PUNCHING SHEAR BEHAVIOR OF RC FLAT PLATE WITH OPENINGS RESTED ON COUPLED COLUMNS

[1]ALAA ELSAYED, [2]MAHMOUD ELSAYED, [3]DOAA M. SAAD

Faculty of Engineering- Fayoum university- Fayoum-Egypt
E-mail: [1]alaa_elsayed2009@yahoo.com , [2]mms03@fayoum.edu.eg , [3]dm1150@fayoum.edu.eg

Abstract - Supporting a reinforced concrete slabs by coupled columns may cause them to behave as one column or as two separate columns according to the distance in between. In this research, the punching shear behavior of RC flat slabs with openings supported by square interior coupled columns were investigated. A total of twelve two-way RC slabs with interior two columns were constructed and tested. All the test specimens were quadratic with 1000 mm length and 65 mm thick., and have a centrally coupled square column stubs of 100 mm sides and 150 mm height. Three variables were considered in this research which is, the separation distance of the columns (d, 2d, 3d, and 4d), the location of the opening, and the distance from column face to the opening. The test results indicated that the punching shear capacity increased gradually by increasing the clear distance between columns. The experimental results showed a decrease in punching shear capacity in specimens with opening ranged between 10 % and 32% in comparison to the control specimen without opening.

Index Terms - Coupled columns, Flat plate slab, Punching Shear, Opening.

I. INTRODUCTION

The reinforced concrete flat plate is one of the most common systems in construction, as it provides architectural flexibility, large span, less building height…etc. One of the main problems in the flat plate is its capability to punching failure. These are the local failure of the slab-column connections in which the column together with a portion of the slab pushes through the slab. The unpredictable nature type of failure is a major drawback to flat plate construction. ACI [1] and ECP [2] assume that the critical section of punching shear is at (0.5d) from the column face, however, the critical section was adopted by the BS-8110 [3] at 1.5d from the column face. The presence of opening near the column reduces the volume of concrete resisting transverse shear, hence increasing the probability of punching shear failure of the connection. Several studies have been performed to investigate the punching shear behavior of RC flat-plate slabs with or without opening. Sagaseta et al. [4] studied the punching shear strength of RC flat slab with rectangular interior columns under the different loading conditions. Mamede et al [5] carried out both experimental and numerical investigations to study the effect of reinforcement ratio, slab thickness, concrete strength and column dimensions on punching shear of flat plate. Hoang [6] performed an experimental test to investigate the effect of initial cracking on the punching shear behavior of RC slabs. El-Salakawy et al. [7] carried out an experimental study on the punching shear strength of RC flat-plate edge connections with an opening. Teng et al. [8] studied experimentally the punching shear strength of flat plate rested on rectangular column and containing a large cut-outs. It was observed that the holes decrease the punching shear capacity of the slab. Borges et al. [9] carried out a laboratory test to investigate the effect of size and numbers of openings in punching shear strength of slab supported in rectangular columns. An experimental program were performed by Ha et al [10] to evaluate the punching shear capacity of flat-plate slabs without shear reinforcement and includingan openings. Anil et al [11], Oukaili and Salman [12], and Al-Shammari [13] carried out an experimental program to investigate the effect of opening position and size on the punching shear capacity of two-way RC slab. It was observed that, increasing the opening size led to a decrease in punching load. Aikaterini et al [14] carried out nonlinear finite element analysis to study the punching shear behavior of RC flat plate with an opening. Rashied [15] compiled the state of the art on the evaluation of the predicted punching shear strength of flat plate with an opening. Al-Shammari [16] investigated the effect of separation distance of the columns on punching pattern of flat plates with high and normal strength concrete. In this research, the behavior of flat plate with coupled columns with or without opening is presented. The effect of the clear distance between the coupled columns and opening locations are investigated.

