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Numerical Investigation of Punching Shear Pattern of Flat Plate Supported By Coupled Columns

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Abstract : *In this study, non-linear 3D numerical analyses were performed to investigate the influence of separation distance of the columns on the punching shear capacity of the flat plate supported by coupled columns. Verification models have been carried out by simulating available experimental data. A total of 135 models was analyzed and examined numerically by the 3-D nonlinear finite element package (ANSYS 14.5). The effects of three variables on the punching strength of RC slabs; the separation distance, the concrete strength, and the reinforcement ratio were considered. Finally, the BS8110 code equation and Rankin's approach, were compared with the numerical results. The results presented that increasing the concrete strength results on an increment of the FEA predicted punching load. It was observed thatpunching load capacity was improved by increasing the reinforcement ratio. The FEA punching shear strength was increased gradually by increasing the separation distance between columns and maximum ultimate load reaches at clear distance between columns equal to 8d. The BS 8110 equation and the Rankin formula give a good correlation with the finite element analysis.*

Keywords–*ANSYS, Coupled Columns, Flat Plate, Punching*

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I. INTRODUCTION

Punching in the vicinity of a column is a possible failure mode for reinforced concrete flat slabs. The undesirable suddenness and catastrophic nature of punching failure are of concern to structural engineers. The critical sections of the slab for moment and shear are either at or close to the perimeter of the loaded area, and hence it would be expected that moment-shear interaction would occur. Many codes and studies have presented various formulae for calculating punching shear strength of slabs based on their understanding of punching behavior. Generally, punching strength is predicted by considering a nominal shear stress, a control perimeter, and an effective depth. The main differences of approaches depending on the assumed location of the different control perimeter, the concrete strength, the size effect and the reinforcement ratio. Both the ACI code [1] and ECP.203 [2] assume that the critical section for punching shear placed at (d/2) from the column face, while the BS8110 [3] code considers the control perimeter located at 1.5d from loaded area. Several previously established types of research concerning the experimental and numerical studies of material factors affect punching behavior in RC flat slabs. Aziz et al. [4] studied experimentally the influence of concrete strength and dimensions of the critical area on the behavior of hybrid flat plate. The results indicated that using steel fiber reinforced concrete enhances the punching shear strength. Zhang [5] carried out an experimental study to investigate the punching shear strength of high strength flat slab. Four parameters were considered such as concrete strength, tension reinforcement ratio, the column size, and the depth of the slab. Elshafey et al. [6] used both neural networks and new simplified punching shear equations to estimate the punching shear capacity of two way flat slabs without shear reinforcement and without unbalanced moment transfer. All the parameters that may affect the punching load included the concrete strength, column size, slab depth, reinforcement ratio, and the yield strength of the steel reinforcement. Alkarani and Ravindra [7] developed an evaluating of punching shear and shear reinforcement in flat slabs. The main parameters are the aspect ratio of the slab and the corresponding variation of punching shear for the four types of column. Al-Quraishi [8] carried out an experimental and numerical analysis to investigate the punching shear pattern of ultra-high performance concrete. The effect of concrete strength, flexure reinforcement ratio, size effect, and yield stress of tension reinforcement was considered. It was realized that increasing of steel fiber content in UHPC slabs will delay the appearance of flexural cracks and increase the first flexural crack load. The thickness of the slab is a very important factor governing the final shape of the punching cone. Mamede et al. [9] performed an experimental and 3D nonlinear finite element analysis on punching of flat slabs. A parametric study was; the reinforcement ratio, slab thickness, concrete strength and column dimensions. A prediction equation to estimate the punching shear strength was proposed based on the numerical results. Chaudhari and Katti [10] studied numerically the effect of using shear reinforcement via shear studs to enhance the punching shear strength of flat slabs. The results show that the suggested shear reinforcement system and drop panel have a positive influence on the improvement of the punching shear capacity. Ramadan et al. [11] carried out nonlinear finite element models to perform studied parameters on the interior, edge, and corner slab-column connections. Three variables were considered such as concrete compressive strength, load eccentricity to slab thickness ratio (e/ts), and column dimensions to slab thickness ratio (b/ts). It was observed that column dimension to slab thickness (b/ts) approximately had also the main influence on punching strength. Al-Khafaji et al. [12] carried out the experimental program to study the punching shear behavior of reinforced concrete flat plate slabs rested on coupled columns. The parametric studies are the column shape and the separation distance between columns of the slab specimen. Al-Shammari [13] investigated the influence of clear distance of the columns on punching pattern for flat plates with high strength concrete. The obtained results were compared with another one of flat plates with normal strength concrete. It was observed that the ultimate load changes linearly with the distance between columns. El Sayed et al. [14] performed a laboratory program to investigate the punching shear pattern of the flat plate with opening supported by coupled columns. The effect of 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 were considered. The results show that the punching shear strength increased gradually by increasing the clear distance between columns. The presence of opening led to a decrease in punching shear capacity by about 32%.

II. RESEARCH SIGNIFICANCE

The literature on the subject of punching shear behavior of flat slabs rested on coupled columns is thus limited. Because of this lack of information and experimental and numerical data related to the behavior of the flat slab with coupled columns, a numerical model using Finite Element Analysis (FEA) for slabs supported by coupled columns is presented. Some influence variables on punching shear are studied such as flexure reinforcement ratio. Concrete strength, and clear distance between columns. The numerical results were compared with the equations proposed by BS 8110 Cod [3] and Rankin [15].

III. FINITE ELEMENT ANALYSIS

Finite element analysis is a numerical technique used by engineers to find the solution for different problems. A fundamental assumption of the method states that the domain can be divided into smaller regions in which the equations can be solved approximately. By understanding concrete material properties, various concrete constitutive laws and failure criteria have been developed to model the behavior of concrete.

