies: [±θ/0], [0/±θ], and [+θ/0/-θ]. Notch geometry is limited to circular holes of which four different diameters were used. Specimens were tested monotonically to failure tension. Unnotched specimens of each laminates were also tested. The data shows that there is a distinct stacking sequence effect on notched fracture stress. Numerical results are compared with experimental results. The fracture stresses of the notched [+θ/0/-θ], laminates differ significantly from those of the [±θ/0], and [0/±θ].

Keywords: Composite laminates, Stacking sequence, Angled plies, Notch strength, Fracture criterion.

1.0 INTRODUCTION

The effect of laminate stacking sequence and lamination angle on the notched strength of Carbon/epoxy and plain woven Glass/epoxy composite laminates is investigated. The fracture stresses of the notched specimens are correlated using the method proposed by Mar and Lin and a modified version of the point stress criterion of Whitney and Nuismer.

The notch sensitivity of composite laminates in the presence of holes, as well as cracks, is well-documented phenomenon from early investigations[1,2] composite materials with holes are being used more frequently as primary load bearing structural composites. It is well known that holes introduce stress concentrations with significantly reduce the fracture the fracture strength of composites both in tension and compression. However the problems of the strength reduction and unstable fracture criterion are not completly understood. Several models have been developed to predict the effect of notches, either circurlar hole or slits, upon the tensile strength of composites. One model developed by Waddoups et al[3] employs the principle of Linear Elastic Fracture Mechanics (LEFM). The other modell for predicting the effect of notches upon the tensile strength of composites was developed by Whitney et al.[4,5] as an altenative to the LEFM model. In these models it is assumed that the charateristic dimension has the same values for all notch sizes. But, this assumption has been shown to be invalid[6,8], Pipes et.al[9,10] extended Whitney model and introduces a three parameter notch strength model. In this model, the charateristic length is assumed to be function of the hole size, reference radius and notch sensitivity factor. However no physical factors varies with the selection of the reference radius.
A number of different approaches have been developed an d proposed to correlate the fracture stresses of composites with notches [3,4]. A common shortcoming of these methods is their lack of consideration of out-of-plane effects,like interlaminar stresses and thus an inability to account for failure at holes due to delamination.The existance of interlaminar stresses at straight free edges was shown by Pipes et al[9,10].

2. EXPERIMENTAL RESULTS AND DISCUSSION

Plain Woven glass/epoxy is cosidered for investigation.

The geometry &the dimensions of the straight-sided tension specimen with a hole in the middle are shown in fig(1)

All the static tension tests are conducted on UTM. The specimens are loaded in tension to failure at room temperature.
Unnotched and notched failure stresses were calculated from the maximum applied load using the measured width and calculated nominal thickness.The notched fracture stresses are correlated using two methods.
The first is suggested by Mar and Lin[16,17] and the second correlation used is the point stress criterion proposed by Whitney and Nuismer[4,5]
Mar and Lin equation for the fracture stress of notched composites

$$\sigma_f = H_c (2r)^{-m} \tag{1}$$

Were σ_f=Fracture stress

2r=Notch length

m=0.35 for glass/epoxy

H_c=Composite fracture toughness parameter

By setting vaue of m to .35 to determine the value of H_c for each hole size from the experimental failure stress.
Whitney and Nuismer[4,5] used point stress criterion.They proposed that failure would occure when the stress at some characteristic distance,d_0,ahed of a notch reached the unnotched failure stress, σ_0.
The normal stress (σ_y) along the X-axis ahead of the hole can be expressed approximately by Reference[11].

$$\sigma_y(x,0) = \frac{\sigma^\infty}{2}\left[2 + \left(\frac{R}{x}\right)^2 + 3\left(\frac{R}{x}\right)^4 - \left(K_T^\infty - 3\right)\left\{5\left(\frac{R}{x}\right)^6 - 7\left(\frac{R}{x}\right)^8\right\}\right], x > R \tag{2}$$

where K_T^∞ is thestress cocentration factor for an infinite orthotropic plate [12]

σ^∞=Uniform stress applied parallel to the Y-axis for an orthotropic plate containing a circular hole of radius R.

$$K_T^\infty = 1 + \left\{\frac{2}{a_{22}}\left(\sqrt{a_{11}\, a_{22}} - a_{12} + \frac{a_{11}a_{22} - a_{12}^2}{2a_{66}}\right)\right\}^{\frac{1}{2}} \tag{3}$$

where a_{ij}=orthotropic in-plane stiffness of the laminate.

