Influence of hole-hole distance and orientation on strength of composite laminae

T. R. SreeSastha Ram, Anoop Kumar S
Department of Mechanical Engineering
S.C.T. College of Engineering, Trivandrum, India
sastha123@gmail.com
tvm.anoopks@gmail.com

***Abstract*- Numerical analysis of 0 degree ply orientation of fibre glass with polyester resin with Open hole test model as per ASTM standards is carried out using ABAQUS CAE. The result is validated against experimental results available in literature. Numerical simulation of ASTM D5766 standard specimen containing 2 holes with varying hole-hole distance is carried out, It is clear from the results that holes aligned perpendicular to the loading direction displays greater values of stress concentration. Analysis was done by varying hole orientation with different hole-hole distances. From these results it is found that as hole orientation increases the value of stress concentration increases gradually for laminae with multiple holes. For experimental validation tensile test with single hole and multiple (2 holes) is carried out in UTM. Based on the results, an empirical relation for determining the effect of stress concentration on varied hole-hole distance and hole-hole orientation is achieved to predict the strength of the composite laminae.**

I. INTRODUCTION

Composite materials are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components. In structural assemblies, joining two composite structural parts by fastening has been one of the most commonly used methods in manufacturing and repairing of composite structures. Holes are provided in various shapes known as cut outs for weight reduction and for providing fastened joints. The presence of holes in a structure results in a high stress gradient at the vicinity of their edges. The strength prediction of isotropic material with a hole can be accurately predicted since the stress gradient around the hole is not dependent of the material. The ratio of the maximum stress at the cut-out edge to the nominal stress is called the stress concentration factor (SCF). The behavior of material with stress concentration is of great importance to design engineer because of the resulting reduced strength of components and higher amount of damage around this region. Stress concentration is an important parameter to be taken into consideration, because the point near maximum stress concentration is often the location of initialization of damage in the structure. The presence of multiple holes in composites is of great concern such that study on hole to hole interaction in composite laminate is of great importance.

Ghezzo et. al., [2] investigated the numerical and experimental investigation conducted on thin T300/epoxy carbon fibre laminates with multiple cut outs subjected to in-plane loads. When holes are arranged in a row aligned with the loading direction as the hole-hole distance increases stress concentration also increases. It is found that with notches set along the direction of loading inter hole distance is not affecting the stress concentration factor. For the case of laminate with 2 and multiple holes experimental stress concentration factor is defined as strength of the un-notched laminate to the strength of laminate with 2 or multiple holes. Soutis et. al., [4] described the static compressive response of carbon fibre/epoxy laminate containing single or two holes. Analysis is carried out to study the interaction effect between a pair of 5mm diameters holes as function of hole spacing. It was found from the analysis that for no interaction the hole centers should be placed at least four hole diameters apart. Lotfi Toubal et. al., [8] studied stress concentration in a circular hole in composite plate, It was stated in his work that as the hole size decreases, the stress concentration factor decreases and finally approaches unity. K.Vasantha Kumar et. al., [9] investigates that the effects of angle ply orientation on tensile properties of a woven fabric bi-directional composite laminate experimentally. It is observed from the result that glass/Epoxy with 0deg fibre orientation Yields' high strength when compare to other degree of orientations for the same load, size & shape In addition, failure analysis for glass/Epoxy to evaluate different failure modes was also conducted. Nahla Kamal Hassan [10] studied about the geometrical parameters involved in the design of multi-bolted connections for fibre reinforced plastics structural members. Also rational analysis was carried out to determine the joint efficiency. The maximum efficiency point was chosen and the corresponding geometrical parameters was considered efficient in joint design. Also in his work it is clear that stress concentration factor directly influences the efficiency of the joint design. Dong Kwan Lee [11], investigated the stress concentration effects of plates with notches by experiment and theoretical methods. An empirical equation describing the hole diameter, hole distances and maximum stress was proposed based on analytical results for design purpose.

II. Finite Element Modelling

To understand the influence of inter hole distance and hole orientation on strength of composite laminae numerical simulation is carried out using Abaqus CAE software.

A. Material for study

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 was obtained from literature [11].

