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Effect of Openings on Punching Shear Strength of Flat Slab According to Egyptian and American Codes

A.M., Faisal, H.M., Ibrahim, S.R., Raghib, M.A., Arab

Assistant Lecturer, Civil Engineering Department, Faculty of Engineering, Sinai University, North Sinai, Egypt
Prof. of Reinforced Concrete Structures, Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt.
Assistant professor, Civil Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt.
Associate professor, Civil Engineering Department, Faculty of Engineering, Beni-Suef University, Beni-Suef, Egypt.

ABSTRACT: Flat slab is a popular structural element used in many concrete projects. Further loading of flat slab than ultimate load can cause punching shear failure due to a large concentration of shear and bending loads. The presence of openings in the areas close to the column can reduce the punching shear capacity of flat slabs, as the opening had a negative effect on the slabs' punching strength. This paper reviews the effects of load eccentricity and the existence of openings on the behavior of punching shear capacity of reinforced concrete flat slabs. Most punching experiments on flat slabs with openings have focused on the effect of openings size and location with concentric punching shear, while comprehensive research on eccentric punching shear and the punching shear behavior of slabs considering variations in the shape of openings has not been found. Egyptian (ECP 203) and American (ACI 318) design codes use close design equations and assumption provisions in calculating punching shear strength.

KEY WORDS: Flat slab, punching, opening, concentric, code provision, shape, size, location

I.INTRODUCTION

In many concrete projects, including rumps, hotels, and the roofs of multi-story buildings, reinforced concrete flat slabs are the most often utilized structural systems [1]. In North America and Europe, flat slab building first became popular in the early 20th century. Such a building method is effective, affordable, and offers numerous benefits, including the lack of beams, absence of obstructions above, increased ceiling height, and ease of construction [2]. A flat slab system exhibits complicated behavior, particularly in the slab-column connection where it transmits loads directly to the columns without the need of beams or girders while carrying both vertical and horizontal stresses. As a result, one of the most important factors that may cause punching shear failure is the large concentration of shear and bending loads [3]. Flat slab punching failures manifest as brittle failures with small deflections, which are followed by a nearly complete loss of load-bearing capability. The punching shear failures happen suddenly and without any prior notice. Also, the slab's top face developed fissures, which are frequently covered by the flooring. Thus, in the design phase, the punching shear must be carefully examined [4].

On the other hand, openings are usually located next to the columns for providing many purposes, including ventilation, heating, sanitary, electrical ducting, and air conditioning. These openings might lessen the amount of concrete required to withstand shear strength and unbalanced torque, which in turn lessens the capacity of the concrete to punch in the slab-column connecting area [5]. Although Elstner and Hognestad (1956) and Moe (1961) began doing substantial research on concrete flat slabs in the 1950s, the phenomena of openings in these slabs were first primarily studied on interior slab-column connections. No study on slabs with openings was reported in the following years. Recent researchers began to examine the effects of reinforced concrete slab openings again in the 1990s [6].

The presence of openings in the areas close to the column is one of the issues that might reduce the resistance to punching of flat slabs. As the opening had a negative effect on the slabs' punching shear strength. The punching shear strength of flat slabs with openings that vary in size, shape, number, and location must thus be precisely estimated [7]. Columns in structures exist mainly to convey vertical loads to the foundation. Nonetheless, the transmission of a moment due to span, differential shrinkage between two slabs, creep, and horizontal forces like wind or earthquakes cannot be completely avoided [8]. Although there are relatively few studies examining the impact of the eccentric load on the punching shear

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strength of these slabs, the majority of experimental and numerical investigations for the slab with an opening close to the support were done for punching owing to the centric load [9].

II. RESEARCH SIGNIFICANCE

The main goal of this paper is to study the effect of openings on the behavior of reinforced concrete flat slab in punching and comparing experimental results with Egyptian (ECP 203) and American (ACI 318) design codes.

III. PUNCHING SHEAR FAILURE MECHANISM

Punching shear collapse of reinforced concrete slabs happens when focused loads are started causing a high value of shear. Firstly, stress combination presentation leads to radiated cracks starting at the edge of the load application zone. Cumulative load causes, tangential cracks nearby, the load application zone [10].
The failure stage is reached when the inclined cracks form around the column with a usual cylindrical punching collapse cone as shown in figure (1) the column splits from the slab. Without shear reinforcement, the punching shear collapse achieves a brittle mode within the gap region of the highly stressed slab at the column [11].

