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An Investigation on Strength of Composite Laminates with Cutouts Under Tensile Loads

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***Abstract*—**Holes/cutouts helps in lightening composite laminates used as aerospace structures. However, they create stress concentration in the vicinity of the discontinuities resulting in low strength of the structure. Unlike isotropic materials, composite materials experience change in stress values due to different parameters such as geometric, material and loading parameters. The present study is devoted to primarily determine whether geometric or material parameters have dominant influence on strength of composite laminates under tensile loads. Geometric parameters such as cutout shape, size, orientation, proximity (in case of multiple holes) as well as edge interaction are taken into consideration. Among material parameters, fiber material, fiber orientation and stacking sequence are varied. Numerical study using ABAQUS CAE software is employed for the analyses. The numerical model is validated against experimental results of Open Hole Tension specimen from literature. Results reveal that geometric parameters have much significant influence on stress concentration factor and thereby the strength of composite laminates, when compared to material parameters. Among the geometric parameters, edge interaction is the most critical factor affecting the stress concentration. An elliptical cutout is seen to have comparatively more adverse effect on strength of laminate, when compared with other cutout shapes.

***Keywords*—** *Stress Concentration Factor, Composite Laminate, Edge Interaction, Open Hole Tension*

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I. INTRODUCTION

Though composites have many advantages over conventional metallic materials, they often exhibit notch sensitivity. In the presence of a hole, crack, or other discontinuity, the strength reduction of a composite from its unnotched strength, can be very severe. The reduction of strength due to a hole/cutout is often the critical design driver and therefore failure prediction is of significant practical importance. Holes/cutouts in composites will create stress concentrations and hence will reduce the mechanical properties. The proximity of multiple holes with respect to each other can affect the stress distribution and strength of the structure. A “hole interaction effect” occurs when the stress field from one hole interacts with the stress field from an adjacent hole.

Different sized and shaped holes/cutouts are used in composites structural members, which may serve for different purposes, such as material removal for lightening, hole for rivets, bolts, or pins, and man hole used for inspection and repair purpose. These cutouts, in turn, introduce stress concentration near the cutout in such members leading to weakening of the structure. The stresses developed near the cutout itself depends on many factors such as shape of the cutout, size of the cutout, proximity of another hole, edge interaction etc. For fiber composites, the stress concentration effect also depends on other factors like fiber orientation, fiber material, matrix material etc. In short, the strength of composite with hole mainly depends on three major parameters – geometrical, material and loading.

Research in this area has been carried out by many researchers to study behavior of composite plates with holes and cutouts. Effect of geometric parameters was first hinted by Okutan[1]. The stress concentration due to multiple notches was studied by many researchers [2-5]. Material parameter study was also attempted by some authors [7,9].Influence of cutout orientation was also studied by Mohan Kumar et. Al. [13].Higgins et.al.[19] carried out experimental study to determine the open hole tension (OHT) characteristics of carbon fiber-reinforced plastic (CFRP) and glass fiber reinforced plastic (GFRP). Experimental and theoretical investigation of the effect of cutouts on the stress of composite laminate plates subjected to tensile loads for different shapes of cutouts by Riyadh and Ahmed [18]. Guo [3] conducted numerical and experimental studies on composite plates with four shapes of cutouts under in-plane shear. Extensive studies by many scientists like Wu and Mu [5] have been conducted on composites with circular holes. However, studies on composites with cutoutswhich comprehensively investigate the influence of all parameters – geometric, material and loading are rarely available in literature.

The aim of this paper is to primarily investigate whether geometric or material parameters have a leading influence on the stress concentration around holes in composite laminates under tensile loading. Among geometric parameters, study is conducted based on varying hole shapes, hole size,hole to hole distance as well as edge interaction. Whereas, among material parameters, the study reveals the effect of matrix material, ply direction as well as stacking order on stress concentration.