II. EXPERIMENTAL PROGRAM

A. Material Properties

All the test specimens have the same concrete mixture based on the design compressive strength of 30 Mpa. The actual concrete strength after 28 days was determined from compression test performed for stander cubes. The compressive strengths of the test specimens were obtained in the range of 31.8-33.4 MPa and in the average of 32.4 MPa. In this investigation two types of steel reinforcement bars

were used. The first type was high-grade steel of Φ10 mm diameter with a yield strength of 413 MPa which was used as main reinforcement for slab and column stubs. The other type was normal mild steel of Ø 6 mm diameter with a yield strength of 293 MPa which was used as stirrups of the column stubs.

B. Test Specimens

In the scope of the research program, a total of twelve two-way RC slabs with dimensions of 1000 X 1000 X 65 mms were prepared and tested experimentally. The test specimens were manufactured with two square RC columns stubs with 100 mm length and 150 mm height. The column stubs are located at the center of the slab and all slabs stay symmetric about the two axes as the place of the columns were changing with respect to the centreline of the slab. All the test specimens have Φ 10 mm@190 mm in each direction as the slab flexural steel reinforcement in tension side, with the clear concrete cover for steel bars of 15 mm. The column stubs have Φ10 at each corner as longitudinal reinforcement and φ 6 mm @65 mm as stirrups. The specimen details and dimensions are presented in Figure 1. The test program divided into four slabs without opening and with a different separation distance between columns. The remaining eight slabs having a square opening of 100 mm length, and constant separation distance of 50 mm between coupled columns. The studied parameters are the separation distance between the two columns (X= d, 2d, 3d, and 4d), location of opening (Parallel, diagonal, and perpendicular) to the axis of the two columns, and the distance from the opening to the column face (S= 0, 0.5d, d, 1.5d, 2d, and 3d). Details of the test specimens are shown in Figure 2. The properties and descriptions of the test specimens are given in Table 1.

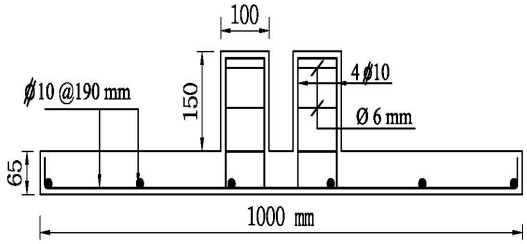


Figure1 Reinforcement Details of Test Specimens

C. Test Setup

At the beginning of the slab test, it was placed over a square steel box which supported on six RC blocks. Hinged supports at the slab edge were provided using a round bar of 4 cms diameter. All specimen were simply supported along the four edges and tested in horizontal positions with 920 X 920 mm as effective spans. The vertical load was applied gradually with constant rate through I.P.E # 30 placed over the center of the two column stubs using a hydraulic jack of 60-ton capacity. The central deflection of the specimens was measured using LVDT which placed centrally on the tension side of the specimen. The test setup is shown in Figure 3.

III. EXPERIMENTAL RESULTS AND EVALUATIONS

In this section, the results obtained from the experimental study are presented and compared. The cracking pattern, failure modes, ultimate punching shear load, and ultimate deflection were observed. The yield load and related deflection, the ductility index, energy absorption capacities, and initial stiffness were calculated from the load-deflection curve for the test specimens.

A. Load-Defection Response

Figure 4.a shows the comparison between the load - central deflection curves for specimens (S1, S2, S3, and S4) to investigate the effect of clear distance between the columns on punching pattern for flat plates. The test results show that, the ultimate punching load increases with increasing the distance between columns. From the figure, it can be observed that, the test specimens (S2, S3, and S4) failed in punching shear but the specimen S1 failed in flexural punching after relatively large displacement. The results indicated that the punching shear capacity of specimen S4 of separation distance (X=4d) was 30% greater than that of control specimen S1 of (X=d). The specimens S2 and S3 of clear distance (X=2d and X=3d) respectively, showed nearly the same behavior with a small difference in ultimate load. Figure 4.b and Figure 4.c show the load-deflection relationships of the test specimens incorporating the influence of the location of the openings. From the figures, it was observed that, the existence of cut-out adjacent to the column reduces the punching shear strength by about 29 %. The ultimate punching loads of the test specimens having openings located parallel or perpendicular to RC columns (specimens; S5, and S7) are smaller than that of the test specimen with an opening located diagonally to RC columns (specimens; S6). The results indicated that the punching shear capacities of the specimens (S8, S9, S10, S11) with openings located at distance (0.5d, d, 1.5d, and 2d) far from the column face were 23%, 16%, 14%, and 9% smaller than that of the control solid slab (specimen S1) respectively. It can be seen that, the effect of opening on punching shear strength has vanished when the opening is located at 3d far from the column face. Another observation from the figures is that, the specimens with openings failed in a brittle mode with a sudden drop in their load displacement showing a typical punching shear failure.