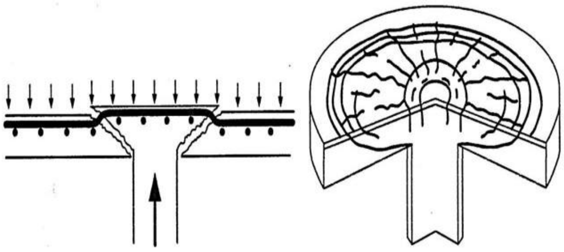

Fig 1. Cracking, pattern and cylindrical, cone of the punching shear failure [12].

A) Effect of openings on punching shear failure mechanism

The presence of the opening conduces to the smaller number of cracks in the direction of the opening and the concentration of cracks in the y-direction, changing the slab behavior from a bidirectional action to a unidirectional action. As the distance between the opening and the column increase, a greater amount of cracks could be observed as shown in figure (2) [4].
The existence of opening in concrete slab-column connection reduces the rigidity of the connection depending on the size and location of this opening and that reflects the increase in the crack width [17].
The cracks start with radial cracks running from the column stub toward the slab edges. The cracks start at the middle of the bottom layer from opening corners near column. This shortly follows by the formation of circumferential cracks around the column stub and, as the load increases circumferential cracks occur at a location farther away from the column stub [18].

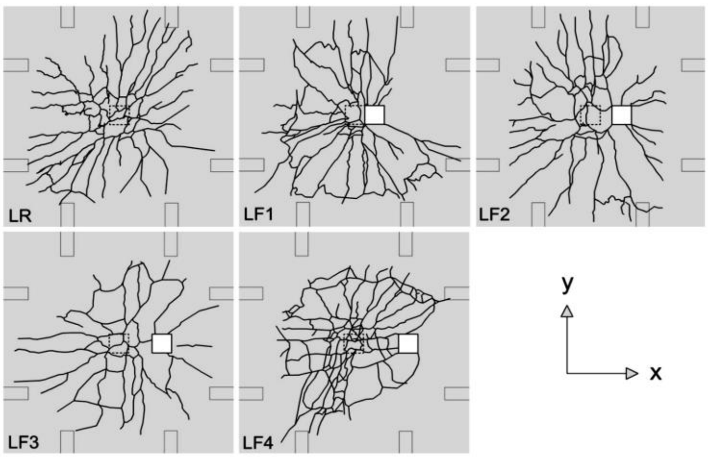

Fig 2. Crack pattern after failure at top surface of slabs [4].

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IV. DESIGN CODE PROVISIONS OF THE PUNCHING SHEAR OF FLAT SLAB

Several design codes deal with the issue of punching failure in different ways. For instance, the American code (ACI 318) [19] and the current Egyptian Code of Practice [20] both ignore the effects of horizontal reinforcement. Moreover, the crucial section of the punching's location varies from half to twice the effective slab depth measured from the column face depending on the design code.

A) Egyptian Building Code (ECP 203) [20]

The Egyptian code (ECP 203) [20] state that the smallest of the following three values as shown in Eqs. (1) to (3) represents the ultimate punching shear capacity (Vc):

$$v_c = 0.316(0.5 + \frac{a}{b}) \times \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d \quad \text{Eq. (1)}$$

$$v_c = 0.8\left(\frac{\propto d}{b_o} + 0.2\right) \times \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d \quad \text{Eq. (2)}$$

$$v_c = 0.316 \times \sqrt{\frac{f_{cu}}{\gamma_c}} b_o d \le 1.7\ N/mm^2 \quad \text{Eq. (3)}$$

Where: a: is the column dimension in the analysis direction, b: is the column dimension in the perpendicular direction, ∝: equals 4,3,2 for interior, exterior, corner column respectively, b_o: is the critical section for punching shear strength is located at 0.5d from the column face (d: the effective slab depth).

