STRESS CONCENTRATION EFFECTS ON GFRP COMPOSITE PLATES WITH CIRCULAR CUT-OUTS

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ABSTRACT: Structures which find their applications in various industries like aerospace, marine etc are subjected extreme loading conditions under practical situations. Composite materials are effective alternatives to the conventional isotropic materials which efficiently withstand the extreme forces coming on these structures. One of the important criteria for the design of these structures is the stress concentration effect due to the non uniform stress distribution in the components of the structure. The present study aims to obtain the effect of stress concentration on GFRP laminated composite plates with multiple cutouts consisting of 8 plies, with different layup sequences subjected to uniaxial in plane loading. The effect of various parameters like number of cut-outs, layup sequences and the distance between the centers of cut outs to diameter of the cut out in the direction of loading (ℓ/d ratio) in the stress concentration are considered.

KEYWORDS: Laminated composites, Cut-outs, Layups, Stress concentration.

INTRODUCTION

A composite material is a combination of two or more materials with different properties which gives enhanced properties than the parent materials. For aerospace structures, and marine structures 90% of the body parts are constructed using most modern composites like carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) etc. One of the main limitations of the composite material to use in ordinary industry is its high cost. Normally, composite structures are of thin walled type, in the form of plates or shells. Cut outs of various shapes may be made into these structures for practical reasons which may cause a reduction in strength due to stress concentration around these holes. In order to evaluate the failure strength of these structures, it is necessary to determine the stresses around the holes. In case of structures with multiple cut outs, the size and proximity with respect to each other would also adversely affect the stress concentration.

So to minimize the effect due to the proximity of the holes, the cut outs have to be spaced apart such that the interaction of stress field is not significant. Though the composites have greater advantages over other conventional materials, in the presence of cut out or crack, the reduction in strength will be very severe and unpredictable. So the behavior of these composite laminates in the presence of discontinuities is of greater importance in practical applications which makes it very much significant for research purpose.

The failure due to stress concentration is sudden and severe. Due to its intensity of damage this has to be considered with greater importance in the design. But for these composite materials which are anisotropic in nature, the calculation of stress concentration is complex since no direct solutions are available and also for different cutout shapes the intensity and position of stress concentration will be different. The other factors that may affect the stress concentration in composites are fiber orientation, size of the cut out and the number of layups.

The stress concentration factor (SCF) is a dimensionless quantity which is used to express the intensity of stress concentration in a structure. It is a ratio which is obtained by dividing the maximum localized stress (σ_m) and the average stress (σ_a) in the plate (Eqn.1)

$$SCF = \frac{\sigma_m}{\sigma_a} \qquad (1)$$

or an isotropic material, the SCF can be obtained from the general theory of elasticity solutions. For the better design of a composite structure it is necessary to understand the significance of the hole-interaction effect in a composite structure with cut-outs. A hole- interaction effect occurs when the stress field from one interacts with the stress field from an adjacent hole. Holes may be spaced apart such that the interaction of stress field is not significant.

