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Evaluation of Stress Concentration in Plate with Cutout and its Experimental Verification

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Abstract

The plates with cutouts are widely used in structural members. These cutout induces stress concentration in plate. A Plate is considered with different cutouts, such as circular, triangular and square cutout. The main objective of this study is to find out the stress concentration in plate with various cutouts and bluntness with different cutout orientation. For finding the stress concentration, a finite element program ANSYS is used. In this study three parameter are used as the shapes of cutout, the bluntness and the rotation of cutout. From analysis it is found that as the bluntness increases, stress concentration increases. The more important finding is that the stress concentration increases as the cutout become more oriented from baseline. This fact demonstrates that orientation is also relatively significant factor to reduce stress concentration factor. The experimental photoelastic test is carried out on Araldite model loaded in one direction for circular, square and triangular cutout. Results are compared with FE results. By comparing the results, it is found that the stress concentrations by Experimentation and by FEM are in good agreement.

Keywords: stress concentration, perforated plate, finite element analysis

1. INTRODUCTION

The plate with cutout or holes is called as perforated plate. The different types of shapes of cutout are used for different application. In general plates are easily manufactured and are widely used for fabrication of structural members and eventually for construction of civil and mechanical structures. The plate with holes are used in heat exchanger, coal washer, thresher machine, shadow masks, washing machine and many more. The holes in plate are arranged in circular, triangular and square pattern. Making cutout is not only for connecting but also reducing the weight of structural member. In most application the plate with cutout causes stress concentration near the cutout. It is predicted that the stress pattern near the cutout will be different as compared to plate without cutout. Actually stress concentration depends upon the different parameter; the type of shape of cutout, the plate with linear or nonlinear elastic material, orientation of cutout, and loading condition etc.

Most research on stress concentration focuses on structural member that are mostly subjected to stress concentration. This study mainly focuses on stress concentration analysis of steel plate with different type cutout and at different cutout orientation. In reality, other cutout shapes, rather than circulars, are widely used for plate-like structures. In the polygonal cases, it is known that significant design variables or factors are edge bluntness and rotation. The present FE analysis is based on the approach suggested by Jinho Woo and Won-Bae Na[1]. The comparison of FE results is carried out with photoelastic analysis.

2. FINITE ELEMENT MODEL

Finite element analyses are carried out for the stress concentration of perforated steel plates. The steel plates having dimensions 200 mm (x-direction), 200 mm (y-direction), and 5 mm (z-direction) is shown in Fig. 1. Material properties are Young's modulus of 200 GPa and poisons ratio of 0.3. The location of cutout is at the center of the plates. To clearly observe the concentration effect, the plate size is modeled as rather large for the cutout size. ANSYS, a general purpose finite element program, is used for analysis. An eight-node solid element is used for modeling. To investigate stress concentration in an elastic range, the plates are modeled as a linear elastic material. The plate is fixed at one edge and the loading condition is 20 MPa pressure is applied at other edge as shown in Fig. 1),

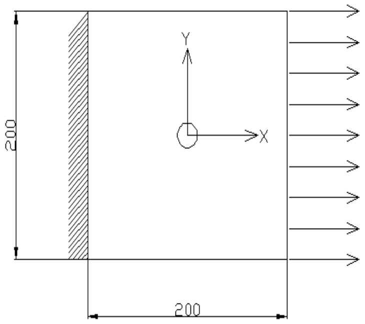
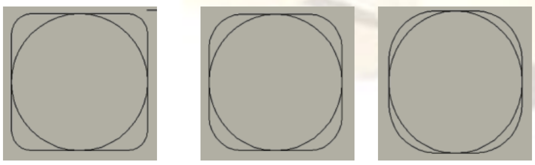


Fig.1 Loading condition ; Axial tensile pressure (all dimensions in mm)

3. CUTOUT SHAPES, BLUNTNESS AND ROTATION

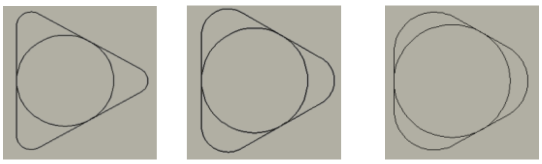
For analysis three cutout shapes – are considered as circular, square, and regular triangular. For the square and triangular cutouts the concept of inscribing circular is used, as shown in Figs. 2 and 3, to compare with the corresponding circular cutout. In the figures, the solid lined circle are the inscribing circle in the polygons.