B) American Concrete Institute (ACI 318) [19]

The punching shear strength of concrete (v_c) of slabs can be determined from the lowest of the following expression as shown in Eqs. (4) to (6):

$$v_c = 0.33\,\lambda\sqrt{f_c}'\, b_o d \quad \text{Eq. (4)}$$

$$v_c = 0.17(1 + \frac{2}{\beta})\,\lambda\sqrt{f_c}'\, b_o d \quad \text{Eq. (5)}$$

$$v_c = 0.083(2 + \frac{\alpha_s d}{b_o})\,\lambda\sqrt{f_c}'\, b_o d \quad \text{Eq. (6)}$$

Where: fc': is concrete cylinder compressive strength = 0.85 fcu for cube strength the compressive strength of concrete in MPa. The requirement of the ACI code that is not exceed 68MPa was disregarded in computations, β: (Long Side/Short Side) of column or support, αs: Parameter Considering the effect of the location of column, αs= 40 For interior column; αs= 30 For exterior (edge) column; αs= 20 For corner, bo: Perimeter along the critical section located at 0.5d from the column face and λ: is taken as 1.0 for the normal-weight concrete.

D) Effect of openings on the critical shear perimeter

Egyptian code (ECP 203) [20] and American Concrete Institute (ACI 318) [19] adopt that punching shear strength in flat slabs is affected with the existing of openings within the loaded area of slab-column connection by affecting on the critical perimeter. Both the codes require that the critical perimeter be reduced if openings are located less than or equal to 10 times the slab thickness. All design codes reduce the critical shear perimeter based on the size and the location of the opening, where a part of the controlled perimeter contained between two tangents drawn to the outline of the opening from the center of the column is considered to be ineffective, as illustrated in figure (3) [22].

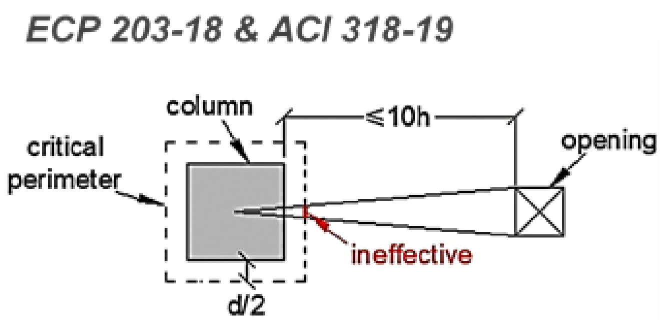

Fig 3. Critical perimeter near opening according to ECP 203 [20] and ACI 318M [19].

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V. EFFECT OF OPENINGS ON PUNCHING SHEAR STRENGTH IN VARIOUS RESEARCHES

The discussion below presents a brief review on the punching shear strength of flat slabs with opening differing in size, shape, number and location in various previous researches.

El-Shafiey et al. (2022) [24] investigated the effect of opening size and location on the punching shear behavior of Reinforced Concrete (RC) flat slabs. Six two-way slabs with openings and a control slab without openings were tested under a static load applied on a central stub column. Three slabs with three different opening sizes (200×200, 300 × 300 and 400 × 400 mm2) were tested, while three slabs with the same opening size of 300 × 300 mm2 were tested, when the openings were at different locations. The distances between the opening edge and the column face were 100, 200 and 300 mm.

The results showed that introducing an opening beside the column significantly reduced the punching shear capacity of tested slabs. As the opening width increases, the reduction in ultimate capacity increases, reaching 51%. The capacity of the slab with an opening 300 mm far from the column was 36% higher than that of the slab having an opening next to the column. The ultimate experimental punching shear capacities of slabs with openings were compared to those obtained by the equations of ECP-203, ACI-318 and EC2 codes. ECP-203 and ACI-318 showed higher factors of safety than EC2 [24].

To study the effect of opening shape, El-Shafiey et al. (2022) [24] investigated the slabs having circular openings with diameters were 250, 350 and 450 mm, these values were configured to equalize the areas of the square openings. The test results showed that the punching shear capacity of slab having a circular opening with a diameter of 250, 350 and 450 mm were 2.85, 18.88 and 30.43%, respectively, than that of slab having a square opening with a size of 200 × 200, 300 × 300 and 400 × 400 mm2. They also compared the ultimate experimental punching shear capacities of slabs with openings with those obtained by the equations of ECP-203, ACI-318 and EC2 codes. ECP-203 and ACI-318 showed higher factors of safety than EC2.

Lourenço et al. (2021) [4] studied the structural behavior of flat slabs subjected to concentric punching shear with openings at different distances from the column (0, d, 2d, 3d), where d is the depth of the slab, through five square slabs (1,800 mm x 1,800 mm x 130 mm) supported on five square columns (150 mm x 150 mm) until failure.