Studies have been conducted all around the world to ascertain the effect of stress concentration around cut-outs in composite plates. Both analytical and experimental investigations have been conducted. Xun fan et al. studied the stress concentration of a laminate weakened by multiple circular holes. However, the parametric study was limited to two circular cut-outs in a particular laminate. Ukadgaonker et al, carried out studies to provide a general solution for stresses around holes in orthotropic plates under in plane loading. The study was not intended to be carried out on composite laminates. Arz Y R conducted experimental study to measure the normal strain (ε_x) at the edges of circular & square holes in GFRP composite plates. Stress concentration effects were not given due emphasis on this study. Nageswara Rao et al, studied the effect of stress concentration around square and rectangular cutouts in symmetric laminates. Sharma obtained a general stress function for determining the stress concentration around circular, elliptical and triangular cutouts in laminated composite plate subjected to biaxial loading. Zappalorto et al, obtained a formula for the theoretical stress concentration factor of orthotropic notched plate under tension as a function of material elastic constants and stress concentration factor corresponding to isotropic case. Ramesh N R et al, conducted experimental and finite element studies were made on buckling of rectangular plates made of laminated E-glass woven fabric epoxy composite plates with and without cut-outs. The effects of (i) fabric orientation angle and (ii) shape of cut-out (circular, square and rectangular) on the critical buckling load were determined. It has been seen that in most of the literatures reviewed above, the effects of the parameters like shape of cut-out, number of layups and number of cut-outs have been studied to arrive at finding the effect of strains and stresses in orthotropic as well as composite laminates. However, not much of studies have been conducted on the effect of stress concentration factors (SCF's) on GFRP composite laminates with multiple circular cut-outs. Moreover, the effect of the parameter like ℓ/d ratio (distance between the centers of cut outs to diameter of the cut out in the direction of loading) and the effect of layup sequences have not been studied in detail. Hence, the emphasis of this study is laid up on the effect of the parameters like ℓ/d ratio and layup sequences on SCFs of GFRP composite laminates with multiple circular cut-outs.

Different layup sequences such as $[0°/0°/0°/0°]_s$, $[0°/45°/-45°/0°]_s$, $[0°/90°/-90°/0°]_s$, $[0°/30°/-30°/90°]_s$, $[0°/45°/-45°/90°]_s$, $[0°/60°/60°/90°]_s$, $[90°/30°/-30°/90°]_s$, $[90°/45°/-45°/90°]_s$, and $[90°/60°/-60°/90°]_s$ were considered for the study for various ℓ/d ratios ranging from 1.2 to 2 . The numerical analysis is done by using the finite element software ABAQUS standard/explicit.

PROBLEM

Laminated composite plate

GFRP composite plates of size 300mm X 300mm X 1mm and consisting of eight plies are used in the study. In this the analysis is done for composite plates with two, three, and four cut outs arranged in a manner as shown in Fig.1. The effect of ℓ/d ratio (distance between the centers of cut outs to diameter of the cut out in the direction of loading) on the composite plates with multiple cut outs subjected to in-plane loading is studied. The effects of different layup sequences in the stress concentration effects of laminated composite plates are also studied. Each ply is 0.125 mm thick and has the material properties are given Table 1.

Table. 1. Mechanical properties of GFRP laminate

PROPERTY	VALUE
Longitudinal Tensile Modulus E_{11} (MPa)	39860
Transverse Tensile Modulus E_{22} (MPa)	10800
	3650
In Plane Shear Modulus G_{12} (MPa)	0.3
Poisson's Ratio	

Methodology

The non linear analysis of the GFRP plate is carried out using a commercial finite element code, ABAQUS version 6.13. ABAQUS is a general purpose finite element program with linear static, dynamic and non-linear analysis capabilities. Each laminated plate had two, three and four cut-outs each, with circular shapes. The distance between centres of cut-outs to diameter of the cut-out (ℓ/d ratio) was varying as 1.2, 1.5, 1.8 and 2. In plane tensile loading is given along the edges of the plate in the X direction (Fig.1).

Finite Element Analysis

All the laminated plates are modelled in order to get accurate visualisation of the effect of stress concentration around cut-outs under in plane tensile loading. Discretisation of laminar plates are done using 8-noded linear shell elements, S8R, provided by the finite element code, which can be used for static analysis. All the six degrees of freedom, three translations and three rotations, are suppressed at the left hand top corner of the plate and the in plane tensile loading is given along the edges in the X-direction of the plate. Load is applied as uniformly distributed edge load to the plate.

