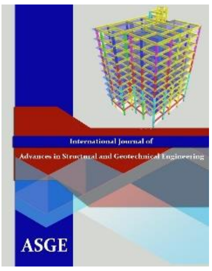

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Effect of Openings' Configurations on the Stress Concentration Factor of RC Beams under Different Loading Conditions

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ABSTRACT:

Nowadays, providing web openings in RC beams became a common practice in order to allow the utility ducts to pass through them. These openings interrupt the loading trajectories and result in the presence of weak points around the openings owing to the stress concentrations. Accordingly, stress concentration factor (SCF) is used to measure these concentrations of stresses. The current paper investigates numerically the effects of different parameters on the SCFs for RC beams such as the shapes of opening (circular, octagonal, hexagonal, square), size of openings (small, medium, large) having opening size-to-beam depth ratios of 0.25, 0.5 and 0.625, respectively. The beams having various combinations of sizes and shapes are subjected to different types of loading conditions such as bending moment, bending moment accompanied by axial tension force, bending moment plus axial compression force and shearing force. 2D linear finite element analysis was employed to estimate the SCFs for different combinations. It was found that under bending moment, the SCFs ranged from 1.07 to 2.1. For large and medium openings, the best shape of opening is the square one and the worst one is the octagonal. However, for small openings, the best shape is the octagonal and the worst one is the circular opening. Under bending moment and axial force either tension or compression, the SCFs ranged between 1.7 and 4.24. Similar observations as those for the bending moment case were noticed for the best and the worst opening shape and size from the viewpoint of the SCF. Under shearing force, SCFs ranged from 1.04 to 6.8. For large and medium openings, the best shape is the octagonal one and the worst shape is the square. However, for small openings, the best shape is the square one and the worst shape is the circular.

Keywords: Concrete, Stress Concentration Factor, Finite Element Method, beam with Opening.

1. INTRODUCTION

Openings in general are areas of weakness and stress concentration needed essentially for passing ducts and piping for different service facilities such as air conditioning, sewages water supply and computer networks. They can take any shape such as circular, rectangular, square, hexagonal and oval; however the circular and the rectangular configurations are the most common shapes [1, 2]. With regard to the size of openings, many researchers use the terms ''small'' and ''large'' without drawing any clear-cut demarcation line. The classification as small or large opening is based on either the size of opening and/or the overall structural performance of the beam containing this opening. Mansur et al. [3] and Hasnat and Akhtaruzzaman [4] classified all circular and nearly square openings as small openings. However, Somes and Corley [5] classified the circular opening of diameter less than 0.25 times the total depth of the beam as small one; otherwise the opening may be classified as large opening. Mansur and Tan [6] classified the small opening as that the opening whose diameter is less than 0.40 times the total depth of the beam, otherwise, the opening may be considered as large one where the beam theory could not be applied.

The presence of shoulders, grooves, holes, keyways and threads results in modifications of the simple stress distributions to peak local stress around the opening.as depicted in Fig.1, [9]. Thus, the stress concentration factor **K** can be defined as the ratio of the peak stress in the body to the nominal stress:

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}} \quad (1)$$

$$K_{ts} = \frac{\tau_{max}}{\tau_{nom}} \quad (2)$$

Where the stresses σ_{max}, τ_{max} represent the maximum stresses to be expected in the member under the actual loads and the nominal stresses σ_{nom}, τ_{nom} are reference normal and shear at the undisturbed locations. The subscript **t** indicates that the stress concentration factor is a theoretical factor. That is to say, the peak stress in the body is based on the theory of elasticity, or it is derived from a laboratory stress analysis experiment.

