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Analyzing Stress Concentration Factor in Finite Plate with Different Polygonal Discontinuities Under Uniaxial Compression Using FEM

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ABSTRACT

A geometric, or theoretical, stress-concentration factor is the ratio of the actual maximum stress at the discontinuity to the nominal stress. Stress concentrations occur when there are irregularities in the geometry or material of a structural component that cause an interruption to the flow of stress. This arises from such details as holes, grooves, notches, and fillets. A detailed understanding of the stress concentration around the hole is essential for optimal design and resilience to mechanical failure. Therefore, in the design of structures, it is essential to study the effects of polygonal discontinuities in structures to achieve convenient and efficient designs. The current paper investigated the stress concentration factor around the polygonal holes in the finite structural steel plate, assuming a plane stress state and uniaxial compression loading. The present study provides a complete finite element analysis of stress concentrations in structural steel plates with polygonal cutouts (triangular, square, pentagonal, and hexagonal), in contrast to the side ratio of a polygonal hole, and the length, and height ratio of a square hole. The increasing order of stresses and SCF are square, triangular, pentagonal, and hexagonal. Due to the more edges of polygonal shapes parallel to the loading direction and minimum corners positioned in the direction of loading, a square-shaped hole produces 40% less SCF than a hexagonal-shaped hole.

Keywords: *Stress concentration factor, finite plate, finite element method, polygonal cutout, structural discontinuity*

ABBREVIATIONS

SCF - Stress concentration factor, FEA - Finite element analysis, FGM - Finite graded material, FEM - Finite element method

NOTATIONS

L- length of plate (mm), H- height of plate (mm), l-side of polygonal hole (mm), *l*- length of square hole (mm) , h- height of square hole (mm), t-thickness of hole (mm), N - Number of side of polygonal cutout in a plate, P- Applied load (N), σ_{max} - maximum stress at the discontinuity (N/mm^2), σ_{nom} - nominal or background stress (N/mm^2), l/L – side ratio of polygonal hole, *l*/L – length ratio of square hole, h/H- height ratio of square hole, d – polygonal cutout maximum length along the loading direction.

INTRODUCTION

In marine and aerospace structures, thin plates are frequently used. For practical purposes, such as to lighten the system's weight and to allow access to system components, various types of holes or openings are typically made in the plates. Its many applications require different geometric discontinuities of different sizes and shapes. Due to the presence of holes or openings, high stresses and stress concentrations are produced around holes or openings when a plate is subjected to tension or shear loading. The size of the plate and the material anisotropy both have an impact on the stresses in the plate and increase the stress concentration around the hole (Patel et al. 2022).

A stress concentration is a ratio of the maximum (highest) stress in the element to the nominal (reference) stress.

$K_t = \frac{\sigma_{max}}{\sigma_{nom}}$	(1)
$\sigma_{nom} = \frac{P}{(H-\mathrm{d}) \times t}$	(2)

A detailed understanding of the stress distribution around the hole is very important for optimal design and resilience to mechanical failure. A numerical approach can be used to find the maximum stress concentration for different complex geometries with considering time or cost constraints. Figure 1 shows the geometry of plate with pentagonal hole. Here, distance d is varied as per the shape of polygonal hole. The side ratio (l/L) of polygonal hole and length ratio (*l*/L) and height ratio (h/H) of square hole are three parameters taken into account in the calculation.