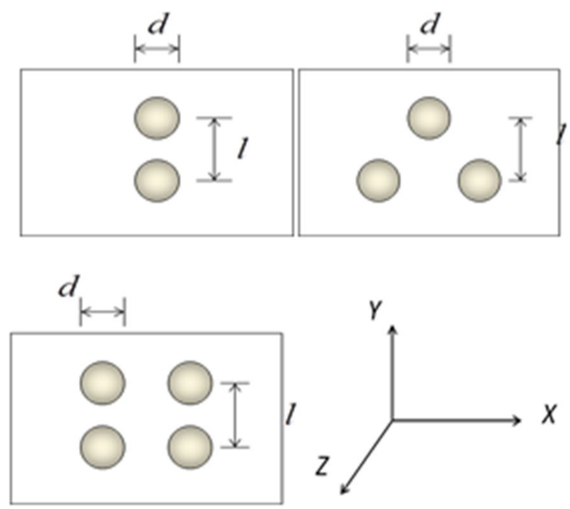
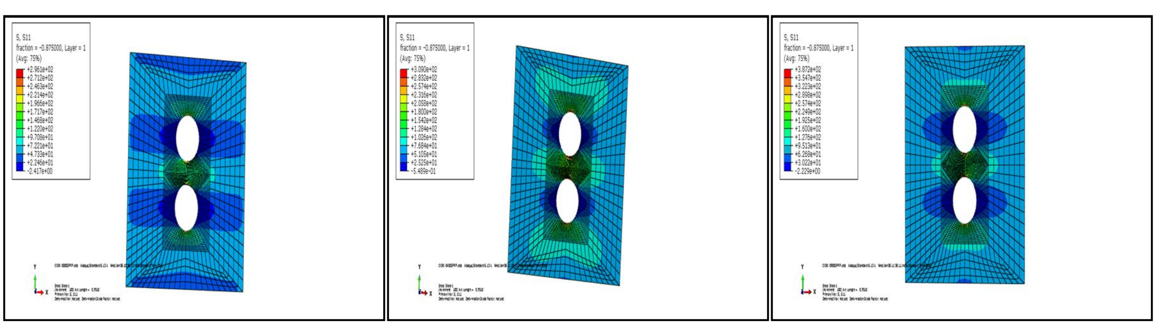
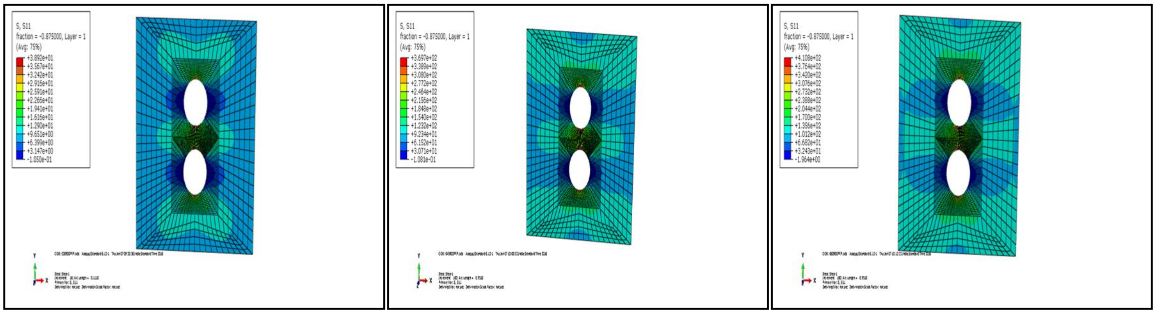