IV. DEFINING MATERIAL PROPERTIES

i. CONCRETE

In this study, the three-dimensional, eight-node solid element (SOLID65), available in the ANSYS [16] library, was used to model both concrete. SOLID65 element is an eight-node solid element used to model the concrete with or without reinforcing bars, as shown in Fig. 1. The solid element has eight nodes with three degrees of freedom at each node translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. Fig.2 shows the uniaxial compressive stress-strain relationship for the concrete model. The initial modulus of elasticity (E_c) and the uniaxial tensile strength (f_t) of concrete is calculated by Eq. (1) and (2) respectively. In this analysis the Poisson's ratio is assumed to be 0.2 and the shear transfer coefficients for an open and closed crack β_0 and β_t are taken 0.2 and 0.8 respectively.

$$E_c = 4400\sqrt{fcu}\ \text{MPa} \quad \text{Eq. 1}$$

$$f_t = 0.6\sqrt{fcu}\ \text{MPa} \quad \text{Eq. 2}$$

ii. REINFORCING BAR

The reinforcing steel bars were simulated using a 3-D link element (ANSYS-Link180). The link element is a 2-node uni-axial tension-compression element with no bending capability. This element has three degrees-of-freedom at each node; translations in the x, y, z directions. In this analysis, the yield strength (fy) and the ultimate strength (fu) of the main reinforcement of the models are provided with 420 MPa, and 640 MPa respectively. The elastic modulus and passion's ratio of the steel reinforcement is assumed 200000 MPa and 0.3 respectively.

iii. ANALYTICAL MODEL

Finite element model using ANSYS 14.5 [16] was proposed to investigate the punching shear load of flat plate rested in coupled columns. In this study, taking advantage of the symmetry in geometric model, reinforcement distribution, and loading conditions, the quarter of the models are constructed. At the plane of symmetry, the displacement perpendicular to the plane is held zero. Rollers are used to show the symmetry condition on the internal face. The support is modeled as a roller by giving constraint to a single line of nodes on the plate. A displacement control incremental loading was applied through column stubs with 1000 increments. The geometry of quarter of full slab for ANSYS modeling is shown in Fig. 2.

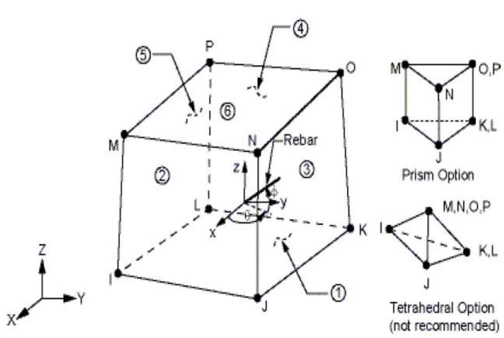


Fig. 1 Solid65 3-D reinforced concrete solid

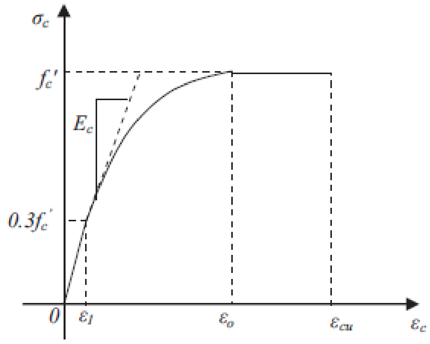


Fig. 2 Uniaxial compressive stress–strain curve for concrete

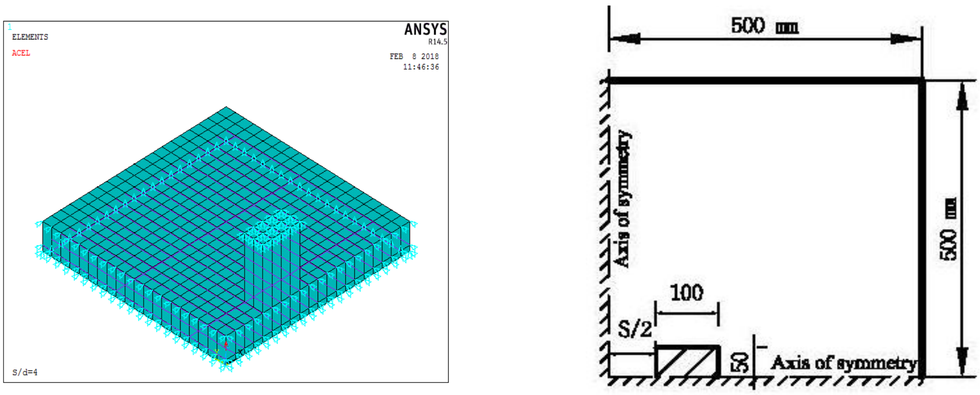


Fig. 3 Geometry of quarter of full slab for ANSYS modeling.

V. VERIFICATION OF THE NUMERICAL ANALYSIS

In order to authorize the validity of the numerical model to study the punching shear behavior of flat plate rested on coupled columns, the comparison of the results from the numerical model to the obtainable experimental one has been verified. The analysis investigations were performed on four R.C. slabs (S1, S2, S3, and S4) which were tested experimentally by Elsayed, et al [14]. The geometry and reinforcement details of the experimental specimen are shown in Fig.4. The performance of the suggested models with respect to the effect of the separation distance between the columns. The descriptions of the test specimens and comparison between experimental and numerical results are shown in Table 1. Fig.5 compares the load-deflection curves for experimental and numerical analysis. The percentage of errors in the ultimate punching capacity is found to be 1%, 2.8%, 4.5%, and 1.6% for specimens S1, S2, S3, and S4 respectively, which shows a good prediction of the adopted model. The results indicated that the comparison between the numerical and experimental results is acceptable enough to agree. The finite element modeling is quite accurate in representing the test slab specimens. Thus the ANSYS package can be used to extend the work for studying the punching behavior of flat plate supported by coupled columns.

Table 1: Comparison between experimental and numerical results

Specimens	Clear distance between two columns (S)		Concrete strength (fcu) MPa	Experimental Results		Numerical Results		Exp./ Num.	
	S (mm)	S/d		Ultimate load (kN)	Defl. (mm)	Ultimate load (kN)	Defl. (mm)	Ultimate load	Defl.
S1	50	1	32	96	17.00	97	12.78	99.0	133.0
S2	100	2	32	103	13.00	106	12.8	97.2	101.6
S3	150	3	32	108	14.00	113	14.30	95.5	97.9
S4	200	4	32	124	13.25	122	13.56	101.6	97.7