The radius of the circular cutout is 10 mm. In general, to reduce the stress concentration at the edges of cutouts, the edges are rounded. In the study, rather than 'roundness', the term 'bluntness' is used as a physical terminology to effectively describe stress concentration. As shown in Fig. 4, a term 'radius ratio' is defined as the ratio of the edge radius (*r*) to the inscribing circular radius (*R*). Accordingly, bluntness is a counter measure to the radius ratio (*r/R*), because bluntness decreases as the radius ratio increases. For an extreme example, a circular cutout has a unit radius ratio but it has zero bluntness. In other words, the degree of bluntness decreases as *r/R* increases. Here, the term 'bluntness' is used to describe that the edges of polygons are blunt. For analysis consider a total of six different degrees of bluntness, including 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0 for the polygon cutouts are considered. Figs. 2 and 3 only show three of the six cases for the square and triangular cutouts as an illustration.



r/R=0.3 r/R=0.5 r/R=0.7

Fig.2. Square cutout



r/R=0.3 r/R=0.5 r/R=0.7

Fig.3. Triangular cutout

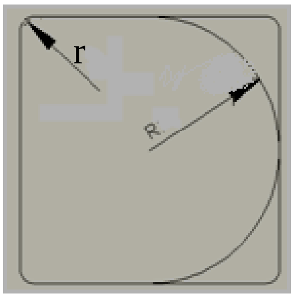
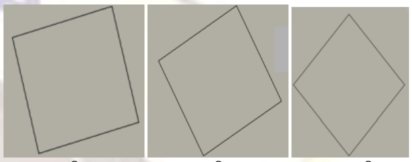
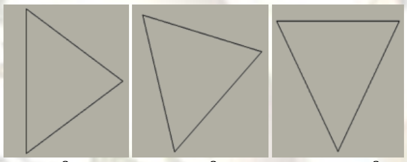


Fig.4.Radius ratio (r/R) defined by edge radius (r) and inscribing circular radius (R)



θ=15° θ=30° θ=45°

Fig.5. Square cutout



θ=0° θ=15° θ=30°

Fig.6. Triangular cutout

4. RESULTS

By considering the design variables or factors like cutout shapes, the degree of bluntness, and cutout rotations, the stress concentration pattern, the maximum von-Misses stress, and the stress concentration factor are evaluated. These results are presented in the forthcoming sections.

4.1 ANALYSIS WITH RESPECT TO CUTOUT SHAPES AND BLUNTNESS

As mentioned previously, there are three different cutout shapes as circular, square and triangular. In addition, for considering bluntness (a counter measure of *r/R*), a total of six radius ratios are considered as *r/R* = 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0, respectively. This section discusses the variation of stress concentration with respect to the cutout shapes and bluntness. All of the other factors remain the same.

Table 1: Maximum von-Misses stress and stress Concentration factor with respect to bluntness.

r /R	Triangular cutout		Square cutout	
	MPa	SCF	MPa	SCF
0.1	130.27	6.57	95.67	4.7835
0.3	103.419	5.17	70.12	3.506
0.5	89.246	4.46	62.32	3.116
0.7	75.85	3.77	58.8	2.94
0.9	69.407	3.47	58.15	2.9075
1	62.266	3.12	62.1	3.105

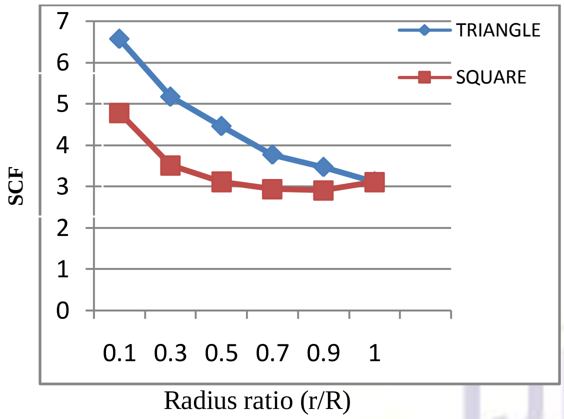


Fig 7. SCF with respect to radius ratio

In the case of the circular cutout, the maximum stress is 62.26 MPa and the stress concentration factor is 3.12.

