Effect of opening size and location on punching shear resistance for edge and corner column-slab connection

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Abstract— Punching is one of the most important phenomena to be considered during the design of reinforced concrete flat slabs. There are many factors affecting the punching behavior of flat slabs, the most critical factor of them is the presence of opening adjacent to column which reduces the punching shear strength of slab-column connection. The effect of opening size and location on punching shear strength of edge and corner column – slab connection are investigated in this paper. finite element models for eight specimens were developed using Finite Element Program (ABAQUS). The studied specimens were divided to two groups; the first group represents edge column- slab connection and consists of four specimens including adjacent openings with slab dimensions (4000x2000x200) mm, and one control specimen without opening. The second group represents the corner column-slab connection with slab dimensions (2000x2000x200) and consists of four specimens including adjacent opening and one control specimen without opening. All specimens were supported on a square column of dimensions (400x400) mm. It was found that for edge column –slab connection, increasing opening size from size equal to column size to 1.5 column size, the cracking load decreased by 21.40% and 32.41% respectively when compared to control specimen without opening, and the ultimate punching load decreased by 31.65% and 43.80% respectively when compared to control specimen without opening. And for corner column –slab connection, the cracking load decreased by 29.60% and 46.30% respectively when compared to control specimen without opening, and the ultimate punching load decreased by 39.20% and 51.10% respectively when compared to control specimen without opening. Also, the location of opening has a significant effect on the cracking and ultimate loads. When the opening was located at column's corner the cracking and ultimate loads decreased by 12.10% and 21.30% respectively compared to control specimen without opening for edge column-slab connection and the cracking and ultimate loads decreased by 18.50% and 28.80% respectively for corner column-slab connection, but when the opening was located in front of column the cracking and ultimate loads decreased by 21.40% and 31.65% respectively for edge column-slab connection and decreased 29.60% and 39.20% respectively for corner column-slab connection.

INDEX TERMS— flat slabs, punching strength, openings, edge column, corner column, slab-column connection.

1.INTRODUCTION

Punching shear is a critical design factor of reinforced concrete flat slabs since it is associated with brittle failure. There are many parameters that have a great effect on punching shear capacity of flat slabs, the first parameter is opening size and location. Oukaili and salman[1] tested six half-scale reinforced concrete specimens with an opening in the vicinity of the column were studied and they concluded that the size of the opening affects the capacity of the flat slab, the ultimate strength of specimen with the larger opening decreased by 29.25% with respect to the ultimate strength of solid specimen. For the specimen with a smaller opening, the decrease in capacity was12.42%. The farther the opening from the column, the higher the ultimate strength of the connection. For the specimen with opening at distance h (70mm) from the front face of the column, the punching shear capacity decreased by 13.47% from solid control specimen and for specimen with the opening next to the column, the decrease in capacity was 19.65%. while the specimen that has opening at column's corner decreased the capacity by 11.43%. Ismail [2] studied the effect of opening size and location on twenty-seven specimens with dimensions of (2000x2000x155) mm subjected to concentric and eccentric punching loads were evaluated using FE software. They concluded that Opening size and location affects the punching capacity of the flat slab, especially when the opening is located near to the column face. Increasing the opening size adjacent to the face of the column may lead to a brittle punching failure, and the ultimate strength for the opening of size (225x450) mm decreased by 45%, while the ultimate strength for the opening of size (225x225) mm decreased by about 30% when compared to the ultimate strength of the control specimen without openings. the second parameter is concrete compressive strength Ebada Ahmed et al [3] tested six specimens one of them was self-compacted concrete and the others were normal strength concrete Specimens were with dimensions (1200x1200x140) mm and they concluded that the increase of concrete compressive strength leads to increase the ultimate punching load of the slab by 30%. The third parameter is column size, Jales Almeida Silva et al [4] tested nine specimen for reinforced concrete flat slab with dimensions (1800x1800x130) mm and the effect of column shape and size was studied on three specimen , L1 was a slab specimen with square column with dimensions (150x150), L2 was a slab specimen with rectangular column with dimensions (150x300)mm and L9 was a slab specimen with circular column with diameter 402 mm , they concluded that there is an increase in the failure load of slabs L2 of 46 % and L9 92 %, when compared to the rupture load of slab L1. The fourth parameter is the effect of unbalanced moment, DC. Olivera et al [5] tested eight specimens with dimensions (2400x2400x150 mm) and they concluded that the punching shear capacity was affected by the transferred moment from slab to column as noted for slab with applied moment, showed failure load 38% lower than reference slab without applied moment.

2. Finite element model

In this study, a finite element model was developed to simulate the behavior of a two-way flat slab for edge and corner column-slab connection under punching load and unbalanced moment. The model was verified using experimental results from the literature. The modelling and simulations presented in this paper have been performed using the computer software ABAQUS version 2016[6]. Implemented theories and modelling considerations are presented in this part.