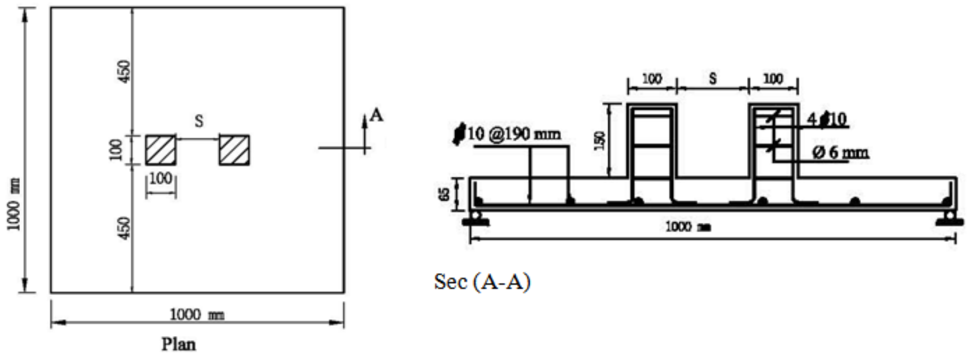


Fig. 4 Geometry and reinforcement details of full tested model

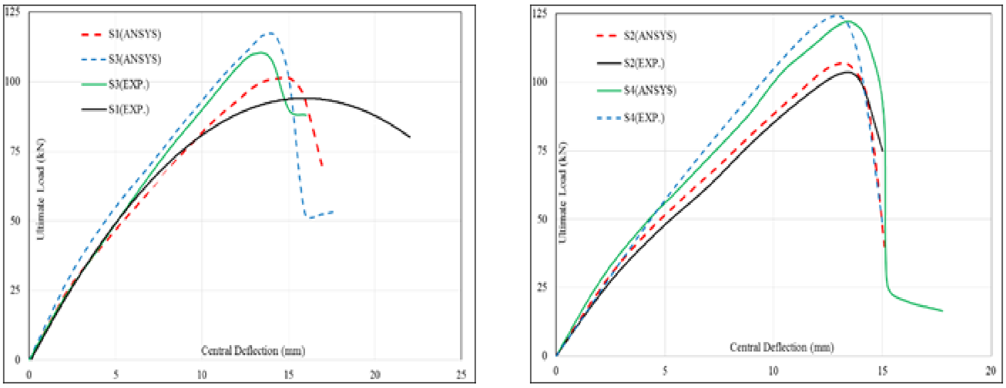


Fig.4 Load-deflection curves for experimental versus numerical specimens

VI. PARAMETRIC STUDY

The analysis of using ANSYS program was developed in the 15 main series, each series consists of 9 numerical model. A total of 135 numerical simulations have been carried out. The changing parameters were the concrete strength, the reinforcement ratio, and the separation distance between the columns. The tension reinforcement ratio was considered with five different values: 0.40, 0.78%, 1.13%, and 1.53%, and 2%. The studied concrete strengths were 25 MPa, 30 Mpa, and 40 Mpa. The clear distance between the columns was considered (0.1, 1, 2, 3, 4, 5, 6, 7, and 8) of effective depth (d), and specimen with a single column. Table 2 shows the description of the suggested models.

Table 2: Main parameters of the proposed models.

Series number	Model	S (mm)	Effective depth (mm)	fcu MPa	ρ%				
Series 1-5	S/d=0.1	5	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 1	50	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 2	100	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 3	150	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 4	200	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 5	250	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 6	300	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 7	350	50	25	0.40	0.78	1.13	1.53	2.01
	S/d= 8	400	50	25	0.40	0.78	1.13	1.53	2.01
Series 6-10	S/d=0.1	5	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 1	50	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 2	100	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 3	150	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 4	200	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 5	250	50	30	0.40	0.78	1.13	1.53	2.01

	S/d= 6	300	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 7	350	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 8	400	50	30	0.40	0.78	1.13	1.53	2.01
	S/d=0.1	5	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 1	50	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 2	100	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 3	150	50	30	0.40	0.78	1.13	1.53	2.01
Series 11-15	S/d= 4	200	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 5	250	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 6	300	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 7	350	50	30	0.40	0.78	1.13	1.53	2.01
	S/d= 8	400	50	30	0.40	0.78	1.13	1.53	2.01

VII. PARAMETRIC ANALYSIS RESULTS

I. LOAD –DEFLECTION RESPONSE

Based on the FE analysis, load-deflection curves, ultimate loads, ultimate deflections, and stiffness were calculated. The failure load and its corresponding deflection, and stiffness were calculated and listed in Table 3. From the figure, it can be seen that all the models failed suddenly in punching shear in a brittle manner.

i. EFFECT OF SEPARATION DISTANCE BETWEEN THE COLUMNS.

The load versus the deflection for FE models to study the influence of separation distance between the coupled columns were plotted in Fig 6. Nine clear spacing between columns were considered (S= 0.1d, d,2d,3d, 4d, 5d, 6d, 7d, 8d, 9d). From the load-deflection curves, it can be seen that the ultimate punching load is significantly affected by increasing separation distance between coupled columns and increased gradually with increasing the clear distance. The numerical results show that the ultimate punching capacity reaches the maximum value at the clear distance between columns equals 8d. The increasing of the separation distance between coupled columns from S/d= 0.1 to S/d= 1, 2, 3, 4, 5, 6, 7, and 8 led to an increase of the ultimate load by 4%, 9.6%,14.6%,20.6%, 25.7%,30.3%,36.9%, and 44.6% respectively for models with concrete strength 25 Mpa and ρ=0.40%. The punching strength increased by 6.6%, 15.7%, 23.1%, 29.4%, 35.4, 40.7%.48.7%, and 55.2% respectively for models with concrete strength 40 MPa and ρ=2.01%. With an increase of the clear spacing between columns, there is an increase of the FEA predicted stiffness. The stiffness is decreased by about 68.7% to 24.4% and then to 5.1% with decreasing the separation distance from 8d to 4d and then to d respectively. The ductility is decreased with increasing the clear distance between two columns.

ii. EFFECT OF REINFORCEMENT RATIO

Fig.7 shows the compassion between the load-deflection curves to investigate the effect of the reinforcement ratio on punching load for models of S/d = 0.1, 2, 4, 5, and 8. From load deflection relationships and from Table 3, it can be seen that the ultimate strength is significantly affected by the main reinforcement ratio. The results showed that increasing the reinforcement ratio causes an increment of the slope of the curves. It can be realized that increasing the reinforcement ratio from 0.4% to 0.78% and then to 2.01% increased the punching load capacity by 18.1% and 38.8%, respectively, and increased the stiffness by 17.40 % and 37.50 % respectively. Concerning the relation between the reinforcement ratio and the obtained defection, it can be seen that increasing the reinforcement ratio significantly reduces the deflection at any load level.

iii. EFFECT OF CONCRETE STRENGTH

Fig.8 shows the compassion between the load deflection curves to study the influence of the concrete strength on punching shear strength for models of S/d = 0.1, 2, 4, 5, and 8 with reinforcement ratios 0.4%, 1.13%, and 2.01 %. The results indicated that, the concrete strength has a significant effect on the punching capacity. Increasing the concrete strength causes an increment of punching shear strength. Increasing the compressive strength from 25 MPa to 40 MPa results in an increase in the punching load in ranging from 38% to 74 %. It is shown in table 3 that with an increase of the concrete strength, there is an increase of the ultimate deflection. It can be realized that increasing the concrete strength from 25 MPa to 30 MPa and then to 40 MPa increased the stiffness by 3.7% and 6.8%, respectively.