In the case of the square cutouts, It is interesting to note that: (1) the stresses for *r/R* = 0.7 and 0.9 are smaller than that of *r/R* = 1.0 which is the circular cutout case, and (2) the maximum stress (95.67 MPa) occurs in the case of *r/R* = 0.1

In the case of the triangular cutouts, the results are quite consistent because: (1) all the stresses exceed that of the circular cutout case, and (2) unlike the square cases, starting from the maximum stress (130.27 MPa) the stresses decrease as the degrees of radius ratio increases. In other words, the stresses increase as the degree of bluntness increases.

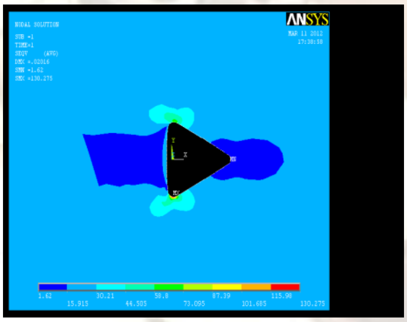


Fig 8. Von-misses Stress contour for plate with triangular cutout (r /R = 0.1)

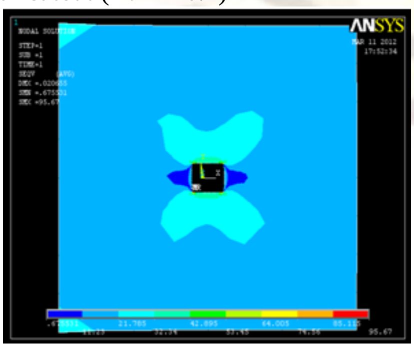


Fig.9.Von- Misses Stress contour for plate with square cutout (r /R =0.1)

To visualize the stress patterns, two Von-Misses stress contours are shown in Figs. 8 and 9. Fig. 8 shows the Von misses stress contour in the case of the triangular cutout with *r/R* = 0.1. Fig. 9 shows the von-misses stress contour in the case of the square cutout with *r/R* = 0.1.

It is interesting to note that stress concentration occurs in the broad range of the top and bottom sides in the case of the square cutout while stress concentration occurs in the narrow range of the top and bottom edges in the case of the triangular cutout. From the observation, it is conclude that the bluntness effect on the stress concentration patterns is also dependent on cutout shapes. However, in general, as bluntness increases, stress concentration increases.

4.2 ANALYSIS WITH RESPECT TO ROTATION OF CUTOUTS

This section discusses the stress analysis results by considering the rotation of the cutouts. In the cases of the triangular cutout, three rotation angles are considered, 0°, 15°, and 30°,while four angles,0°, 15°, 30° and 45° are considered in the case of square the cutout.

Table 2 shows the maximum von-Misses stresses and stress concentration factors for the steel plates with triangular cutouts, which have the three rotations. For all of the cases, the stresses increase as the rotation angles increase, as clearly shown in Fig. 10. With both effects of the rotation angle and bluntness, the maximum stress (174.29 MPa) occurs in the case of the bluntness of *r/R* = 0.1 (maximum bluntness) and the rotation of 30° (maximum rotation) shown in fig.12

Table 3 shows the maximum von-Misses stresses and stress concentration factors for the steel plates with square cutouts, which have the four rotations. From the results, it is observed that large differences occur in the maximum stresses, depending on the rotation angle. However, for all of the cases consistently, the stresses increase as the rotation angles increases. By combining the rotation effect with the bluntness effect, the maximum stress (181.74 MPa) occurs in the case of the *r/R* = 0.1 (maximum bluntness) and the rotation of 45° (maximum rotation). In addition, it is observed that with the exception of the zero rotation case, all the cases show that the maximum stress increases as the bluntness increases, as shown in Fig. 11

Fig. 13 shows the stress contour in the case of the square cutout with *r/R* = 0.1 and rotation 45°, which gives the maximum stress. This figure represents different patterns from that of Fig 9 showing the case of 0°. The maximum stress concentration occurs in the top and bottom edges. Fig. 12 shows the stress contour in the case of the triangular cutout with *r/R* = 0.1 and rotation 30°, which also gives the maximum stress. The maximum stress concentration occurs in the top edge.