2.1 Constructive model for reinforced concrete

The nonlinear behavior of structural concrete under static loading conditions can be described in two stages. The initial stage represents the behavior prior to the crack initiation where the material is generally modeled using a linear-elastic relationship. After the cracking, the non-linear behavior of concrete was modeled in ABAQUS using concrete damage plasticity model. This model combines the constructive relations for tensile (fracture) and compressive (plastic) responses.

The parameters defined in ABAQUS for the concrete damage plasticity model in compression and tension behavior are presented here. The concrete damaged plasticity model considers a constant value for the Poisson's ratio, Ʋ, even for cracked concrete. Therefore, in the analyses presented herein, the value Ʋ was assumed=0 in plastic stage. The dilation angle Ψ was considered as 40, the shape factor; Kc = 0.667, the stress ratio $\sigma b0/\ \sigma c0$ = 1.16 and the eccentricity e = 0.1. All values of these parameters are used based on the results from the finite element model proposed by Genikomsou and Polak [7].

G_f denotes the fracture energy of concrete that represents the area under the tensile stress-crack displacement curve as shown in **Fig.1**

The fracture energy G_f depends on the concrete quality and aggregate size and can be obtained from Eq.1according to (CEB-FIP, 1990)[8].

$$Gf = Gf0\ (fcm\ /\ fcm0\ )^{0.7} \qquad (1)$$

Where $fcm0$ = 10 MPa and G*f0 is* the base fracture energy depending on the maximum aggregate size, dmax. The value of the base fracture energy G*f0* is 0.026 N/mm for maximum aggregate size dmax equal to 10 mm that was used in the tested specimens.

According to (CEB-FIP, 1990)[8] , $f$cm is the mean compressive strength of concrete and its relationship with the characteristic compressive strength $f$ck, is obtained from Eq.2

$$fcm = fck + 8\ \text{MPa}. \qquad (2)$$

For the concrete damage plasticity model it is required to define the compressive damage parameter (dc) and the tensile damage parameter (dt), so these two parameters can be obtained from Eq 3 and Eq 4.

$$dc = 1 - \frac{\sigma}{fc'} \qquad (3)$$

$$dt = 1 - \frac{\sigma}{ft} \qquad (4)$$

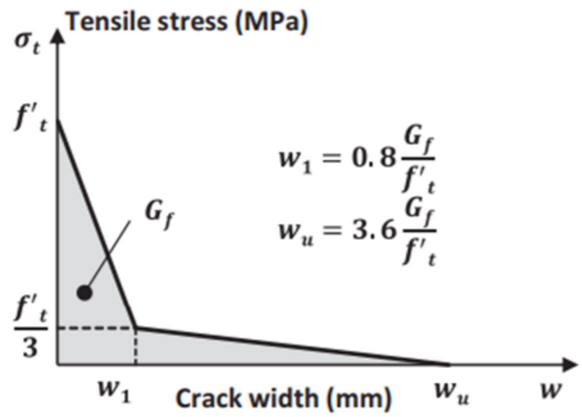

Fig.1 Uniaxial tensile stress–crack width relationship for concrete.

The stress strain curve proposed by (Todeschini) [9] is used to get the compressive and tensile stresses of concrete, and the compressive and tensile strains for elastic and plastic behavior of concrete. Todeschini concrete compression and tension model is shown in Fig.2

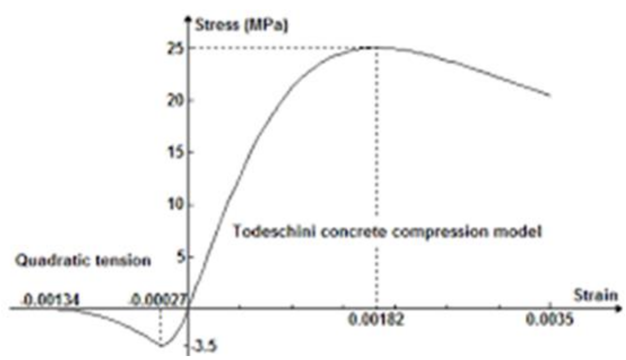

Fig. 2 Todeschini concrete compression and tension model, (Todeschini) [9]

The proposed used numerical expressions are explained by the following three equations from Eq.5 to Eq7, so that the stress-strain curve can be easily plotted. but it should be noted that the first point is assumed as 0.4 fc ' for calculating the linear part of curve in elastic behavior of concrete.

$$f = \frac{2\,fc'\left(\frac{\varepsilon}{\varepsilon 0}\right)^2}{1+\left(\frac{\varepsilon}{\varepsilon 0}\right)^2} \quad (5)$$

$$\varepsilon_{\circ} = \frac{1.7(\,fc')}{Ec} \quad (6)$$

$$Ec = 4700\sqrt{fc'} \quad (7)$$

Where:

f = stress at any strain (Ɛ).

Ɛ=strain at stress (f).

$\varepsilon_{\circ}$= strain at the ultimate compressive strength (fc').

Ec = modules of elasticity of concrete.

2.3 Constructive model for steel reinforcement

Steel reinforcement behaviour is defined in elastic and plastic behavior according to relationship shown in Fig.3. The modules of elasticity of steel is used to be equal 200000 MPa and poison ratio = 0.3.