II. CRACKING PATTERNS AND FAILURE MODE

For space reasons only some graphs of the cracks and crushing for a sample of proposed numerical models (fcu= 25 MPa and ρ=0.78 %) are shown in Fig.9. All models failed in a brittle punching mode. It was noticed that the columns penetrated the slab at failure load, and cracks started with radial cracks running from the column circumference towards the slab edge. It was observed that the coupled columns behave as one column with the separation less than or equal 4d.

Table 3: Numerical results of the proposed models.

Model	Series 1: Fcu = 25 MPa, ρ =0.40%			Series 2: Fcu = 25 MPa, ρ =0.78%			Series 3: Fcu = 25 MPa, ρ =1.13%		
	Load (kN)	Def. (mm)	Stiffness (kN/ mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)
S/d=0.1	72	11.20	7.02	85	11.95	8.34	92	11.92	9.07
S/d= 1	76	12.80	7.39	88	12.04	8.77	93	12.04	9.49
S/d= 2	84	12.80	7.65	93	12.03	9.25	100	12.09	9.97
S/d= 3	93	13.56	8.25	95	12.05	9.76	102	12.1	10.54
S/d= 4	95	13.54	8.77	104	12.79	10.35	104	11.26	11.14
S/d= 5	98	12.78	9.37	105	12.03	11.07	113	11.99	11.92
S/d= 6	102	12.40	10.11	105	10.44	11.87	117	10.46	12.62
S/d= 7	107	11.92	10.89	108	9.71	12.67	125	8.94	13.37
S/d= 8	110	11.08	11.71	114	9.64	13.46	130	10.96	14.09

Model	Series 4: Fcu = 25 MPa, ρ =1.53%			Series 5:Fcu = 25 MPa, ρ =2.01%			Series 6: Fcu = 30 MPa, ρ =0.40%		
	Load (kN)	Load (kN)	Load (kN)	Load (kN)	Load (kN)	Stiffness (kN/mm)	Load (kN)	Load (kN)	Stiffness (kN/mm)
S/d=0.1	96	100	90	90	90	8.61	90	15.70	7.24
S/d= 1	101	105	97	97	97	8.98	97	16.61	7.61
S/d= 2	103	106	105	105	105	9.77	105	16.55	8.28
S/d= 3	106	111	109	109	109	10.22	109	16.69	8.67
S/d= 4	111	120	112	112	112	10.65	112	15.78	9.02
S/d= 5	117	124	120	120	120	11.35	120	15.74	9.67
S/d= 6	124	131	127	127	127	12.21	127	15.68	10.42
S/d= 7	136	141	130	130	130	13.11	130	14.57	11.24
S/d= 8	140	149	132	132	132	14.03	132	14.68	12.23

Model	Series 7: Fcu = 30 MPa, ρ =0.78%			Series8: Fcu = 30 MPa, ρ =1.13%			Series 9: Fcu = 30 MPa, ρ =1.53%		
	Load (kN)	Def. (mm)	Stiffness (kN/ mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)
S/d=0.1	94	14.19	8.61	98	12.68	9.26	107	13.42	9.76
S/d= 1	101	15.11	8.98	109	14.35	9.72	112	13.59	10.26
S/d= 2	106	12.77	9.77	118	13.51	10.61	121	12.75	11.18
S/d= 3	117	13.53	10.22	120	13.52	11.23	123	12.77	11.83
S/d= 4	122	13.56	10.65	123	12.76	11.53	125	12.75	12.15
S/d= 5	124	13.52	11.35	126	11.98	12.29	129	13.47	12.86
S/d= 6	127	13.48	12.21	130	11.93	13.04	135	11.18	13.72
S/d= 7	131	11.93	13.11	137	11.89	13.89	142	11.83	14.85
S/d= 8	137	11.81	14.03	145	11.79	14.66	153	12.31	15.19

Model	Series 10:Fcu = 30 MPa, ρ =2.01%			Series 11: Fcu = 40 MPa, ρ =0.40%			Series 12: Fcu = 40 MPa, ρ =0.78%		
	Load (kN)	Def. (mm)	Stiffness (kN/ mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)
S/d=0.1	111	13.42	10.24	111	21.73	7.54	124	19.43	8.85
S/d= 1	117	12.78	10.71	118	21.92	7.93	133	20.42	9.28
S/d= 2	123	12.77	11.66	129	23.49	8.35	138	19.74	9.81
S/d= 3	131	13.50	12.3	133	21.98	8.82	144	19.02	10.43
S/d= 4	134	13.48	12.58	137	20.33	9.38	157	19.78	11.01
S/d= 5	138	12.65	13.42	144	19.36	9.75	166	18.83	11.68
S/d= 6	145	12.54	14.17	155	21.53	10.73	170	17.41	12.55
S/d= 7	152	12.54	14.92	163	19.85	11.66	188	18.52	13.52
S/d= 8	153	12.31	15.19	171	19.54	12.72	195	17.72	14.61

Model	Series13: Fcu = 40 MPa, ρ =1.13%			Series 14: Fcu = 40 MPa, ρ=1.53%			Series 15:Fcu = 40 MPa, ρ =2.01%		
	Load (kN)	Def. (mm)	Stiffness (kN/ mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)	Load (kN)	Def. (mm)	Stiffness (kN/mm)
S/d=0.1	128	17.92	9.56	132	17.16	10.12	141	18.65	10.53
S/d= 1	135	18.85	10.01	140	18.81	10.58	152	18.12	11.05
S/d= 2	148	19.76	10.59	156	19.35	11.16	165	17.49	11.67
S/d= 3	163	20.57	11.17	170	18.43	11.78	174	18.33	12.29
S/d= 4	171	20.59	11.86	177	18.02	12.52	182	17.98	13.02
S/d= 5	182	19.87	12.64	185	17.77	13.28	185	17.89	13.82
S/d= 6	187	19.33	13.53	190	17.91	14.21	193	18.15	14.71
S/d= 7	194	17.82	14.53	196	16.93	15.09	201	16.03	15.61
S/d= 8	201	16.68	15.48	208	15.94	15.94	212	16.39	16.28