The results showed that openings led the tested models to present smaller displacements, but for the final stages of loading, the specimen with the opening positioned at 2d from the column face presented higher displacements. The slabs with the opening at d and 3d presented failure loads 1% and 11% larger than the control specimen without opening, respectively. The ACI 318 was the most conservative code, with an average expected failure load 41% higher than the tested load. The Eurocode 2 was the best estimate of punching resistance, with previsions 22% smaller than the tested loads [4].

Also, Mostofinejad et al. (2020) [7] used finite element modeling to investigate the effects of openings varying in size and location on the punching shear strength of slab-column connections, 8 interior connections and 8 edge connections. Each connection had one opening with the dimensions of 150 ×150 mm and 250 ×250 mm located 0, 75, 150, and 300 mm far from the column in a parallel position. Results showed that near-column openings caused an increase in shear stress, which was reduced by increasing the dimensions and reducing the distance from the column.

Sheta et al. (2020) [25] conducted a parametric study on ten full-scale reinforced concrete flat slabs modelled using ANSYS 19 to investigate the effect of different opening sizes and locations on the punching shear behavior of flat slabs with openings. The investigated specimens were of dimensions 3000x3000x200 mm and had flexural top reinforcement over the column with a constant ratio equal to 0.80%. The punching shear strength decreased by 10% when the size of opening increased from (400x400) mm to (600x600) mm. However, the punching shear strength of a specimen was directly proportional to the distance from the opening to the column's face, regardless of the size of the opening. Specimens with an opening size of 600x600 mm and located at a distance "d" away from the column face increased by 21%, while those with an opening of 400x400 mm increased by 8.7%.

Kadam and Ingole (2019) [26] studied the effect of the size and location of the opening on the punching shear strength of the flat slab using a finite element analysis-based software CSI SAFE 2016. Their experiment was based on seven different models/specimens studied in which six models had an opening of 1.2 x 1.2 m, 2 x 2 m and 3 x 3 m respectively. Openings were placed parallel or diagonal to the face of the column.

The results showed that the punching shear capacity of the flat slab without an opening was higher than the flat slab with an opening, but the opening of size 1.2 x 1.2m was the lowest by 82.40%. It was also concluded that adjacent openings diagonal to the face of the column were more efficient than the openings parallel to the column [26].

Balomenos et al., (2018) [22] performed parametric studies to examine the effect of opening size and location on the punching shear resistance of reinforced concrete flat slabs without shear reinforcement. They used 12 slabs with two opening sizes, 150 × 150 mm and 70 × 70 mm, with different distances 0, d, 2d, 3d, 4d and 5d. They used a previously calibrated coupled plasticity-damage model for SB1, which was tested under gravity loading and was analyzed using ABAQUS software by Genikomsou and Polak (2015) [27]. Also, they compared their results with punching shear predictions according to ACI 318-14, Eurocode 2-2004, and fib Model Code 2010.

In their study, they found that when the opening was located further from the column, the punching shear capacity of the slab was increased. However, the punching shear capacity for any opening size located at a distance 4d from the column's face remains almost the same with the slab that has no openings. They found also, in all cases, the design codes appeared safe results; while fib Model Code 2010 gave the most conservative punching shear loads for both sizes of openings when the openings were located between distances 180 mm (2d) to 450 mm (5d) from the column [22].

Genikomsou and Polak (2017) [28] used finite element formulation with the damaged plasticity model for concrete in ABAQUS to simulate and analyze the effect of the location and size of the opening on the punching shear resistance of previously tested nine edge slab-column connections in reinforced concrete slabs without shear reinforcement by El-Salakawy et al., (1999) [29]. They calculated the shear capacity of the tested specimens using the equations of ACI 318-14 and compared them with the test and numerical results. They also performed parametric investigation on the edge and interior specimens having openings with different sizes and located at different distances from the column.

The results of the nonlinear finite element analysis (FEA) accurately described the response of the tested slabs, predicting a 10% lower punching shear capacity. Three slabs were compared in terms of ultimate load and displacement: Slab XXX was the control specimen without opening; Slabs SF0 and CF0 had openings located at the front column face, with sizes 150 x 150 mm and 250 x 250 mm, respectively. Both experimental and analytical results showed that as the opening increased, both stiffness and strength were reduced [28].

Oukaili and Salman, (2014) [17] studied the effect of openings location and size on the punching shear behavior of slab-column connections. Six half-scale specimens were cast with normal-density concrete of 30 MPa compressive strength and three sizes of openings were used. The specimens showed a decrease in punching shear capacity ranging between 11.43% and 29.25%. The stiffness decreased between 0.31% and 83.00%, depending on the size and location of these openings with respect to the column. The further the opening from the column, the higher the ultimate strength of the connection. The opening located at the front of the column decreased the shear capacity of the flat plate more than the same-size opening at the corner of the column.