TABLE I: Properties of Fibre glass epoxy considering 30% fibre volume fraction

Density	1.8 x 10^{-6} kg/mm^3
E_{11} (along longitudinal direction)	18576 N/mm^2
E_{22} (Along lateral direction)	9976 N/mm^2
Poisson's ratio (ν_{12})	0.29
Shear modulus (G_{12})	4128 N/mm^2

The numerical & experimental model are prepared based on ASTM standard D5766 as in Fig 1

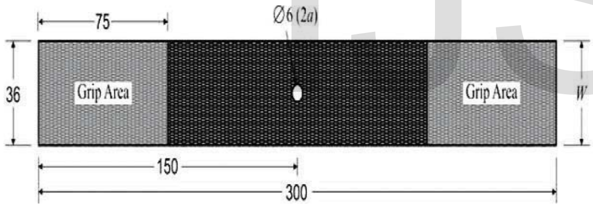

Fig.1. ASTM D5766 specimen

Open Hole Tensile ASTM D5766 measures the force required to break a polymer composite laminate specimen with a centrally located 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. ASTM D5766 is commonly used in the aerospace industry as a practice to develop notched design allowable strengths. Numerical simulation of composite plate with single hole is analysed first and on the later stages numerical analysis is carried out for multiple holes (2 holes) for different hole-hole orientation by varying hole-hole distance.

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

<u>Load applied:</u>
Direction: Along x- direction
Magnitude: 50 N/mm^2

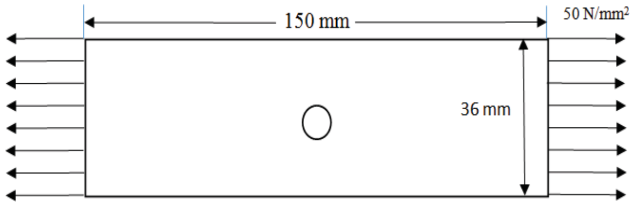

Fig. 2. Schematic diagram of plate with central hole under uniaxial tension

B. Numerical model of composite plate with single hole

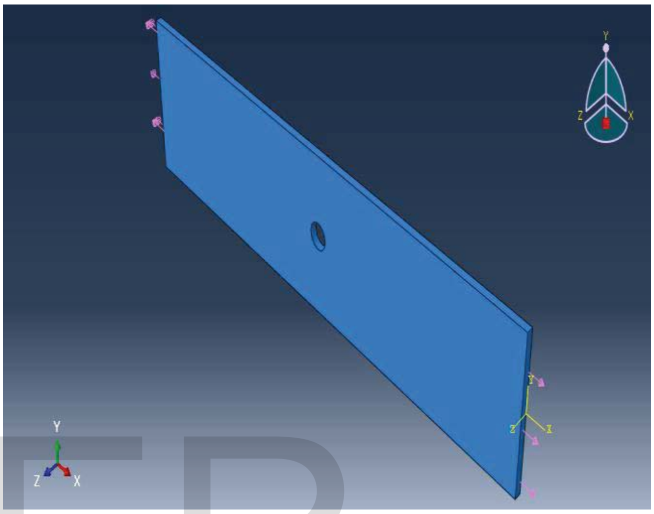

Fig. 3. Numerical model of composite plate with single hole

ASTM D5766 (Open hole tension) specimen with gauge dimension 150mm x 36mm x 2mm is considered for the analysis as shown in Fig. 3. 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.

C. Numerical model of composite plate having 2 holes with varying hole orientation having different hole-hole distance

Since hole-hole interaction plays an important role in the strength of composite laminae, Analysis is carried out to determine the effect of stress concentration factor for varied hole-hole orientation. For various hole-hole orientation, hole-hole distance is also varied to study the influence of stress concentration on varied inter hole distances. Same mesh specification and same loading condition as that with plate with single hole is followed in this model. Hole-hole orientation is varied from 0 degree to 90 degree with respect to loading direction. Fig.4 shows numerical model with hole-hole distance of 7mm (1mm gap apart) with holes aligned different hole orientation to the loading. At each hole-hole orientation hole-hole distances is varied to determine the influence of stress concentration having varied hole-hole distances.