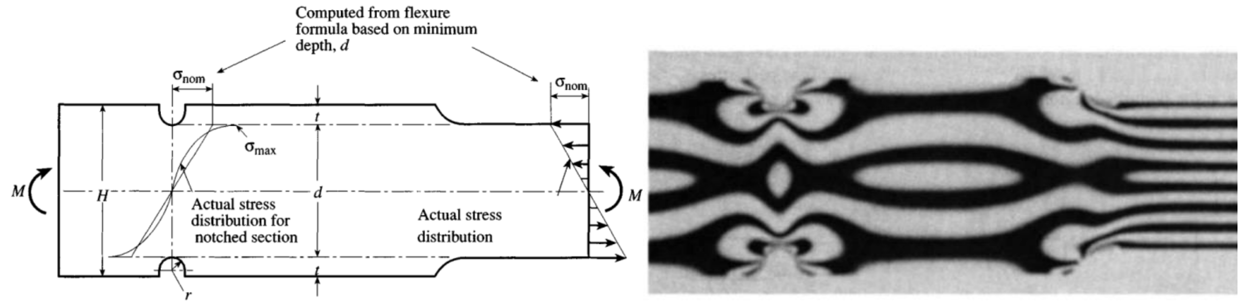


Fig.1. Stress concentrations introduced by a notch and a cross-sectional change which is not gradual (Peterson1974 [9]).

Stress concentration factor (SCF) is dependent on the following parameters:

1. The geometry or shape of the structure, but not its size or material.
2. The type of loading applied to the member; (axial, bending, torsion, or combined).
3. The shape, size and location of hole and opening; (fillet, radius, …).

The maximum local stress around openings is usually more than the nominal stress, and it correlates to the maximum stress. Failure can be predicted by the use of SCF, which is determined by several manners. For simple geometries and loadings, it may be determined exactly using the theory of elasticity. For more complex problems, the stress concentration factor is determined numerically or experimentally. [7-9]. However, Finite element Analysis is the common way to investigate stress concentration factors. [10-17].

In the current paper, the stress concentration factors in the beams is investigated for different shapes of openings (circular, octagonal, hexagonal, square) with various depth (D/H= 0.25, 0.5, 0.625) under different types of loading (bending moment, bending moment and axial tension force, bending moment and axial compression force, shear force). That is to find out the best and the worst shape to be executed in the web of RC beams taking into account the size of the opening as well as the acting load combinations.

2. FINITE ELEMENT MODEL

The study of stress and strain state in the concentration zone is one of the most difficult problems of the theory of elasticity and plasticity owing to the complexity of the geometrical model. In addition, the necessity to consider the physical and geometric nonlinearity of the elastic problem adds additional complexity. Furthermore, the need to account for the plasticity and creep complicates the material model. So far, many important aspects of the phenomenon of stress concentration are not completely addressed. The SCF can be derived through experimentation, analysis or computation. Experimental method (optical method) such as photo elasticity is widely used for experimentally determining the SC at a point. However, several alternative methods have been used such as the brittle-coating method, grid method, strain gauge. Analytical method such as the theory of elasticity can be implemented. Finally, finite element methods as a computational method can be used to determine the SCF.

The first mathematical analyses of stress concentrations were published in 1937. Recommendations form solutions are available for the simple stress states and not complex geometries. However, for more complex cases, experimental methods for measuring highly localized stresses (photo elastic tests, precision strain gage tests, membrane analogy for torsion, etc.) and computerized finite element solutions have been used. The results of the studies are available in the form of published graphs. It will be observed, that the stress concentration graphs are theoretical factors based on a theoretical homogenous, isotropic, and elastic material. On this basis, the performed finite element models was aimed to investigate the SCF for beam with different shapes of openings under different cases of loading, and to study and define the stress concentration factor for concrete beam with different openings size. This work describes an analytical model, which was developed using the finite element program SAP2000, to investigate the SCF around openings in the concrete beam.

