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Experimental and numerical analysis of cross-ply and angle-ply composite laminated plates having various shapes of cut outs

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Abstract
In this study, the experimental and numerical work is presented to study the effect of cut out size, shape, and number on the deflection and stresses in x and y-directions for simply and clamped supported boundary condition of cross and angle-ply laminated plates. The experimental work involved the effect of the cut out size, shape, and number on the deflection and stresses. A comparison study for the deflection and stress results have been achieved between the experimental and those obtained numerically using the finite element method employing ANSYS program Ver. 14. Various support conditions for the plates were adopted with different number of layers and fiber orientations. The shapes of cut out are square, circular, and fillet for different aspect ratios AR=1 and 2. The results showed that the amplitude values of square one are less than that for other types in cross-ply laminated plates and more than that for other cutouts in angle-ply laminated plates for aspect ratio a/b=1. Also the amplitude values of plates with square hole are more than that for circular hole for laminated plates with aspect ratio a/b=2. The stresses increase with increasing of the cutout size, and the increasing of fillet radius decreases the stresses. The comparison study shows a maximum discrepancy of deflection about (9.54%) and maximum discrepancy of stress results about (12.45%).

Keywords: Composite laminated plate; Cutout; Stress; Deflection.

1. Introduction

Composite plates are widely used in manufacturing of structural members such as those found in marine and civil applications. The structures are usually constructed by fastening plates by bolts which are inserted in the creating holes. The cut outs positions are designed according to the applications that the plates are to be designed and may be found in the structures for reducing the weights of the members of the structure [1]. The composites plates are used in many aerospace, civil and mechanical works due to their high strength / weight ratio which results in a light weight structure and gives an optimized shape .In order to reduce the weight of the structure and provide the required access, different types of cut outs are required which are considered as stress raisers and a highly localized stresses regions [2, 3]. Fiber Reinforced Plastics (FRP) is a general term for composite materials or parts that consists of a resin matrix that contains reinforcing fibers such as glass or fiber and have greater strength or stiffness than the resin. FRP is most often used to denote glass fiber-reinforced plastics. Fiber hybrids capitalize on the

best properties of various fiber types, while reducing raw material costs [4]. Many researches were achieved to in the paper topics. Jinho Woo and Won-Bae Na [1] presented a study for finding the stress concentrations in perforated plates taking into account the various types of cut outs and bluntness in addition to their orientations of .Recently, the structural members become more complicated and the emphasis on the different configurations of cut outs and orientations are investigated. The finite element technique was adopted in this work using the ANSYS package which offers a powerful and cheap solution. J. M. Henshaw et. al. [5] employed the finite element technique for the analysis of laminated composite plates with multiple holes. The stress concentrations were determined for the two types of laminated plates homogenous orthotropic and which consist of lamina of various orientations. T. Hasan et. al [6], investigated plates with central holes. They solved the problem by using the finite element method to obtain the stress distribution. The effects of hole shape, size and orientations of the hole on stress-strain distributions have been determined. A comparison study between the analytical by modeling and the numerical technique has shown a good agreement for different cases. Minoru Harada and Masahiko Fujikubo [7] analyzed large deflection of simply supported plates subjected to in-plane loading with cut outs and investigating the elastic-plastic and buckling eigenvalue problem by using the finite element method. Firstly, an advanced simple formula for the estimation of elastic buckling strength has been derived based on the results of eigenvalue analysis. Secondly, the relationship between the ultimate strength and the buckling strength evaluated by the existing plastic correction methods has been examined. Maziar Janghorban and Amin Zare [8], investigated functional graded plates containing different types of cut outs. They studied the vibration analysis of circular and non-circular types taking into consideration the effects of thermal state and the material properties which are graded across the thickness with linear variation on natural frequencies. Mohsin Abdullah Al-Shammari [9] investigated the free vibration of unidirectional composite laminated plates experimentally and numerically. The natural frequency and deflection response are obtained using rectangular, triangular, square, ellipse or circular shape, for simply supported and clamped plates.
In this work, the effect of different cut out shape, size, and number on the stresses and deflection of various cross-ply and angle-ply laminated plate, with different number of layers; aspect ratio; fiber orientation; and boundary condition effect of composite laminated plate, under static loading.

2. Experimental work
The experimental work included the evaluation of the maximum deflection and strain measurement from which the stresses are calculated using Hooke's law of simply supported cross ply and angle ply (with orientation fiber 45^o) composite laminated plate with square and circular cutout holes effect with various sizes. The composite plate sample, investigated experimentally with square and circular cutout holes, is shown in Figure 1.

(a) Plate without cutout hole (b) Plate with circular cutout (c) Plate with square cutout

Figure 1. Plate samples of experimental work with and without cutouts.

The plate sample was manufactured from unidirectional glass fiber, with 30% volume fraction, and polyester resin materials, with 70% volume fraction. The mechanical properties of plate sample are evaluated by using tensile test (Figure 2), using five samples (Figure 3) according to ASTM (D3039/D03039M) [10], as shown in Figure 4, where the tensile results evaluated are shown in Table 1. The deflection measurements by using dial gauge and the strains are recorded by using strain gauges on the sample plate shown in Figure 5 manufactured from four layers with the types ,cross ply (0°, 90°, 0°, 90°) and angle ;ply (45°, -45°, 45°, -45°) composite laminated plate.

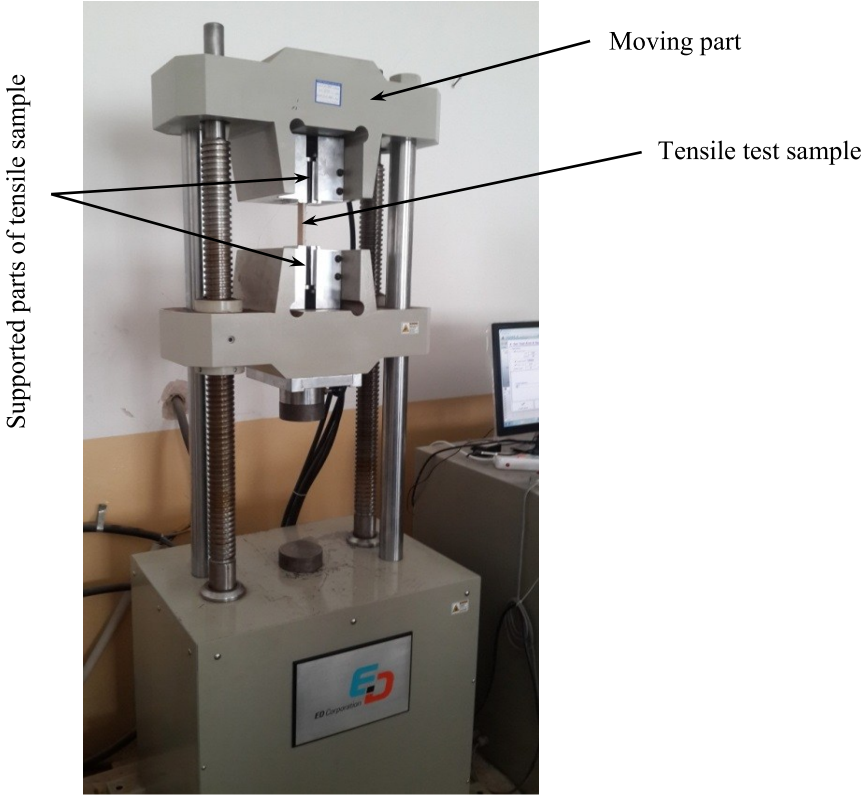

Figure 2. Tensile test machine.