Anil et al. [2014] [30] investigated how the size and position of openings affected the punching shear behavior of RC flat slabs. Eight two-way RC flat slabs with openings in various places were used for the experiments, each test slab contains a single 300 mm x 300 mm or 500 mm x 500 mm opening that is either 300 mm adjacent to the center column or 300 mm away from it in a parallel or diagonal orientation. The punching shear capacity reduces as the opening size increases, and according to Anil et al., the percentage of the decrease for openings beside columns is larger than that for openings farther from columns. A slab achieved the greatest decrease in the ultimate capacity with a 500 mm x 500 mm opening, the eventual capacity was around 40% of the control slab's capacity.

The effect of opening size and location on the punching shear behavior of RC flat slabs was investigated by El-shafiey et al. (2012) [18] The punching shear strengths of examined specimens with openings were drastically decreased, according to El-Shafiey et al. The percentage of these decreases carrying the control slab varied from 20.61 to 50.82% [18].

Yooprasertchai et al., (2021) [31] studied the experimental results of 14 flat specimens to investigate the effects of the number (2 and 4) and location (1 and 4 times of slab's thickness from the column's face) of openings on punching shear strength. It was found that placing openings at a distance of four times the slab's thickness had minimal impact on punching capacity while increasing the number of openings from 2 to 4 substantially reduced the punching capacity. Peak loads for the same specimens but with 4 circular, square, and rectangular openings (at 1H) were reduced by 30.06, 36.65, and 44.56%, respectively. The Mean of the ratio of experimental to analytical results and standard deviation of ACI equations were more accurate than those of Eurocode 2 predictions.

In the same research paper of Yooprasertchai et al., (2021) [31], they also investigated the effect of the shape (circular, square, and rectangular) of openings on punching shear strength. It was found that circular openings had least influence on punching capacity followed by square and rectangular openings.

Liberati et al. (2019) [32] studied the effect of the number of openings (1, 2, 4 openings) on the structural behavior of flat reinforced concrete slabs with openings in the region around internal columns. They found that all specimens failed in punching, exhibiting the extremely brittle concrete failure modes typical of punching without shear reinforcement. The ultimate strength of the flat slabs with two openings decreased by 16%, while those with four openings decreased by 23.2%. All specimens presented lower maximum displacements than the specimens without openings, making them less rigid than slabs without openings. The punching loads for slabs without shear reinforcement provided by Eurocode 2, 2010 (EC2) agree well with the test results.

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Taehun et al., (2015) [33] evaluated experimentally the effects of openings on the punching shear strength of a flat plate, considering the layout and number of circular openings of eight flat-plate slab specimens. They used specimens with openings located in horizontal (H) and vertical directions with different numbers (1, 2 and 3) and also, openings located as L-shaped. Also, they compared the measured punching shear strengths of test specimens to the ACI 318-11, CEB-FIP 1990/Eurocode 2, and Fib model codes. The study found that all test specimens showed highly brittle punching shear failure modes and that the punching shear strength decreased as the number of openings increased. The L-shaped opening layout around the corner of a column may result in a further reduction in effective critical sections due to the existence of openings. CEB-FIP model code 1990 and LoA II of fib model code 2010 were able to predict punching shear strengths almost equal to test results, while ACI 318-11 and LoA I underestimated the strength by 20% [33].