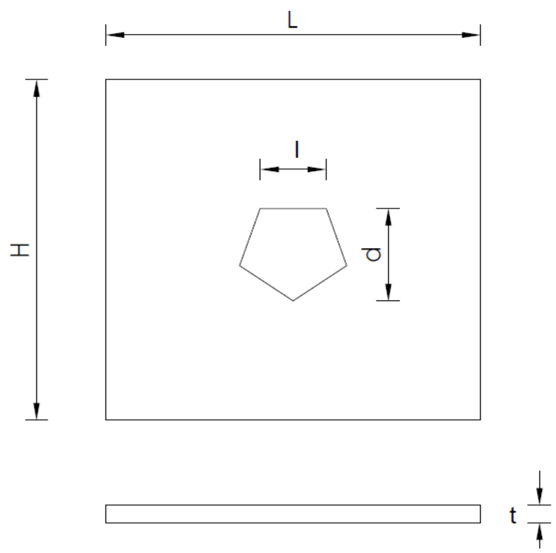


FIGURE 1. The geometry of plate with pentagonal hole

Many researchers are constantly concerned with the stress concentration issue of a plate with a hole, which must be taken into account in the design of structures. Danish Handa et al. determined stress concentration by FEA on metallic flat plates with circular and elliptical holes under uniaxial tensile load for varied diameters. They compared it with the experimental literature evaluated. When results are compared, there is a significant difference in stress concentration between the same design of circular and elliptical holes (Handa 2017). Investigation of stress generation in a plate with an inclined circular hole under different uniaxial tensile loading was presented by M. Pandey. He had done FEA in ANSYS for finding stresses with a circular hole with an inclination angle 30°, 45°, and 90° and minimum SCF was found at an inclination angle of 45°. Maximum SCF was generated at the vertical hole, with an inclination angle of 90° (Manish Pandey et al. 2021). The modified mapping collocation approach was used by E. Madenci et al. to investigate the behavior of finite composite laminates with multiple circular holes under suitable material and geometric symmetry criteria. Without the need for symmetry criteria, the analysis can accommodate the direct imposition of traction conditions and displacement limits in the case of a laminate with a single hole (Madenci et al. 1993). To determine the impact of auxiliary holes surrounding the primary (central) hole in a finite plate under uniaxial tension, Rajaiah et al. used two-dimensional photoelasticity methods and got an isochromatic fringe pattern. Then, two different sequences of the circular hole and auxiliary hole layouts are optimized with the optimization process, and SCF is reduced to produce results for a variety of diameter-to-width d/w ratios (Rajaiah and Naik, 1984).

FEA, analytical study, and experimental analysis performed by Laxman Bharambe et al. for circular, square, and triangular cutouts without bluntness in mild steel plates (Bharambe and Kolhe, 2019) The complex variable method of Muskhelishvili's with the stress functions was used by Zuxing Pan et al. for the study of stress concentration around a rectangular hole in a finite plate subjected to uniaxial tension (Pan et al. 2013).

Investigation of the effects of cut-out orientation and bluntness in an aluminum plate with a triangular and square cut-out under uniaxial loading was done by M. M. Kumar et al. subjected to uniaxial loading (M Mohan Kumar et al. 2013). Determination of the impact of hexagonal cutout roundness and orientation on stress concentration in a plate under tensile loading was obtained by M. Patil et al. (Patil and Ajay More, 2021). Analysis of stresses and stress intensity factor around the hypocycloidal hole-shaped holes and polygonal in anisotropic finite plates was found by M.M. Chauhan et al. with use of generalised method under in-plane loading in conjunction with the boundary collocation method. He had reduced the stress concentration at the edges of hole using variation in FGM thickness material. (Chauhan and Sharma, 2016) (Chauhan and Sharma, 2015) (Chauhan et al. 2016). O. Maksymovych et al. obtained the effect of stress concentration near dies, holes, and cracks in the half plane and dynamic loading plate using integral equations based on Green-type solutions (Maksymovych et al. 2021) (Maksymovych and Solyar, 2022).

Sachin. D et al. investigated the effect of stress concentration due to regular and oblique tapered holes in the finite plates subjected to tensile loading. They obtained the value of maximum equivalent von-mises stress generated with the help of analysis software. He concluded that the load applied had an equal distribution of the highest stress along the perpendicular side of the tapered hole (Sachin, S.G. Gopal Krishne and B. Mallikarjun 2015). In the era of finding stress concentration, R. H. Patel et al. have pointed out various parameters affecting stress concentration due to the different shaped holes (Patel and Patel, 2022). Impact of a Shoulder Fillet Round Bar's Curved Surface on the Stress Concentration Factor for Axial Tension Loading was done by H. Prajapati et al. (Prajapati and Patel 2022).

Rani et al. extended more study to employ the extended finite element method to quantitatively investigate the stress concentration surrounding the center elliptical inclusion covered in functionally graded material (Rani et al. 2022). Jaiswal et al. used a method for modeling functionally graded material (FGM) in the finite element method (FEM)-based software ANSYS and to lower the stress concentration by applying the FGM ring around the rounded rectangular slot subjected to tensile loading (Jaiswal et al. 2022). Most researchers applied the boundary collocation method to map the function infinite/finite, composite/isotropic/ anisotropic plate with circular, polygonal, elliptical, multicircular, hypocycloidal, and hypotrochoids holes while also using the analytical Muskhelishvili's complex variable method to analyze the stress function.

The stress concentration caused by u-shaped notches, circular, square, triangular, rectangular, and elliptical cutouts without bluntness was found by the author in a plate subjected to uniaxial tensile loading (Louhghalam et al. 2011; Rahman 2018; Santos et al. 2016; Farande and Kulkarni 2016; Rajaiah and Naik 1984; Jabur 2016; Handa 2017; Gunwant et al. 2016). To illustrate the impact of stress concentration on a plate with a central circular and central triangular hole, the author chose biaxial loading (Sahu 2017) (M. Dehgani 2018) (M. Jafari et al. 2018) (Bayati Chaleshtari & Jafari 2018). To determine stresses produced in orthotropic plates with circular holes during bending, C.A. Penaloza et al. used FEA (Penaloza et al. 2018).