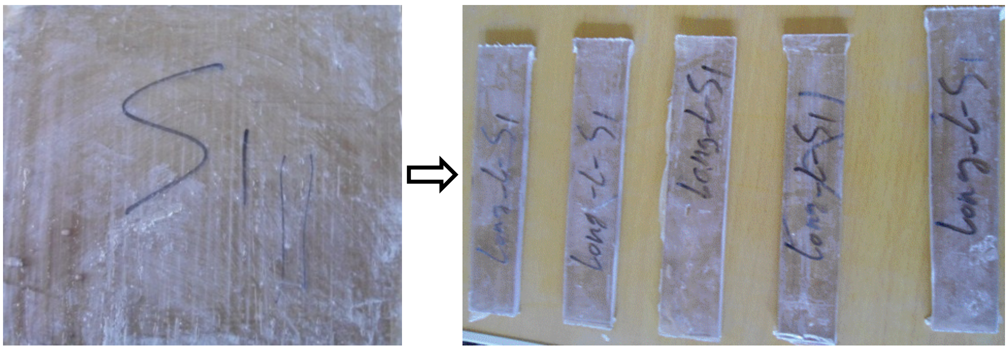

Figure 3. Tensile test samples used in experimental work.

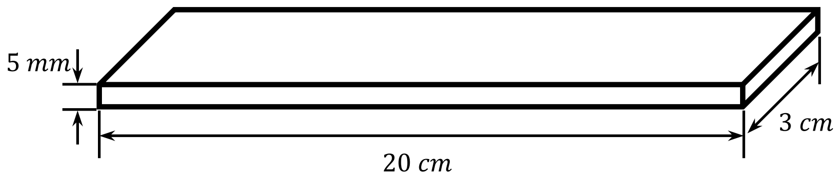

Figure 4. Dimensions of tensile test samples.

Table 1. Tensile test results of five samples of composite materials.

Sample Number	E_1 (GPa)	E_2 (GPa)
S_1	23.15	16.86
S_2	22.58	16.28
S_3	22.15	15.27
S_4	23.58	17.86
S_5	21.34	17.83
Average	22.56	16.82

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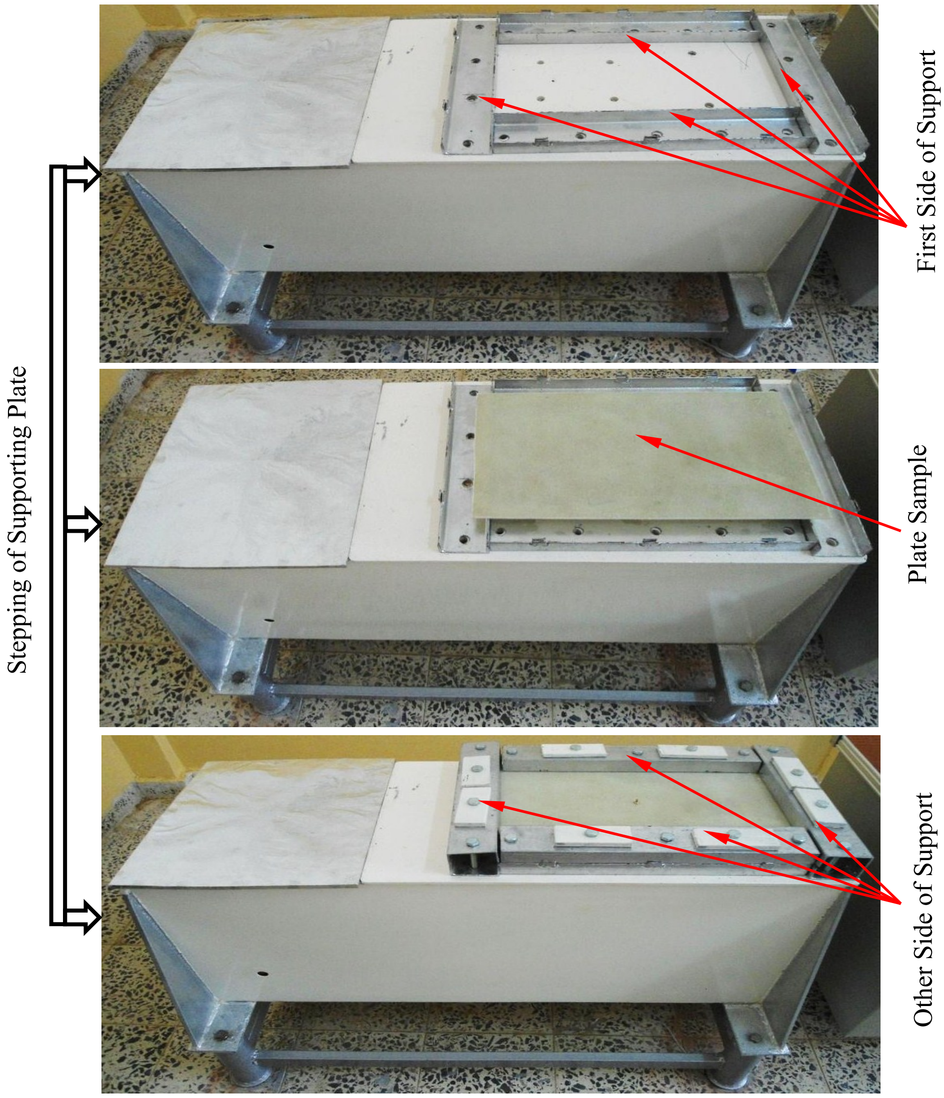


Figure 5. Test rig of the supported plate.

3. Numerical modeling

The numerical solution is achieved using the FEM which can be used for modeling the complex structures under specified loading which cannot be solved by an analytically for determination of deformations , stresses and natural frequencies. The FEM involves the replacement of the actual structure by elements which are connected by points known as nodes [11].

The numerical study of different composite laminated plate with cutout effect (shape, size and number) on deflection and stresses calculated by using the FEM using the ANSYS program (Ver. 14). Many types of elements are coded in ANSYS package such as the three dimensional shell elements shell 8 node and shell 281 which are convenient for the analysis of thin and moderately thick-shell problems .The element has 8 nodes, three translations about the three directions x,y and z axes and three rotations about the three axes x, y and z axes. Figure 6 shows the 8 nodes (I, J, K, L, M, N, O and Q) isoparametric shell element [12, 13]. The element shown is the SHELL 281takes into consideration the effects of transverse shear deformation. The stiffness due to transverse shear is given by [14]:

$$E = \begin{bmatrix} E_{11} & E_{12} \\ E_{12} & E_{22} \end{bmatrix} \quad (1)$$

The shell 281 is used in different applications such as linear, elastic-plastic, and hyper-elastic using different types of materials isotropic, orthotropic and anisotropic .The solution output are the nodal displacements and the stress resultants shown in Figure 7. The FE meshes are shown in the Figures 8 and 9 for different cutout shapes and number.

4. Results and Discussion

The results of cross ply and angle ply (with fiber orientation 45°) composite included the evaluation the deflection with various holes types with various sizes effect by using experimental and numerical investigation.

The results of composite cross-ply and angle-ply laminated plate have shown the effect of different cut out shape and size on the deflection and stresses in x-direction and y-direction of plate with different aspect ratio, boundary condition and laminated types shown in Figure 10. The materials properties and geometry of the four layers (N = 4) plate are [15]:

$E_1 = 20.4$ Gpa , $E_2 = 18.5$ Gpa , $\nu_{12} = 0.23$, $G_{12} = 5.59$ Gpa

And, $a = 1$ m , $b = 1$ m , $h = 0.02$ m

The static uniform distribution load applied on the plate are $q_o = 10\ \mathrm{kN/m^2}$, [16].

The results are divided for two parts, the first are the deflections evaluated experimentally and numerically with square and circular cutout size effect. The second are the deflection and stresses in x and y-directions evaluated numerically with square, circular and fillet cutout size effect.

The comparison between the experimental and numerical maximum deflection and stress results of simply supported cross ply and angle ply plate with aspect ratio (AR=1) with various cut outs sizes , are shown in Tables 2 to 5, for square and circular shapes, respectively. The results in tables have shown a good agreement between experimental and numerical investigation with a maximum discrepancy of deflection results about 10.5% and maximum discrepancy of stress results about (12.45%).