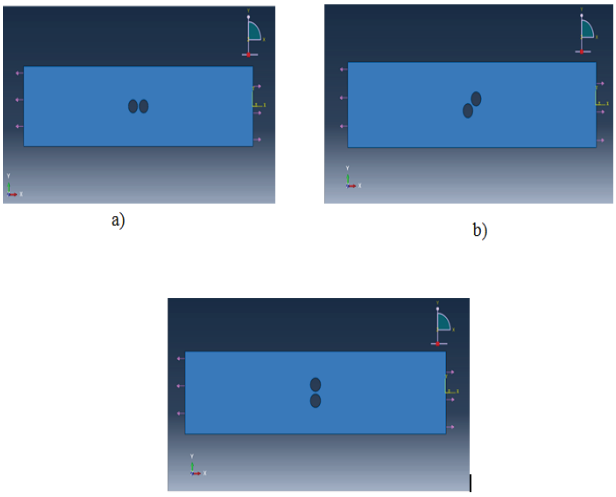

Fig. 4. Numerical model with various hole orientation with respect to loading direction a) 0 degrees b) 45 degrees c) 90 degrees

D. Numerical model of square composite plate having 2 holes to study the influence of edge distance

Numerical analysis is carried out on a square plate (150 mm × 150 mm) having 2 holes to determine the effect of stress concentration factor on edge distance and to find optimum e/d value for minimizing the edge effect. Square plate is chosen for analysis in order to have uniform edge interaction an all the four sides of the plate. Mesh specification and loading condition is same at that with single hole. The value of edge distance "e" measured from top edge of the plate is varied on descending order and the variation in stress concentration factor is noted.

III. Experimental Investigation

In comparison to numerical results, experiment results gives correct and accurate results. So experimental investigation is conducted to validate the numerical model.

A. Preparation of specimen for tensile test

Fibre reinforced plastic (FRP) is the material chosen for experimental study. Initially unidirectional fibre glass was obtained in raw form as shown in Fig. 5

Fig. 5. Unidirectional fibre glass material

The matrix material used for study is Polyester Resin GP 002 It is used to bind the fibre materials, to transfer stress between broken fibres or whiskers and to protect phases from environment. Typically matrix is of considerably lower density, stiffness, and strength than fibres or whiskers.

B. Experiment test

To understand the strength of composite laminae, tensile test is carried out using Computerised Universal Testing Machine. The UTM employed for tensile test is computerised universal testing machine UTC-100 which is having maximum capacity of 100 tonne. The experiment test is conducted in order to validate the numerical model so analysed earlier.

1) Composite plate without hole:

Experiment test is performed on composite plate having geometry same at that chosen for numerical model (300mm × 36mm × 2mm). Gripping area is marked according to ASTM D5766 standard that is 75mm length is marked on both of the sides. After fixing the specimen on to the jaw initial load or set load has to be entered in the computer system. Set load of 30 kN is entered in the computer system this is being sensed by the loading unit with the help of load transducer. For better accuracy 3 specimens are analysed. Failure results of composite plate without hole is shown in the Fig. 6 below:

Fig. 6. Composite plate without hole - Failed specimen

The observed results for 3 specimen shown in the Table II

TABLE II : Observation for composite plate without hole

Specimen No.	Set Load (kN)	Peak Load (kN)
1	30	20.5
2	30	18
3	30	22.5

2) Composite plate with single hole

Experiment is carried out on composite plate having central hole of diameter 6mm. Test is made on composite plate with single hole in order to obtain stress concentration factor for single hole. Initial set load is again 30 kN which is entered on to the computer system of the UTM, For better accuracy 3 specimen are chosen for the study. But with plate having a central hole, the specimen is prone to failure with lighter load as compared to plate without hole this is because of irregularity in the stress field lines. Failure results of composite plate without hole is shown in the Fig 7.below.

Fig. 7. Composite plate with single hole – Failed specimen

The observed results for 3 specimen shown in the Table III

TABLE III: Observations for composite plate with a hole

Specimen No.	Set Load (kN)	Peak Load (kN)
1	30	15.0
2	30	12.7
3	30	15.2

3) Composite plate with 2 holes aligned perpendicular to the loading:

Tensile test is carried out on a composite plate having 2 holes which are arranged perpendicular to the loading direction (90 degrees). Distance of one hole centre to the adjacent hole centre is kept as 12mm such that providing a gap of 6mm between the holes.

Here also initial set load is 30 kN, which is fed on to the computer system of the UTM. But in this case composite plate has 2 holes, so the specimen is prone to failure with lesser load as compared to plate with single hole this is because of higher discontinuity for the stress field lines. Failure results of composite plate with 2 holes is shown in the Fig. 8 below.