The PSC equation,

$$\frac{\sigma_N^\infty}{\sigma_o} = \frac{2}{2 + A_1^2 + 3A_1^4 - \left(K_T^\infty - 3\right)\left(5A_1^6 - 7A_1^\infty\right)} \quad (4)$$

$A_1 = R/(R+d_0)$

σ_0= Unnotched tensile strength of the laminate

σ_N^∞ = Notched strength of an infinite width plate.

The form of this equation suggests that the notched fractute of various stacking sequence,with the same value of $K\frac{\infty}{T}$,should be ranked accourding to their unnotched failure stress.The experimental data shows that this is not so,as out of plane effects are neglected.To generalize the Whitney-Nuismer correlation,rather than using the unnotched fracture stress,a notched fracture stress parameter ''$б_p$'' is proposed. $Б_p$ can be determined using d_0 and the experimental fracture stress.An average value $б_p$ are tabulated in table 2,3,4 for the [±θ/0], [0/±θ], and [+θ/0/-θ] laminates.

2.1 Effect of stacking sequence

The experimental results clearly indicates that there is an important stacking sequence effect on the strength of notched composites. The dependence is not the same as the dependence of the unnotched tensile strength on the stacking sequence.For the cases of θ equal to 30^θ ,the [+θ/0/-θ], laminate has the highest notched fracture stresses. But not possessing the highest unnotched fracture strength. This trend is reversed for lamination angles of 60^θ, and 90^θ. For θ equal to 45^0, the three stacking sequences do not have significant differences in notched or unnotched tensile strength.

2.2**.**The correlation of the Notched strength and the Characteristic length **:**

It is observed that the notched strength is increased due to damage at the notch tip as a result of stress relaxation.The damage zone at the notch tip is observed directly.It is observed that the crack appeared at the edge of a circular hole under an applied load of 90% of failure load.As the load is increased,the damage is grown rapidly,which causes the unstable fracture. Fig(3)indicates the relationship between the notched strength and characteristic length in plain woven glass/epoxy composites.

2.3.The corrélation of the unstable Fracture criterion and the Notched strength

The unstable fracture criterion has been investigated by the critical stress intensity factor(K_C) or the critical energy release rate(G_C).

$$K_C = \sigma_N \sqrt{\pi a_C}\, F\left(\frac{a_C}{R}\right) \quad (5)$$

Where a_C is the equivalent critical crack length emanating from either side of the hole. The relationship of K_C and G_C for an orthotropic plate is given by[15]

$$G_c=\left[\left(\frac{a_{22}}{a_{11}}\right)^{\frac{1}{2}}+\frac{2a_{12}+a_{44}}{2a_{11}}\right]^{\frac{1}{2}}\cdot\left[\frac{a_{11}a_{22}}{2}\right]^{\frac{1}{2}}K_C^2 \tag{6}$$

a_{ij} can be expressed with effective elastic constants.

Fig(4) shows the relationship between d_o and a_C for each specimen.The study shows that a_C is approximately twice the characteristic length(d_o)

$A_C \cong 2d_0$

3.0 CONCLUSIONS

The effect of the hole size and the specimen width on the fracture behavior of the plain-woven glass/epoxy reinforced composites was investigated experimentally. On the basis of the results of this study, the following conclusion is made.

- The characteristic length(d_o) decreases with an increase in $(\sigma_N/\sigma_O)_{EXP}$.
- Critical crack length (a_c) is approximately twice the characteristic length(d_o).
- There is a definite staking sequence dependence on the notched strength of laminates with holes.Dependence can be explained by delamination caused by interlaminar stresses.