The modeling is performed using 2D-shell element and calculated stresses of the beam are normal stresses σ_x, σ_y, and shear stress τ_{xy}. The differential equations of equilibrium together with equation for these stresses in a plane elastic body are:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \bar{P}_{\upsilon x} = 0 \quad (3)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \bar{P}_{\upsilon y} = 0 \quad (4)$$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)(\sigma_x + \sigma_y) = -f(\upsilon)\left(\frac{\partial \bar{P}_{\upsilon x}}{\partial x} + \frac{\partial \bar{P}_{\upsilon y}}{\partial y}\right) = 0 \quad (5)$$

where ρ^{-}_{vx}, ρ^{-}_{vy} denote the components of the applied body force per unit volume in the x, y directions and f(v) is a function of Poisson's ratio:

$$f(\upsilon) = \begin{bmatrix} 1+\upsilon & \text{for plane stress} \\ \frac{1}{1-\upsilon} & \text{for plane strain} \end{bmatrix} \quad (6)$$

3. Test Specimens

All investigated beams in this work are made of concrete having stiffness (E) of 22 GPa and Poisson's ratio (v) of 0.2. The beams have center-to-center span of 2600 mm and rectangular cross-section of 150mm width by 400 mm total depth as depicted in Fig. 2. The studied parameters are summarized as follows:

1. Shape of the opening (circular, octagonal, hexagonal, square) as depicted in Fig.3.
2. Height of the opening (100, 200, 250) mm (D/h= 0.25, 0.5, 0.625).as depicted in Fig3.
3. Type of loading (bending moment, combined bending moment with either axial tension or axial compression, shear force).

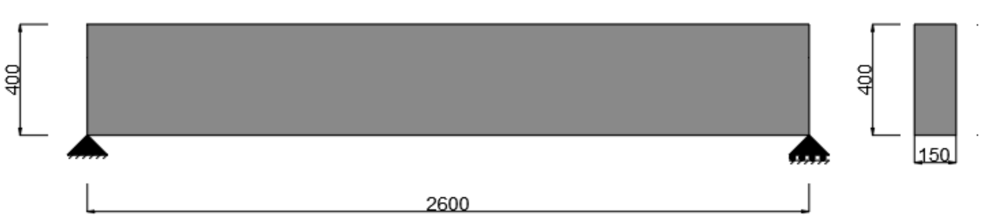


Fig.2.Concrete dimensions of the beam studied beams.

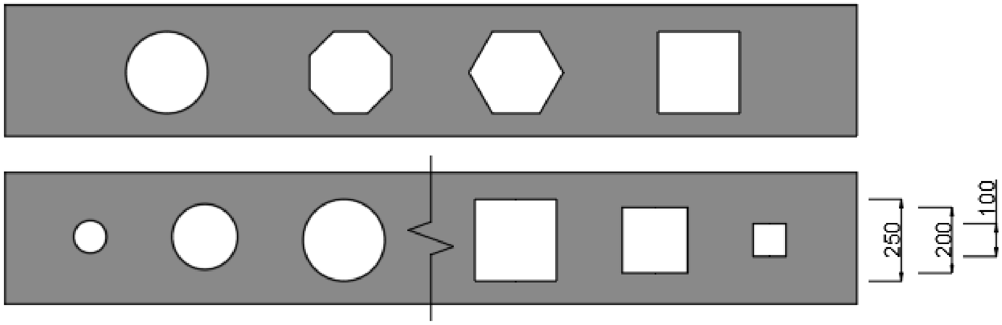


Fig.3. Shapes and dimensions of the studied openings.

4. RESULTS AND DISCUSSION

4.1 Beams subjected to pure bending moment

Figure 4 show the adopted loading scheme for beams subjected to pure bending moment where the acting loads was constant bending moment at both ends. Three different sizes of the opening were considered for four different configurations of the openings; circular, octagonal, hexagonal and square. For each case, the SCF were obtained and summarized as given in Table 1.