Fig. 1. Schematic representation of GFRP composite plates with circular cut-outs

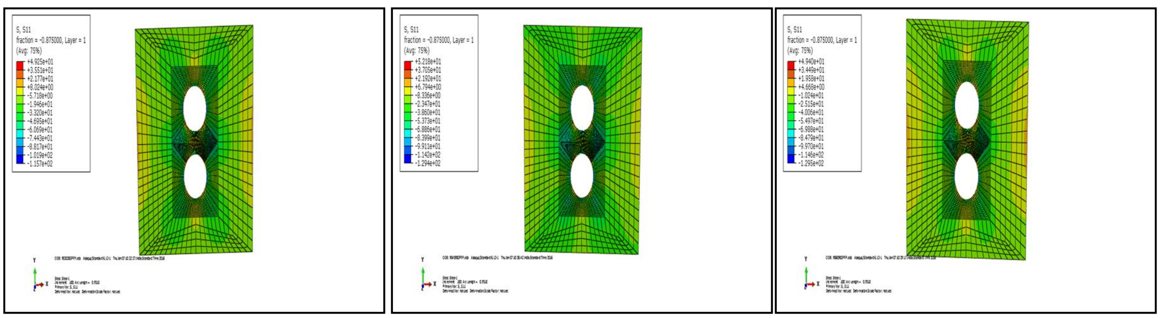
Non linear static analysis is conducted on each of the plates to get the position and magnitude of the maximum stress and these were obtained for each of the layups. Stress contours of each of the laminated composite plates with two circular cut-outs of ℓ/d ratio = 2, and having layup sequences of $[0°/0°/0°/0°]_s$, $[0°/45°/-45°/0°]_s$, $[0°/90°/-90°/0°]_s$, $[0°/30°/-30°/90°]_s$, $[0°/45°/-45°/90°]_s$, $[0°/60°/60°/90°]_s$, $[90°/30°/-30°/90°]_s$, $[90°/45°/-45°/90°]_s$, and $[90°/60°/-60°/90°]_s$ due to in plane loading are given in Fig 2. Similar analysis procedure is carried out for GFRP laminated composite plates with three and four circular cut-outs, with varying ℓ/d ratios. The SCF's obtained in all the above cases are given in Tables 2, 3 and 4.



(i) $[0°/0°/0°/0°]_s$ (ii) $[0°/45°/-45°/0°]_s$ (iii) $[0°/90°/-90°/0°]_s$



(iv) [0°/30°/-30°/90°]s (v) [0°/45°/-45°/90°]s (vi) [0°/60°/60°/90°]s



(vii) [90°/30°/-30°/90°]s (viii) [90°/45°/-45°/90°]s (ix) [90°/60°/-60°/90°]s

Fig.2. Stress contours of GFRP composite plates with circular cut-outs (ℓ/d ratio = 2)

Table 2. SCF's of GFRP plates with **two** circular cut-outs with varying ℓ/d ratios

Layup Sequence	ℓ/d=1.2	ℓ/d=1.5	ℓ/d=1.8	ℓ/d=2.0
[0°/0°/0°/0°]s	3.81	3.76	3.66	3.80
[0°/45°/-45°/0°]s	4.07	4.01	3.90	3.42
[0°/90°/-90°/0°]s	3.65	3.61	3.71	3.58
[0°/30°/-30°/90°]s	4.06	4.01	4.03	4.05
[0°/45°/-45°/90°]s	3.65	3.61	3.55	3.36
[0°/60°/-60°/90°]s	4.19	4.11	4.05	3.45
[90°/30°/-30°/90°]s	3.79	3.43	3.19	3.29
[90°/45°/-45°/90°]s	3.82	3.64	3.33	3.45
[90°/60°/-60°/90°]s	3.62	3.99	3.14	3.72

Table 3. SCF's of GFRP plates with **three** circular cut-outs with varying ℓ/d ratios

Layup Sequence	ℓ/d=1.2	ℓ/d=1.5	ℓ/d=1.8	ℓ/d=2.0
[0°/0°/0°/0°]s	4.33	4.13	4.18	4.04
[0°/45°/-45°/0°]s	4.08	3.93	3.97	3.86
[0°/90°/-90°/0°]s	4.11	4.16	4.01	3.91
[0°/30°/-30°/90°]s	4.28	4.11	4.16	4.04
[0°/45°/-45°/90°]s	3.94	3.82	3.86	3.76
[0°/60°/-60°/90°]s	3.90	3.80	3.83	3.74
[90°/30°/-30°/90°]s	3.55	3.90	3.26	3.73
[90°/45°/-45°/90°]s	3.71	3.64	3.31	3.11
[90°/60°/-60°/90°]s	3.55	3.49	3.22	3.74