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II. OPEN HOLE TEST FOR COMPOSITE LAMINATES

Open Hole Tensile (OHT) ASTM D5766 [19] measures the force required to break a polymer composite laminate specimen with a hole. The hole allows for stress concentration and reduced net section while the test method calculates ultimate strength based on gross cross-sectional area, disregarding the hole.This test is commonly used in the aerospace industry as a practice to develop notched design allowable strengths. It is used to generate data where the final application of the product may require fastener holes or to simulate a flaw in a material component. The test is used for composite material forms (including tape or fabric) and limited to continuous fiber or discontinuous fiber reinforced composites with balances and symmetrical test direction. Since the physical properties of many materials can vary depending on ambient temperature, it is sometimes appropriate to test materials at temperatures that simulate the intended end use environment.

Test specimens are placed in the grips of a universal tester at a specified grip separation and pulled until failure as per protocol of ASTM D3039. A typical test speed for standard test specimens is 2mm/min. Failure must occur at the hole to be an acceptable failure. The test setup and the OHT specimen (dimensions in mm) are shown in Fig.1 and Fig.2 from ref. [19].

Fig. 1 OHT testing

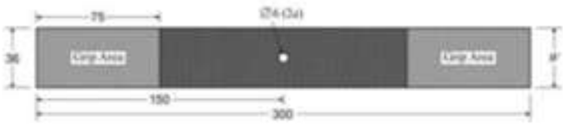

Fig.2 OHT specimen

III. NUMERICAL MODEL

Finite element methods were employed for studying multiple hole scenario in composites previously itself. In this work, the finite element simulations are performed in the commercial finite element code ABAQUS. A schematic diagram of the OHT specimen for preparing the finite element model is shown in Fig. 3

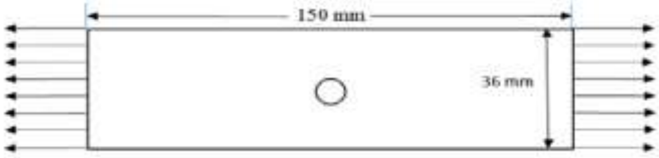

Fig. 3 Schematic of OHT specimen

Three dimensional modeling of the OHT specimen is done for conducting FE analysis by varying geometric and material parameters. The Material used for this study is Fibre reinforced plastic (FRP), in this fibre glass acts as fibre and matrix material used is Polyester Resin GP 002. Fiberglass is a lightweight, extremely strong, and robust material. Its bulk strength and weight properties are also very favourable when compared to metals. Properties of Fibre glass epoxy considering 30% fibre volume fraction (E-Glass) with polyester resin is used in this study. The properties were obtained from literature [11].

Table 1. Properties of Glass-Epoxy

Density	1.8×10^{-6} kg/mm^3
E_{11} (along longitudinal direction)	39000 N/mm^2
E_{22} (Along lateral direction)	4800 N/mm^2
Poisson's ratio (ν_{12})	0.3
Shear modulus (G_{12})	4800 N/mm^2

<u>Mesh Specification:</u>
Element size: 4
Element shape: Hex

<u>Load applied:</u>
Direction: Along x- direction

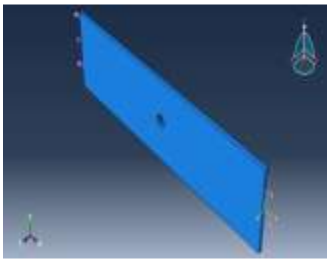

Fig.4 Numerical model of OHT specimen

ASTM D5766 (Open hole tension) specimen with gauge dimension 150mm x 36mm x 2mm is considered for the analysis as shown in Fig. 4. Tensile load of 50 N/mm^2 is applied as pressure load at the side edges of the plate such that maximum stress occurred at the periphery of the hole. The numerical model was validated with the experimental value available in the literature [12]. The numerical model is extended for further studies involving variations in geometric and material parameters. Different numerical models thus formed are illustrated in the following figures.