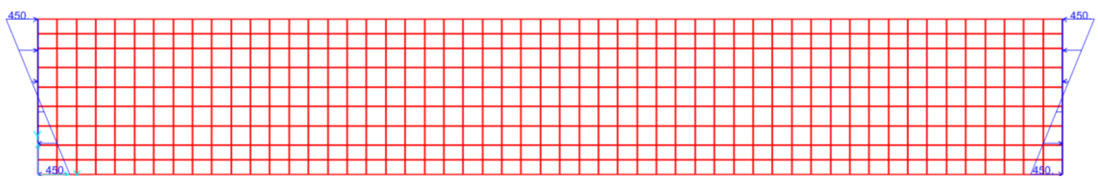


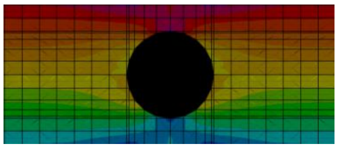
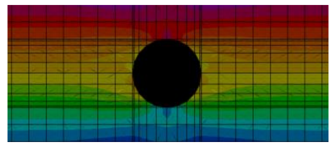
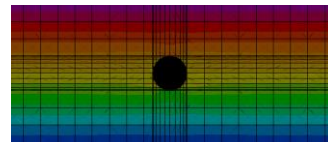
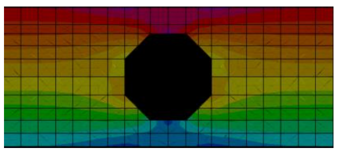
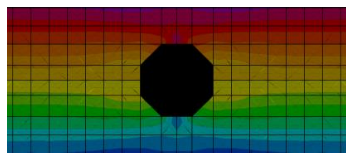
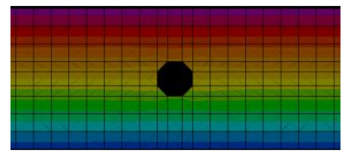
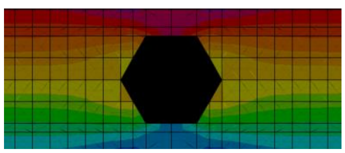
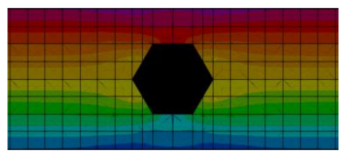
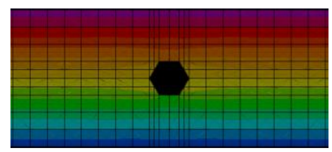
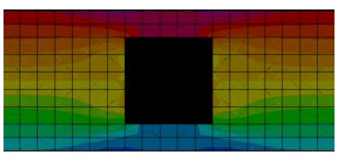
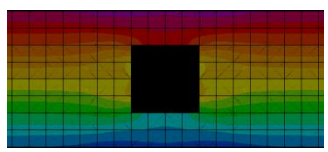
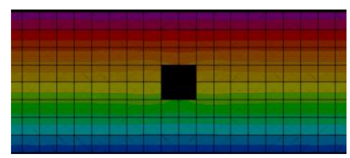
Fig.4. loading value under pure bending moment.

For circular openings, increasing the size of openings results is increase the SCF where the SCFs were about 1.52, 1.79, and 2.07, respectively, for small, medium and large openings. It can be noticed that the SCF for circular small openings showed the highest SCF among all shapes. That could be attributed to the concentration of stresses at one point. On the other hand, increasing the base of the opening resulted in the decrease of the SCF. This observation was confirmed for the medium and large openings.

In general, when the beam contains discontinuity region, such as openings, sudden change in the cross-section was happened leading to high localized stresses around the opening. When the size of the opening increases, the normal stress around openings increases. Thus, the SCF, Kt, increases. The SCFs ranged between 1.07 and 2.1. For both medium and large openings, the best shape of opening is the square opening and the worst shape is the octagonal opening. On the other hand, for small openings, the best shape of opening is the octagonal opening and the worst shape is the circular one.

Figure 5 shows comparisons among the SCFs for different shapes of opening considering the different sizes under the effect of bending moment.