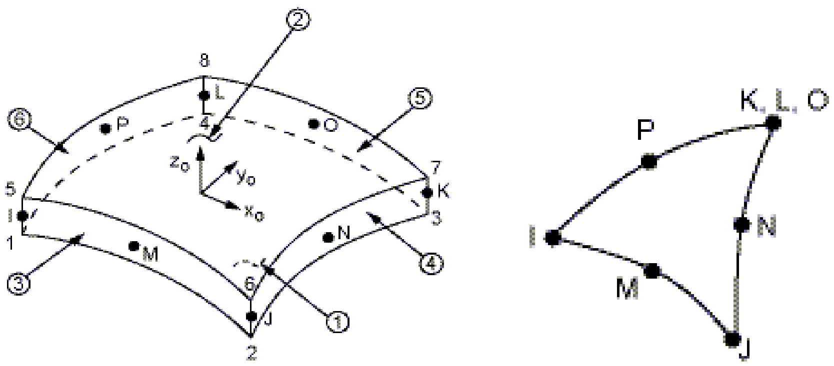


Figure 6. Shell 281 geometry.

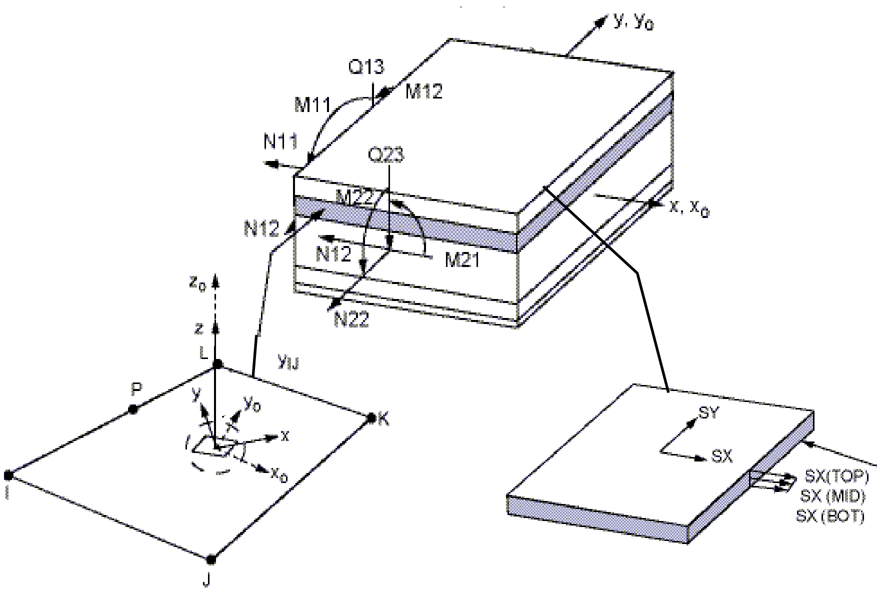


Figure 7. Shell 281 stress output.

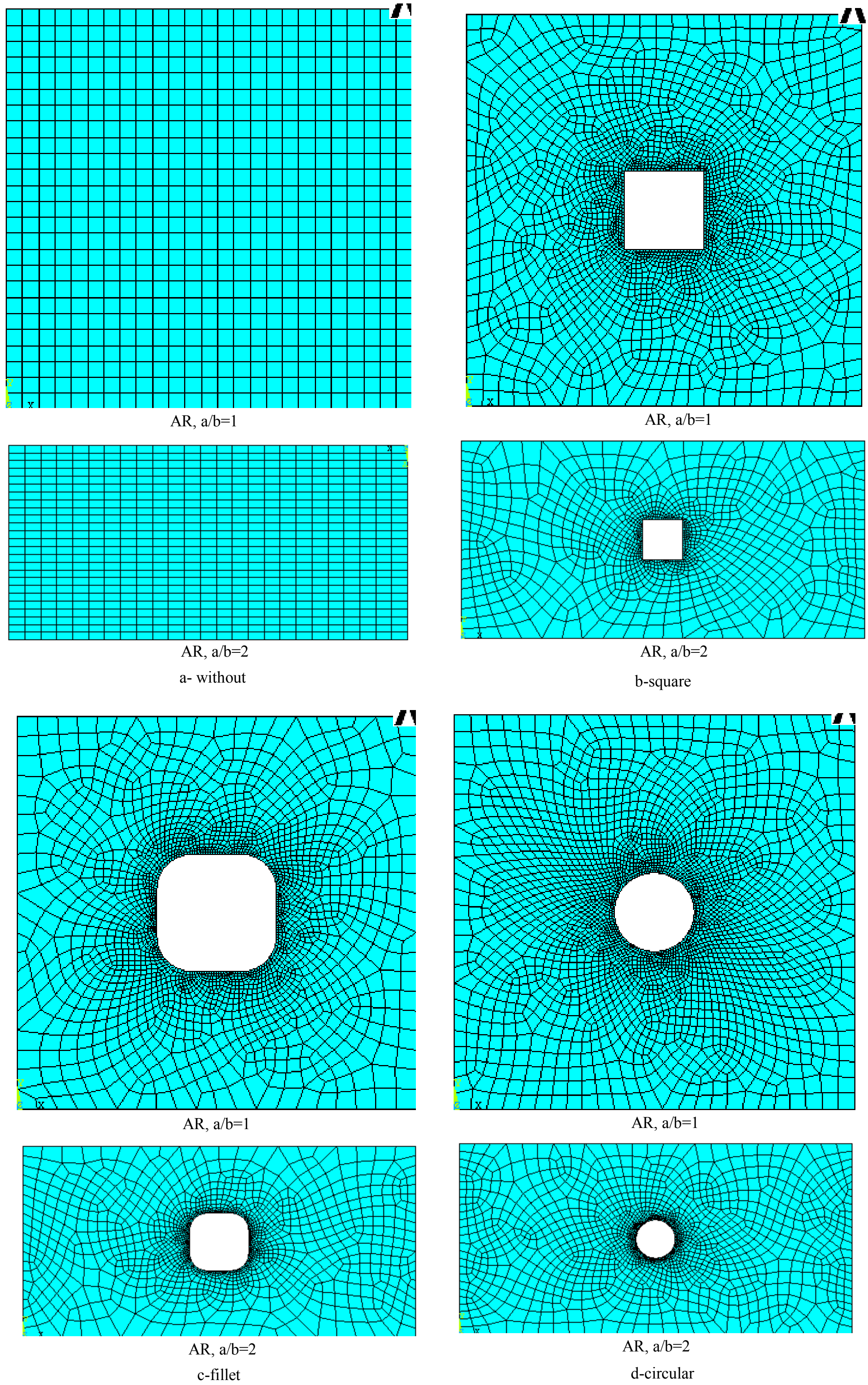


Figure 8. Finite element meshes of laminated plate with cut outs (AR =1,2).