REFERENCES

1.Vnderveldt.H.and Liebowitz.H,1968,Journal of composite materials,Vol.2, pp 254-260.

2. Wu.E.M. 1968, Composites Materials Work shop, Technomic publications, Lancaster, PA, pp 20-43

3. Waddoups, M.E., J.R.Eisenman and B.e.Kaminski.1971.”Macroscopic Fracture Mechanics of Advanced Composite Materials”, Journal of Composite Materials, Vol. 5, pp.446-454.

4. Whitney, J.M. and R.J. Nuismer.1974. “Stress Fracture Criteria for Laminates containing Stress Concentrations,” Journal of Composite Materials, Vol.8, pp.253-265.

5. Nuismer, R.J and J.M.Whitney.1975.”Uniaxial Failure of Composite Laminates Containing Stress Concentrations,”ASTM STP 593. Pp.117-142.

6. Agarwal, D.C., B.D. Agarwal and K. Banerji.1985.”Fracture Behaviour of Glass-cloth-Reinforced Composites,” Polymer Composites Vol.6.pp.29-33.

7. Lagace, P.A.1986.”Notch Sensitivity of Graphite/Epoxy Fabric Laminates, “Composites Science and Technology, Vol.26.pp.95-117.

8. Ghasemi Nejhad, M.N.and T.W.Chou.1990.”A Model for the Prediction of Compressive Strength Reduction of Composite Laminates with Molded-In Holes,” Journal of Composite Materials, Vol.24.pp.236-235.

9. Pipes, R.B., J.W.Gillespie, Jr.and R.C. Wetherhold.1979.”Superposition of the Notched Strength of Composite Laminates.” Polymer Engineering and Science, Vol.19.pp.1151-1155.

10. Pipes, R.B., R.C.Wetherhold and J.W.Gillespie, Jr.1980.Macroscopic Fracture of Fibrous Composites,” Material Science and Engineering, Vol.45.pp.247-253.

11.Konish,H.J.andJ.M.Whitney.1975. Approximate Stresses in an Orthotropic Plate Containing a Circular Hole, Journal of Composite Materials,Vol.9pp.157-166.

12.Lekhnitskii,S.G.1968.Anisotropic Plates.Translated from the Second Russian Edition,byS.W.Tsai andT.Cheron,New York :Golden and Breach, Science Publishers.

13.Jung-Kyu Kim and DO-Sik Kim,1995,’’Notched Strength and Fracture Criterion in Fabric Composite Plates Containing a Circular Hole’’Journal of Composite Materials,Vol.29,pp.992998.

14.Tan,S.C.1988.’’Finite-Width Correction Factor for Anisotropic Plates Containing a Central Opening,’’ Journal of Composite Materials,Vol.22,pp.1080-1097.

15. Paris, P.C. and G.C.Sih.1964,”Stress Analysis of Cracks”, ASTM STP 381, pp.30-81.

16. Mar, J.W. and Lin, K.Y., Journal of composite Materials, Vol.11.1977, pp. 405-421.
17. Mar, J.W. and Lin, K.Y., Journal of Aircraft, Vol.14.1977.pp.703-704.

TABLES

Table 1.Elasic Properties

V_f %	E_{xx} Gpa	E_{yy} Gpa	G_{xy} Gpa	γ_{xy}	t mm
60	22.7	22.7	3.9	0.16	2.0

E_{xx}=Longitudinal youngs modulus
E_{yy}=Transverse youngs modulus
V_f=Fiber volume fraction
γ_{xy}=Poissons ratio
t=laminate thickness

Table 2 : Unnotched fracture stress and notched fracture Parameter for [$\pm\theta$/0] laminates.