Table 2: Maximum Von Misses stress and Stress concentration factor of triangular cutouts with rotation angle.

r/R	0^0 (MPa)	15^0 (MPa)	30^0 (MPa)	45^0 (MPa)
0.1	130.27	169.56	174.29	N/A
0.3	103.419	117.37	114.14	
0.5	89.246	80.87	85.37	
0.7	75.85	77.59	77.87	
0.9	69.407	66.18	66	
1	62.266	62.4	62.4	

r/R	0^0 (SCF)	15^0 (SCF)	30^0 (SCF)	45^0 (SCF)
0.1	6.51	8.478	8.7145	N/A
0.3	5.17	5.8685	5.707	
0.5	4.46	4.0435	4.2685	
0.7	3.77	3.8795	3.8935	
0.9	3.47	3.309	3.3	
1	3.12	3.12	3.12	

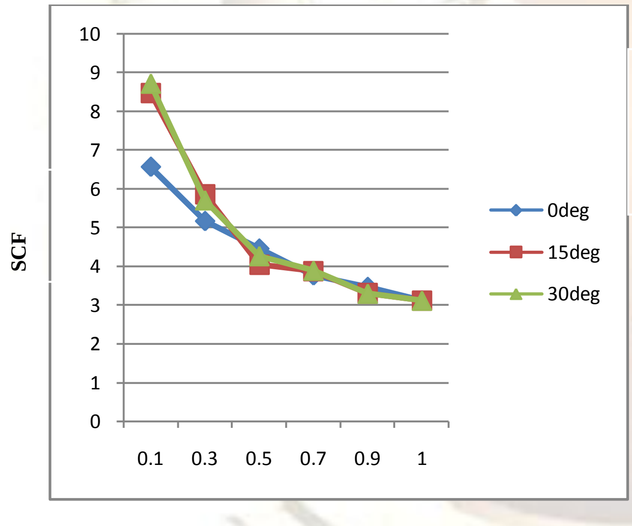
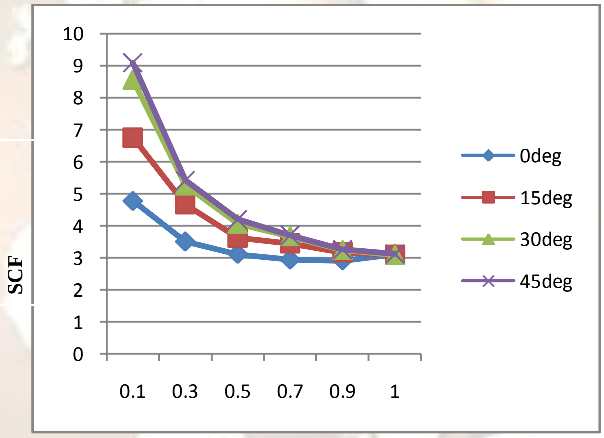


Fig.10. SCF with respect to rotation for triangular cutout

Table 3.Maximum Von Misses stress and Stress concentration factor for square cutouts with rotation angle

r/R	0^0 (MPa)	15^0 (MPa)	30^0 (MPa)	45^0 (MPa)
0.1	95.67	135.17	171.42	181.74
0.3	70.12	93.33	105.25	108.31
0.5	62.32	72.62	81.32	84.09
0.7	58.8	68.87	73.51	74.12
0.9	58.15	63.21	64.82	65.18
1	62.1	61.79	61.79	62.42

r/R	0^0 (SCF)	15^0 (SCF)	30^0 (SCF)	45^0 (SCF)
0.1	4.7835	6.7585	8.571	9.087
0.3	3.506	4.6665	5.2625	5.4155
0.5	3.116	3.631	4.066	4.2045
0.7	2.94	3.4435	3.6755	3.706
0.9	2.9075	3.1605	3.241	3.259
1	3.105	3.0895	3.0895	3.121



Radius ratio (r/R)

Fig.11. SCF with respect to rotation of square cutout

From the results (Figs. 8, 9,12, and 13), in the case of the square cutout, it is more advantageous to orient two sides of the square cutout to be perpendicular to the applied load because this reduces the maximum stress. For example, in the case of square cutouts with *r/R* = 0.1, the maximum stress decreases from 181.74. (θ = 45°) to 95.67 MPa (θ = 0°), which is a 86.07 MPa or 190% decrease. Similarly, in the case of the triangular cutout, it is also preferable to orient one side of the triangular cutout to be perpendicular to the applied load because of stress reduction. For example, in the case of triangular cutouts with *r/R* = 0.1, the maximum stress decreases from 174.29 (θ =30°) to 130.27 MPa (θ = 0°), which is a 44.02 MPa or 133% decrease. Accordingly, at the design stage, determining the direction of a major tensile load is required. By aligning these polygon cutouts as observed here, it can then reduce stress concentration.