B. Cracking Pattern and Mode of Failure

The cracking pattern at both the compression and tension sides of the test specimens is noticed and recorded after the completion of the test as shown in Figures 5 and 6 respectively. It was noticed that, the test slabs failure accompanied by main cracking around the face of the column stubs and slight cracks appear in the part of heel post. It was observed that, all the test specimens failed in brittle punching shear failure except the control specimens (S1), and (S12), failed in a mode of flexural punching which correspond to the load-deflection curve. Hair cracks at the bottom side underneath the column sides appear firstly. For the specimens (S1), diagonal cracks started and going from the corners of the column stubs toward the slab edges on the tension side. For the test specimens with the opening, the cracks started firstly in the nearest corners of the opening to the column and propagated to the edges of the slab. The radial cracks in the opening side widened and failure occurred with spalling of the concrete cove at some location of tension steel. At failure, it was observed that the column penetrated the slab.

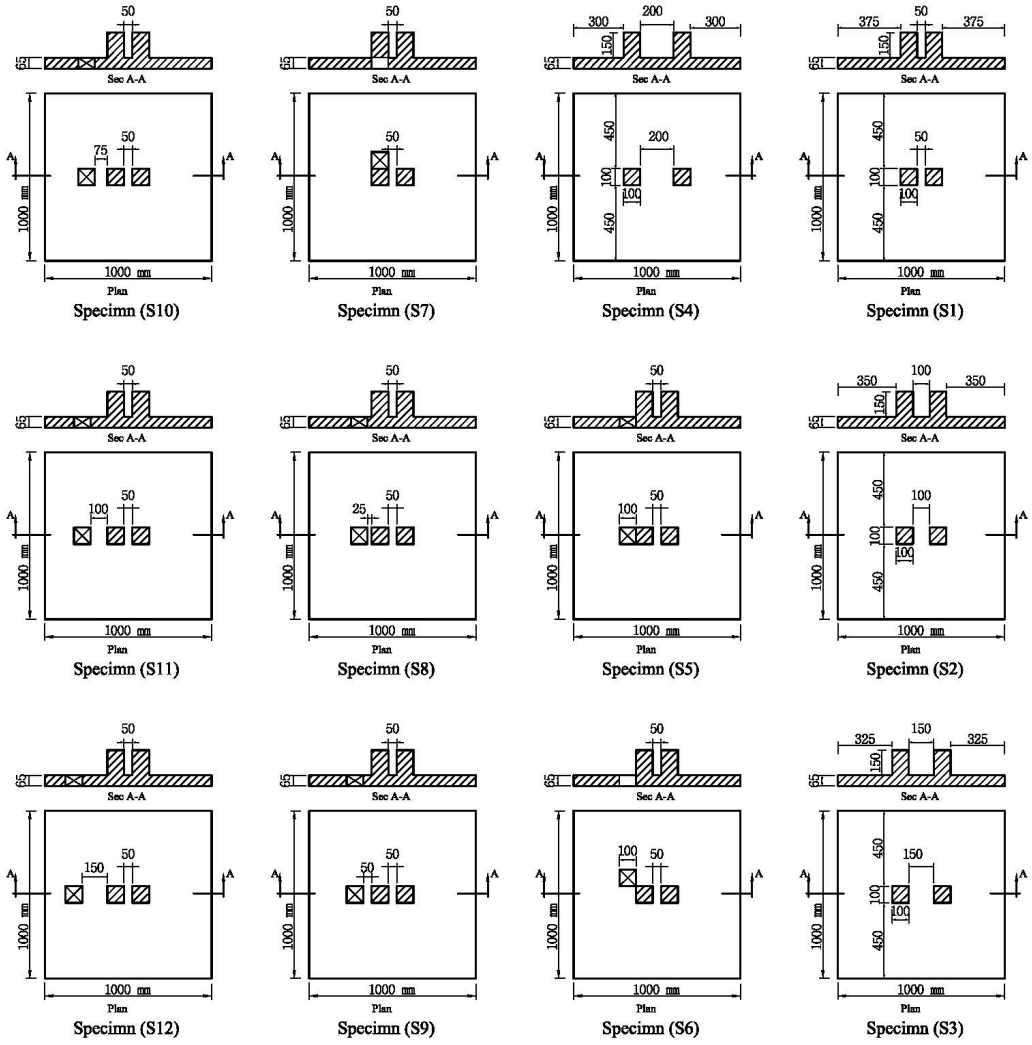


Figure 2 Layout Scheme of Specimens. (Dimensions in mm.)

Table1: Properties of the Test Specimens.

specimen	Clear distance between two columns (X)		Distance from column face to the opening (S)		Opening Location
	X (mm)	X/d	S (mm)	S/d	
S1	50	1	Without opening		
S2	100	2	Without opening		
S3	150	3	Without opening		
S4	200	4	Without opening		
S5	50	1	0	0	Parallel (adjacent of two column)