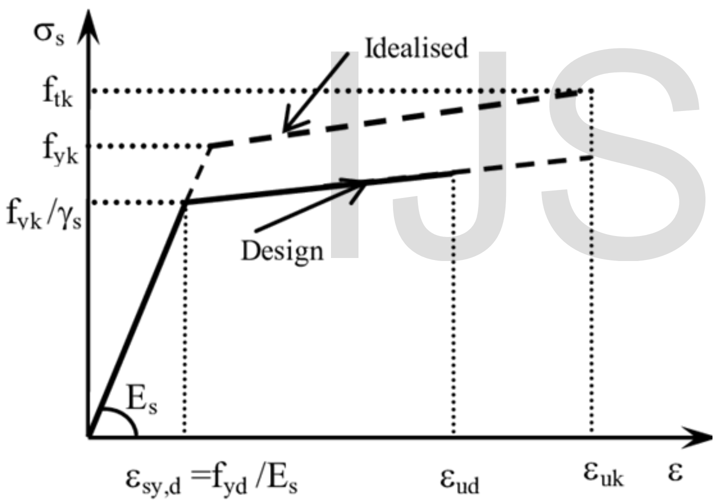

Fig. 3 Idealized and design stress-strain curve for reinforcing steel

2.4 Element types

To model the flat slab with its reinforcing rebar, two types of elements are used. 8-noded hexahedral (brick) elements were used for concrete with reduced integration (C3D8R) to avoid the shear locking effect. And 2-noded linear truss elements (T3D2) were used to model reinforcement.

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Elementtype T3D2 is a two-node, 3-dimensional truss element used in two and three dimensions to model slender, line-like structures that support only axial loading along the element. No moments or forces perpendicular to the centerline is supported. The embedded method was adopted to simulate the assumed perfect bond between the concrete and the reinforcement. The embedded region constraint method in ABAQUS embeds a region of the reinforcement model within a "host" region of the concrete model.

2.5 Mesh and boundary condition

For specimens in the parametric study in group A which represent edge column-slab connection and group B which represent corner column-slab connection, the mesh size used in the finite element model for all specimens was 50 mm to reduce time of running these models as the finite element models were constructed with full scale, so for slabs specimens with thickness 200 mm it was used 4 bricks and each brick with dimension 50 mm.

Displacement boundary conditions are necessary to constrain the finite element model to get an accurate solution. For group A (edge slab-column connection) three lines of nodes are given constraint in the vertical direction (Y-Direction), where (U2=0) at the bottom face of slab and the free edge of slab was kept without any constrains, for the horizontal movement, there are four-quadrant nodes constrained in two main directions (X and Z), where (U1=U3=UR1=UR2=UR3=0) to create roller support and prevent the rotation of the slab at the support. For group B (corner slab –column connection) two lines of nodes are given constraint in the vertical direction (Y-Direction), where (U2=0) at the bottom face of slab and the other two free lines of slab was kept without any constrains.

loads were applied in the finite element models as displacement control, so to apply the vertical loads a vertical displacement was applied at upper column's stub, and to apply unbalanced moments two horizontal displacement were applied at the upper and lower column's stub in two opposite directions. The upper and lower column's stubs were spaced at 0.6 m from the top and bottom face of slabs specimens. The ratio between the unbalanced moment and the applied vertical displacement (M/V) was kept constant for all specimens and equals 0.7 m.

3. Validation model

To check the accuracy of the proposed model to calculate the punching shear resistance of flat slab, two specimens tested by Oukaili & Salman [1] were modeled and loaded till failure. Slabs specimens used in verification model are XXX as a control slab without opening and CF0 with opening (150x150) mm in front of column face. the yield strength for steel reinforcement for steel bar diameter 6mm was 598 MPa and for steel bar with diameter 12 mm was 648 MPa. Table 1 and Fig.4a and b show the details of slabs' dimensions, reinforcement layout and opening locations.

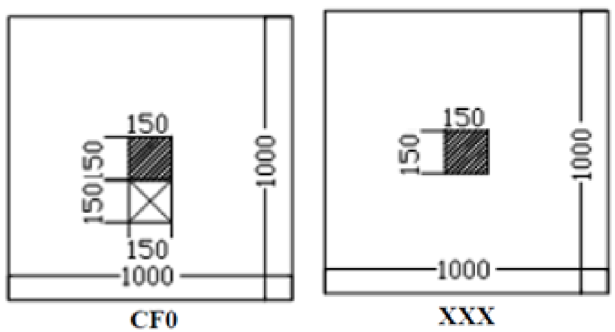

Fig. 4a Plan View of Test Specimens, oukaili and Salman [1]

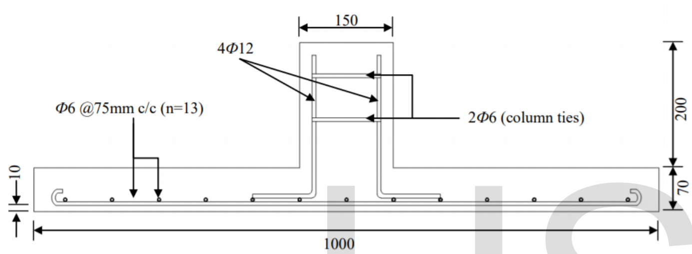

Fig.4b Elevation View of Reinforcement Details of test specimens, oukaili and Salman [1]

