A Study on Stress Concentration Factor in Woven E-Glass/Epoxy Composite having an Elliptical Cut Out

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Abstract- *Composites materials are formed by the combination of two different materials in order to obtain desired material properties. Polymer matrix composites (PMCs) is a type of composite material in which polymers are used as matrix and fibers are used as reinforcing material. These PMCs is widely used in structural applications e.g. aerospace and automobile structures because of their excellent directional properties and high stiffness to weight ratio. In a structure there will be many discontinuities created for assembly purpose and for many designing purposes, so when this structure is subjected to load, then its failure occurs at these discontinuities because of stress concentration. In the present study initially,effect of fibre orientation on stress concentration in a woven E-Glass/Epoxy lamina having two different elliptical cut out at the center is investigated using theoretical and finite element results. Based on the results of the laminas a suitable laminate sequence is selected and fabricated to analyze its strength.From the results it was found that lamina havingfibre orientation **45°** exhibits least stress concentration factor for both **elliptical cut outs. Hence incorporating a number of 45°** layers in a laminate sequence reduces the stress concentration at the elliptical cut outs, but cannot be used more in number because it reduces the load carrying capacity of the laminate.*

Key Words:Fibre Orientation, Woven E-Glass/Epoxy, Stress concentration, Polymer Matrix Composite (PMC)

1. INTRODUCTION

Composite material can also be named as tailored material because it is manufactured by combining two different materials in order to obtain desirable properties for different purposes.One of the materials in composite act as reinforcement and the other act as the matrix material.

There are many kinds of composite material introduced;in that Polymer MatrixComposite (PMCs)/Fibre Reinforced Plastics (FRPs) is one among them. In PMCs/FRPs fibre acts as a reinforcing material and polymers act as a matrix material. These PMCs are widely used in structural applications because of their directional properties and high strength to weight ratio[1-10].

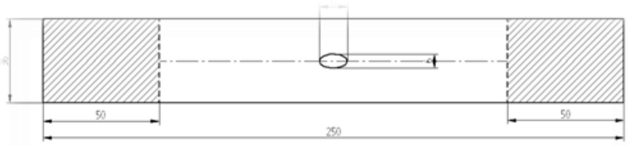
In structures, many discontinuities will be created for the purpose of assembly and for many other design aspects. These discontinuities will be one of the main spots for the failure to initiate, because of the concentrated stress at the discontinuities [1-5, 11]. Hence the stress concentration at the discontinuities has to be minimized. It has been found in the literature that stress concentration at the discontinuities depends on fibre orientation in laminate stacking sequence of a FRP [1-3].

In this study, initially, effect of fibre orientation from 0° to 45° on stress concentration factor for an elliptical cut out lamina made of woven E-glass/epoxy composite is analyzed by theoretical analysis and Finite Element Analysis (FEA). Based on this result a suitable stacking sequence is selected, fabricated and analyzed for its strength.

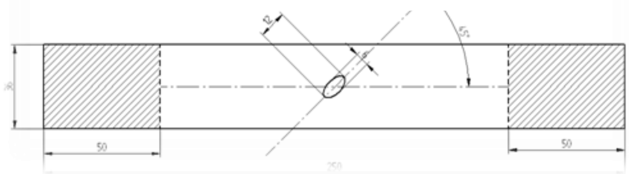
2. THEORETICAL AND FINITE ELEMENT ANALYSIS OF LAMINA

Elliptical cut out of two types are chosen as mentioned below.

a) Having its major axis along the loading direction shown in figure2.1(a)
b) Having its major axis tilted at an angle of 45° with respect to the loading direction as shown in fig 2.1(b).



(a) Straight hole



(b) Inclined hole

Fig-2.1 Elliptical cut out configuration

The theoritical analysis is carried out only for the straight hole laminas because the theoritical analysis of inclined hole laminas is under research.Therefore based on the comparision between theoritical and FEA results of staright hole , for inclined hole ,directly the FEA results will be considered.