From the results it is also observed that the stress concentration decreases as the bluntness of the cutouts decreases. For example, in the case of square cutouts with 45° rotation, the maximum stress decreases from 181.74 (*r/R* = 0.1) to 65.18 MPa (*r/R* = 0.9), which is a 116.56 MPa or 278.82% decrease. Similarly, in the case of triangular cutouts with 30° rotation, the maximum stress decreases from 174.29 (*r/R* = 0.1) to 66.00 MPa (*r/R*= 0.9) with 108.29 MPa or 264% decrease.

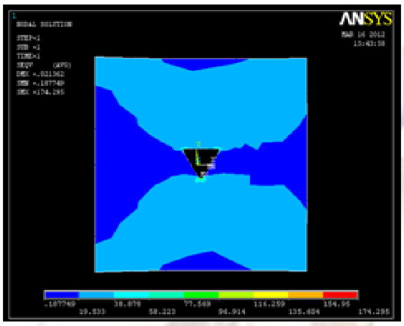


Fig.12. Stress contour for triangular cutout (r/R =0.1, $\theta=30^0$)

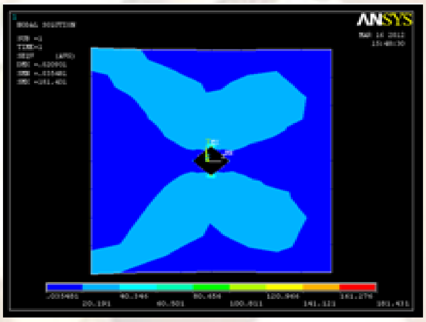


Fig.13. Stress contour for square cutout (r/R =0.1, $\theta=45^0$)

To minimize the stress concentration of the steel plates with polygon cutouts, the cutouts should have smooth edges and proper rotations. In other words, by controlling the smoothness (or bluntness) and rotation, we can minimize the stress concentration of the perforated steel plates. Among bluntness and rotation, controlling bluntness is analytically preferable to minimize the stress concentration. It is seen that the FE results obtained are in good agreement with the results reported by Jinho Woo and Won-Bae Na[1].with few deviations.

5 EXPERIMENTAL VERIFICATION OF STRESSES USING PHOTOELASTICITY

To study the stress distribution in a plate with cutout a Photoelastic test is done on Araldite model uniformly loaded in one direction. The models are prepared with dimensions 140 mm in x direction and 50 mm in y direction and 6 mm thick. For photoelastic test three cutout shapes are considered i.e. circular, square and triangular without bluntness. For square and triangular cutout inscribing circle is used. The radius of circular cutout is 9 mm. The location of cutout is at the centre of plate. The plate is fixed at one edge and the loading condition 2 MPa is applied at other edge.

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5.1 CASTING PROCEDURE FOR PREAPARATION OF SHEET

Araldite AY-103 along with hardener HY-951 is used for casting the sheets. For every 100 cc of araldite 10.5 cc of hardener is mixed. The resin is heated in oven up to 50° C to 80°C for about one hours to remove all air bubbles and moisture. Then it is cooled down slowly to the room temp. The hardener is added slowly by stirring the mixture continuously. The mixture should be stirred in one direction for ten minutes till it is transparent, clear and homogeneous.

The mould is completely filled by the mixture, i.e. up to the top surface. The mould is kept at this position for proper curing at room temperature. For easy removal of the sheet from the mould, the curing time of sixteen to eighteen hours is sufficient. After curing time the sheet is removed from the mould carefully. The sheet in this stage is slightly plastic. So it is kept on the perfect flat transparent glass for further curing. The total curing time is about one week.

5.2 PREPARATION OF PHOTOELASTIC MODEL WITH CUTOUT AND CALIBRATION DISC

The drawing of plate is prepared on AUTOCAD to the actual size of plate with circular, triangular and square cutout. Then the drawing is pasted on the Photoelastic sheet and it is cut by using model cutter, providing 2 to 3 mm allowance. Finally model is finished to the required size by filing and using fine emery paper. The required holes are drilled in the model for proper mounting in the loading fixture. The model of plate with circular, triangular and square cutout is used for analysis.