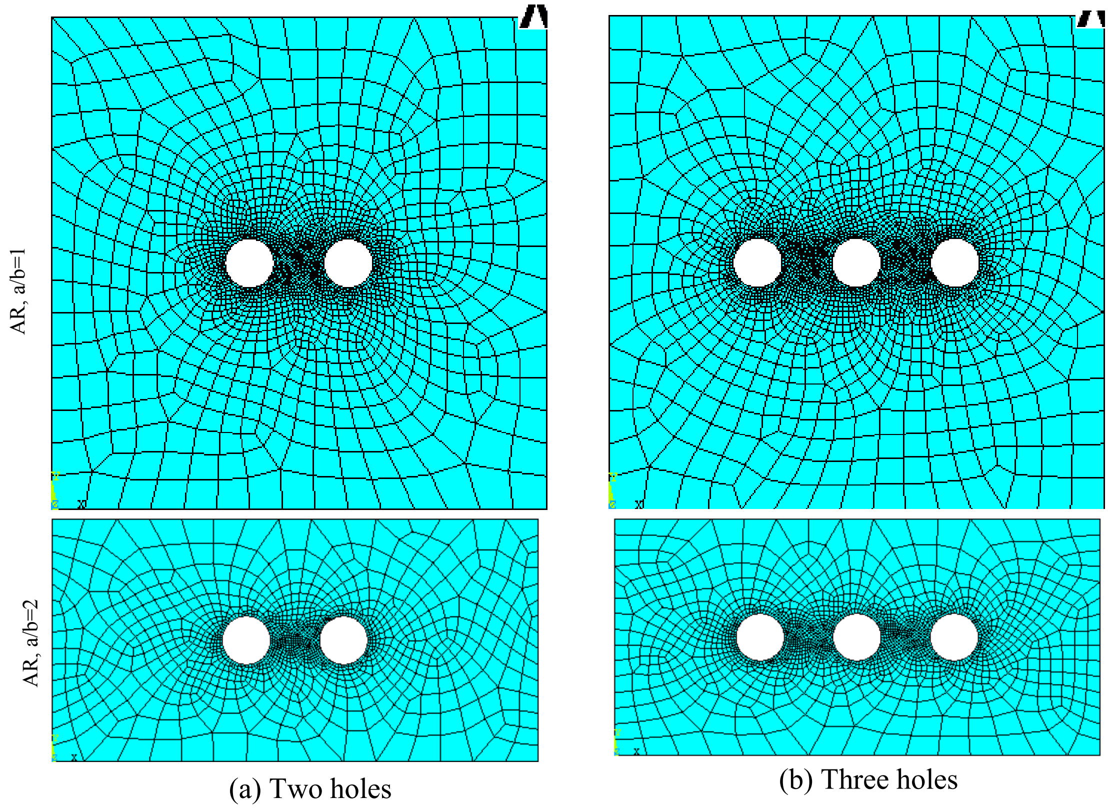


Figure 9. Finite element meshes of multi cut outs in laminated plate (AR=1,2).

The results are divided for two parts, the first are the deflections evaluated experimentally and numerically with square and circular cutout size effect. The second are the deflection and stresses in x and y-directions evaluated numerically with square, circular and fillet cutout size effect.
The comparison between the experimental and numerical maximum deflection and stress results of simply supported cross ply and angle ply plate with aspect ratio (AR=1) with various cut outs sizes , are shown in Tables 2 to 5, for square and circular shapes, respectively. The results in tables have shown a good agreement between experimental and numerical investigation with a maximum discrepancy of deflection results about 10.5% and maximum discrepancy of stress results about (12.45%).

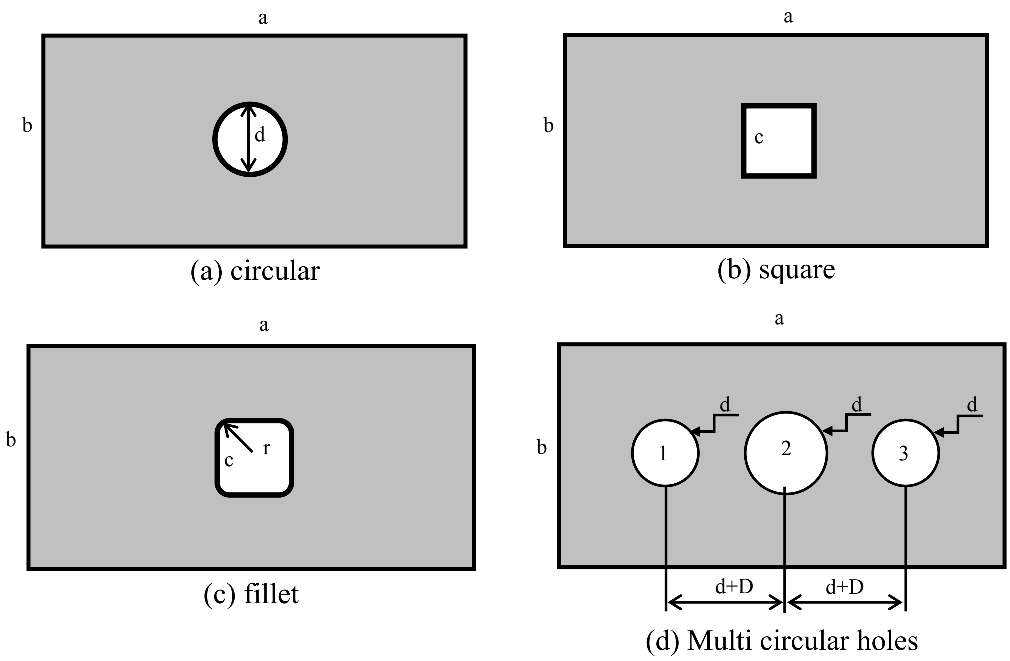


Figure 10 . Dimensions and shapes of cut outs in composite laminated plate.

Table 2. Deflection results of cross-ply and angle ply simply supported laminated plate with different square hole sizes.

Composite Laminated Plate Types	c/b	Exp.	Nu.	Discrepancy %
Cross Ply	0.0	1.0	1.105	10.5
	0.1	1.1	1.009	8.27
	0.3	1.15	1.226	6.61
	0.5	1.05	1.121	6.76
Angle Ply	0.0	0.60	0.629	4.83
	0.1	0.95	1.028	8.21
	0.3	1.20	1.290	7.50
	0.5	0.80	0.864	8.00

Table 3. Deflection results of cross-ply and angle ply simply supported laminated plate with different circular holes size.

Composite Laminated Plate Types	d/b	Exp.	Nu.	Discrepancy %
Cross Ply	0.0	1.05	1.105	5.24
	0.1	1.15	1.060	7.83
	0.3	1.30	1.350	3.85
	0.5	0.90	0.863	4.11
Angle Ply	0.0	0.60	0.629	4.83
	0.1	0.85	0.891	4.82
	0.3	1.00	0.93	7.00
	0.5	0.85	0.889	4.59

Table 4. Stress in x and y-direction results of cross-ply and angle ply simply supported laminated plate with different square hole sizes.

Composite Plate Types	c/b	σ_x (MPa)			σ_y (MPa)		
		Exp.	Nu.	Discrepancy %	Exp.	Nu.	Discrepancy %
Cross Ply	0.0	15.800	17.0	07.59	15.80	17.0	07.59
	0.1	34.890	37.7	08.05	32.15	34.4	07.00
	0.3	28.449	30.5	07.21	28.24	30.3	07.29
	0.5	19.587	21.9	11.81	18.23	20.5	12.45
Angle Ply	0.0	5.8430	6.35	8.68	05.89	6.35	07.81
	0.1	63.217	68.5	8.36	64.28	68.4	06.41
	0.3	43.289	47.3	9.27	48.32	52.6	08.86
	0.5	32.825	36.0	9.67	28.97	31.8	09.77

Table 5. Stress in x and y-direction results of cross-ply and angle ply simply supported laminated plate with different circular hole sizes.