S6	50	1	0	0	Diagonal (adjacent of column)
S7	50	1	0	0	Perpendicular (adjacent of two column)
S8	50	1	25	0.5	Parallel 25 mm far from column
S9	50	1	50	1	Parallel 50 mm far from column
S10	50	1	75	1.5	Parallel 75 mm far from column
S11	50	1	100	2	Parallel 100 mm far from column
S12	50	1	150	3	Parallel 150 mm far from column



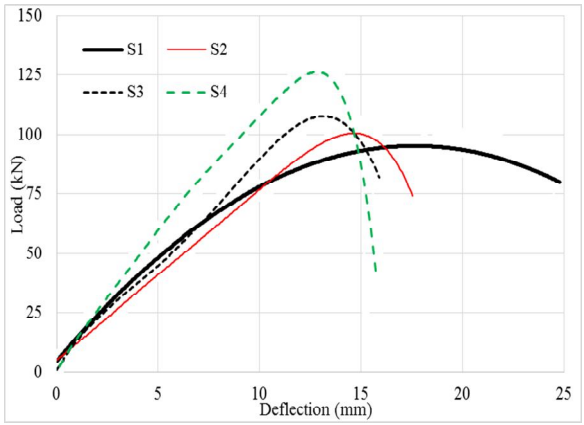
Figure3: Test set up.

Ductility Index, Energy Absorption and Initial Stiffness

The uncracked stiffness, ductility ratio, and energy dissipation capacities of the test specimens were calculated from the experimental results and listed in Table 2. The displacement ductility ratio was obtained from the load-displacement curve as the ratio between the deflection at yield load and the deflection at ultimate load. The results indicated that, the presence of opening leads to a decrease in initial stiffness, ductility, and energy dissipation by about 47%, 34%, and 64% respectively, compared to that of the solid specimen (S1). The Initial stiffness and ductility of the slab contained opening located diagonally to RC columns (specimens; S6), are greater than that of the test specimens with cut-outs parallel or perpendicular to RC columns (specimens; S5, and S7). The results indicated that, the influence of the cut-out has approximately vanished on the uncracked stiffness, ductility index, and energy dissipation whereas the opening placed at 3d or more away from the column side. As the separation distance of the coupled columns increased the ductility and energy absorption values decreases, while the initial stiffness value increases.