Fig. 8. Composite plate with 2 holes - Failed specimen

The observed results for 3 specimen shown in the Table IV

TABLE IV: Observation for composite plate with 2 holes

Specimen No.	Set Load (kN)	Peak Load (kN)
1	30	11.0
2	30	10.2
3	30	9.7

IV. Results & Discussions

A. *Composite plate with single hole (ASTM D5766 OHT specimen)*

1) Numerical results of composite plate with a hole

The maximum value of stress occurs near the discontinuity, in this case discontinuity is the presence of hole. 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 as obtained from the literature [12].

TABLE V: Comparison of stress concentration factor values of numerical with experimental results (literature)

Numerical results	Experimental results [12]
1.435	1.46

2) Experimental results

From the test observation results of composite plate with single hole, It is very much clear that with set initial load of same 30 kN the material got ruptured at earlier stages when the peak load reached 14.05 kN. The value of stress concentration factor for single hole was found as 1.4. The table below shows comparison of stress concentration values obtained by experimental results and numerical results.

TABLE VI: Comparison of stress concentration factor values of numerical with experimental results

	Numerical results	Experimental results
ASTM D5766 OHT specimen (Plate with single hole)	1.435	1.4

B. Composite plate with 2 holes

1) Numerical analysis with different hole orientations

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

TABLE VII: 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).

2) Experimental result with 2 holes aligned perpendicular to the loading

Tensile test is carried out on composite plate with 2 holes to validate the results obtained by numerical analysis. It is seen that with set initial load of 30 kN specimen got ruptured when the peak load reached 11 kN. This is due to greater localised stress concentration region near the holes.

The value of stress concentration factor for 2 holes was found as 1.81. Holes are kept perpendicular to the loading direction because at this position stress concentration factor shows maximum values which is of greater concern. Table below shows the comparison of numerical values with that of experimental test results for composite plate having 2 holes.

TABLE VIII: Comparison of stress concentration factor values by numerical and experiment for composite plate with 2 holes

	Numerical results	Experimental results
Multiple holes (2 holes) Hole-hole distance: 12mm Hole- hole orientation: 90 degree	1.77	1.81

C. Effect of edge distance on composite laminae

Table below shows the variation of stress concentration with varied edge distance. 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.

TABLE IX: 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

From the Table IX, it is clear that stress concentration factor value decreases till edge distance reaches 6mm such that e/d ratio equal to 1. So it is concluded that e/d ratio must be greater than 1 for minimising the edge effect phenomenon in composite laminae. This result of e/d ratio clearly matches with that with the experimental results available in the literature [13].

V. Empirical relation for stress concentration factor

An empirical relation to determine the stress concentration factor is found out with varying hole-hole orientation and distances. This is obtained by making use of surface plot as obtained from table VII with the help of online function finder [20].

$$SC = A \times \exp\left(\left(\frac{-B}{h^{C}}\right) \times \exp(-D \times h^{E} \times \theta)\right) + F$$

Where, SC = Stress concentration factor
h = Hole-hole distance θ = Hole-hole orientation
A = .2558 B = -1.291 C = .05525
D = -33.695 E = -2.2868 F = .76173

To estimate to estimate whether the error are within the acceptable limits an error analysis is carried out as shown in the figure below.

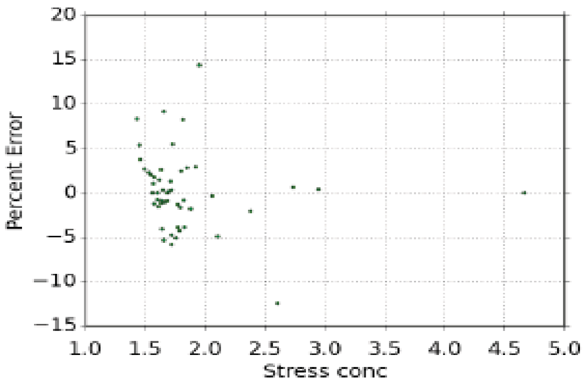

Fig. 9. Percent error vs Stress concentration

From the Fig. 9 an error of nearly +/- 5% is observed which is very small, It is again observed from the error plot that error is very less or is negligible at higher stress concentration factor. Higher stress concentration occurs when the holes are aligned perpendicular to the loading direction which is of greater concern. As the error is very less in such cases, the empirical relation is proved to be valid. So the equation generated can be made as general equation for finding the stress concentration factor for various hole-hole distances and hole-hole orientations.