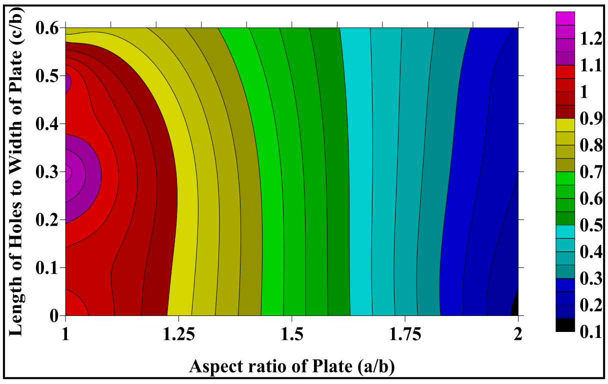
Composite Plate Types	d/b	σ_x (MPa)			σ_y (MPa)		
		Exp.	Nu.	Discrepancy %	Exp.	Nu.	Discrepancy %
Cross Ply	0.0	15.80	17.0	07.59	15.80	17.0	7.59
	0.1	50.24	52.6	04.70	40.27	43.4	7.77
	0.3	43.89	46.2	05.26	60.14	63.4	5.42
	0.5	16.54	18.5	11.85	30.87	32.9	6.58
Angle Ply	0.0	5.89	06.35	07.81	05.89	06.35	7.81
	0.1	22.65	24.00	05.96	18.89	20.60	9.05
	0.3	18.14	20.20	11.36	16.23	17.80	9.67
	0.5	14.21	15.50	09.08	17.11	18.50	8.12

The deflection and stress results for cross and angle-ply laminated plates included cut out under uniform bending loading are discussed as follows,

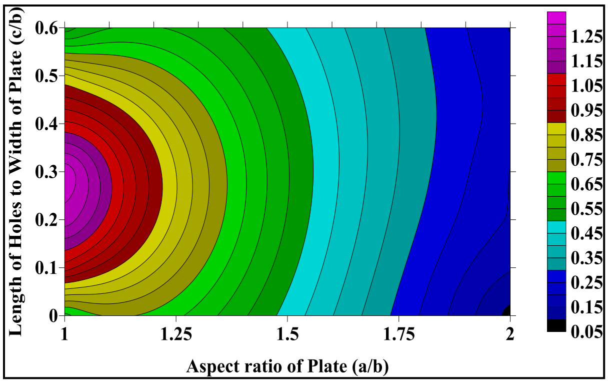
Figure 11 shows the contours of the effect of square with and without fillet, and circular , on maximum deflection (W) for cross-ply and angle-ply laminated simply supported plate, with N=4 and a=1 m, using different aspect ratios. Figure 12 shows the effect of square and circular cutout size, on maximum deflection (W) for cross-ply and angle-ply laminated clamped plate, with N=4 and a=1 m, and various aspect ratios.

Figure 13 Shows the contours and the effect of square with and without fillet, and circular cutout hole, on maximum stress in x-direction (σ_x) for cross-ply and angle-ply laminated simply supported plates, with N=4 and a=1 m, and different aspect ratios.

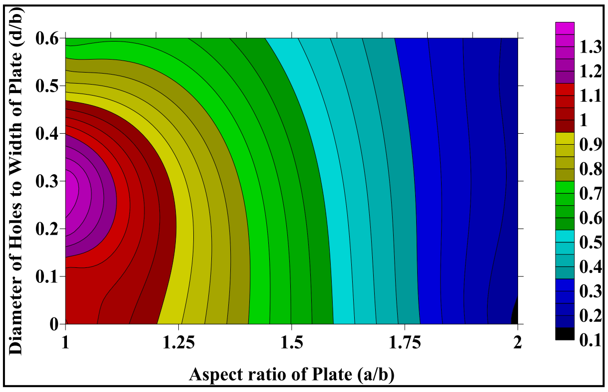
Figure 14 shows the contours of the effect of square and circular hole size, on maximum stress in x-direction (σ_x) for clamped cross-ply and angle-ply laminated plates, with N=4 and a=1 m, for different aspect ratios.



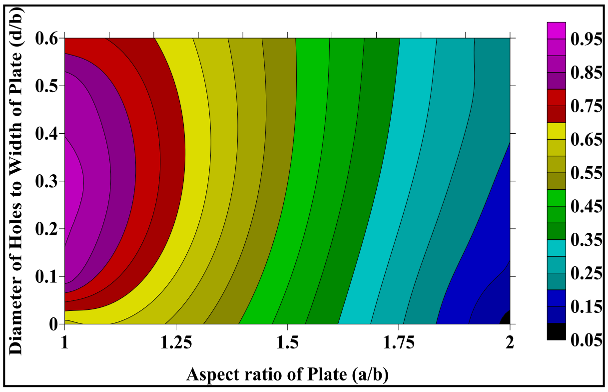
a. Square cutout effect-cross ply laminated plate.



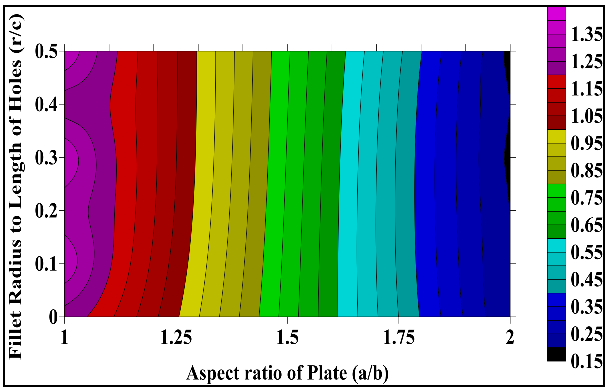
b. Square cutout effect-angle ply laminated plate.



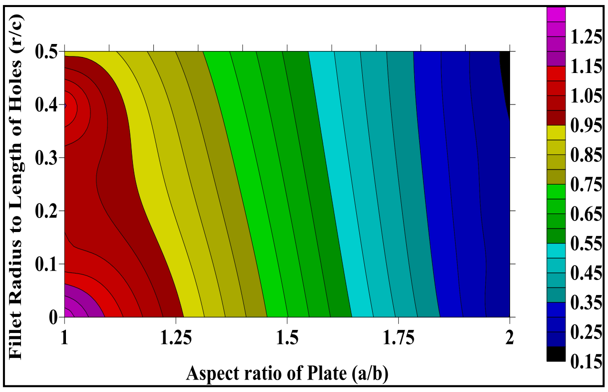
c. Circular hole effect-cross ply laminated plate.



d. Circular hole effect-angle ply laminated plate.

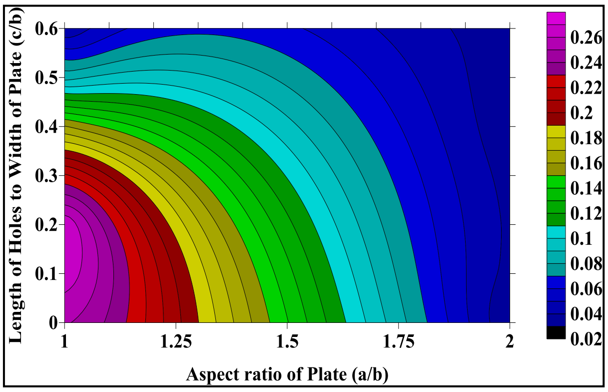


e. Fillet effect-cross ply laminated plate.

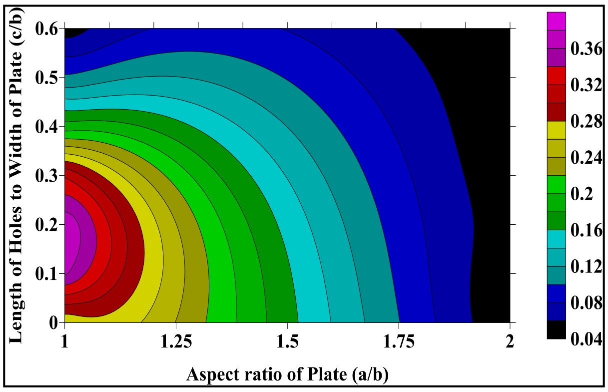


f. Fillet effect-angle ply laminated plate.