To prepare circular disc of 6.5 cm. diameter, The Photoelastic sheet is cut and fixed between two cylindrical wooden pieces by giving the rubber packing for proper grip. One wooden piece is fixed in the chuck and other is supported by tail stock and dead center of the lathe. The machining is done at high speed and low feed, with low depth of cut. Coolant is added continuously to avoid the stress locking.

5.3 DETERMINATION OF FRACTIONAL FRINGE ORDER

To determine the accurate fringe order, first the lower order fringe is passed through point of interest by rotating analyser in clockwise direction and analyser reading is noted down. The actual fringe order is calculated by adding analyser reading to lower order fringe. Then higher order fringe is passed through point of interest by rotating analyser in anticlockwise direction and analyser reading is noted down. The actual fringe order is determined by subtracting analyser reading from higher order fringe.

The average of both the readings are taken to determine actual fringe order for calculation of material fringe value.

The isochromatic fringe pattern in loaded specimen for calibration disc and plate with circular, square and triangular cutout is shown in fig. 14 to 17.

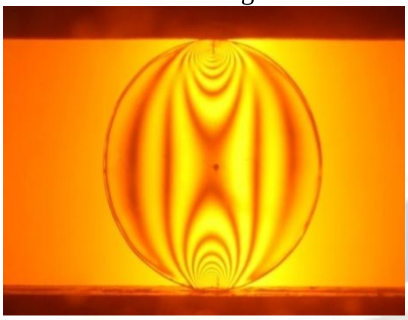

Fig. 14 Isochromatic Fringe pattern for calibration disc

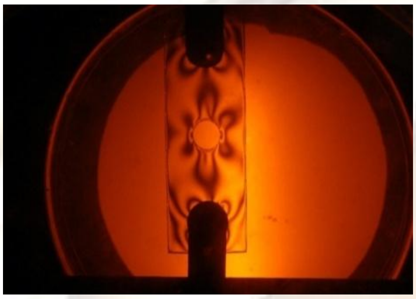

Fig.15. Isochromatic Fringe pattern for circular cutout.

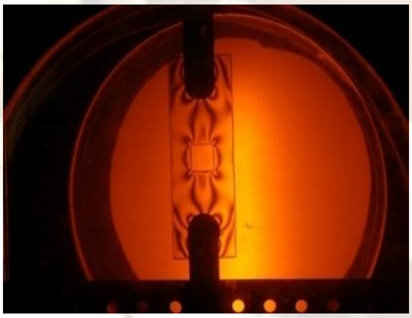

Fig.16. Isochromatic Fringe pattern for square cutout.

Fig.17. Isochromatic Fringe pattern for triangular cutout.

From Experimental analysis it is found that the stress concentration for circular cutout is less than square and triangular cutout and the stress concentration for square cutout is less than triangular cutout. The triangular cutout has highest stress concentration. The same analysis is also carried out by FEM. The results by experimentation and by FEM are compared in the table 4.

TABLE 4:COMPARISION OF STRESSES

Sr. no.	Shape of cutout	Experimental stress (MPa)	FEM stress (MPa)
1	Circular	7.58	7.17
2	Square	10.99	10.10
3	Triangular	23.65	23.52

From table it is observed that the stress concentration for cutout by experimentation and by FEM, are in close agreement for various cutout and shapes.

6. CONCLUSION

From the finite element analyses, the following findings are reported.

From analysis it is observed that the maximum stress in the perforated steel plate with the circular cutout is about three times the applied load. Depending on cutout shapes, bluntness and rotation effects on stress concentration vary. However, in general, as bluntness increases, the stress concentration increases,. The more important finding is that as the stress concentration increases ,as the cutout become more oriented from baseline. In general, in the case of the triangular cutout, it is preferable to orient one side of the triangular cutout to be perpendicular to the applied load. Similarly, in the case of the square cutout, it is more advantageous to orient two sides of square cutout to be perpendicular to the applied load. Therefore, at the design stage, determining the direction of a major tensile load is required. By aligning these polygon cutouts properly, it can then reduce stress concentration.

From the experimental analysis for plate with circular, square and triangular cutout without bluntness, the stress concentration for circular cutout is less than the square and triangular cutout and the stress concentration for square cutout is less than the triangular cutout. The stress concentration for triangular cutout is highest. By comparing the results it is found that, the stress concentration by experimentation and by FEM are in close agreement.

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