Table 1 properties and data of slabs used to verify the analytical model

Specimen ID	Slab dimensions (mm)	Opening location Around column	Opening size(mm)	f′c (Mpa)	Tensile steel reinforcement
XXX	1000x1000x70	Not provided	Not provided	35.69	Φ6@75 (at both directions)
CF0	1000x1000x70	front	150x150	34.13	Φ6@75 (at both directions)

3.1 Mesh and Boundary Condition

The specimens were loaded in the finite element model using uniform displacement load at column stub. The boundary conditions were applied at the location of line of supports (U2=0) as mentioned in the experimental data.

3.2 Comparison between Experimental and Model Results

Table 2 shows the maximum punching shear force and the corresponding maximum vertical deflection from the experimental work and those obtained from the finite element. The load versus deflection curve for both analytical and experimental results for specimens (XXX and CF0) are presented in Fig.5 and Fig.6 respectively. A good agreement between the experimental and theoretical results are shown from both curves.

During loading cracks propagated from the middle of slab outwards at radial direction and reached the edges of the slab for both experimental and analytical work as shown in Fig 7 and Fig. 8. As the load increased, the cracks grew wider and a circular stress concentration was formed around the column stub indicating a punching shear failure. It can be noted that the analytical models indicated a crack pattern similar to the experimental specimens.

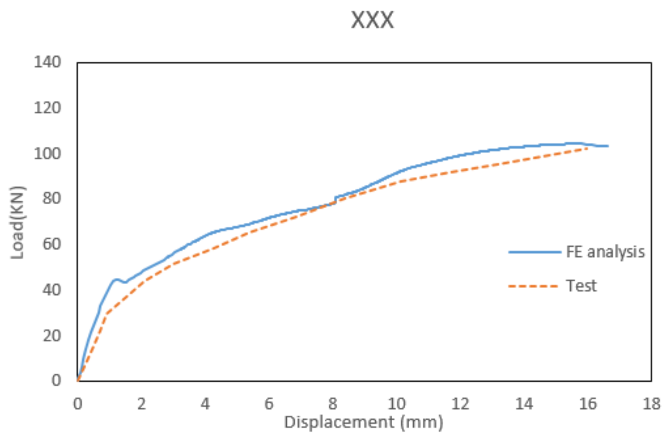

Fig. 5 Comparative load-deflection plot of control specimen XXX.

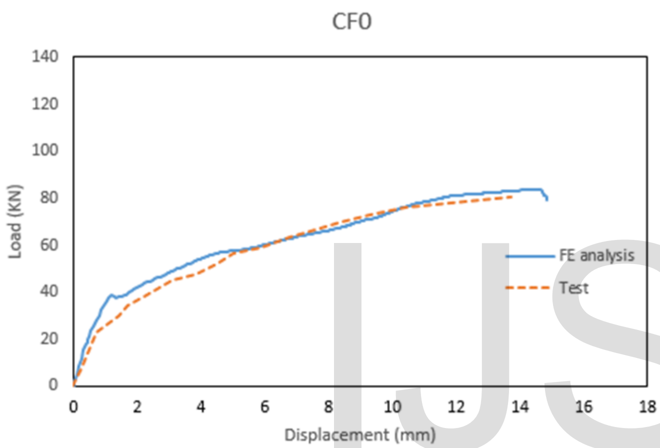

Fig. 6 Comparative load-deflection plot of specimen CF0.

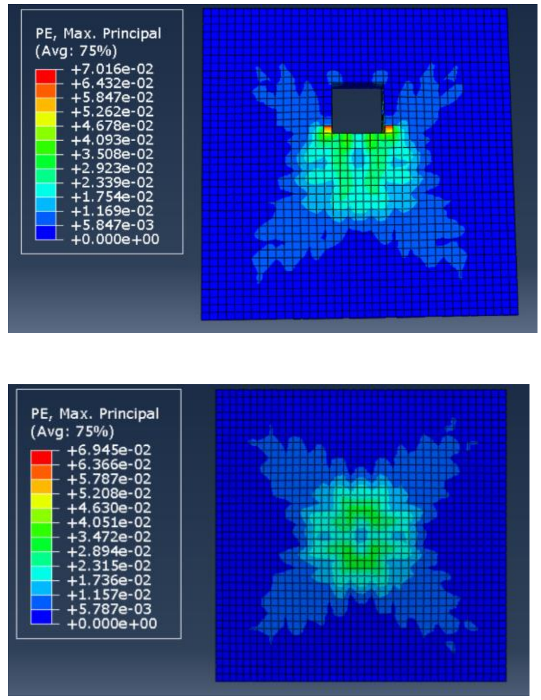

Fig. 7 plastic strain on tension surface at ultimate load for slab XXX and CF0 from FEM.