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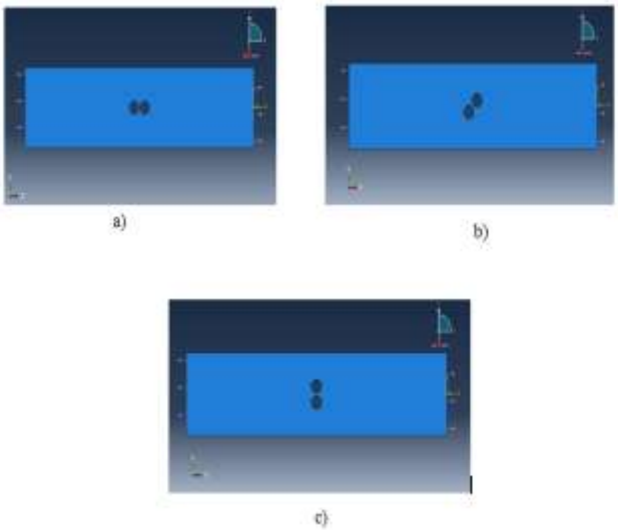

Fig. 4. Numerical model with various hole orientation with respect to loading direction a) 0 degrees b) 45 degrees c) 90 degrees

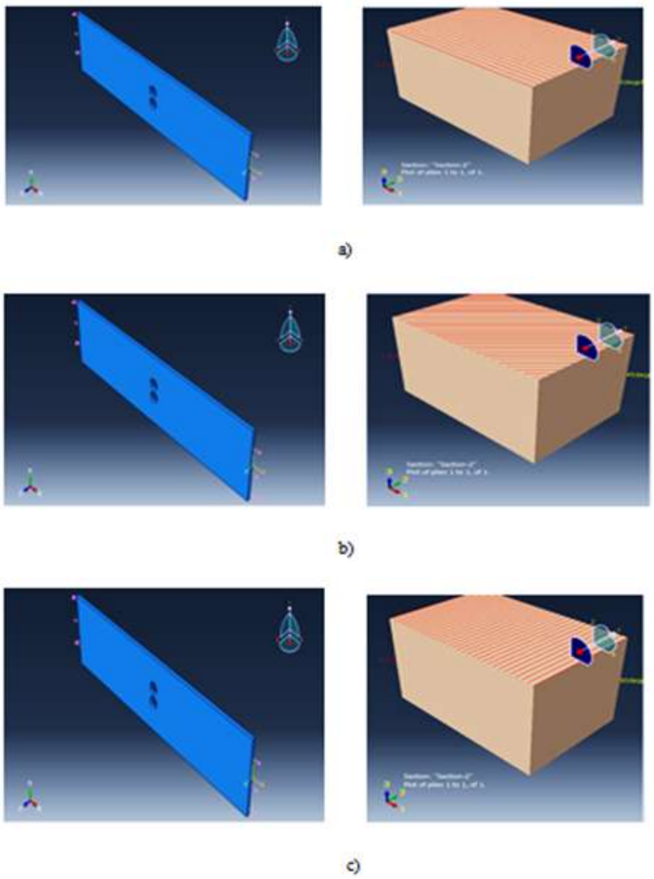

Fig. 5. Numerical model with various fibreorientation with respect to loading direction a) 0 degrees b) 45 degrees c) 90 degrees

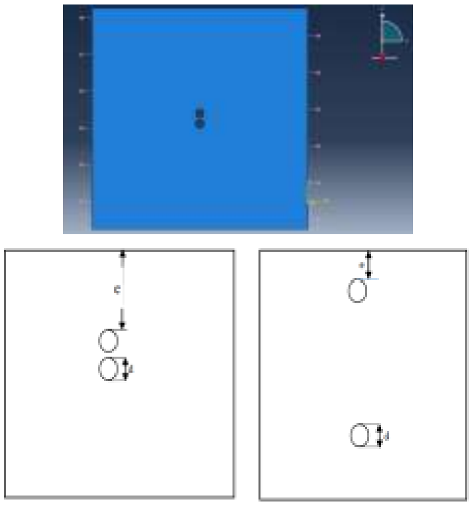

Fig. 6. Numerical model of square plate with two holes to study edge interaction

In addition to the above, different shapes of cutouts – ellipse, square and triangle, were also modeled in OHT specimens. The size of the cutouts was also varied.

Along with the geometric parameters, numerical models with different material parameters are created. Glass-epoxy and carbon-epoxy composite models are used for comparison study. Further, models are created to study whether stacking order has a significant influence on stress concentration. The stacking orders under consideration are 0/90, 0/90/90/0 and 90/0/0/90.