Most of the researcher considered the uni-axial tensile force and suggested that to be considered the uni-axial compressive load for future work. In our case, the uni-axial compressive load considered for investigation.

Here, we have studied a major area related to stress concentration. For the designing task, significant applications are in the mechanical field, so we need to select appropriate polygonal shapes in the plate and optimize the shape for particular applications. It's necessary to study all the shapes under the various loading conditions and check the side, length, and height ratio on the stress concentration in various polygonal holes in a plate. The information regarding the effect of the side ratio of a polygonal hole, the length and height ratio of the square hole, and their results were not mentioned in any available literature within the referred literature review. Here, an effort is made to measure the stresses and the stress concentration factor at the regular polygonal cutouts in the finite isotropic plates subject to compression loading. The FEA approach is used to determine the SCF. The impact of increasing side ratio (area of polygonal cutouts) and loading direction on the length and height ratio on SCF is identified. This research gap has been supported with the followed literature review presented in the literature section.

MATERIALS AND METHODS

As per the IS standard addresses the specifications for steel used in structural work, including micro-alloyed steel plates, strips, forms and sections (angles, tees, beams, channels, flats, bars, etc.) The steels are appropriate for general technical applications and for welded, bolted, and riveted structures (*Indian Standard Hot Rolled Medium and High Tensile Structural Steel — Specification*, 2011). In the current study, structural steel has been considered for stress concentration. Our intention in selecting the material is not to find stress concentration directly; still, stress concentration is a function of the geometry only, and for the identify maximum stresses and SCF, structural steel has been taken for the study. The automotive industry uses the finite element method (FEM) as the standard method for predicting the vibrational response of vehicles. The discretization process represents a body by dividing it up into an equivalent system of smaller bodies or units (finite elements) connected at nodes or places that are shared by two or more elements, boundary lines, or surfaces (Shinde and Thombare, 2014).

TABLE 1. Material properties of Structural steel IS 2062 (Isotropic properties) (*Indian Standard Hot Rolled Medium and High Tensile Structural Steel — Specification*, 2011)

Property	Value	Unit
Density	7850	Kg/m^3
Young's modulus	200	GPa
Poisson's ratio	0.26	--
Bulk modulus	140	GPa
Shear modulus	79.3	GPa
Tensile Yield strength	250	MPa
Tensile strength	410	MPa
Tensile Ultimate strength	550	MPa

MODEL FORMULATION AND FINITE ELEMENT ANALYSIS

The plate is considered to be finite, isotropic, and linearly elastic. A finite plate implied that one side of the polygonal hole should be parallel to the x-axis. ANSYS 2020 R1 is the finite element program used in this study to calculate the equivalent von Mises stresses for isotropic finite plates with central polygonal holes of different configurations.

PLATE GEOMETRY PARAMETERS

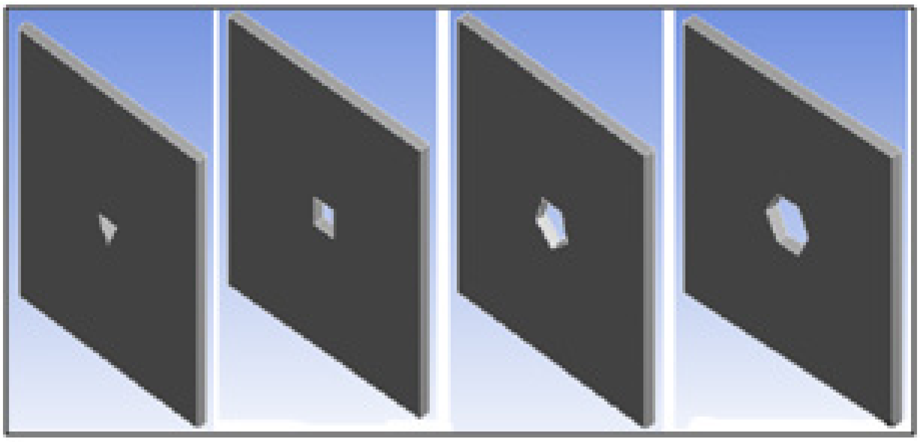


FIGURE 2. Plate with polygonal hole ((a) Triangular hole, (b) square hole, (c) pentagonal hole, (d) hexagonal hole)