Table 2 Comparison of experimental and numerical analyses results

	Test results		FEM results		%error	
Specimen ID	**Failure load (KN)**	**Displacement at failure load (mm)**	**Failure load (KN)**	**Displacement at failure load (mm)**	**Failure load**	**Displacement at failure load**
XXX	101.65	15.91	104.64	15.5	2.91	2.58
CF0	79.87	13.81	83.73	14.61	4.83	5.79

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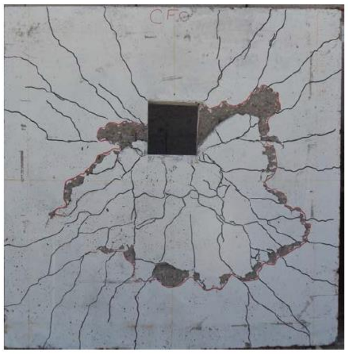

Fig. 8 Cracking pattern on tension surface at ultimate load for slab XXX and CF0 from experimental results.

The above comparison between the experimental and theoretical results shows that the discussed model can be used to represent punching shear behavior of slab-column connection under the effect of different parameters. Following, a parametric study based on the suggested model to calculate the effect of several factors on the ultimate punching strength of flat slab is presented and discussed.

4. PARAMETRIC STUDY

Table 3 and Table 4 summaries the configuration of FE models and variables of the parametric study. The analysis was performed for eight slabs divided into two groups based on slab –column connection type. The first group; group A, presented edge column-slab connection while the second group; group B, presented corner column-slab connection. Based on the opening size and location and as shown in Table 3, group A is divided to four slabs (SE, SE-400-F, SE-400-C and SE-600-F) of which specimen SE (without opening) was considered as the control specimen for this group. Also, group B is divided to four slabs (SC, SC-400-F, SC-400-C and SC-600-F) where slab SC was considered as control specimen without opening for this group.

In each group the variable parameter was opening size and location according to column and the other variables were kept constant such as the compressive strength for reinforced concrete; fcu = 35 MPa, the yield strength for steel reinforcement; fy = 400 MPa, and the steel reinforcement ratios were 1.16% for flexural reinforcement of slabs and 0.46% for steel reinforcement in compression and 1.9% for columns longitudinal reinforcement. Specimens' geometry and reinforcement details are presented in Fig.9 and Fig.10.

Table 3 Description of FEM specimens

Specimen ID	**Slab dimension (mm)**	**Column dimension (mm)**	**Opening size (mm)**	**Opening location With respect to column**
SE			-	-
SE-400-F	4000x2000x200	400x400	400x400	front
SE-400-C			400x400	corner
SE-600-F			600x600	front
SC			-	-
SC-400-F	2000x2000x200	400x400	400x400	front
SC-400-C			400x400	corner
SC-600-F			600x600	front

Table 4 group number and studied factors

Group Number	**Studied factors**	**Specimen ID**
Group A (Edge column)	Effect of opening size	SE, SE-400-F, SE-600-F
	Effect of opening location	SE-400-F, SE-400-C
Group B (Corner column)	Effect of opening size	SC, SC-400-F, SC-600-F
	Effect of opening location	SC-400-F, SC-400-C

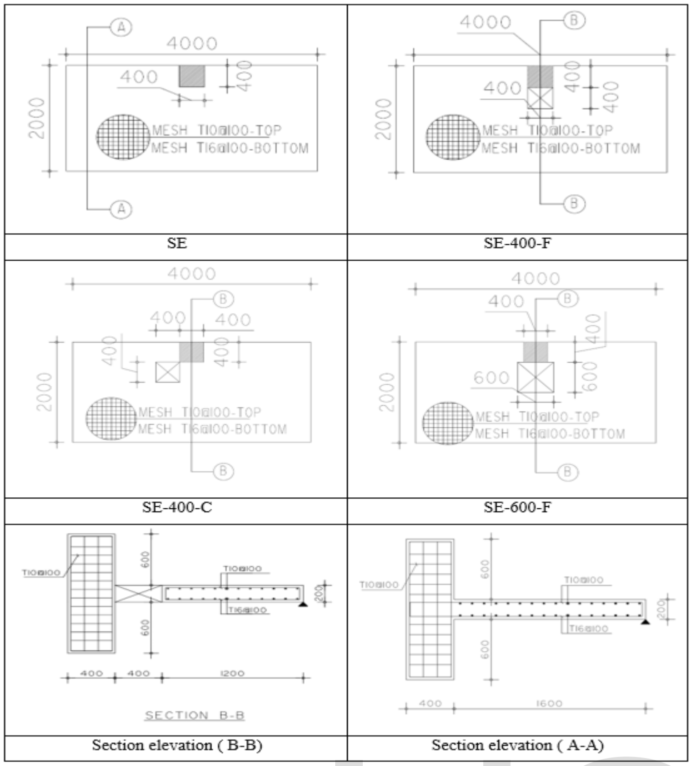

Fig. 9 Geometry and reinforcement details for specimens in group A

5.Results and Discussion

5.1 Crack Pattern and Failure Criteria

In this section, the cracking patterns and the cracking behavior of the slab specimens during loading are discussed and compared. The cracking load at which the cracks were observed is used to compare the cracking patterns of the slab specimens. In ABAQUS16[7] the cracking pattern for the slab and slab-column connections can be identified based on the concrete strain of the slab. From the results of all models, it was observed that the location and shape of the initial crack changed based on the loading condition and the presence of an opening.