CONCLUSION

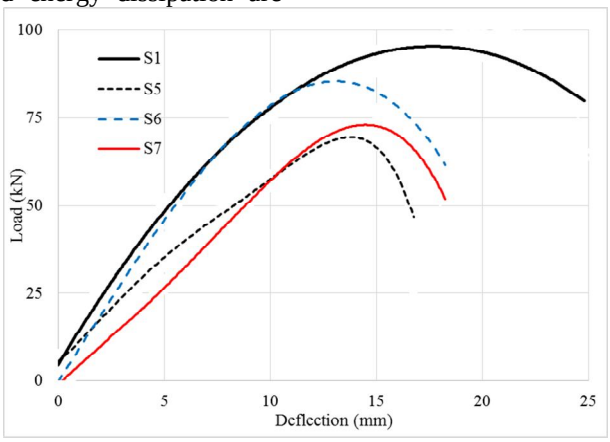
This study investigated experimentally the structural behavior of flat plate rested on coupled columns and evaluated the effects of opening on their punching shear capacities. Depending on the presented experimental results, the following conclusions are obtained:



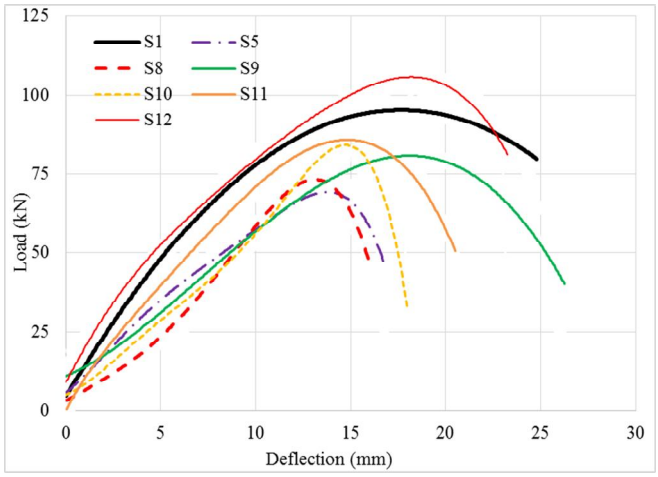
a. Effect of Clear Distance between the Columns

1. The results indicated that, increasing the clear distance between the coupled columns leads to an improvement in the punching load capacity. For flat plate with the distance between the coupled columns greater than or equal 4d each column behave in a separation manner.
2. The presence of opening adjacent to the coupled columns not only reduces the punching shear strength but also increases the post punching shear behavior. The experimental results showed that the specimen with opening failed at ultimate punching load with 33 % smaller than that of the specimen without opening.
3. The existence of opening in flat plate rested in coupled columns decreases the initial stiffness,

and ductility ratio depending on the locations of the opening. The results indicated that the initial stiffness, ductility, and energy dissipation are decreased up to 47%, 34%, and 63% respectively, compared to that of the slab without opening.



b. Effect of Opening Location Adjacent the column



c. Effect of Distance from Column Face to the Opening

Figure 4 Load –deflection relationship for different specimens

4. The punching shear capacities of flat plates is affected by the opening positions from the column face. The influence of opening location is disappeared by placed the opening at a distance greater than or equal to 3d from the column face.
5. Flat plate with opening placed diagonally to the column, have punching shear greater than that of the slab with cut-out located parallel or perpendicular to RC column. The punching shear strength of specimen (S6) is more than that of specimens (S5 and S7) by about 28% and 19% respectively.
6. The existence of opening in flat plate rested on coupled columns decreases the initial stiffness, and ductility ratio depending on the locations of the opening. The results indicated that the initial stiffness, ductility, and energy dissipation are decreased up to 47%, 34%, and 63% respectively, compared to that of the slab without opening.

Table 2 Ductility Ratio, Initial Stiffness, and Energy Absorption of the Test Specimens

Slab	Load (kN)		Deflection (mm)		$\frac{P_u}{P_u(S1)}$	Ductility ratio	Initial stiffness (kN/mm)	Energy dissipation capacity (kN.mm)
	At Yield	At Ultimate	At Yield	At Ultimate				
S1	72.8	97.5	12	17.5	1.00	1.85	8.97	1793.5
S2	76.5	102.4	13	14.75	1.05	1.13	8.50	1084.13
S3	84.8	113.2	12	13.75	1.16	1.15	9.00	1034.76
S4	94.5	126	11.17	13.25	1.30	1.19	12.00	1182.85