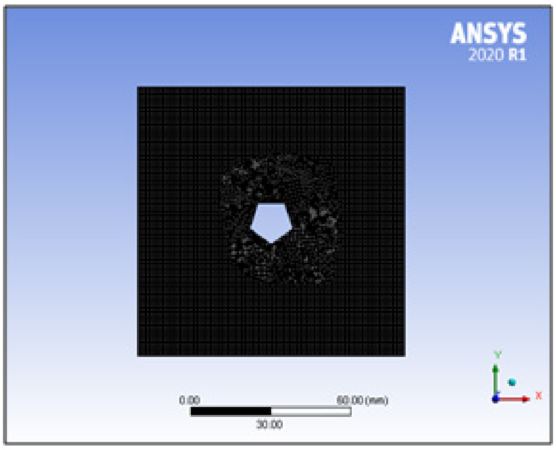
FEA is done for the regular finite plate with polygonal holes subjected to uniaxial compression loading. Various side ratio (l/L) of polygonal hole; and length ratio (*l*/L) and height ratio (h/H) of the square hole in the square plate is considered and found equivalent (von Mises) stresses using ANSYS 2020 R1. Here, we are not comparing areas for different shapes, but for a particular shape, we would like to check what would happen if we changed the side dimension of the polygonal hole. And we found that SCF increases as the side ratio increases. Fig. 2 represents the 3D model for the plate with holes of various geometric shapes like triangle, square, pentagon, and hexagon at the center of the plate. The units for geometrical dimensions and force are millimeters and Newton, respectively. Here plate is selected with 100 X 100 X 5 mm dimensions.

MECHANICAL PROPERTIES OF MATERIALS

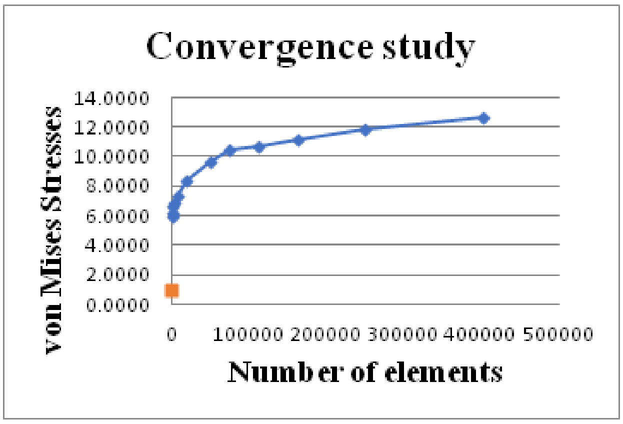
Special polygonal shaped cutouts are made in a plate for specific structural requirements made by structural steel like IS 2062, as it is used widely in industries. In the present work, IS 2062 material is considered for plate material as per standard industrial practice. Table 1 shows the material properties of IS 2062. American equivalent standard is ASME SA 36/ASTM A36 steel.

MESH GENERATION, MESH SENSITIVITY ANALYSIS AND BOUNDARY CONDITION

The plate with various polygonal shape holes is meshed with more than 396000 solid elements and has more than 1716880 nodes. Hence, a mapped meshing with the quadratic element (higher precision) has been used for meshing the region around the hole. Several simulations have been run for more mesh refinement in a plate with a hole for mesh sensitivity analysis. For the flat plate with a hole, Figure 3 (a) and (b) show the mesh sensitivity of normalized maximum stress with several elements, respectively. The normalization was carried out about the plate's maximum stress value. In the case of other polygonal shape holes in a plate, a similar technique was used to produce the refined mesh size. Model quality depends on various mesh quality parameters like skew, aspect ratio, Jacobian, etc., which have been taken care for the present study. (Shinde and Thombare, 2014), (Bugvi et al. 2021). The model is fixed from the plate side lower end and compression load is applied to the upper side.