In general, for specimen without opening, the cracks propagated inside the slab adjacent to the column at tension side of slab and then the cracks propagated and extended from inside of the slab near column to slab edge. As the load

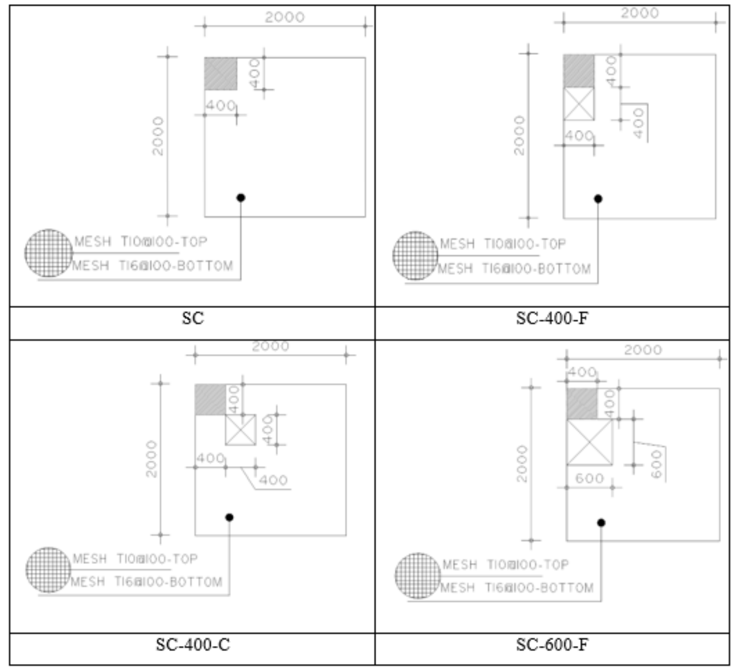

Fig.10 Geometry and reinforcement details for specimens in group B

increased, the radial cracks propagated from column face to the slab edge. While for specimens with openings the cracks started from the inner corners of the openings and developed. It was noted that increasing the opening size led to increase the concrete strains of slabs and more cracks were propagated at opening's corner as a result of loss of specimen's strength and stiffness.

Fig. 11 shows the concrete principle strains on tension surface for group A. as can be seen, the opening size has a significant effect on increasing the concrete crack stains around the opening when comparing specimens SE-400-F and SE-600-F. For specimen SE-400-C the concrete strains were less than the propagated one in specimen SE-400-F as the opening was located at distance away from column's face and subject to lower flexural moment.

As shown from Fig.12 for group B, the max concrete strain was at column's corner due to the presence of the unbalanced moment in two directions. The opening size significantly increased the concrete crack stains around the opening as can be seen when comparing specimens SC-400-F and SC-600-F. while, for specimen SC-400-C, the concrete strains were less than that of specimen SC-400-F as the opening was located at distance away from column's face and subjected to lower flexural moments.

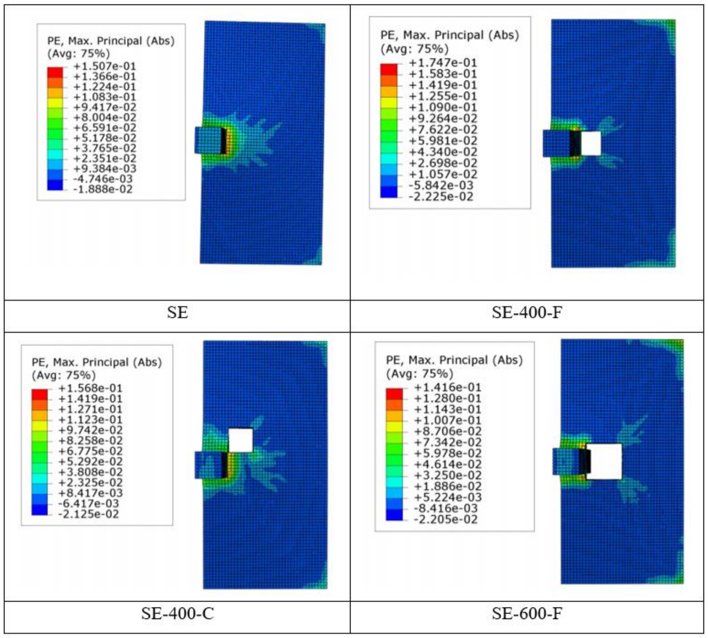

Fig. 11 Concrete principle strains on tension surface at ultimate load for group A.