S5	51.8	69.3	11.7	15	0.71	1.28	7.01	758.85
S6	66.4	88.5	8.4	12.5	0.91	1.49	8.50	1182.55
S7	55.5	74.3	13	16.5	0.76	1.27	5.71	822.32
S8	55.9	74.5	13	20.25	0.77	1.56	5.46	647.72
S9	60.8	81.3	14	21.25	0.84	1.52	7.05	1471.83
S10	62.3	83.7	14.65	17.75	0.86	1.21	5.60	875.71
S11	66.4	88.5	11.45	14.5	0.91	1.27	7.48	1192.77
S12	79.9	106.5	10.85	19	1.10	1.75	11.12	1767.56

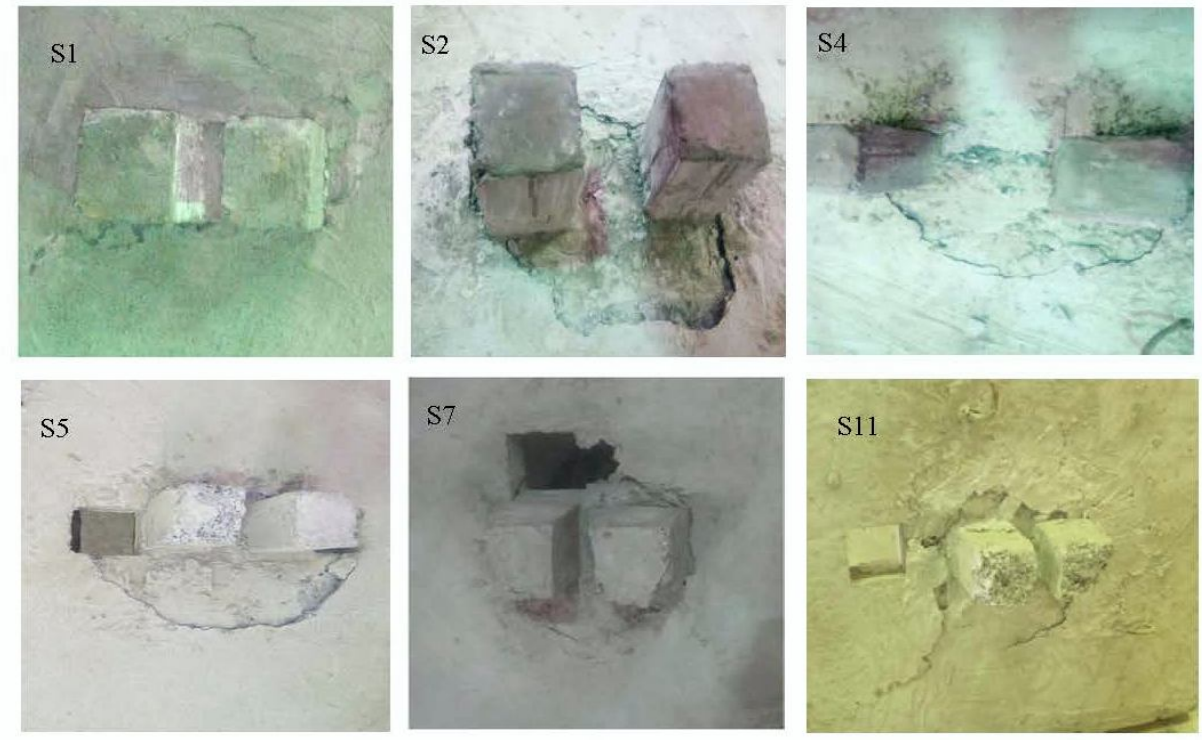
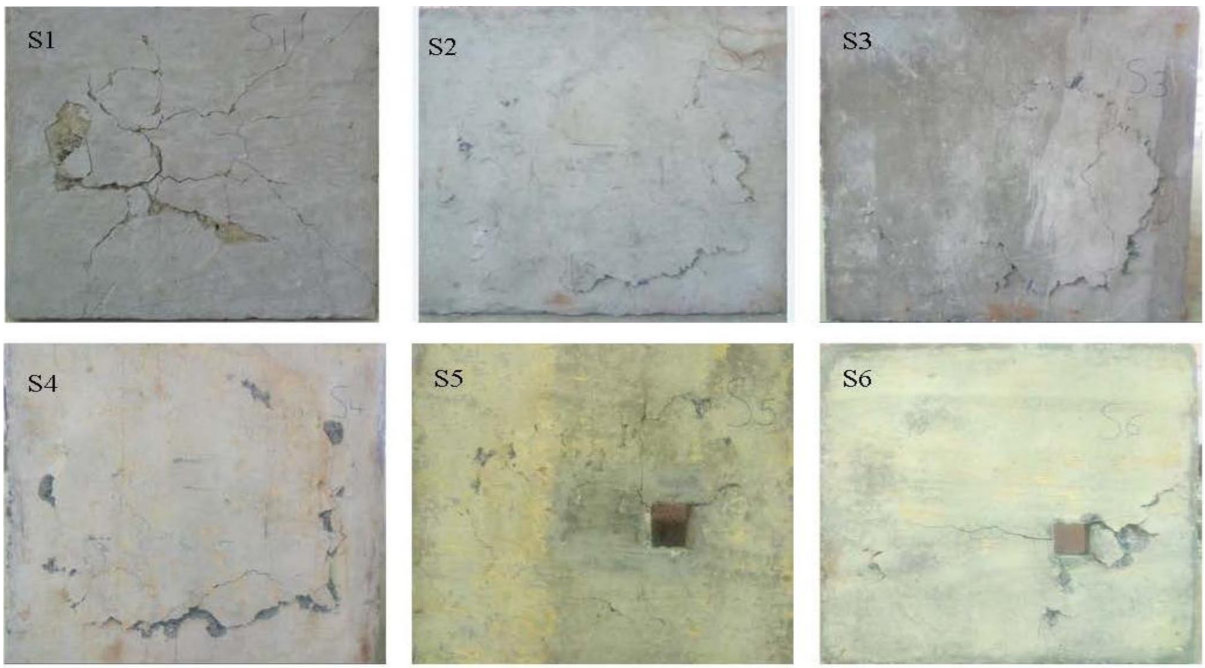