Authors	Speci men	Specimen dimensions, mm^3	Column dimensions, mm^2	fc, Mpa	μ, %	Opening size, mm2	Opening location to column	Pu, kN	R, %
El-Shafiey et al. (2022) [24]	1	1700x1700x 120	150x150	24	1.13	-	-	235	-
	2					200x200	Adjacent, parallel	175	25.53
	3					300x300	Adjacent, parallel	143	39.15
	4					400x400	Adjacent, parallel	115	51.06
	5					300x300	Parallel, 100 mm far	160	31.91
	6					300x300	Parallel, 200 mm far	176	25.11
	7					300x300	Parallel, 300 mm far	195	17.02
	8					1 φ 250 mm	Adjacent to column	180	23.40
	9					1 φ 350 mm	Adjacent to column	170	27.66
	10					1 φ 450 mm	Adjacent to column	150	36.17
Lourenço et al. (2021) [4]	1	1800x1800x 130	150x150	39.8	1.58	-	-	247	-
	2			46	1.23	150x150	Adjacent, parallel	221	10.53
	3			46.3	1.26	150x150	Parallel, 90 mm far	250	-1.21
	4			45.9	1.23	150x150	Parallel, 180 mm far	231	6.48
	5			41.2	1.49	150x150	Parallel, 270 mm far	273	-10.53
Yooprasertchai et al., (2021) [31]	1	1000x1000x 80	100x100	20.18	0.9	-	-	57.73	-
	2					2 (70x70)	Parallel, 80 mm far	49.09	14.97
	3					2 φ 70 mm	Parallel, 80 mm far	51.10	11.48
	4					2 (70x140)	Parallel, 80 mm far	44.71	22.55
	5					2 (70x70)	Parallel, 320 mm far	57.04	1.20
	6					2 φ 70 mm	Parallel, 320 mm far	56.92	1.40
	7					2 (70x140)	Parallel, 320 mm far	55.50	3.86
	8			29.71		-	-	70.15	0.00
	9					4 (70x70)	Parallel, 80 mm far	45.84	34.65
	10					4 φ 70 mm	Parallel, 80 mm far	49.06	30.06
	11					4 (70x140)	Parallel, 80 mm far	38.89	44.56
	12					4 (70x70)	Parallel, 320 mm far	67.61	3.62
	13					4 φ 70 mm	Parallel, 320 mm far	66.34	5.43
	14					4 (70x140)	Parallel, 320 mm far	63.85	8.98

Table 1, shows a summary of the available experimental works and main results of previous investigations.

Table1. Summary of the experimental works and main results for previous work

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Authors	Specimen	Specimen dimensions, mm^3	Column dimensions, mm^2	fc, Mpa	μ, %	Opening size, mm2	Opening location to column	Pu, kN	R, %
Liberati et al. (2019) [32]	1	1800x1800x130	150x150	41.6	1.62	-	-	249.90	-
	2			41.6	1.65	-	-	216.4	-
	3			41.6	1.58	-	-	259.2	-
	4			39.8	1.58	-	-	232.3	-
	5			44.5	1.28	1 φ 150 mm	Adjacent to column	187.6	24.93
	6			44.5	1.34	1 φ 150 mm	Adjacent to column	178	17.74
	7			44.5	1.26	1 φ 150 mm	Adjacent to column	233.7	9.84
	8			35.2	1.14	2 φ 150 mm	Adjacent to column	187.6	24.93
	9			35.2	1.08	2 φ 150 mm	Adjacent to column	213.9	1.16
	10			35.2	1.12	2 φ 150 mm	Adjacent to column	194.8	24.85
	11			41.4	1.17	2 φ 150 mm	Adjacent to column	208.4	10.29
	12			40	1.29	4 φ 75 mm	Adjacent to column	184	14.97
Taehun et al., (2015) [33]	1	2000x2000x200	300x300	27	1.16	-	-	590.2	-
	2					1 φ 150 mm	Horizontal, 150 mm far	550.2	6.78
	3					2 φ 150 mm	Horizontal, 150 mm far	517.3	12.35
	4					3 φ 150 mm	Horizontal, 150 mm far	452.9	23.26
	5					2 φ 150 mm	Vertical, 150 mm far	556.9	5.64
	6					3 φ 150 mm	Vertical, 150 mm far	546.5	7.40
	7					3 φ 150 mm	Corner, 150 mm far	418.2	29.14
	8					4 φ 150 mm	Parallel, 150 mm far	517.9	12.25
Anil et al. [2014] [30]	1	2000x2000x120	200x200	20.83	0.39	-	-	193	-
	2			20.6	0.39	300x300	Adjacent, parallel	99.03	48.69
	3			20.85	0.39	300x300	Adjacent, diagonal	125.86	34.79
	4			19.63	0.39	500x500	Adjacent, parallel	76.98	60.11
	5			19.61	0.39	500x500	Adjacent, diagonal	94.7	50.93
	6			20.02	0.39	300x300	Parallel, 300 mm far	134.78	30.17
	7			21.24	0.39	300x300	Diagonal, 300 mm far	172.15	10.80
	8			20.05	0.39	500x500	Parallel, 300 mm far	115.53	40.14
	9			20.23	0.39	500x500	Diagonal, 300 mm far	138.83	28.07

Table1 (cont.). Summary of experimental works and main results for previous work

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VI. COMPARISON BETWEEN THE EXPERIMENTAL RESULTS OF PREVIOUS RESEARCH WORK AND CODES' PREDICTIONS

Table 2 presents a comparison between the experimental results of previous work for slabs with openings and those predicted by ECP-203 and ACI-318. As shown in Table 3, the obtained results are consistent with those obtained by the current research. ECP-203 and ACI-318 showed higher factors of safety. The mean values of Pexp/Ppridected for ECP-203 and ACI-318 codes were 1.4 and 1.19 respectively.