2.1 Theoretical Analysis

The stress concentration factor at the edge of the hole of an infinite plate is given by[11],

$$K_T^{\infty} = 1 + \frac{1}{\lambda}\sqrt{\frac{2}{A_{22}}\left[\sqrt{A_{11}A_{22}} - A_{12} + \frac{A_{11}A_{22} - A_{12}^2}{2A_{66}}\right]}$$

Where λ=ratio of half of major axis by half of minor axis; λdenotes the stress concentration factor at the edge of the hole;A_{ij}, i.j=1, 2, 6, are the components of the in-plane stiffness matrix with 1 and 2 parallel and transverse to the loading direction, respectively.

Approximate orthotropic finite width correction factor for circular hole is given by [11],

$$\frac{K_T^{\infty}}{K_T} = \frac{\lambda^2}{(1-\lambda)^2} + \frac{(1-2\lambda)}{(1-\lambda)^2}\sqrt{1+(\lambda^2-1)\left(\frac{2a}{W}M\right)^2} - \frac{\lambda^2}{(1-\lambda)}\frac{\left(\frac{2a}{W}M\right)^2}{\sqrt{1+(\lambda^2-1)\left(\frac{2a}{W}M\right)^2}} + \frac{\lambda^7}{2}\left(\frac{2a}{W}M\right)^6\left(K_T^{\infty} - 1 - \frac{2}{\lambda}\right)\left\{\left[1+(\lambda^2-1)\left(\frac{2a}{W}M\right)^2\right]^{-5/2} - \left(\frac{2a}{W}M\right)^2\left[1 + (\lambda^2-1)\left(\frac{2a}{W}M\right)^2\right]^{-7/2}\right\}$$

Where,

K_T = stress concentration at the hole in finite plate.

a = radius of the hole.

W = width of the finite plate.

M = magnification factor, it is given by

$$M^2 = \frac{\sqrt{1 - 8\left[\frac{3\left(1-\frac{2a}{W}\right)}{2+\left(1-\frac{2a}{W}\right)^3} - 1\right]} - 1}{2\left(\frac{2a}{W}\right)^2}$$

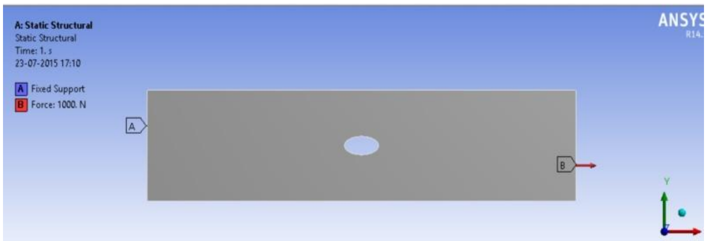
The calculated resultsof straight hole is tabulated in table2.1

TABLE-2.1 Theoretical results of straight holes

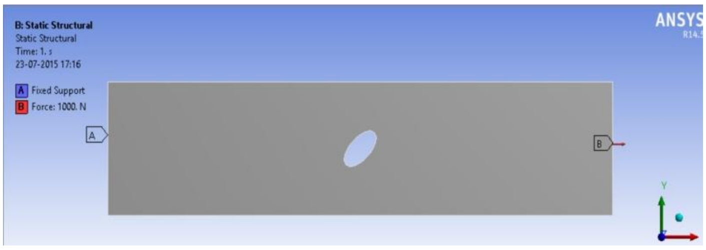
Sl No	Fibre orientation	Stress concentration factor(SCF)
1	0˚	2.538
2	15˚	2.255
3	30˚	1.953
4	45˚	1.894

2.2. Finite Element Results

Finite element analysis was carried out using ansys 14.5 workbench application. Tetrahedral element was chosen for discritisation of the model. At the longitudinal ends of the plate, one of the ends were completely fixed and the other end was applied a tensile load of 1000N as shown in figure 2.2.