Table 2. Properties of Carbon-Epoxy

Density	1.99×10^{-6} kg/mm^3
E_{11} (along longitudinal direction)	127500 N/mm^2
E_{22} (Along lateral direction)	9000 N/mm^2
Poisson's ratio (ν_{12})	0.25
Shear modulus (G_{12})	5700 N/mm^2

IV. RESULTS & DISCUSSIONS

A. *Effect of geometric parameters*

For glass-epoxy plate with single hole, the maximum value of stress occurs near the discontinuity; in this case discontinuity is the presence of hole. The stress plot is shown in Fig. 7 below. Stress concentration factor defined as maximum stress near the hole edges to the nominal stress. The value of maximum stress at the periphery of the hole is 71.76 N/mm^2 with the applied pressure force of 50 N/mm^2. The value of stress concentration obtained numerically for plate with single hole was 1.435. The value obtained is comparable with that of experimental value of 1.46 as obtained from the literature [12].

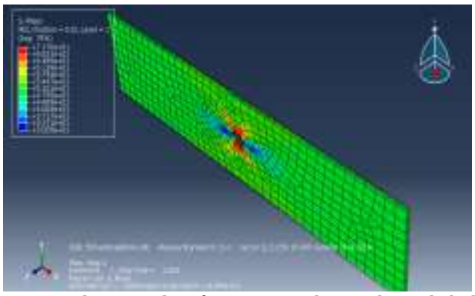

Fig. 7. Analysis results of composite plate with single hole

Stress concentration variation is analysed for composite plate with 2 holes having varied hole-hole orientation with different hole-hole distances. Numerical results for hole orientation of 0 degree, 45 degree and 90 degree with hole-hole distance of 7mm (1mm gap between the holes) with load of 50 N/mm^{2}applied along x direction. A typical stress plot of a composite panel with 45 degree hole orientation is shown in Fig.8 below.

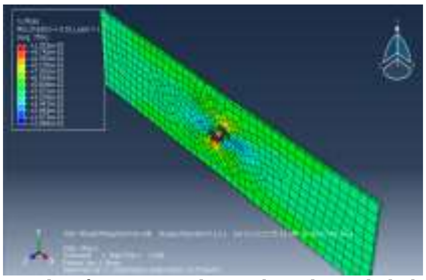

Fig.8 Analysis results of composite plate with 45 degree hole-hole orientation

Variation of stress concentration factor for various hole-hole orientation with different hole-hole distances is shown in the following Table 3.

Table 3. Stress concentration variation for different hole-hole orientation

Hole-hole distance (mm)	Gap between holes (mm)	0° holes	30° holes	45° holes	60° holes	90° holes
6.1	0.1	1.61	1.81	2.61	2.74	4.66
7	1	1.64	1.73	2.11	1.95	2.95
8	2	1.53	1.71	1.88	1.92	2.38
9	3	1.65	1.68	1.83	1.8	2.06
10	4	1.56	1.64	1.77	1.79	1.85
11	5	1.57	1.64	1.75	1.78	1.82
12	6	1.55	1.61	1.72	1.68	1.77
13	7	1.42	1.60	1.71	1.62	1.7

It is inferred from the table that stress concentration factor values shows increasing trends with increase in the hole orientation. Such that stress concentration values shows less influence when holes are arranged along the loading direction The maximum stress concentration is found for composite plate in which the holes are aligned perpendicular to the loading direction (at 90 degree to the loading). The variation of stress concentration v/s hole to hole distance with respect to varying hole orientation is clearly seen in the Fig.9 below.

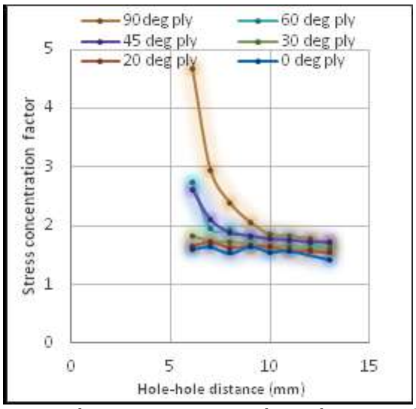

Fig. 9 Variation of stress concentration factor for various hole-hole orientation with varying hole-hole distances

Table 4 below shows the variation of stress concentration with varied edge distance for a square shaped composite plate under uniaxial tension. It is inferred from the table that stress concentration factor values decreases till a particular distance after that stress concentration factor value increases this is due to edge effect phenomenon.