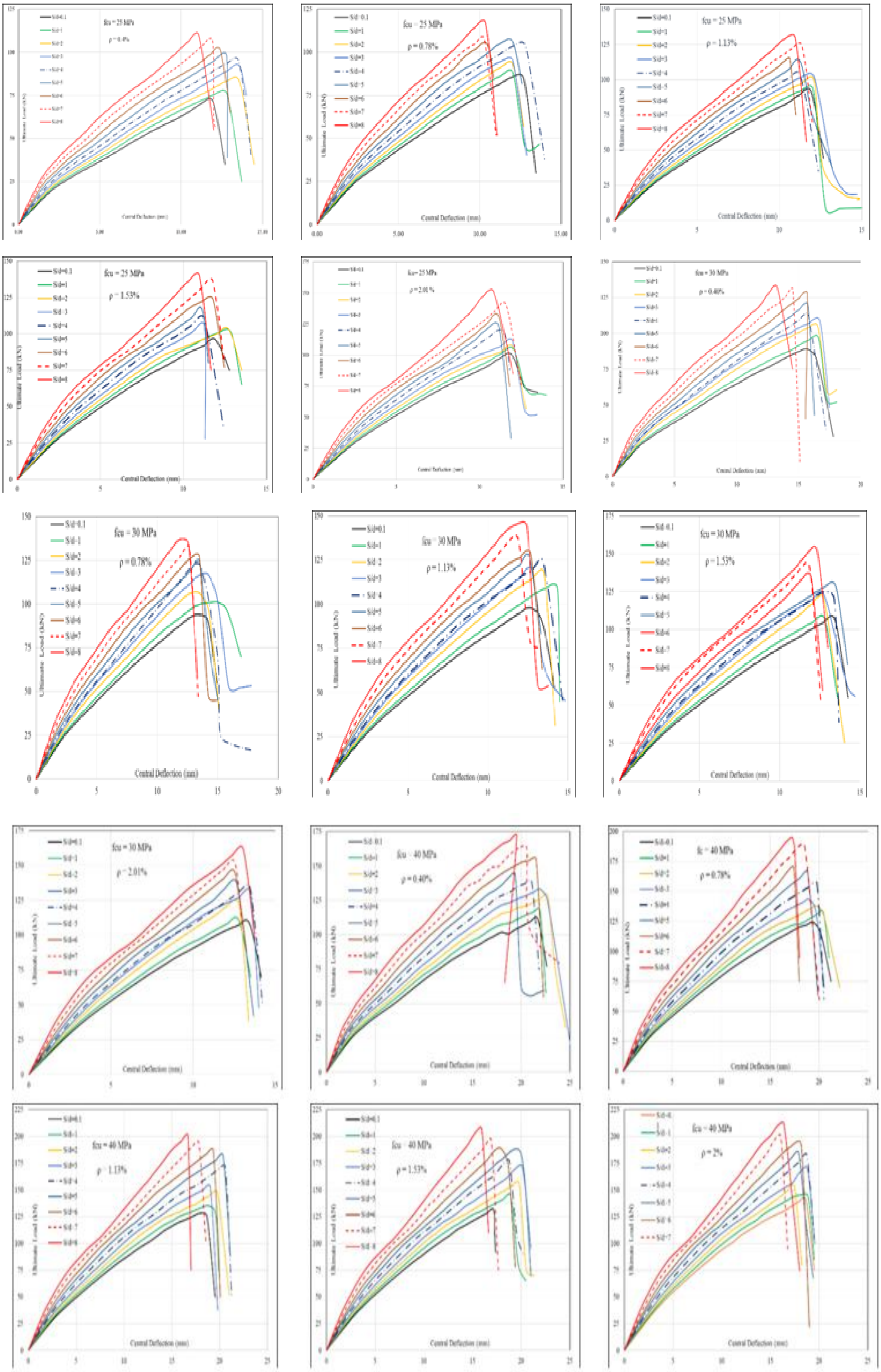


Fig. 5 Influence of separation distance in FEA predicted punching behavior

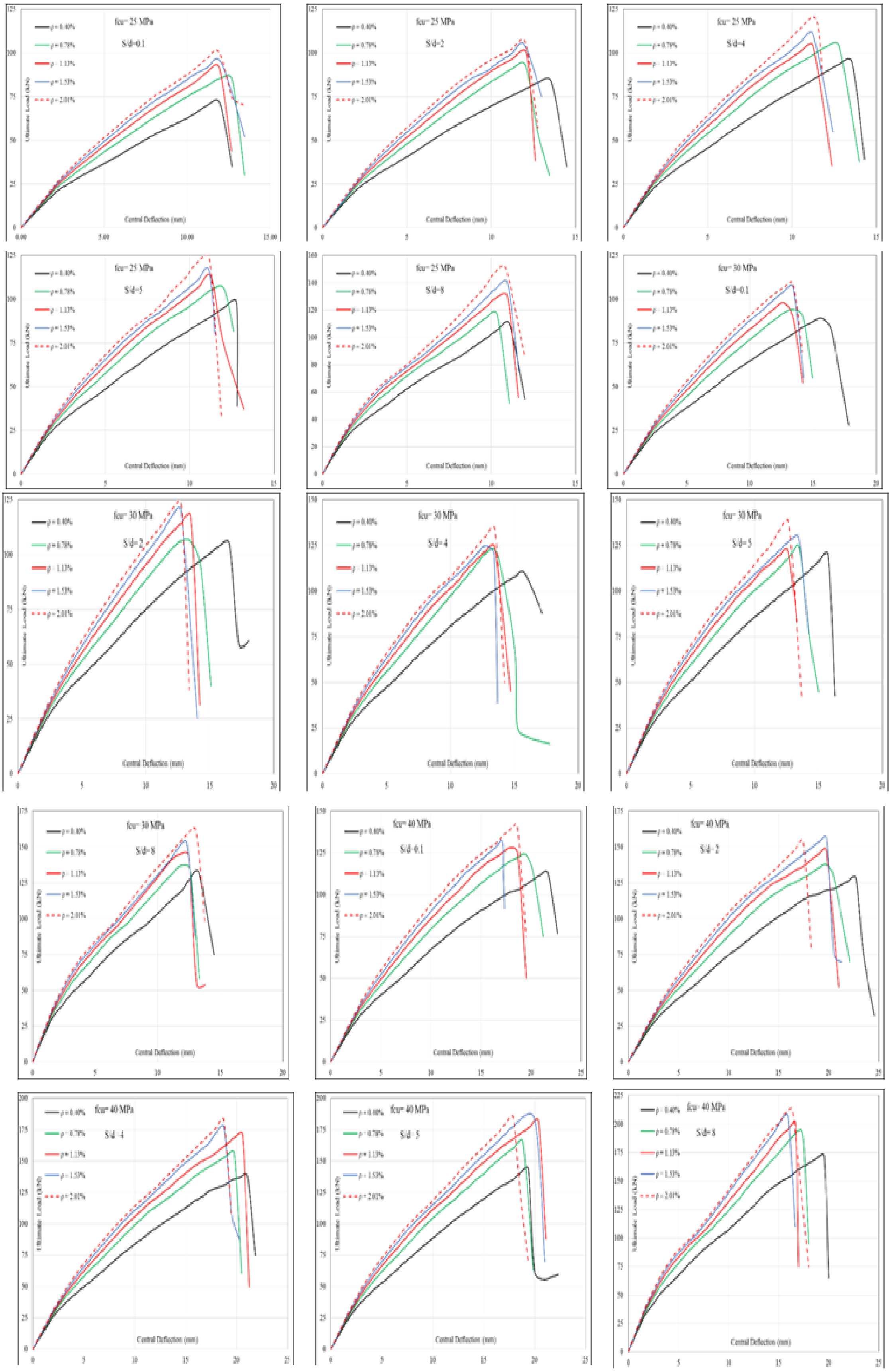


Fig. 6 Influence of reinforcement ratio in FEA predicted punching behavior

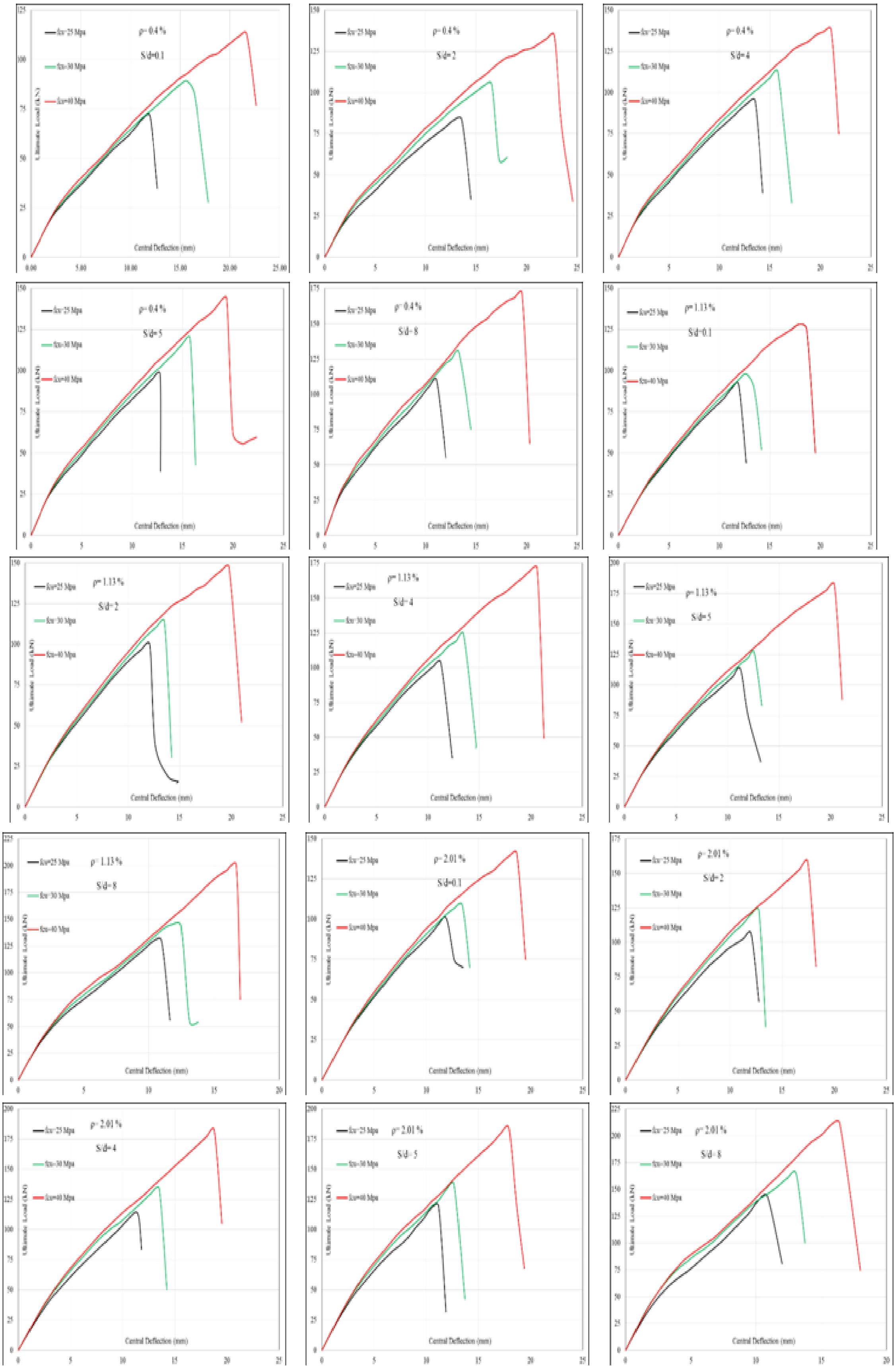


Fig. 7 Influence of concrete strength in FEA predicted punching behavior

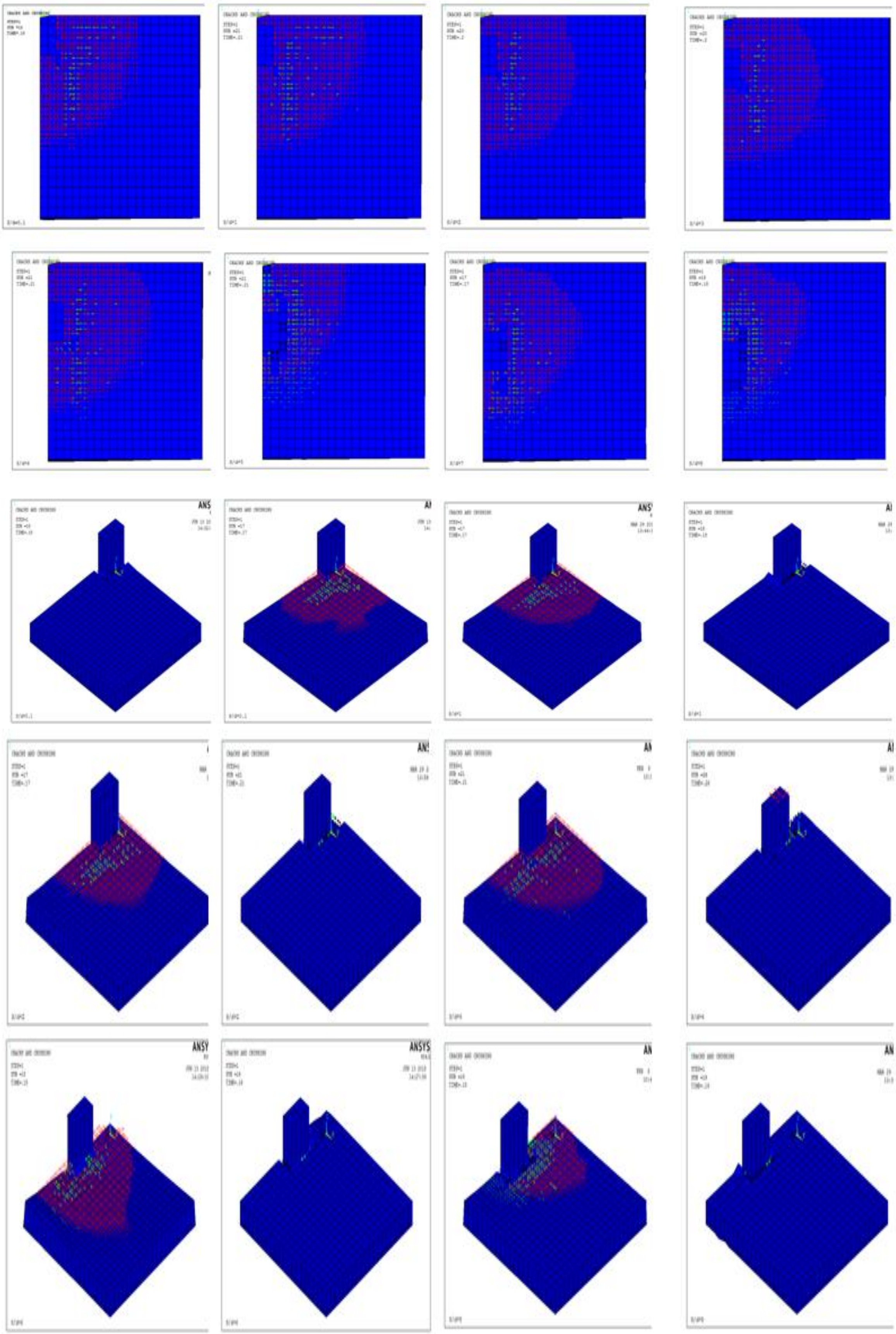


Fig. 8 Cracking pattern and modes of failure for samples of numerical models

VIII. APPROACHES OF PREDICTION

The predicted formula to estimate the punching shear capacity of flat plate has been presented by many codes and researchers based on their understanding of punching behavior. As both the ACI code and ECP.203 neglects the effects of tension reinforcement ratio, whileBS8110 and Rankin and Longformula take it into consideration, so the equations of the two approaches BS8110, and Rankin's approach are considered and compared with the finite element results. The differences between two