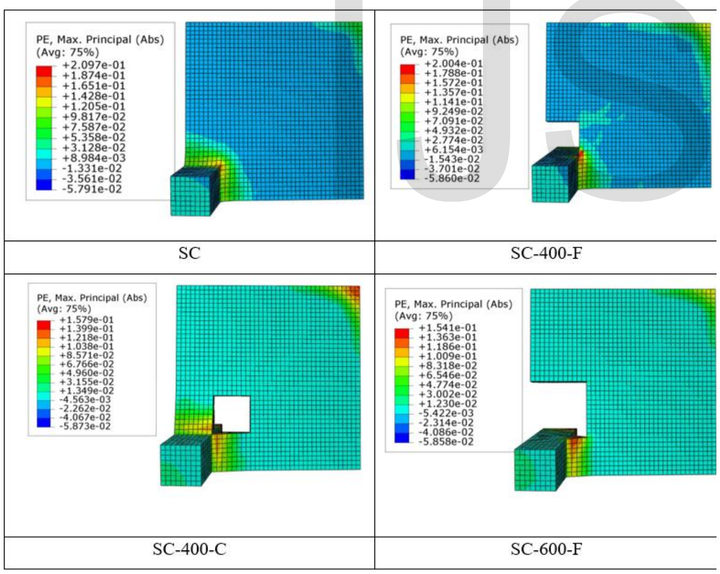

Fig. 12 Concrete principle strains on tension surface at ultimate load for group B.

The failure type for all specimens was a brittle failure in punching mode, the cracks propagated inside the slab adjacent to the column at tension side of slab and then the cracks propagated and extended from inside of the slab near the corner of the column to slab edge. As the load increased, the radial cracks propagated from column face to the slab edge then specimens failed in punching mode.

5.2 Load Deflection Curves

The deflection was obtained at the location of the max deflection for all specimens during loading and up to failure, and then the relation between the load and the deflection was drawn. The mid span deflection was used as comparison between specimens. Generally, two stages were observed. In the first stage, the curves show the linear elastic behavior associated with an un-cracked section, all curves are linear up to the cracking load and the extent of this stage is a function of the tensile strength of the concrete

The second stage of the load-deflection curve is characterized by a constantly increased rate of deflection with the applied load and represents the behavior of slabs after the concrete reaches the cracking stage. All values of deflection and loads at cracking at failure stages are presented in Table 5. Also the load deflection curves for all specimens are presented in Fig.13 for group A and Fig.14 for group B.

5.2.1 Effect of Opening Size and Location on Deflection at Cracking and Ultimate Stage.

Table 5 shows the deflection values at cracking and ultimate loads for specimens in group A and in group B. As can be seen from Table 5, for group A, the deflection at cracking stage for SE-400-F, SE-400-C and SE-600-F increased by 16%, 13% and 28%, respectively and the deflection and reduced at failure load by 16.5%, 9.61% and 31.49%, respectively when compared to the control specimen SE without opening.

It could be concluded that, when the opening size increased from (400x400) mm to (600x600) mm, the deflection at cracking load increased by 10%, and the deflection at ultimate load decreased by 18%. Also, the comparison between specimen SE-400-F in which the opening is located adjacent to column and specimen SE-400-C in which the opening is located at column’s corner, shows that the diagonal location of the opening results in less degradation in punching strength and stiffness of slab than when the opening in the direction of unbalanced moment.

For group B, the deflection at cracking stage for SC-400-F, SC-400-C and SC-600-F increased by 14.60%, 6.60% and 20.43%, While at failure load, deflection reduced by 23%, 15% and 37%, respectively when compared to the control specimen SC without opening.

Table 5 shows that when the opening size increased from (400x400) mm to (600x600) mm, the deflection at cracking load increased by 5%, and the deflection at ultimate load decreased by 17%. Similar to the case of edge column; when the opening located in the direction of the unbalanced moment (SC-400-F) rather than located on diagonal direction (SC-400-C), the reduction in stiffness and punching strength is higher; deflection of SC-400-F at cracking load decreased by 7%, and the deflection at ultimate load increased by 11% relative to SC-400-C.

5.2.2 EFFECT OF OPENING SIZE AND LOCATION ON CRACKING AND ULTIMATE LOADS

As shown in Table 6, for group A, the cracking loads for SE-400-F, SE-400-C and SE-600-F decreased by 21.40%, 12.10% and 32.41%, respectively when compared to the control specimen SE without opening. And the ultimate punching load decreased by 31.65%, 21.30% and 43.80% respectively when compared to the control specimen SE without opening.

The figures show that when the opening size increased from (400x400) mm to (600x600) mm, the cracking load decreased by 13.64%, and the punching shear capacity decreased by 17.80% Also, the reduction in strength of the slab in case of opening along the direction of unbalanced moment (SE-400-F) is higher than that of opening in the diagonal direction (SE-400-C); the cracking load and ultimate punching load of (SE-400-F) were reduced by 11% and 13% when compared to (SE-400-C) respectively.

It has been noted from Table 6, for group B the cracking loads for SC-400-F, SC-400-C and SC-600-F decreased by 29.60%, 18.50% and 46.30%, respectively when compared to the control specimen SC without opening. And the ultimate punching load decreased by 39.20%, 28.80% and 51.10% respectively when compared to the control specimen SC without opening.