θ	Б$_0$ (Mpa)	Б$_p$ (Mpa)
30^0	455	417
45^0	338	270
60^0	290	428
90^0	275	506

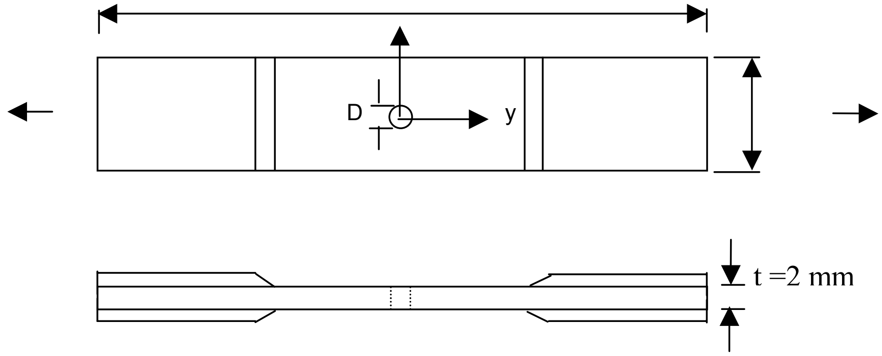
Table 3 : : Unnotched fracture stress and notched fracture Parameter for [0/$\pm\theta$] laminates.

θ	Б$_0$ (Mpa)	Б$_p$ (Mpa)
30^0	503	329
45^0	387	240
60^0	414	356
90^0	372	564

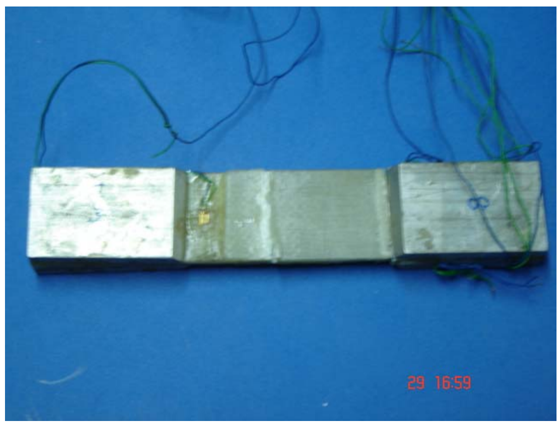
Table 4 :Unnotched fracture stress and notched fracture Parameter for [+θ/0/-θ] laminates

θ	$Б_0$ (Mpa)	$Б_p$ (Mpa)
30^0	518	548
45^0	336	273
60^0	232	241
90^0	261	205

FIGURES



Fig(1) :Configuration of the test specimens.



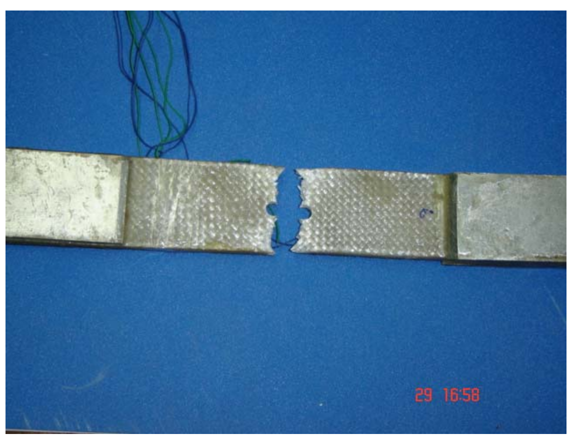


Fig 2: Tested specimens.

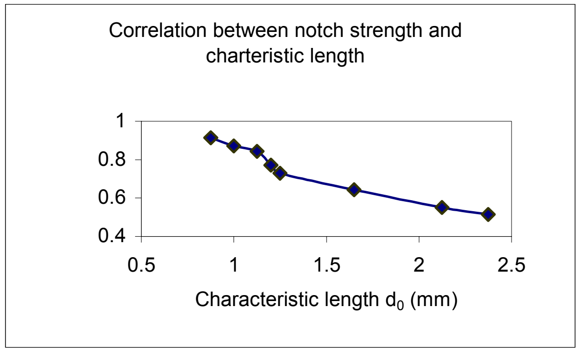


Fig 3.Relationship between notch strength and Characteristic length.