Table 1 Stress concentration factors for different openings under bending moment

shape	large	medium	small
circular	 K_t=2.07	 K_t=1.79	 K_t=1.52
octagonal	 K_t=2.1	 K_t=1.9	 K_t=1.07
hexagonal	 K_t=1.96	 K_t=1.69	 K_t=1.47
square	 K_t=1.64	 K_t=1.4	 K_t=1.32

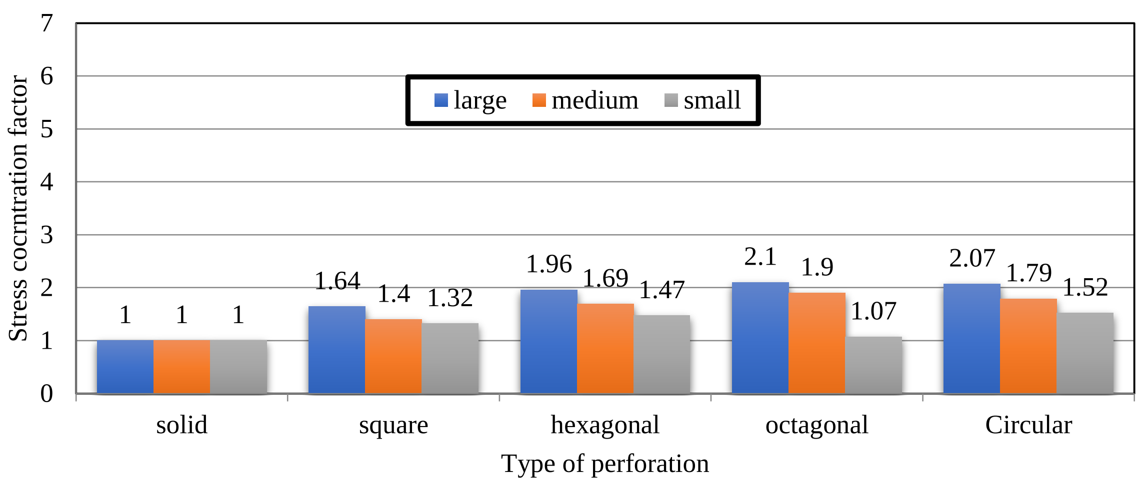


Fig.5 Stress concentration factors for different shape of opening with different height of opening under the effect of bending moment.

4.2 Beams subjected to combined bending moment and tension force

Figure 6 shows the adopted loading scheme under the effect of bending moment combined with axial tension force. It can be observed that the axial tension fore results in increase the SCFs compared to the case of pure bending moment.