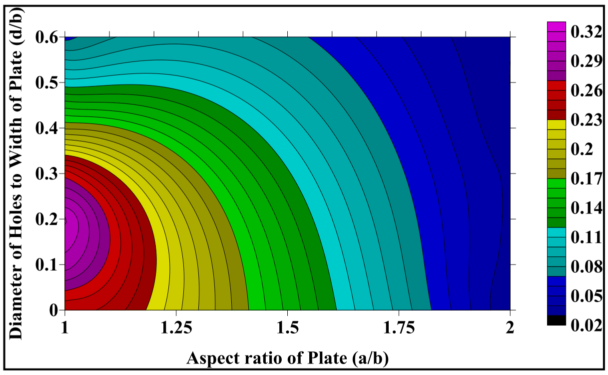
Figure 11. Contours of deflection W (mm) of simply supported cross-ply and angle ply plate with different types cut outs.



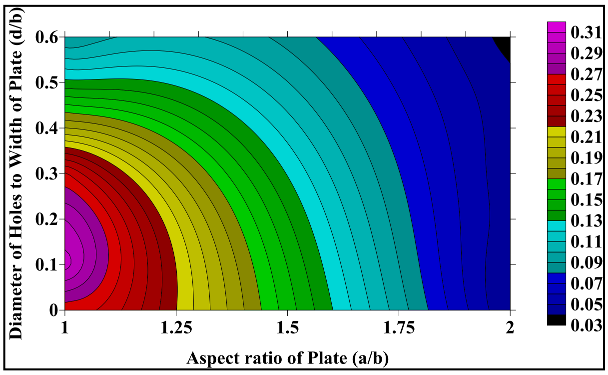
a. Square cutout effect-cross ply laminated plate.



b. Square cutout effect-angle ply laminated plate.

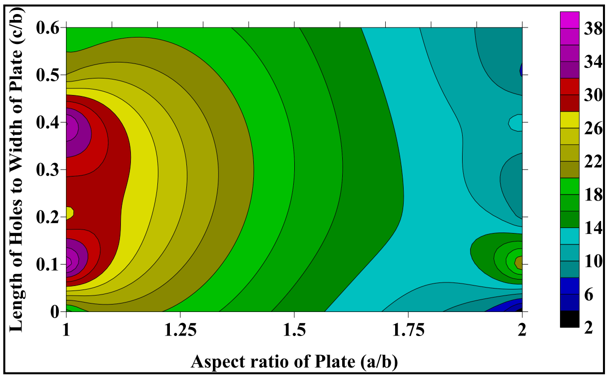


c. Circular hole effect-cross ply laminated plate.

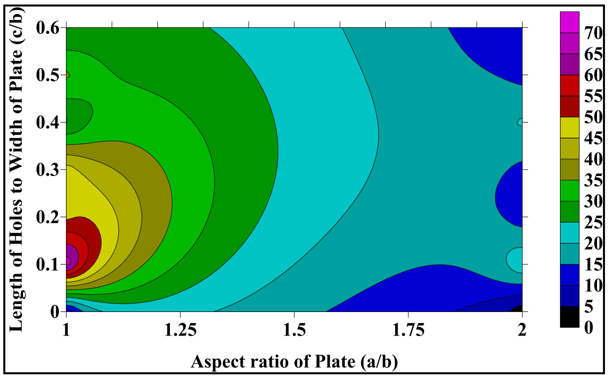


d. Circular hole effect-angle ply laminated plate.

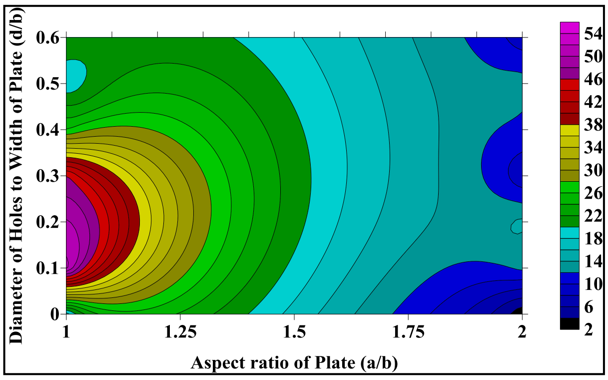
Figure 12. Maximum deflection W (mm) of clamped supported cross-ply and angle ply plate with various cut outs.



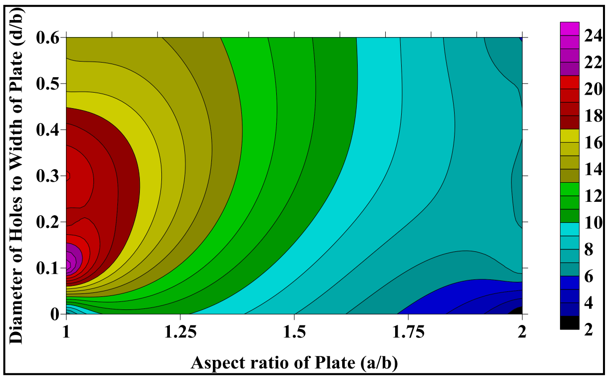
a. Square cutout effect-cross ply laminated plate.



b. Square cutout effect-angle ply laminated plate.

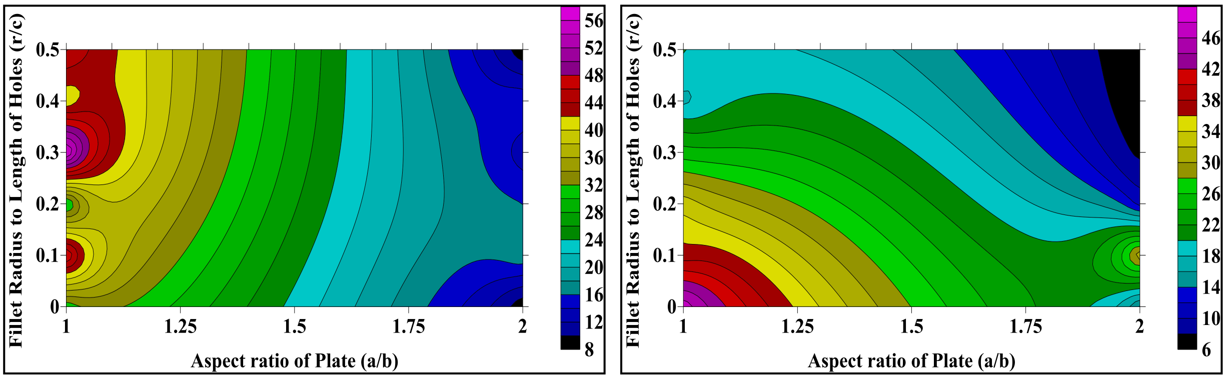


c. Circular hole effect-cross ply laminated plate.



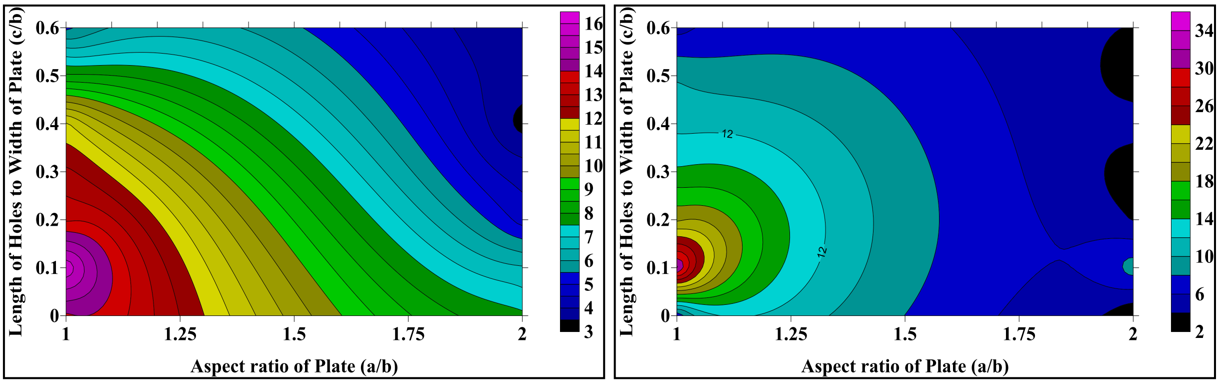
d. Circular hole effect-angle ply laminated plate.