Table4 Stress concentration factor variation at various edge distances

Edge distance, e (mm)	Stress Concentration
68.95	8.668
68	2.024
67	1.852
57	1.54
22	1.5
12	1.49
7	1.568
6	1.624
5	1.62
4	1.6
3	1.82
2	2.646

The diameter of hole circle for standard OHT specimen is 6mm. To study the effect of varying diameter, the analysis is conducted for different diameters from 4 mm to 24 mm, i.e., radius from 2 mm to 12 mm. The stress concentration values (K) obtained are shown in Table 5 below. The variation of K with hole radius is shown in Fig. 10.

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Table 5. Effect of diameter on Stress Concentration Factor

Radius (mm)	Diameter to width d/w	Stress Concentration factor K
2	0.11	1.72
3	0.166	1.88
4	0.222	2.18
6	0.333	2.72
8	0.44	3.59
10	0.55	4.29
12	0.66	5.55

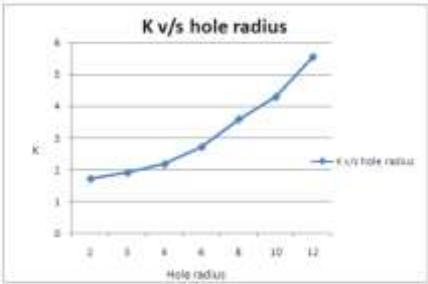

Fig.10 Variation of stress concentration factor w.r.t hole diameter

Analyses are done on FE models of OHT specimen with square cutouts with different dimensions. The stress plot for a glass-epoxy plate with different sizes of square cutout is given in Fig. 11. The variation of stress concentration of various sized cutouts are illustrated in Table 6 in terms of ratio of distance of edge from hole 'e' to the side of hole 'a', as well as distance from cutout to edge 'e'.

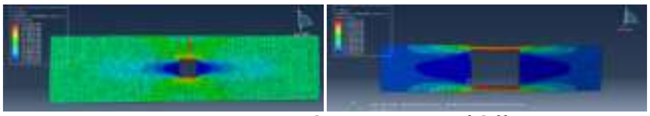

Fig. 11 Stress pattern around square cutouts of different sizes

Table 6. Stress concentration vs cutout size

Edge to cutout distance (e) mm	K
3	7.037
8	3.755
13	2.618

Elliptical cutouts are also analysed in similar fashion, whose results are given below in Fig. 12 and Table 7.

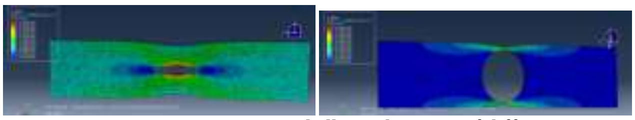

Fig. 12 Stress pattern around elliptical cutouts of different sizes

Table 7. Stress concentration vs cutout size

Edge to cutout distance (e) mm	K
2	16.19
4	9.003
6	5.627
10	3.952
12	2.842

Results of similar analyses done on composite plates with triangular cutouts are shown below in Fig.13 and Table 8.

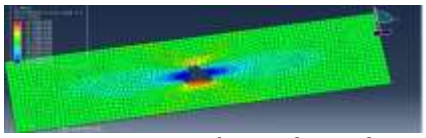

Fig. 13 Stress pattern around a typical triangular cutout

Table 8. Stress concentration vs cutout size

Edge to cutout distance (e) mm	Side of triangle (a) mm	K
5.009	30	4.669
7.174	25	3.288
9.339	20	2.697
11.504	15	2.473
13.669	10	2.091

It can be seen that geometric parameters significantly affect the stress values in the vicinity of cutouts. Edge interaction seems to severely enhance the stress concentration values. In case of multiple holes, when holes are aligned perpendicular to loading direction, stress concentration increases substantially. Among the shapes of cutouts, laminates with elliptical holes seem to be comparatively more susceptible to failure.