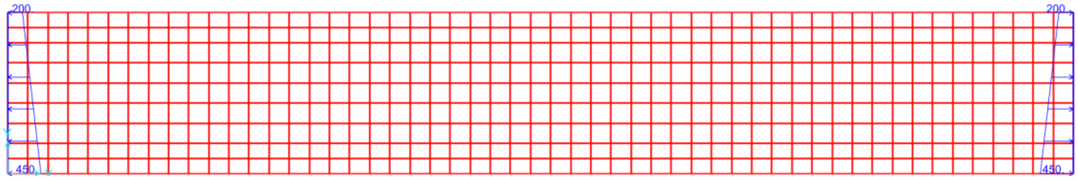
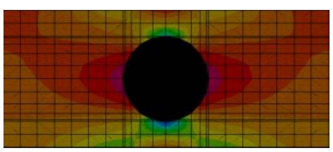
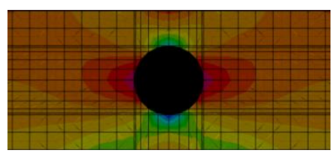
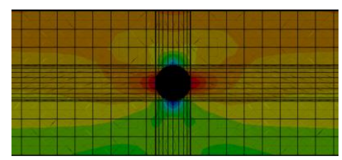
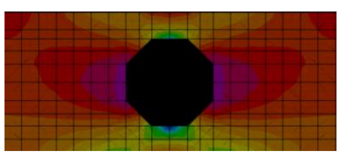
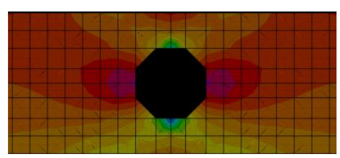
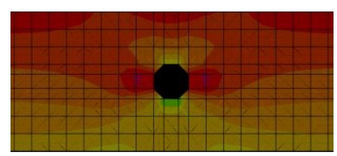
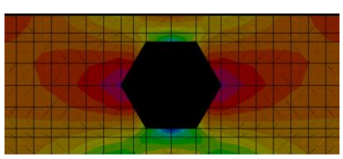
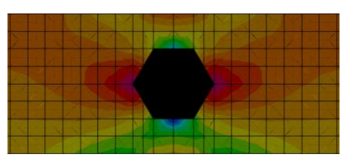
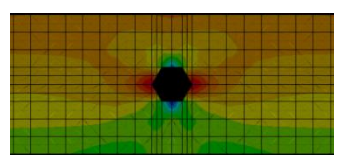
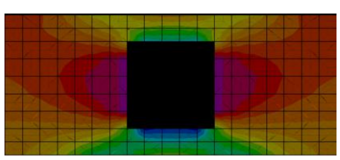
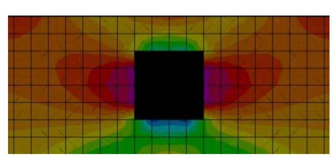
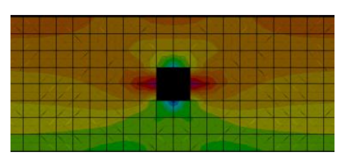


Fig.6. loading value under combined bending moment and tension force.

The SCFs ranged between 1.7 and 4.24 as summarized in Table 2 and illustrated in Fig. 7. For both medium and large openings, the best shape of opening is the square opening and the worst shape is the octagonal opening. On contrary, for small openings, the best shape of opening is the octagonal opening and the worst shape is the circular opening.

Table 2 Stress concentration factors for different openings under combined bending moment and tension force

shape	large	medium	small
circular	 K_t=4.09	 K_t=3.27	 K_t=2.42
octagonal	 K_t=4.24	 K_t=3.49	 K_t=1.7
hexagonal	 K_t=3.93	 K_t=3.14	 K_t=2.35
square	 K_t=3.23	 K_t=2.65	 K_t=2.12

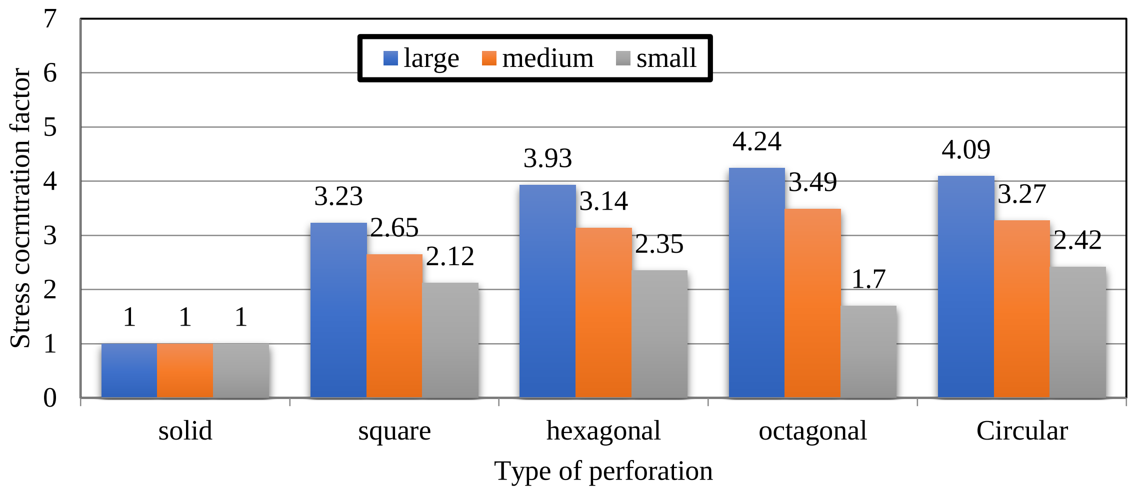


Fig.7 Stress concentration factors for different shape of opening with different height of opening under combined bending moment and axial tension force.