approaches are the BS8110 code assume that the control perimeters is located at a distance of 1.5 times of the effective depth from the edge of the column periphery, while the Rankin's approach considers a smaller control perimeter, 0.5d.In the Rankin's approach, shear stress is expressed in term of square-root relationship with concrete compressive strength, while the BS8110 code considers a cubic-root proportion. The punching shear strength (Vu) according to BS 8110 and Rankin's approach is calculated from Eq. 3 and Eq. 4 respectively.

BS8110

$$Vu = 0.79\sqrt[3]{100\rho}\sqrt[3]{fcu/25}\sqrt[4]{\frac{400}{d}}uo * d \quad \text{(Eq. 3)}$$

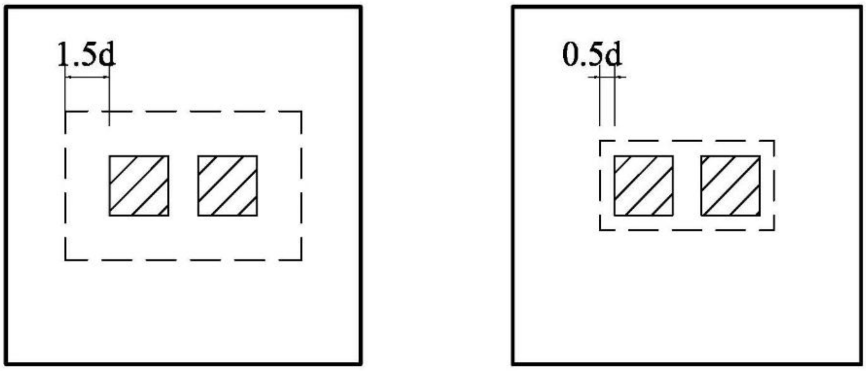
Rankin's approach

$$Vu = 0.415\sqrt[4]{100\rho}\sqrt{fc`}uo * d \quad \text{(Eq. 4)}$$

Where:uois the rectangular critical perimetersin (mm)as shown in Fig.10,
d is the effective depth to tensile reinforcement in (mm),
$\rho = As/b_v d$ is the flexure reinforcement ratio;
$b_v$isthewidth of section in (mm),
Fcu is cube strength of concrete (MPa), and
fc` is cylinder strength of concrete = 0.8* Fcu.

IX. COMPARISON OF NUMERICAL RESULTS WITH BS 8110 AND RANKIN EQUATIONS

The results of the finite element analysis reported in this research are compared with the values obtained from BS 8110 Code and Rankin's formula. Only the punching shear strength of models with S/d= 0.1, 1, 2, 3, and 4 was calculated as for models with S/d greater than 4 the column behave separately. The comparison of the two approaches with numerical data is summarized in Table 3. The average values of Vu (FEA)/Vu (BS 8110) are varying from 0.88 to 1.39 with the standard deviation ranging from 0.022 to 0.051. The mean values of Vu (FEA)/Vu (Rankin) are changing from 0.93 to 1.20 with the standard deviation varying from 0.042 to 0.094. It is interesting to note that the two approaches give a good correlation with the numerical results but the Rankin's approach gives better predictions than the BS 8110 code.