Figure 5 Cracking Patterns of Specimens at Columns Connection



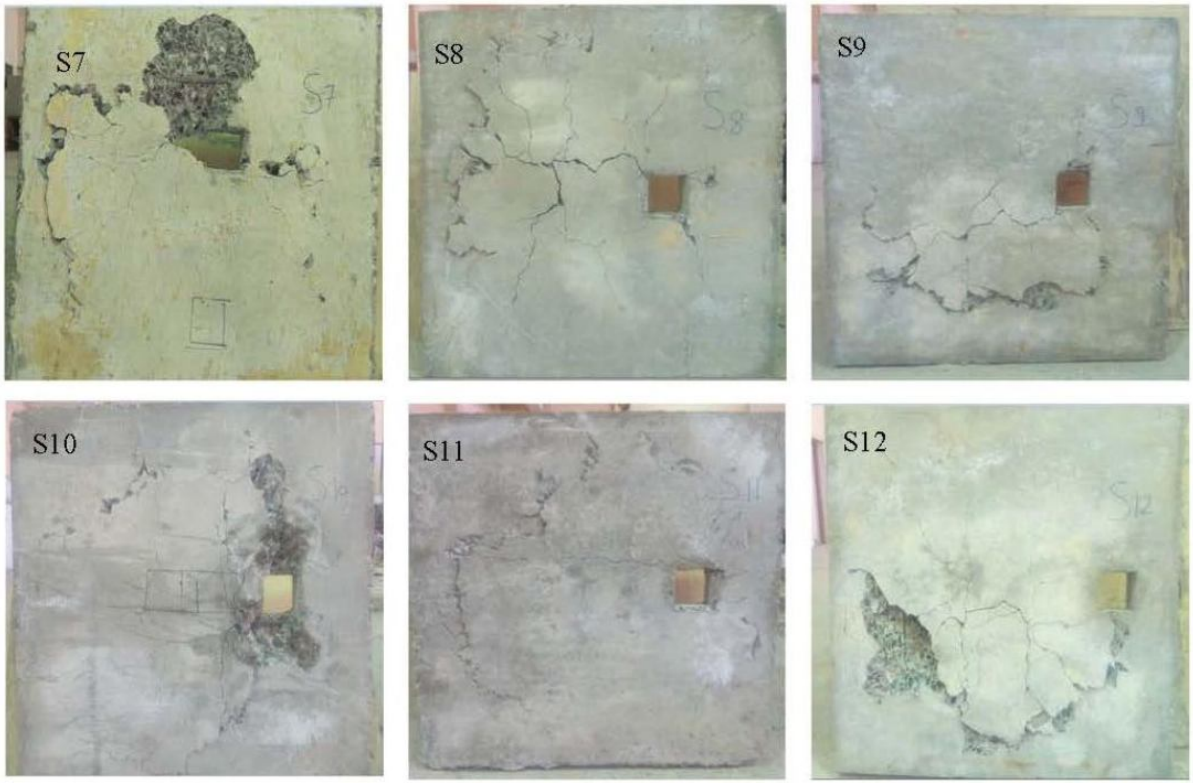


Figure 6 Cracking Patterns of Specimens at Bottom Face

REFERENCES

[1] ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318M.14) and Commentary", American Concrete Institute, Farmington Hills, Michigan, USA, 2014.

[2] ECP 203-2009. Egyptian code of practice for design and construction of Reinforced concrete structures. Third edition.

[3] British Standards Institution, "Structural Use of Concrete, BS – 8110: Part 1 – Code of Practice for Design and Construction", London, 1997.

[4] Sagaseta J, Tassinari L, Ruiz M, Muttoni A. Punching of flat slabs supported on rectangular columns. Engineering Structures journal. vol. 77, pp. 17-33, 2014.

[5] Mamede N, Ramos A, Faria D. Experimental and parametric 3D nonlinear finite element analysis. Engineering Structures journal. vol. 48, pp. 442-457, 2013.

[6] Hoang L. Punching Shear Tests on RC Slabs with Different Initial Crack Patterns. Procedia Engineering journal. vol. 14, pp. 1183-1189, 2011.

[7] El-Salakawy EF, Polak MA, Soliman MH. Reinforced concrete slab-column edge connections with openings. ACI Structural Journal. vol. 96, pp. 79-87, 1999.

[8] Teng S, Cheong HK, Kuang KL, Geng JZ. Punching shear strength of slabs with openings and supported on rectangular columns. ACI Structural Journal. vol. 101, pp. 678-687, 2004.

[9] [Borges LJ, Melo GS, Gomes RB. Punching shear of reinforced concrete flat plates with openings. ACI Structural Journal. vol. 110, pp. 547-556, 2013.

[10] [Ha T, Lee M, H, Park J, Kim D. Effects of openings on the punching shear strength of RC flat-plate slabs without shear reinforcement. Struct. Design Tall Spec. Build. vol. 24, pp. 895-911, 2015.

[11] Anil Ö, Kina T, Salmani V. Effect of opening size and location on punching shear behaviour of two-way RC slabs. Magazine of Concrete Research. vol. 66, no. 18, pp. 955-966, 2014.

[12] Oukaili K, Salman T. Punching Shear Strength of Reinforced Concrete Flat Plates with Openings. Journal of Engineering. vol. 20, no. 1, pp. 1-20, 2014.

[13] Al-Shammari. Effect of openings with or without strengthening on punching shear strength for reinforced concrete flat plates. Journal of Engineering. vol. 17, no. 2, pp. 218-234, 2011.

[14] Aikaterini S. Genikomsou , Polak, Effect of openings on punching shear strength of reinforced concrete slabs—finite element investigation. ACI Structural Journal. vol. 114, no. 5, pp. 1249-1261, 2017.

[15] Rashied S M, Punching shear resistance of flat slabs with opening. IJCIET vol. 6, no. 4, pp. 1-12, May 2015.

[16] (2015); 6(4): 1-12.

[17] Al-Shammari. Effect of separation distance between the columns on punching pattern for flat plates with high strength concrete. Journal of Engineering and Development. vol. 14, no. 13, pp. 162-177, 2010.

★★★