4.3 Beams subjected to combined bending moment and compression force

Changing the axial force from tension force to compression force showed the same effect on the SCF except that the location of the maximum stressed fiber switched from the tension side to the compression side

4.4 Beams subjected to constant shear force

Figure 8 shows the adopted loading scheme to develop constant shear force along the entire beam.

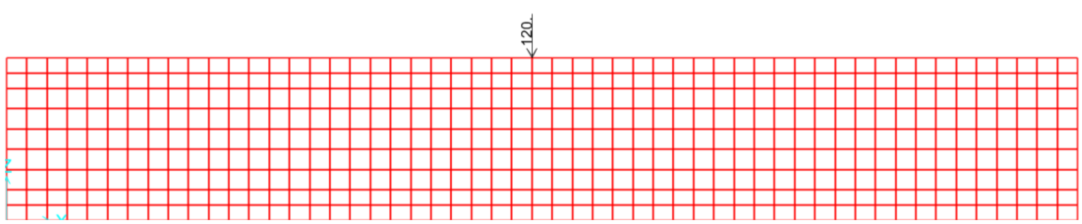
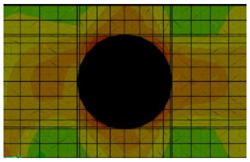
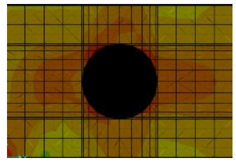
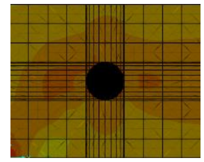
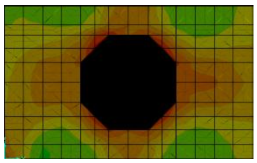
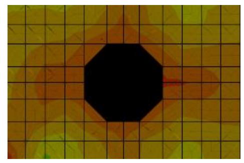
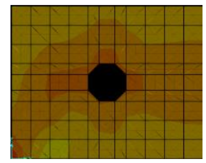
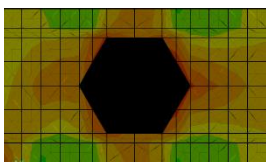
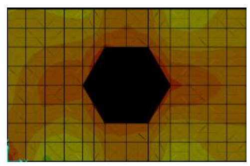
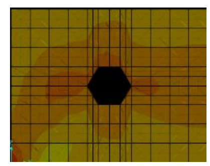
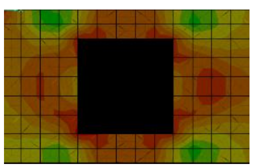
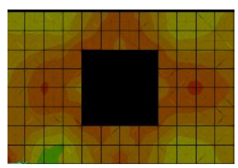
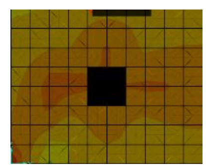


Fig.8. loading value under shear force.

It can be noticed that when the beam contains an opening in the shear zone, high localized shear stresses are developed leading to increase the SCFs. It was found that the SCFs ranged between 1.04 and 6.8 as summarized in Table 3 and illustrated in Fig. 9. For both the medium and large openings, the best shape of opening is the octagonal opening and the worst shape is the square opening. For small openings, the best shape of opening is the square opening and the worst shape is the circular opening.