B. *Effect of material parameters*

The effect of different material parameters such as fiber orientation, fiber material and ply stacking sequence on stress concentration of composite laminates with holes are studied using the numerical model created for OHT.

Stress concentration obtained for different fiber angles of carbon-epoxy and glass-epoxy laminates are shown in Table 9 below. Variation is plotted as shown in Fig. 14.

Table 6. Stress concentration for different fiber angles

Fiber angle(deg.)	Carbon epoxy	Glass epoxy
0	1.843	1.713
45	1.815	1.702
90	1.783	1.688

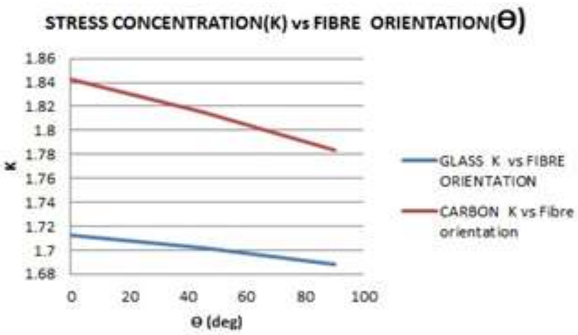

Fig. 14 Comparison of stress concentration factor vs. fiber angle for glass epoxy and carbon epoxy composite laminates with holes

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It is also investigated whether the stacking order of composite laminate significantly affected the stress concentration.Only fiber orientations of 0 deg. and 90 deg. were considered for the analysis. The stacking sequences studied are 90/0/0/90, 0/90/90/0 and 0/90. The study is conducted for both carbon epoxy and glass epoxy laminates.

A typical stress plot of laminate with 0/90/90/0 stacking sequence is shown in Fig. 15 below.

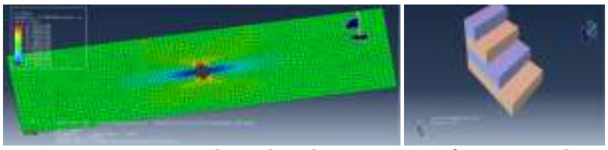

Fig. 15 Stress plot and stacking sequence of a 0/90/90/0 laminate

The values of stress concentration obtained for carbon epoxy and glass epoxy laminates for the three stacking sequences are given in Table 7 below.

Table 7. Stress concentration factors for various stacking sequence

Stacking sequence	Carbon epoxy	Glass epoxy
0/90	1.882	1.671
0/90/90/0	1.877	1.719
90/0/0/90	1.853	1.660

In spite of changing various material parameters, the stress concentration value does not seem to alter much, as can be seen from the analyses. A minor change is noted when fiber material is changed. For carbon epoxy composites, stress concentration value is around 1.8 while for glass epoxy composite, it is around 1.7.

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V. CONCLUSIONS

The effect of holes and cutouts in composite laminates is an ongoing field of study. However, comprehensive studies of such laminates under tensile loads, to determine whether geometric or material parameters seriously affect stress concentration effects, are rarely available.

The geometric parameters considered in the study are hole size and shape, multiple holes as well as edge interaction.It is evident from results that stress concentration factor is directly influencedby hole-hole distance and hole orientation. The value of stress concentration factor decreses as the hole-hole distances increses. As the hole orientation varies from 0 degree to 90 degree corresponding increase in stress concentration factor was observed. The maximum value of stress concentration was found when holes are aligned perpendicular to the loading direction. As the holes come in the vicinity of edges of the plate, an edge interaction is observed which increases the stress concentration factor to very high values.It can also be seen, the stress concentration increases in order of the shapes of cutouts as circular, square, triangular and ellipse. Also, with the increase in size of cutouts beyond certain value, there is an exponential increase in stress concentration for all shapes. This increase can be attributed to edge effect, where the sudden discontinuity due to edge causes increased stress near the vicinity of the cutout.

However variation of material parameters such as fiber orientation and stacking sequence do not seem to much influence stress concentration factor. Fiber material is seen to have minor effect as carbon fiber epoxy exhibits slightly higher value of stress concentration factor compared to glass epoxy composite.

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