Table 4. SCF's of GFRP plates with **four** circular cut-outs with varying ℓ/d ratios

Layup Sequence	ℓ/d=1.2	ℓ/d=1.5	ℓ/d=1.8	ℓ/d=2.0
[0°/0°/0°/0°]s	3.48	3.52	3.44	3.63
[0°/45°/-45°/0°]s	3.19	3.38	3.39	3.30
[0°/90°/-90°/0°]s	3.51	3.81	3.81	3.63
[0°/30°/-30°/90°]s	3.16	3.16	3.15	3.26
[0°/45°/-45°/90°]s	3.36	3.36	3.47	3.47
[0°/60°/-60°/90°]s	3.48	3.79	3.80	3.59
[90°/30°/-30°/90°]s	3.74	3.72	3.55	3.21
[90°/45°/-45°/90°]s	3.52	3.50	3.37	3.50
[90°/60°/-60°/90°]s	3.92	3.88	3.68	3.30

RESULTS AND DISCUSSIONS

The variations of SCF's for different layup sequences have been plotted for with different ℓ/d ratios and are shown in fig 3, 4 and 5

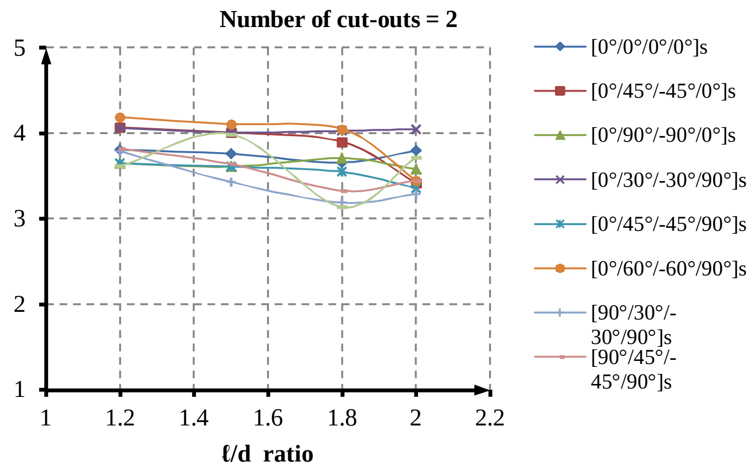


Fig.3. SCF - ℓ/d ratio curves for various layup sequences - Two cut-outs

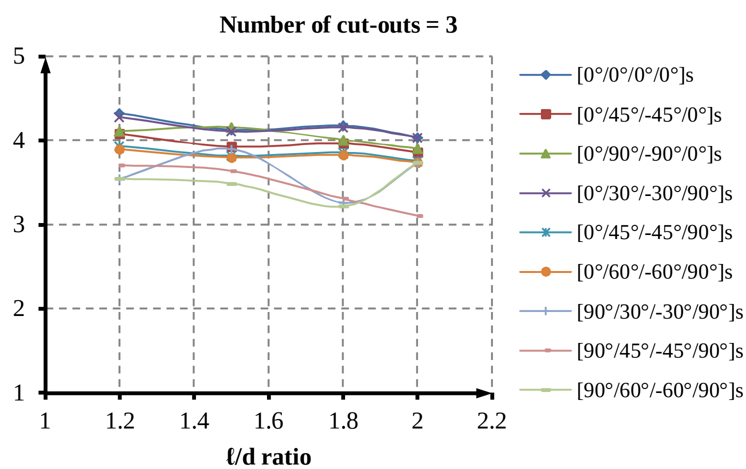


Fig.4. SCF - ℓ/d ratio curves for various layup sequences - Three cut-outs

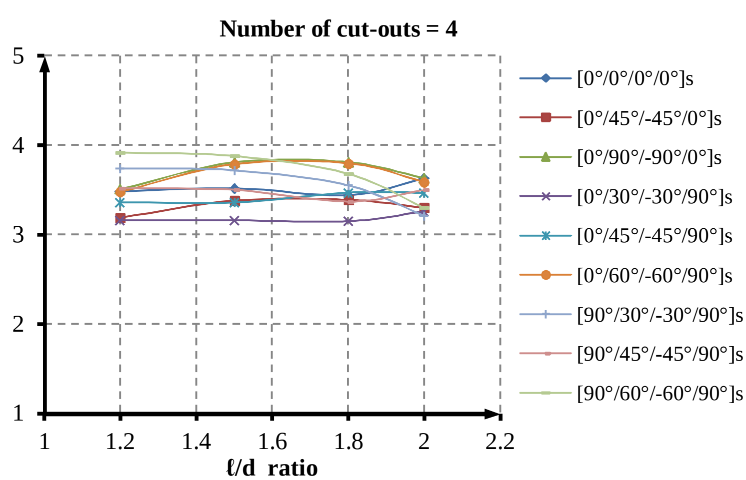


Fig.5. SCF - ℓ/d ratio curves for various layup sequences - Four cut-outs

The results of non linear static finite element analysis conducted on glass fibre reinforced composite plates with multiple cut-outs are discussed below. Laminated plates with two, three and four cut-outs of circular shape were analyzed and the stress concentration factors in each of these cases were obtained and the effects of change in layup sequences and change in ℓ/d ratios also were analyzed. The stress concentration factors obtained are generally greater than 3, which is the theoretical value of stress concentration factor for isotropic plates. Hence, it can be stated that the values of stress concentration factors are higher in composite plates than that of isotropic plates. While analyzing the results, as a general trend, it can be stated that the value of SCF tends to decrease with increase in the ℓ/d ratio. The values of maximum stresses are much higher in case of laminates which has at least one ply oriented in the direction of loading (i.e. at least one 0^0 oriented ply). Hence, the load carrying capacity of the laminate which has at least one 0^0 oriented ply is much higher, compared