Table 3 Stress concentration factors for different openings under shear force

shape	large	medium	small
circular	 K_{ts}=5.52	 K_{ts} =3.58	 K_{ts} =1.73
octagonal	 K_{ts} =5.28	 K_{ts} =2.8	 K_{ts} =1.42
hexagonal	 K_{ts} =5.35	 K_{ts} =3.0	 K_{ts} =1.52
square	 K_{ts} =6.8	 K_{ts} =3.81	 K_{ts} =1.04

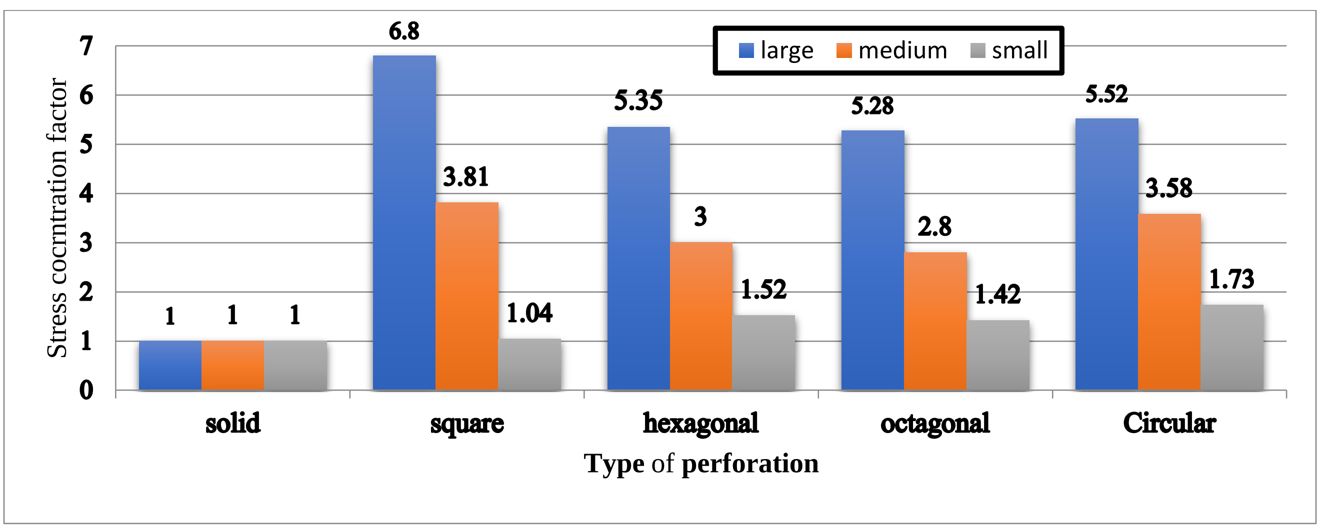


Fig.9 Stress concentration factors for different shape of opening with different height of opening under shear force.

5. CONCLUSION

Based on the considered dimensions of openings and shapes subjected to different loading conditions, the following conclusions may be drawn:

1- The presence of openings changes simple stress distribution to high localized stresses near the openings.
2- The size of the openings proportions with SCF. When the size of the opening increases, the SCF increases.
3- This study shows that under bending moment, SCF ranges between (1.07- 2.1). For large openings, the best shape of opening is square opening and the worst shape is octagonal opening. For medium openings, the best shape of opening is square opening and the worst shape is octagonal opening. For small openings, the best shape of opening is octagonal opening and the worst shape is circular opening.
4- Under the effect of combined bending moment and either axial tension force or compression force, the SCF ranges between (1.7- 4.24). For large openings, the best shape of opening is square opening and the worst shape is octagonal opening. For medium openings, the best shape of opening is square opening and the worst shape is octagonal opening. For small openings, the best shape of opening is octagonal opening and the worst shape is circular opening.
5- Under the effect of shear force, SCF ranges between (1.04- 6.8). For large openings, the best shape of opening is octagonal opening and the worst shape is square opening. For medium openings, the best shape of opening is octagonal opening and the worst shape is square opening. For small openings, the best shape of opening is square opening and the worst shape is circular opening.
6- Axial normal force increases the SCF value around the openings.
7- The SCF is dependent on the type of loading and the most critical case of loading load is under the effect of constant shear force.

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