(a) Mesh model of plate with pentagonal hole



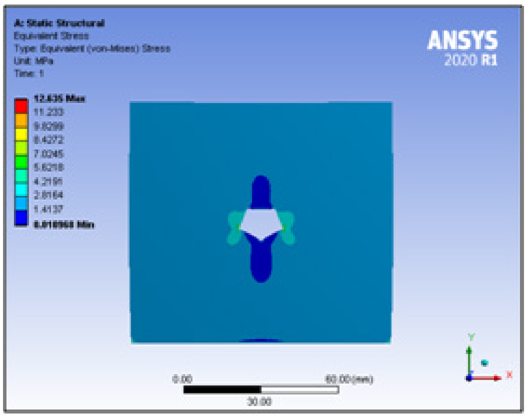
(b) von Mises vs number of elements

FIGURE 3. (a) Mesh model and (b) convergence study of pentagonal hole in a plate

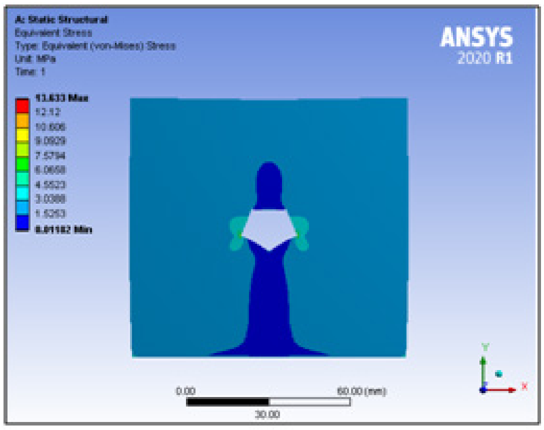
PARAMETER CONSIDERED

For the parametric study, different plate parameters are considered while keeping the edge of every polygonal hole parallel to the x axis, and the orientation angle of hole is 0°. At first, polygonal holes of 10 mm in length are considered for studies on hole size. Further, studies related to variation in the side ratio of polygonal holes and the length and height ratio of square holes are considered. (i) Four different hole shapes as shown in Figure 2, (ii) square plate with various side ratios of the polygonal hole (l/L), (iii) length ratio (*l*/L) and height ratio (h/H) of square holes are considered. Concerning loading direction, we have selected this parameter (Chauhan and Sharma 2016).

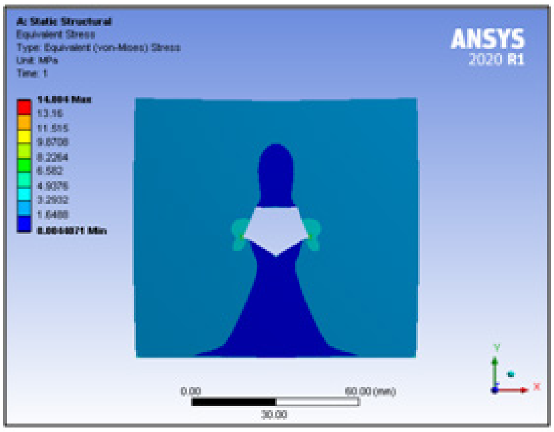
In this part of the study, every polygonal side is between 10 to 18 mm with an increasing 2 mm difference in each case for the triangular, square, pentagonal and hexagonal holes. Fig 4 (a) - (e) shows equivalent (von Mises) stress for the various side ratio of the pentagonal shape hole under uniaxial compression loading is considered constant as 1000 N for all iterations.



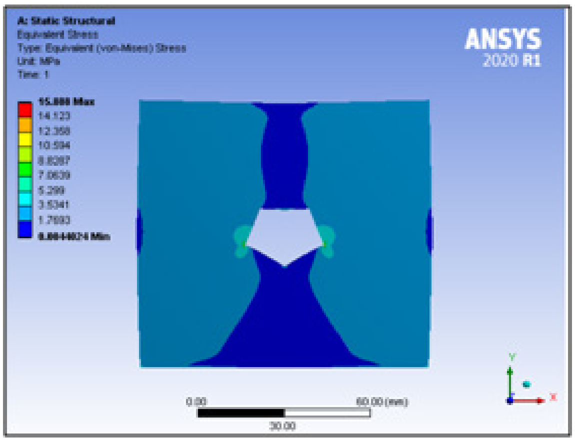
(a) l/L = 0.1 (l=10 mm, L=100 mm) of Pentagonal shape hole



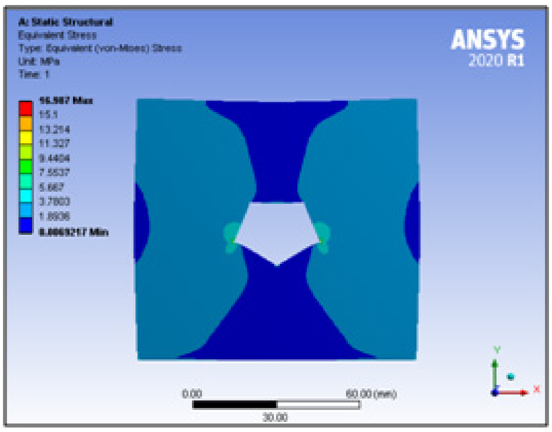
(b) l/L = 0.12 (l=12 mm, L=100 mm) of Pentagonal shape hole



(c) l/L = 0.14 (l=14 mm, L= 100 mm) of Pentagonal shape hole



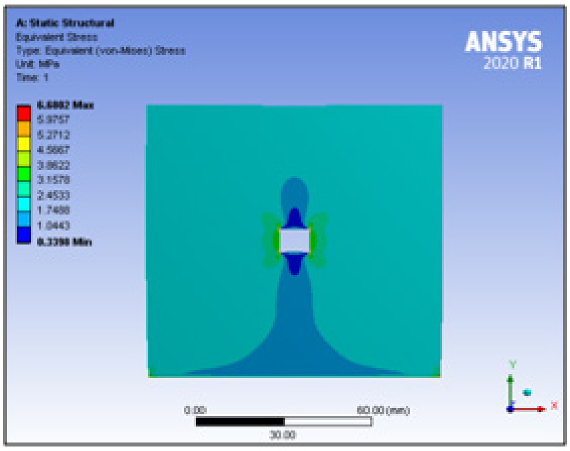
(d) l/L = 0.16 (l=16 mm, L=100 mm) of Pentagonal shape hole