a. Straight hole

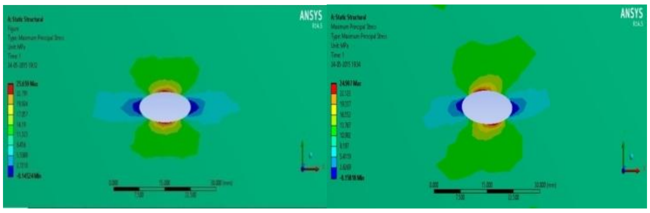


b. Inclined hole

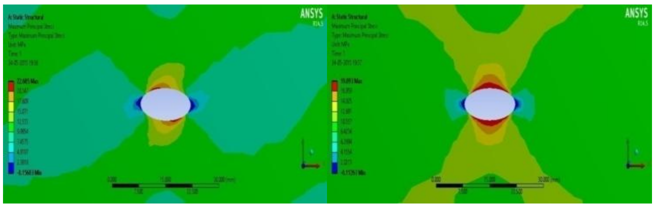
Fig -2.2 Boundary conditions

2.2.1 Results of straight hole

The figure below shows the stress contours of lamina having fiber orientation0˚, 15˚, 30˚and 45˚.



0˚ply 15˚ply



30˚ply 45˚ply

Fig-2.3. Stress contours of straight elliptical hole lamina

It is observed that, the stress concentration region at the hole periphery shifts with fibre angle orientation, i.e approximately perpendicular to the specified fibre angle with respect to the loading direction. But for the 45˚ ply the stress concentration region is found perpendicular to the loading direction at the hole periphery, this is because the length of both the bidirectional fibers in woven fabric are equal in length.

The stress concentration factor for ansys result is found using the formulae given below

$$StressConcentartionFactor(SCF) = \frac{maximummagnitudeofstressaroundholeperiph}{appliedin-planenominalstress}$$

The comparison of stress concentration factors from theoretical calculations and ansys analysis is given in table 2.2

TABLE-2.2 Results Comparison

Sl No	Fibre orientation	Stress concentration factor(SCF)		
		Theoretical results	Ansys results	%error
1	0°	2.538	2.560	0.866
2	15°	2.255	2.295	1.774
3	30°	1.953	2.087	6.861
4	45°	1.894	1.910	0.845

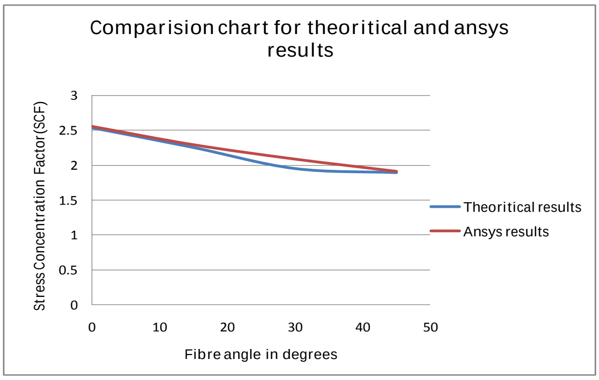
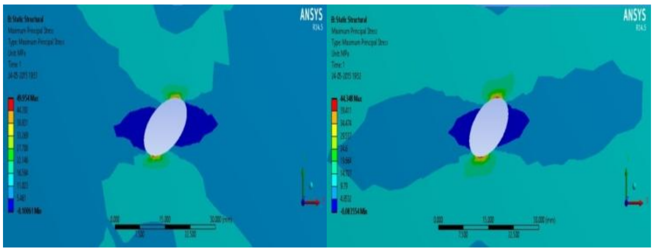


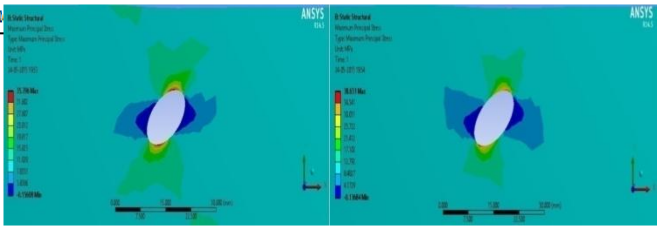
Fig-2.4. Comparison chart for straight elliptical cut outs

2.2.2 Results of inclined hole

Mathematical modeling of inclined elliptical hole is under research. In theprevious section, it was found that the percentage error between theoretical and ansys results was less than 7% forstraight elliptical hole laminas, therefore only ansys results are considered for inclined elliptical hole behavior in laminas having different fibre angles.