Authors	Speci men	Opening size, mm2	Opening location to column	Pu, kN	ECP-203		ACI-318	
					PECP, kN	Pexp/ P_{ECP}	PACI, kN	Pexp/ PACI
El-Shafiey et al. (2022) [24]	1	-	-	235	142.0	1.65	163.00	1.44
	2	200x200	Adjacent, parallel	175	97.63	1.79	112.06	1.56
	3	300x300	Adjacent, parallel	143	88.75	1.61	101.88	1.40
	4	400x400	Adjacent, parallel	115	84.31	1.36	96.78	1.19
	5	300x300	Parallel, 100 mm far	160	111.57	1.43	128.07	1.25
	6	300x300	Parallel, 200 mm far	176	122.64	1.44	140.77	1.25
	7	300x300	Parallel, 300 mm far	195	127.80	1.53	146.70	1.33
	8	1 φ 250 mm	Adjacent to column	180	113.60	1.58	130.40	1.38
	9	1 φ 350 mm	Adjacent to column	170	107.21	1.59	123.07	1.38
	10	1 φ 450 mm	Adjacent to column	150	102.24	1.47	117.36	1.28
Lourenço et al. (2021) [4]	1	-	-	247	152.93	1.62	181.44	1.36
	2	150x150	Adjacent, parallel	221	124.15	1.78	147.67	1.50
	3	150x150	Parallel, 90 mm far	250	146.21	1.71	174.68	1.43
	4	150x150	Parallel, 180 mm far	231	153.56	1.50	182.65	1.26
	5	150x150	Parallel, 270 mm far	273	149.04	1.83	177.19	1.54
Yooprasertchai et al., (2021) [31]	1	-	-	57.73	48.38	1.19	57.60	1.00
	2	2 (70x70)	Parallel, 80 mm far	49.09	41.06	1.20	48.88	1.00
	3	2 φ 70 mm	Parallel, 80 mm far	51.10	42.48	1.20	50.57	1.01
	4	2 (70x140)	Parallel, 80 mm far	44.71	33.73	1.33	40.15	1.11
	5	2 (70x70)	Parallel, 320 mm far	57.04	45.81	1.25	54.54	1.05
	6	2 φ 70 mm	Parallel, 320 mm far	56.92	46.03	1.24	54.79	1.04
	7	2 (70x140)	Parallel, 320 mm far	55.50	43.24	1.28	51.47	1.08
	8	-	-	70.15	48.38	1.45	57.60	1.22
	9	4 (70x70)	Parallel, 80 mm far	45.84	33.73	1.36	40.15	1.14
	10	4 φ 70 mm	Parallel, 80 mm far	49.06	36.57	1.34	43.53	1.13
	11	4 (70x140)	Parallel, 80 mm far	38.89	19.07	2.04	22.71	1.71
	12	4 (70x70)	Parallel, 320 mm far	67.61	43.24	1.56	51.47	1.31
	13	4 φ 70 mm	Parallel, 320 mm far	66.34	43.67	1.52	51.99	1.28
	14	4 (70x140)	Parallel, 320 mm far	63.85	38.09	1.68	45.34	1.41

Table2. A comparison between the experimental results of previous work and the design codes