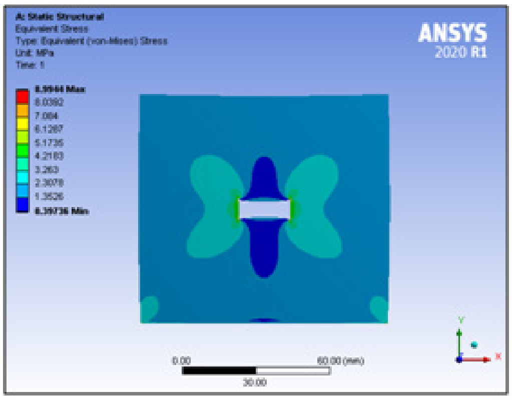
(e) l/L = 0.18 (l=18 mm, L=100 mm) of Pentagonal shape hole

FIGURE 4. Computational model of the finite plate with a pentagonal hole in the centre subjected to a uniaxial compression load.

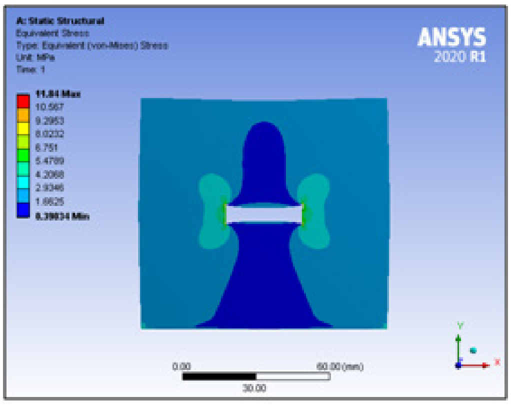
In the current study, stress analysis took into account the generated SCF and changes in stresses caused by changes in the length and height of a square hole in a plate. Fig 5 (a-d) and Fig 6 (a-d) show the effect of length and height ratio for a square hole in a square plate under uniaxial compression loading.



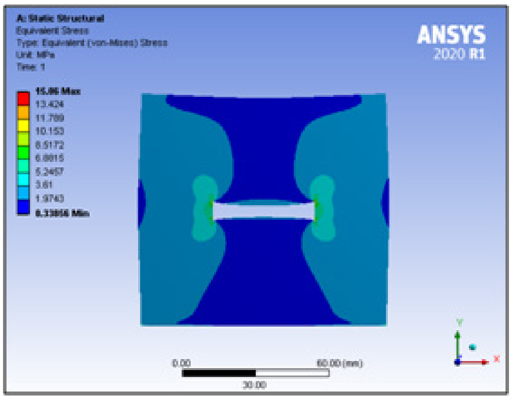
(a) *l*/L = 0.1 (*l* =10 mm, L=100 mm) of square shape hole