BS 8110 Rankin

Fig. 9 Perimeter of critical punching shear section according BS 8110 and Rankin approaches

Table 4: Comparison between numerical and predicted equations

Model	Series 1: Fcu = 25MPa, ρ =0.4 %					Model	Series 2: Fcu = 25MPa, ρ =0.78 %				
	Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Rankin		
S/d=0.1	72	59	60	1.21	1.20	S/d=0.1	85	74	71	1.15	1.20
S/d= 1	76	64	66	1.19	1.14	S/d= 1	88	80	78	1.11	1.12
S/d= 2	84	69	74	1.22	1.14	S/d= 2	93	86	87	1.09	1.07
S/d= 3	93	74	81	1.26	1.15	S/d= 3	95	92	96	1.03	0.99
S/d= 4	95	79	89	1.21	1.07	S/d= 4	104	98	105	1.06	0.99
Mean				1.22	1.14	Mean				1.09	1.08
Standard deviation				0.024	0.042	Standard deviation				0.038	0.081

Model	Series 3: Fcu = 25MPa, ρ =1.53%					Model	Series 5: Fcu = 25MPa, ρ =2.01%				
	Ultimate Load (Vu)(kN)			FEA / BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Rankin		
S/d=0.1	96	92	84	1.04	1.15	S/d=0.1	90	101	89	0.89	0.84
S/d= 1	101	99	93	1.02	1.09	S/d= 1	97	109	99	0.89	0.84
S/d= 2	103	107	103	0.96	1.00	S/d= 2	105	117	110	0.90	0.84
S/d= 3	106	115	114	0.92	0.93	S/d= 3	109	125	122	0.87	0.84
S/d= 4	111	122	124	0.91	0.90	S/d= 4	112	134	133	0.84	0.84
Mean				0.97	1.01	Mean				0.88	0.93
Standard deviation				0.051	0.094	Standard deviation				0.022	0.057

Model	Series 7: Fcu = 30MPa, ρ =0.78 %					Model	Series 8: Fcu = 30MPa, ρ =1.13 %				
	Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Ran kin		
S/d=0.1	94	79	77	1.20	1.21	S/d=0.1	98	89	85	1.10	1.15
S/d= 1	101	84	86	1.20	1.17	S/d= 1	109	95	94	1.14	1.16
S/d= 2	106	91	96	1.16	1.11	S/d= 2	118	103	105	1.15	1.13
S/d= 3	117	97	105	1.20	1.11	S/d= 3	120	110	115	1.09	1.04
S/d= 4	122	104	115	1.17	1.06	S/d= 4	123	118	126	1.05	0.98
Mean				1.19	1.14	Mean				1.11	1.09
Standard deviation				0.014	0.066	Standard deviation				0.037	0.071

Model	Series 9: Fcu = 30MPa, ρ =1.53 %					Model	Series 10: Fcu = 30MPa, ρ =2.01 %				
	Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Rankin		
S/d=0.1	107	98	92	1.09	1.17	S/d=0.1	111	107	98	1.03	1.13
S/d= 1	112	106	102	1.06	1.10	S/d= 1	117	115	109	1.01	1.07
S/d= 2	121	114	113	1.06	1.07	S/d= 2	123	124	121	0.99	1.02
S/d= 3	123	122	124	1.01	0.99	S/d= 3	131	133	133	0.98	0.98
S/d= 4	125	130	136	0.96	0.92	S/d= 4	134	142	145	0.94	0.92
Mean				1.04	1.05	Mean				0.99	1.03
Standard deviation				0.046	0.086	Standard deviation				0.030	0.072

Model	Series 12: Fcu = 30MPa, ρ =0.78 %					Model	Series 13: Fcu = 40MPa, ρ =1.13 %				
	Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Rankin		
S/d=0.1	124	86	95	1.43	1.31	S/d=0.1	128	98	104	1.31	1.23
S/d= 1	133	93	105	1.43	1.26	S/d= 1	135	105	116	1.29	1.17
S/d= 2	138	100	117	1.38	1.18	S/d= 2	148	113	128	1.31	1.15
S/d= 3	144	107	129	1.34	1.12	S/d= 3	163	121	141	1.35	1.15
S/d= 4	157	114	140	1.37	1.12	S/d= 4	171	129	154	1.32	1.11
Mean				1.39	1.20	Mean				1.31	1.16
Standard deviation				0.035	0.077	Standard deviation				0.020	0.039

Model	Series 14: Fcu = 40 MPa, ρ =1.53 %					Model	Series 15: Fcu = 40MPa, ρ =2.01 %				
	Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin		Ultimate Load (Vu)(kN)			FEA/ BS	FEA/ Rankin
	FEA	BS.	Rankin				FEA	BS.	Rankin		
S/d=0.1	132	108	112	1.22	1.18	S/d=0.1	141	118	120	1.19	1.17
S/d= 1	140	116	125	1.21	1.12	S/d= 1	152	127	133	1.20	1.14
S/d= 2	156	125	138	1.25	1.13	S/d= 2	165	137	148	1.21	1.11
S/d= 3	170	134	152	1.27	1.12	S/d= 3	174	147	163	1.19	1.07
S/d= 4	177	143	166	1.24	1.07	S/d= 4	182	156	178	1.16	1.02
Mean				1.24	1.12	Mean				1.19	1.10
Standard deviation				0.022	0.035	Standard deviation				0.014	0.053

X. CONCLUSION

The nonlinear analysis of the punching shear behavior of flat plate supported by coupled columns was simulated to predict the effect of some parameters on the punching shear strength of the flat slabs. The main conclusions of this study were.

1) The nonlinear numerical results provided good agreement with the available experimental results of the punching load capacity and related deflection.
2) The finite element analysis based on 3-D models created by ANSYS can be used to investigate the punching shear capacity in flat plate rested on coupled columns.
3) The increase of the clear distance between coupled columns also increased the FEA predicted ultimate load.
4) Punching shear strength is increased with increasing flexure reinforcement ratio due to the increased depth of compression zone.
5) Increasing the concrete strength leads to an increment of the punching shear strength.

6) For the flat slabs with the distance between the coupled columns less than or equal 4d, the two columns behave in as on column and the influence of coupled columns has vanished.
7) The calculated punching shear strength by BS 8110 code and Rankin`s approaches give a good accordance with the finite element results, but the Rankin's approach gives better estimation than the BS 8110 code.

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