to that of the laminate which does not have at least one 0^0 oriented ply. This is because of the ability of the 0^0 oriented ply to take up a higher fraction of the load, as it is aligned parallel to the direction of loading. The fibres aligned in the direction of loading take up a major portion of the tensile load, and hence the load carrying capacity is very high, in the case of 0^0 oriented ply. In case of plates which did not have a 0^0 oriented ply, the tensile load carrying capacity is very low, since the load has to be taken by the matrix part in the composite. The laminate which had at least one 0^0 oriented ply had a greater SCF than the one which did not have a 0^0 oriented ply. In cases where the 0^0 oriented ply was absent, average stresses were also less compared to that of the laminate which had at least one 0^0 oriented ply.The locations of maximum stress in plates with circular cut-outs were found to be at the edges of the cut-outs. Also from Tables 2 to 4, suitable ply with minimum stress concentration for a particular arrangement of circular cutouts can be selected.

CONCLUSIONS

The effect of stress concentration in GFRP composite plates with multiple circular cut-outs due to in plane tensile loading was analyzed in this study. Various parameters like number of cut-outs, layup sequences and ℓ/d ratio were varied to study their influence in the SCF's. From the study, it has been observed that the values of SCF's are greater for composite plates than that of isotropic plates. The location of maximum stress concentration has been found to be near the edges of adjacent cut-outs in the case of circular cut-outs, which had at least one ply oriented in the direction of the in plane tensile loading. However, in cases where the plates did not have at least one ply oriented in the direction of the in plane tensile loading, the locations of the maximum stress have been found to be distributed all along the surface of the plate. The values of SCF's were seen to be decreasing with increase in ℓ/d ratio.

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