VI. Conclusion

It is concluded from these results that stress concentration factor have direct influence on hole-hole distance and hole orientation. It is clear from the analysis results that 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 comes in the vicinity of edges of the plate, an edge interaction is observed which increases the stress concentration factor. For limiting this effect it was found from the analysis results that the edge to diameter (e/d) ratio must be greater than 1. Based on the obtained results of stress concentration factor with varied hole-hole distances and hole-hole orientation an empirical relation was proposed as design criteria.

References

[1] Buket Okutan, The effects of geometric parameters on the failure strength for pin loaded multi directional fibre glass reinforced epoxy laminate, Composite (2002): 567-578.

[2] Fabrizia Ghezzo, Giovanni Giannini, Francesco Cesari, Gianni Caligiana, *Numerical and experimental analysis of the interaction between two notches in carbon fibre laminates*, Composites Science and Technology (2008): 1057–1072.

[3] Ramazan Karakuzu, Cihan Riza C, Aliskan, Mehmet Aktas, *Failure behaviour of laminated composite plates with two serial pin-loaded holes*, Composite Structures (2008): 225–234.

[4] Soutis C, Fleck N A, Curtis P T, *Hole-hole interaction in carbon fibre laminates under uniaxial compression*, Composites Science and Technology (1991): 31-38.

[5] Eugene Dan Jumbo, Russell Keller, Wen S Chan, Selvaraj, *Strength of Composite laminate with multiple holes.* Thesis report to University of Texas at Arlington.

[6] A R Abu Talib, A A Ramadhan, A S Mohd Rafie, R Zahari, *Influence of cut-out holes on multilayer Kevlar-29/epoxy composite laminated plates*, Materials and design (2013): 89-98.

[7] Ramazan Karakuzu, Zuleyha Aslan, Bucket Okutan, The effect of ply number, orientation angle and bonding type on residual stress of woven steel fiber reinforced thermoplastic laminated composite plates subjected to transverse uniform load, Composite Science and Technology (2004): 1049-1056.

[8] Lotfi Toubal, Moussa Karama, Bernard Lorrain, *Stress concentration in a single hole in composite plate*, Composite structures (2005): 31-36

[9] K Vasantha Kumar, Dr. P Ram Reddy, Dr. D V Ravi Shankar, *Effect of angle ply orientation on tensile properties of Bi Directional woven fabric glass epoxy composite laminate*, International Journal of Computational Engineering Research (2013): 55-61.

[10] Nahla K Hassan, Charles N Rosner, Sami H Rizkalla, *Bolted connection for GFRP laminated structural members*, Thesis report.

[11] Dong Kwan Lee, *Stress concentration effect of plates with circular holes*, Thesis report at Indiana Institute of Technology (2012).

[12] Shih-Ting Yang, *Study of Failure in Fibrous Composites subjected to bending load*s, Thesis report at Naval post graduate school, California.

[13] M Mohan Kumar, Rajesh S, Yogesh H, Yeshaswini B, *Study on the Effect of Stress Concentration on Cutout Orientation of Plates with Various Cutouts and Bluntness*, International Journal of Modern Engineering Research (2013): 1295-1303.

[14] Faruk Sen, Onur Sayman, Resat Ozcan, Ramazan Siyahkoc, *Failure response of single bolted composite joints under various preload*, Indian Journal of Engineering and Material Sciences (2010): 39-48.

[15] S. Kazemahvazi, D. Zenkert, *Strength of multi-axial laminates with multiple randomly distributed holes*, Published paper at 18th international conference on composite materials.

[16] S.R. Hallett , B.G. Green, W.G. Jiang, M.R. Wisnom, An experimental and numerical investigation into the damage mechanisms in notched composites, Composites (2009): 613–624.

[17] Nahla K. Hassan, Mohamed A Mohamedien,Sami H, Rizkalla, *Finite element analysis of bolted connections for PFRP composites*, Composites (1996): 339-349.

[18] Autar K Kaw, “Mechanics of Composite materials”, second edition , CRC press, Taylor and Francis Group, Third edition,2013.

[19] Jones R M, “Mechanics of Composite Materials”, Second edition, McGraw Hill Book Company,1990

[20] http://zunzun.com/ (Online function finder)