Figure 13. Continued.

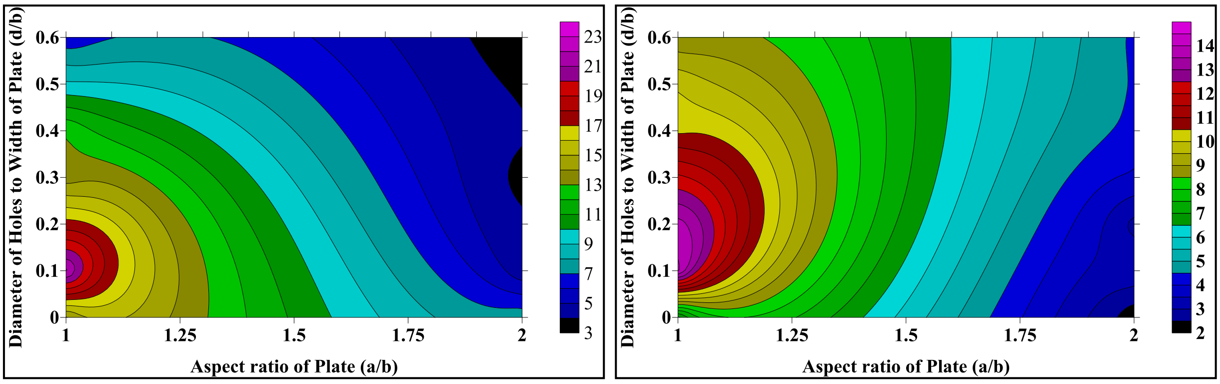


e. Fillet effect-cross ply laminated plate. f. Fillet effect-angle ply laminated plate.

Figure 13. Maximum Stress σ_x (Mpa) of simply supported cross-ply and angle ply plate with different cut outs effects.



a. Square cutout effect-cross ply laminated plate. b. Square cutout effect-angle ply laminated plate.



c. Circular hole effect-cross ply laminated plate. d. Circular hole effect-cross ply laminated plate.

Figure 14.Contours of Stress σ_x (Mpa) of clamped supported cross-ply and angle ply plate with different cut outs.

Also, Figure 15 Shows the contours of the effect of square with and without fillet, and circular, hole size, on maximum stress in y-direction (σ_y) for cross-ply and angle-ply laminate simply supported plates, with N=4 and a=1 m, for different aspect ratios.

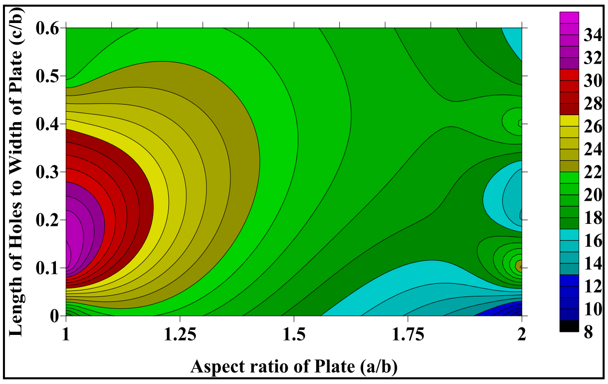
Figure 16 shows the contours of the effect of square and circular hole size, on maximum stress in y-direction (σ_y) for clamped cross-ply and angle-ply laminated plates, with N=4 and a=1 m, for different aspect ratios.

Figure 17 Shows the contours of the effect of number of circular holes on the deflection and stresses in x-direction and y-direction of simply supported cross-ply laminated plates for different aspect ratios , a/b=1 and 2, and hole size (d/b=0.1).

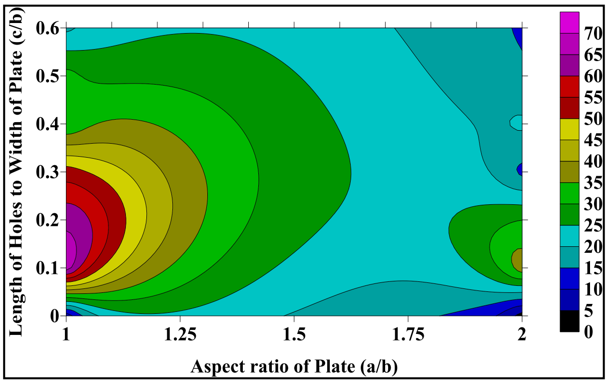
The above Figures show that the amplitude values of square cutout is less than for the circular hole of size (c/b, d/b=0.1 to 0.4), and more than for c (c/b, d/b=0.5 to 0.6) for the simply supported and clamped cross-ply laminated plates (a/b=1) and inversely in the simply supported angle-ply laminated plates (a/b=1), (with 4.8%, 13.76%, 9.16%, 6.975% for "c/b=d/b=0.1, 0.2, 0.3, 0.4" respectively) and (23%, 16.96% for "c/b=d/b=0.5, 0.6" respectively) for simply supported cross-ply laminated plates a/b=1.

Also, the amplitude values for square cut out is more than for circular hole for simply supported and clamped cross-ply and angle-ply laminated plates (a/b=2), with 0.6%, 12.85%, 26.4% for c/b=d/b=0.1, 0.4, 0.6 respectively for simply supported cross-ply laminated plates (a/b=2)) and 8.4%, 9.8% for c/b=d/b=0.1, 0.4 respectively for simply supported angle-ply laminated plates (a/b=2).

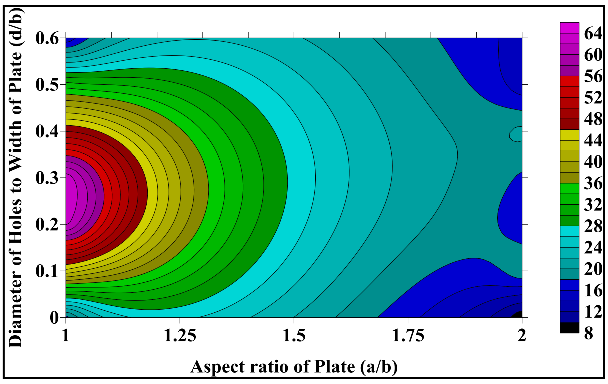
The cutout in the plate causes a stress concentration and decreases the stiffness and toughness of the plate, therefore, increases the developed stresses. The circular shape cut out causes uniform stresses around the hole, but the square type causes non-uniform stresses flow around the hole, therefore, the circular hole causes stress concentration less than that due to square type. Finally, deflection and stresses developed in the circular hole is less than that of square type.



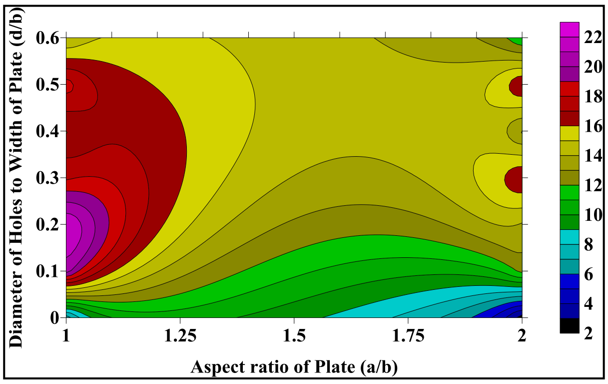
a. Square cutout effect-cross ply laminated plate.



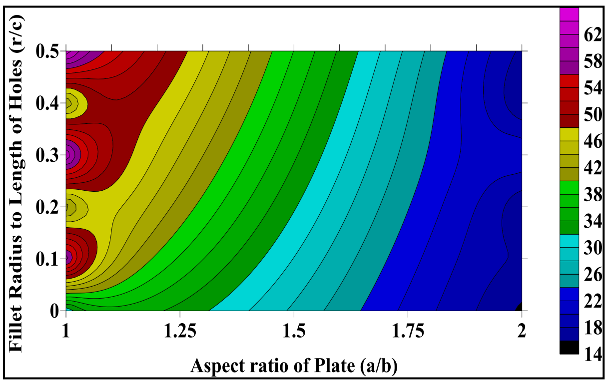
b. Square cutout effect-angle ply laminated plate.