(b) *l* /L = 0.2 (*l* =20 mm, L=100 mm) of square shape hole

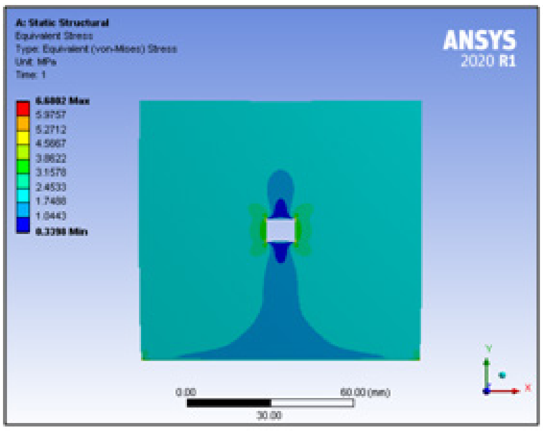


(c) *l* /L = 0.3(*l* =30 mm, L=100 mm) of square shape hole

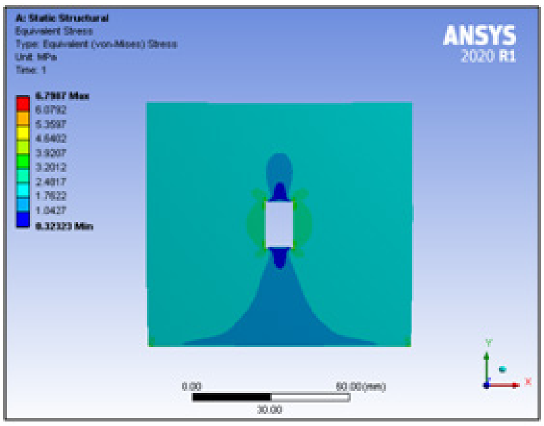


(d) *l* /L = 0.4 (*l* =40 mm, L=100 mm) of square shape hole

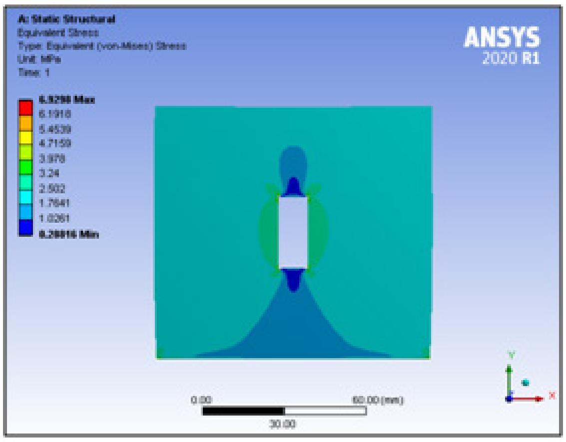
FIGURE 5. Computational model of the finite plate with a square hole in the centre subjected to a uniaxial compression load for different length ratio of square hole in square plate



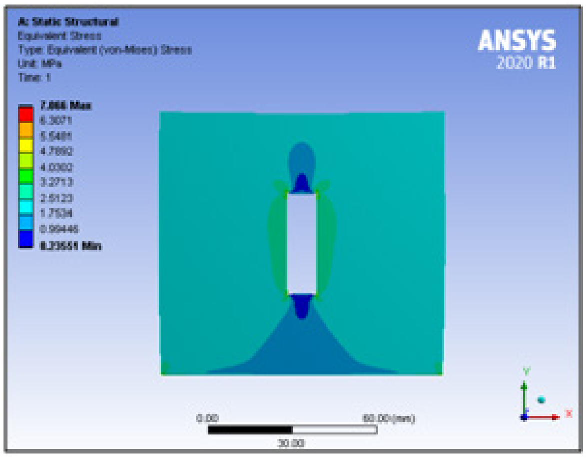
h/H =0.1 (h= 10 mm, H=100 mm) of square shape hole



(b) h/H =0.2 (h= 20 mm, H=100 mm) of square shape hole



(c) h/H =0.3(h= 30 mm, H=100 mm) of square shape hole



(d) h/H =0.4 (h= 40 mm, H=100 mm) of square shape hole

FIGURE 6. Computational model of the finite plate with a square hole in the centre subjected to auniaxial compression load for different height ratio of square hole in square plate.

In the current study, stress analysis took into account the generated SCF and changes in stresses caused by changes in the length and height of a square hole in a plate. Figure 5 (a-d) and Figure 6 (a-d) show the effect of length and height ratio for a square hole in a square plate under uniaxial compression loading. Equivalent (von Mises) stresses of plates with holes are identified from the study and used in the SCF calculation.

TABLE 2. SCF obtained at side ratio of various polygonal shape hole in a plate from FEA

N	Side ratio (l /L)	Equivalent (von Mises) stress (MPa)	Nominal Stress (MPa)	SCF (K_t) based FEA results	N	Side ratio (l /L)	Equivalent (von Mises) stress (MPa)	Nominal Stress (MPa)	SCF (K_t) based FEA results
3	0.1	10.44	2.190	4.768	4	0.1	6.6802	2.222	3.006
	0.12	10.588	2.232	4.744		0.12	6.7595	2.273	2.974
	0.14	12.221	2.276	5.370		0.14	7.1419	2.326	3.071
	0.16	11.635	2.322	5.011		0.16	7.602	2.381	3.193
	0.18	12.283	2.369	5.184		0.18	8.0703	2.439	3.309
5	0.1	12.658	2.364	5.355	6	0.1	12.809	2.419	5.295
	0.12	13.633	2.453	5.558		0.12	15.771	2.525	6.246
	0.14	14.804	2.549	5.807		0.14	17.31	2.640	6.556
	0.16	15.888	2.653	5.988		0.16	18.86	2.767	6.817
	0.18	16.987	2.766	6.141		0.18	20.553	2.906	7.073

TABLE 3. SCF obtained for square shape hole length ratio and height ratio in a square plate from FEA

N	length ratio (*l*/L)	Equivalent (von Mises) stress (MPa)	Nominal Stress (MPa)	SCF (K_t) based FEA results	N	Height ratio (h/H)	Equivalent (von Mises) stress (MPa)	Nominal Stress (MPa)	SCF (K_t) based FEA results
4	0.1	6.6802	2.222	3.00	4	0.1	6.6802	2.222	3.00
	0.2	8.9944	2.222	4.04		0.2	6.7987	2.500	2.71
	0.3	11.84	2.222	5.32		0.3	6.9298	2.857	2.42
	0.4	15.06	2.222	6.77		0.4	7.066	3.333	2.11

RESULT AND DISCUSSION

EFFECT OF SIDE RATIO OF VARIOUS POLYGONAL HOLE IN SQUARE PLATE

Table 2 shows variation in SCF by considering a polygonal side as a variant within the range of 10 to 18 mm. The results show a minor change in SCF for a square shaped hole within the selected range as the polygonal hole side ratio increases. In the case of pentagonal and hexagonal holes, SCF increases with an increasing side ratio. For triangular shape holes, results show less variation and alteration in the value of SCF.