0°ply 15°ply



30°ply 45°ply

Fig-2.5. Stress contours of straight elliptical hole laminas

From the stress contours it can be found that the stress concentration region doesn't shift for different fibreorientation, but the fibre orientation will have an effect on stress distribution at the hole periphery. Table 2.3 gives the stress concentration factor for 0°, 15°, 30°and 45° lamina. Table 2.4 is the comparison table for stress concentration factor for straight elliptical cut out and inclined elliptical cut out laminas

TABLE-2.3 Ansys results of inclined holes

Sl No	Fibre orientation	Stress concentration factor(SCF)
1	0°	4.99
2	15°	4.43
3	30°	3.58
4	45°	3.55

TABLE-2.4 Comparison table

Sl No	Fibre orientation	Stress concentration factor(SCF)	
		Inclined hole	Straight hole
1	0°	4.99	2.560
2	15°	4.43	2.295
3	30°	3.58	2.087
4	45°	3.55	1.910

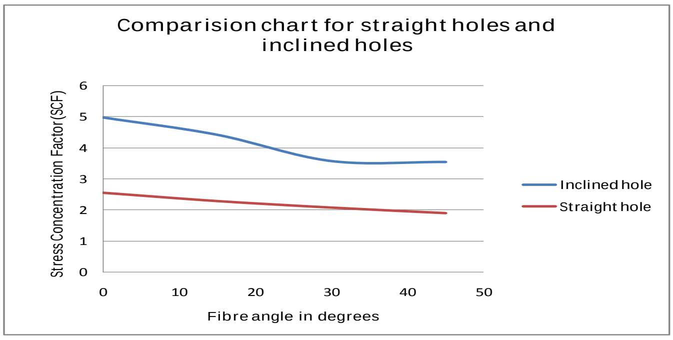


Fig.2.5. Comparison chart for straight holes and inclined holes lamina

3. ANALYSIS OF THE LAMINATE

From the results of laminas from previous section, it was found that the 45° lamina exhibited least stress concentration factor as well as load carrying capacity. Hence, based on this result a laminate sequence is selected and analyzed. The laminate sequence is $[(0/90)/(+45/-45)/(0/90)]_s$.

For the laminate sequence, specimens with straight and inclined elliptical cutouts were prepared as per ASTM standards which are shown in figure-2.1.

The required volume fraction for the laminate is 60:40.The woven E-Glass fabrics are available in the standard form of 10mil (or 0.2mm) thickness. This woven cloth was cut to the required size and shape. The matrix was prepared by mixing the epoxy resin LY 556 and hardener HY 951 in a volume ratio 10:1.Once the matrix is prepared it is applied on the fabric thoroughly, then another layer of fabric is placed on it. This process was carried out for total 6 layers in order to achieve the 2mm thickness of the laminate. Then the laminate was left to cure at room temperature for 24 hours. After this process, post curing was carried out at 100ºC for 2 hours. The completely cured laminate plate is cut to the required standards, and then end tabs were attached to it using glue (AW106 and HY913).The final specimens is shown in figure 3.1

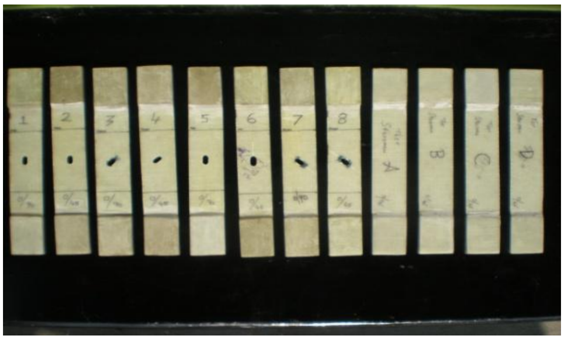


Fig-3.1 Prepared specimens

These specimens were subjected to tensile load in order to find out the ultimate tensile strength(UTS). The tensile test was conducted using computerized universal testing machine (UTM) shown in figure 3.2

Fig-3.2 Computerized UTM

3.1 Straight Elliptical Hole Results

Theoretical results were calculated using the same set of formulas used in section 2.1. Ansys results were obtained by ansys composite prepost14.5. Experimentally stress concentration factor of these laminates was found out by the ratio of UTS of the specimen without elliptical hole to UTS of specimens with elliptical hole.