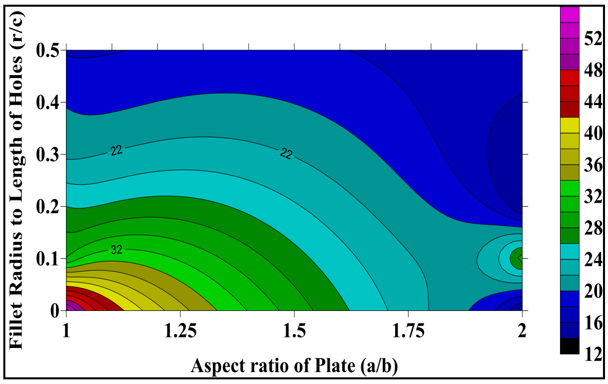
c. Circular hole effect-cross ply laminated plate.



d. Circular hole effect-angle ply laminated plate.

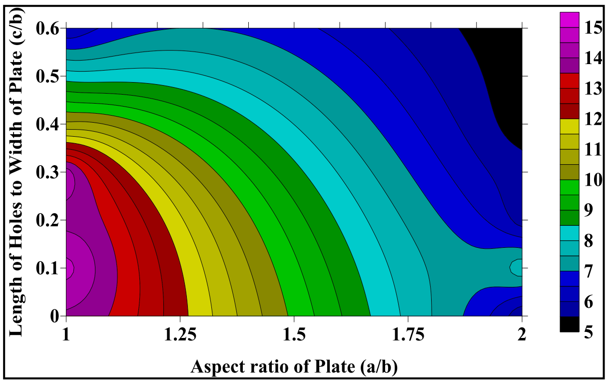


e. Fillet effect-cross ply laminated plate.

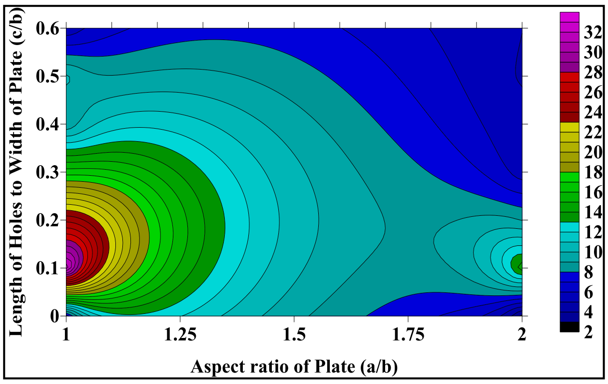


f. Fillet effect-angle ply laminated plate.

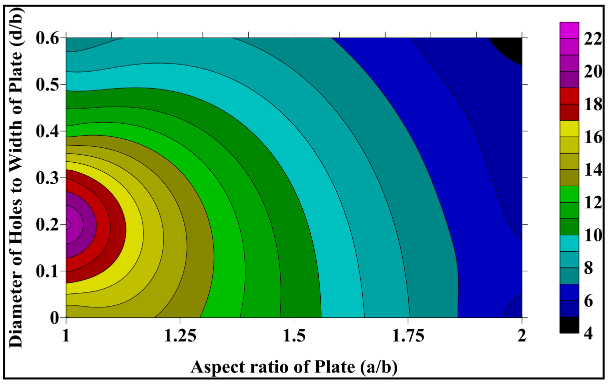
Figure 15. Contours of Stress σ_y (Mpa) of simply supported cross-ply and angle ply plate with different cut outs.



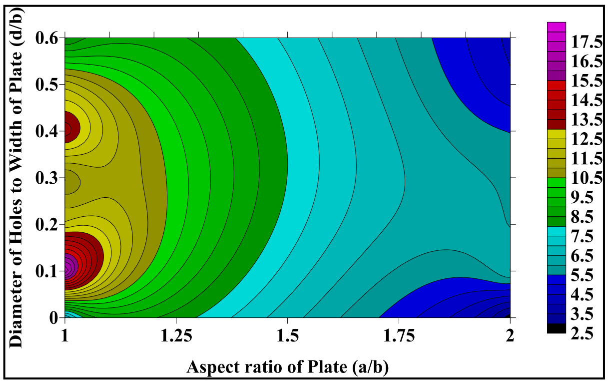
a. Square cutout effect-cross ply laminated plate.



b. Square cutout effect-angle ply laminated plate.

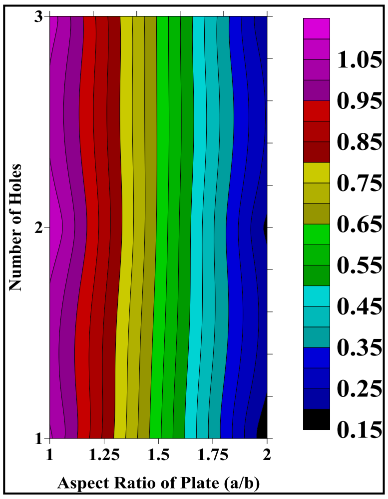


c. Circular hole effect-cross ply laminated plate.

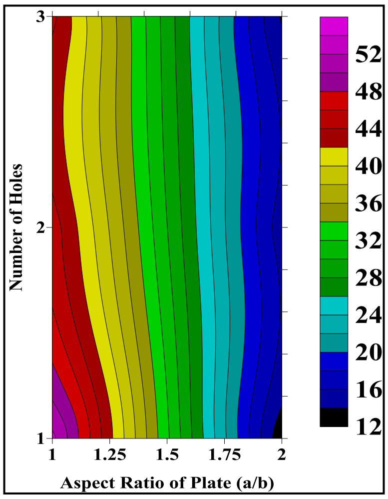


d. Circular hole effect-angle ply laminated plate.

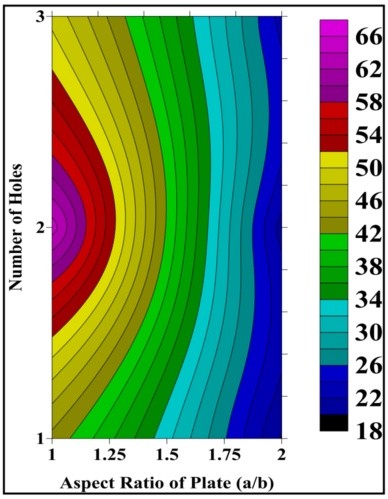
Figure 16. Contours of Stress σ_y (Mpa) of clamped supported cross-ply and angle ply plate with different cut outs.



a. Maximum Deflection W (mm)



b. Maximum Stress σ_x (Mpa)



c. Maximum Stress σ_y (Mpa)

Figure 17. Contours of maximum deflection and stresses in x and y-directions of simply supported cross-ply laminated plate with various number of circular holes, size d/b=0.1 and N=4.

5. Conclusions

The main conclusions for this work with cutout laminated plates are,

1. A good agreement was obtained between experimental and numerical techniques with a maximum discrepancy of (9.54 %).
2. The amplitude values of square cut out are less than that for other types in cross-ply laminated plates and more than in angle-ply laminated plates for aspect ratio a/b=1. Also the amplitude values of square one are more than for circular hole for laminated plates with aspect ratio a/b=2.
3. The stresses values of composite laminated plate with cutout are more than that without one, and the increasing of cutout size increase the stresses of laminated plate.

4. The stresses developed in composite laminated plate are decreased with increasing number of cut outs.
5. The increasing of fillet radius in square hole decreases the stress levels and the effect of circular hole is less than that in square cut out with and without fillet from the deflection and stress levels.

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