As the side ratio of a polygon hole increases for any polygonal hole in a definite square plate, the net area of the plate decreases, generating more stresses at the corners of the hole. The SCF is majorly affected when one of the corners of the polygonal hole is in the direction of loading. Equivalent von Mises is also increasing as hole sizes are increasing.

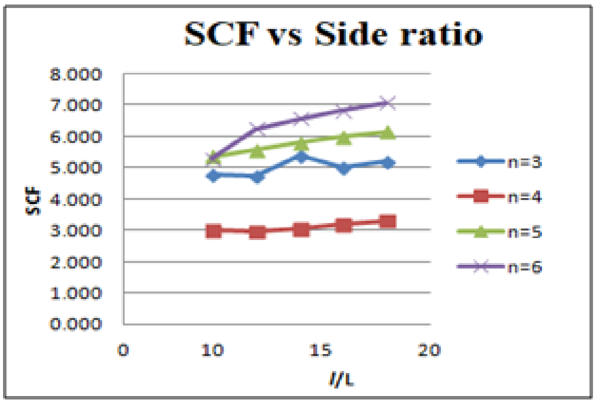


FIGURE 7. SCF vs side ratio

That is why, by increasing the side ratio, a square hole generates minimum SCF compared to triangular, pentagonal and hexagonal. The Stresses are not significantly affected due to the increase in side ratio for particular polygonal hole shapes, still it increases with the increase in the number of sides (refer to Table 2 and Figure 7).

EFFECT OF LENGTH AND HEIGHT RATIO OF SQUARE HOLE IN A SQUARE PLATE

From Table 3 above analysis, equivalent stresses, acting on the edge of the square hole with change in length and height of the hole, are identified.

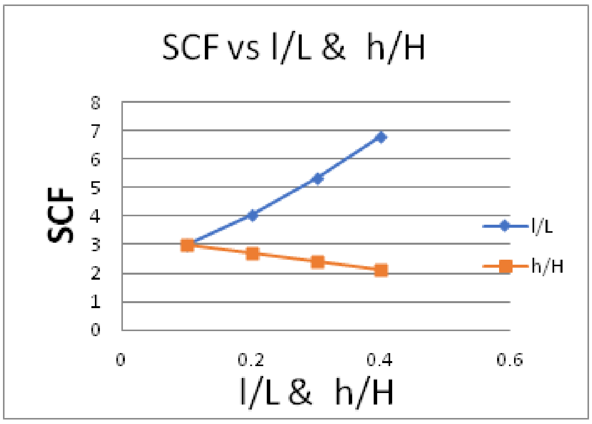


FIGURE 8. SCF vs hole length/height to plate length ratio

It is identified as SCF decreases with the height ratio increase whenever the SCF increases with the length ratio increase. The changes in SCF value may be found because the loading direction is perpendicular to the net cross-sectional area for the length ratio, and the loading direction is parallel to the height ratio. Fig. 8 shows a graph of SCF vs. hole length/height to plate length ratio. For a square polygonal hole shape, it is found that the stresses and SCF both increase with an increases in length ratio and stresses are not significantly affected with an increase in height ratio, but the SCF gets reduced marginally (refer to Table 3 and Figure 8).

CONCLUSION

The present study shows that the stress concentration factor depends on the side ratio and polygonal geometry of the hole, including the number and the size of sides in a plate.

A square shape hole generates a 40% minimum SCF compared to a hexagonal shape hole due to more edges parallel to loading directions (refer to Table 2).

Among all these shapes, the increasing order of stresses and SCF are square, triangular, pentagonal, and hexagonal.

The SCF is significantly affected when a polygonal holes corner faces the loading direction. Creating a hole with many edges parallel to the loading direction should be preferable.

The SCF increases with an increase in the side ratio (*l*/L) for a particular polygonal hole shape due to an increase in the size of the hole and its area. The polygonal hole area and more corners result in a higher value of SCF (refer to Table 2).

The SCF value is directly proportional to the length ratio (l/L) due to the loading direction perpendicular to the net cross-sectional area; whenever the SCF value is inversely proportional to the height ratio (h/H). It should be preferred to enhance the height ratio to minimize the SCF value. (refer to Table 3 and Figure 5 and Figure 6).

ACKNOWLEDGEMENT

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DECLARATION OF COMPETING INTEREST

None

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