Table 5 deflection values for the effect of the opening size and location

Group number	Specimen ID	Cracking Deflection Δcr (mm)	Ultimate Deflection Δult (mm)	Δcr/Δcr,c	Δult/Δult,c
Group A	SE	3.36	54	1	1
	SE-400-F	3.90	45	1.16	0.83
	SE-400-C	3.80	49	1.13	0.91
	SE-600-F	4.31	37.8	1.28	0.70
Group B	SC	1.37	52	1	1
	SC-400-F	1.57	39.8	1.14	0.77
	SC-400-C	1.46	44	1.06	0.85
	SC-600-F	1.65	33	1.20	0.63

The figures show that when the opening size increased from (400x400) mm to (600x600) mm, the cracking load decreased by 23.68%, and the ultimate punching load decreased by 19.62%. Also, the reduction in strength of the slab in case of opening along the direction of unbalanced moment (SC-400-F) is higher than that of opening in the diagonal direction (SC-400-C); the cracking load and ultimate punching load of (SC-400-F) were reduced by 14% and 15% when compared to (SC-400-C) respectively.

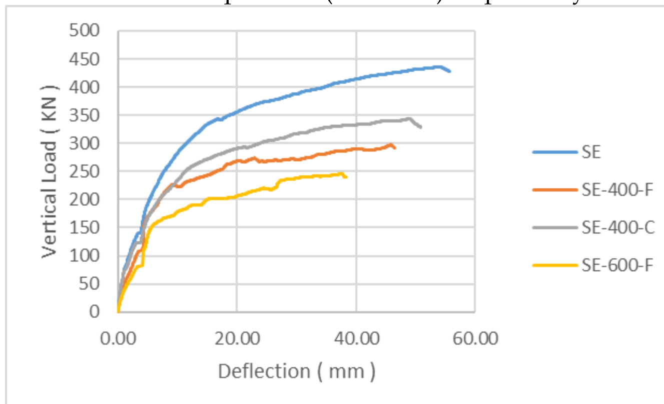

Fig. 13 Load deflection curves of group A.

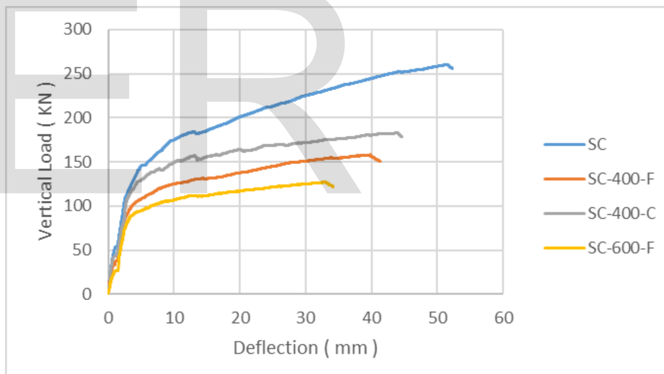

Fig. 14 Load deflection curves of group B.

Table 6 cracking and ultimate loads values for the effect of the opening size and location

Group number	Specimen ID	Cracking load Vcr (KN)	Ultimate load Vult (KN)	Vcr/ Vcr,c	Vult/ Vult,c
Group A	SE	140	436	1	1
	SE-400-F	110	298	0.78	0.68
	SE-400-C	123	343	0.88	0.78
	SE-600-F	95	245	0.68	0.64
Group B	SC	54	260	1	1
	SC-400-F	38	158	0.70	0.61
	SC-400-C	44	185	0.81	0.71
	SC-600-F	29	127	0.50	0.49

6. Summary and Conclusions

A numerical model was based on the FEA theory using ABAQUS to investigate the effect of opening size and opening location on the punching shear strength of flat slabs for both edge and corner column –slab connection. The investigation results of the validation model indicated a good correlation between numerical simulations and experimental data from available experimental tests. The parametric study was developed including eight specimens divided into two groups: the first group for edge column – slab connection and the second group for corner column – slab connection. The analysis results for these numerical models were discussed to investigate the effect of opening size and location on deflection, cracking and failure loads and the following conclusions were obtained:

- The size of the opening affects the deflection of the flat slabs for edge and corner column-slab connections where the increasing in opening size leads to increase the deflection at cracking load and decrease the deflection at failure load because of the reduction of slab stiffness.
- The increase in opening size leads to decrease in the cracking and ultimate loads resistance of the flat slabs for edge and corner column-slab connection.
- The effect of opening size on the punching resistance of the flat slab for corner column-slab connections is higher than that of the flat slab for edge column-slab connections .
- location of the opening with respect to column affects the deflection of the flat slabs for edge and corner column-slab connections. The further the opening from the column the lower the deflection at cracking load and the higher deflection at failure loads.
- location of opening has a significant effect on punching strength of flat slab for edge and corner column-slab connections. Located opening on the diagonal line with respect to the column axes results in less reduction in punching strength of flat slab compared to that of slab with opening located on the column axes
- The effect of opening location on the punching resistance of the flat slabs for corner column-slab connections is higher than that of the flat slabs for corner column-slab connections.

7. References

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