Table 3.1 is the comparison table of theoretical, ansys and experimental results

TABLE-3.1 Result comparison table

Sl No	Fibre orientation	Stress concentration factor(SCF)		
		Theoretical results	Ansys results	Experi mental result
1	$[(0/90)/(+45/45)/(0/90)]_s$	2.28	2.39	2.498

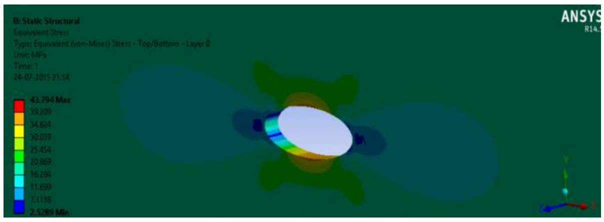


Fig-3.3 Stress contour of $[(0/90)/(+45/-45)/(0/90)]_s$.

Fig-3.4 $[(0/90)/(+45/-45)/(0/90)]_s$ laminate before and after loading

3.2 Inclined Elliptical Hole Results

Ansys results were obtained by ansys composite prepost 14.5. Experimentally stress concentration factor of these laminates was found out by the ratio of UTS of the specimen without elliptical hole to UTS of specimens with elliptical hole.

TABLE-3.2 Result comparison table

Sl No	Fibre orientation	Stress concentration factor(SCF)	
		Ansys results	Experimental result
1	$[(0/90)/(+45/45)/(0/90)]_s$	4.84	4.98

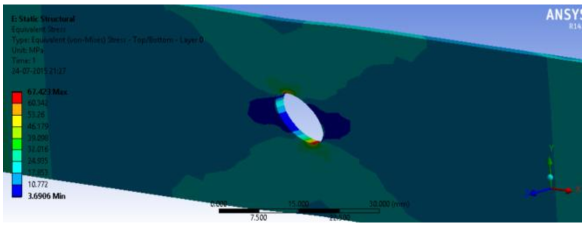


Fig-3.5 Stress contour of $[(0/90)/(+45/-45)/(0/90)]_s$.

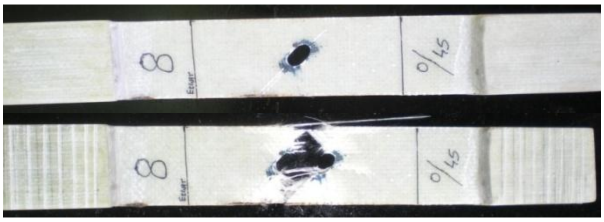


Fig-3.6 $[(0/90)/(+45/-45)/(0/90)]_s$ laminate before and after loading

3.3Discussion of Results

From the results of section 3.1 and 3.2, it is observed that incorporating a 45° layer in the laminate reduces the stress concentration at the elliptical hole periphery, but it cannot be used in excess because it reduces the load carrying capacity of the laminate. In the futher study various combination of laminate stacking sequence using 45° layer can be experimented.

4. CONCLUSION

This study was conducted to investigate the effect of fibre orientation on the stress concentration factor of the composite lamina with elliptical hole with major axis along loading direction and major axis tilted to 45°with respect to loading direction. Theoretical calculations were compared with finite element results. From the results we can conclude that,

1. For all lamina with an elliptical hole the maximum stress region is found at the periphery of the hole.

2. A 45° lamina will have the least stress concentration factor.

3. It is observed that, as the fibre angle increases from 0° to 45° the stress concentration region at the hole periphery will be approximately perpendicular to the fibre angle specified with respect to the loading direction for straight elliptical hole whereas in inclined elliptical cut out the stress concentration region doesn't shift.

4. Stacking sequence has considerable effect in reducing stress concentration for elliptical cutout specimen.

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