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Authors	Specimen	Opening size, mm2	Opening location to column	Pu, kN	ECP-203		ACI-318	
					PECP, kN	Pexp/ P_{ECP}	PACI, kN	Pexp/ PACI
Liberati et al. (2019) [32]	1	-	-	249.90	154.00	1.62	182.93	1.37
	2	-	-	216.4	151.63	1.43	180.12	1.20
	3	-	-	259.2	156.38	1.66	185.76	1.40
	4	-	-	232.3	152.93	1.52	181.44	1.28
	5	1 φ 150 mm	Adjacent to column	187.6	138.60	1.35	164.54	1.14
	6	1 φ 150 mm	Adjacent to column	178	134.36	1.32	159.51	1.12
	7	1 φ 150 mm	Adjacent to column	233.7	140.75	1.66	167.09	1.40
	8	2 φ 150 mm	Adjacent to column	187.6	105.74	1.77	126.13	1.49
	9	2 φ 150 mm	Adjacent to column	213.9	110.69	1.93	132.03	1.62
	10	2 φ 150 mm	Adjacent to column	194.8	107.39	1.81	128.09	1.52
	11	2 φ 150 mm	Adjacent to column	208.4	102.08	2.04	121.36	1.72
	12	4 φ 75 mm	Adjacent to column	184	108.87	1.69	129.79	1.42
Taehun et al., (2015) [33]	1	-	-	590.2	501.12	1.18	597.89	0.99
	2	1 φ 150 mm	Horizontal, 150 mm far	550.2	475.55	1.16	567.38	0.97
	3	2 φ 150 mm	Horizontal, 150 mm far	517.3	446.81	1.16	533.09	0.97
	4	3 φ 150 mm	Horizontal, 150 mm far	452.9	412.69	1.10	492.38	0.92
	5	2 φ 150 mm	Vertical, 150 mm far	556.9	475.55	1.17	567.38	0.98
	6	3 φ 150 mm	Vertical, 150 mm far	546.5	475.55	1.15	567.38	0.96
	7	3 φ 150 mm	Corner, 150 mm far	418.2	399.13	1.05	476.20	0.88
	8	4 φ 150 mm	Parallel, 150 mm far	517.9	446.81	1.16	533.09	0.97
Anil et al. [2014] [30]	1	-	-	193	158.02	1.22	180.71	1.07
	2	300x300	Adjacent, parallel	99.03	105.21	0.94	119.82	0.83
	3	300x300	Adjacent, diagonal	125.86	129.10	0.97	165.74	0.76
	4	500x500	Adjacent, parallel	76.98	95.05	0.81	116.95	0.66
	5	500x500	Adjacent, diagonal	94.7	125.52	0.75	160.75	0.59
	6	300x300	Parallel, 300 mm far	134.78	144.11	0.94	160.57	0.84
	7	300x300	Diagonal, 300 mm far	172.15	139.25	1.24	160.13	1.08
	8	500x500	Parallel, 300 mm far	115.53	133.08	0.87	149.61	0.77
	9	500x500	Diagonal, 300 mm far	138.83	135.26	1.03	150.71	0.92

Table 2 (cont.). A comparison between the experimental results of previous work

VII. CONCLUSION

Based on the previous review, the following conclusions can be drawn:

- Punching shear collapse of reinforced concrete slabs happens when focused loads are started causing a high value of shear. The failure stage is reached when the inclined cracks form around the column with a usual cylindrical punching collapse cone the column splits from the slab.
- The majority of punching studies in the literature use a concentrated punching shear and insufficient researchers who studied the effect of eccentric punching shear.

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- The presence of the opening conduces to the smaller number of cracks in the direction of the opening and the concentration of cracks in the y-direction, changing the slab behavior from a bidirectional action to a unidirectional action.
- The existence of an opening in a concrete slab-column connection reduces the rigidity of the connection depending on the size and location of this opening and that reflects the increase in the crack width.
- The Egyptian and American codes both ignore horizontal reinforcement. The crucial section of the punching's location half the effective slab depth measured from the column face depending on the design code.
- Egyptian and ACI codes require the critical perimeter to be reduced if openings are less than 10 times the slab thickness.
- Most previous studies have focused on the effect of openings size and location on the punching shear behavior of flat slabs subjected to concentric loading, but research has not been conducted on variations in shape or the number of openings.
- Based on literature review, the presence of openings near column caused a significant reduction in punching shear capacity, which was increased by increasing dimensions and reducing the distance from the column.
- Adjacent openings diagonal to the face of the column were more efficient than those parallel to the column.
- Based on the comparison between the results of a series of experimental works versus those predicted by ECP-203 and ACI-318 equations, ACI-318 showed higher compatibility than ECP-203. The mean values of Pexp/ Ppridected for ECP-203 and ACI-318 codes were 1.4 and 1.19, respectively.

According to the previous conclusions, more research on studying the effect of varying opening shapes, numbers and locations on the punching shear response of flat slabs taking into account the effect of the transferred moment from the slab to the column is recommended to better understand their effect

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