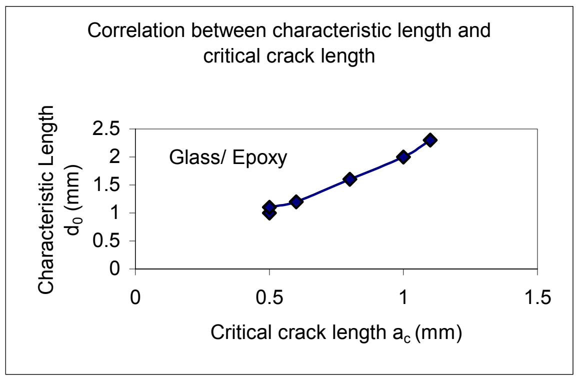


Fig 4. Relationship between Characteristic Length and critical crack length

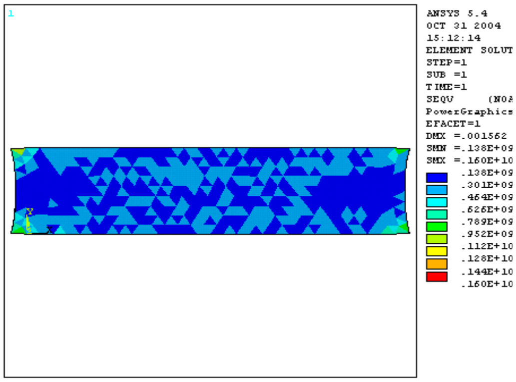


Fig. A: 30/-30/0 UNNOTCED

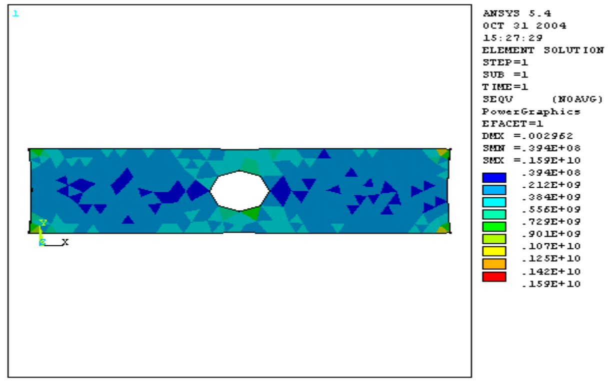


Fig.B: 30/-30/0 NOTCHED

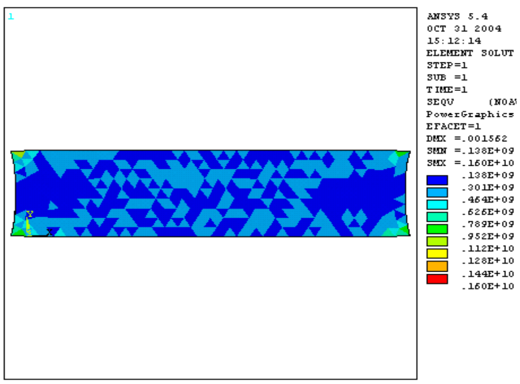


Fig.C:30/0/-30 UNNOTCHED

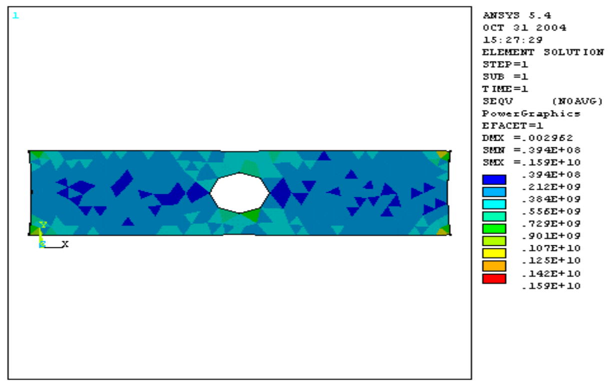


Fig.D:30/0/-30 NOTCHED

Fig 5 : FEA Analysis(Fig.A,B,C,D)