Research Article

New Methods to Resisting Punching Shear Stress in Reinforced Concrete Flat Slabs

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Abstract

Punching shear failure is a major problem encountered in the design of reinforced concrete flat slabs. The utilization of shear reinforcement via shear studs or other means has become a choice for improving the punching shear capacity. In this study, a new alternative of reinforcement modalities were tested and demonstrated the effect of self-compact concrete on the punching shear capacity, beside that compared between the difference codes to identify the suitable one for determining the position of critical section of punching shear. Nevertheless, in this investigation, the proposed reinforcement system is examined for interior columns only. An experimental work consisting of six specimens: five of them were cast with normal reinforced concrete and one was cast with self-compact strength concrete. The obtained results indicate that the proposed shear reinforcement system has a positive effect in the enhancement of the punching shear capacity of interior slab–column connection of self-compact strength concrete.

Keywords: Flat slab; Punching shear; Crack pattern; Ductility; Self-compact concrete.

Introduction

Punching shear is a critical design factor of reinforced concrete flat slabs since it is associated with brittle failure. The punching shear strength and deformation capacity are strongly influenced by the type and characteristics of the shear reinforcing system. Ruiz and (Muttoni et al, 2010) carried out a series of a six full scale slab tests (3.0 x 3.0 x 0.25 m) with the same flexural and shear reinforcing ratio. The slabs were different punching shear reinforcing systems; e.g., separated stirrups, continuous stirrups, bonded reinforcement with anchorage plates, vertical studs and inclined studs. The improvement in punching shear strength and ductility as a result of these systems increased with the same order as they have been mentioned, with the vertical and inclined studs giving the best results; 77% and 119% improvement, respectively. Bent-up bars also improve the punching shear strength and deformation capacity as reported by (Tassinari et al, 2011). (Lips et al, 2012; Muttoni et al 2010) demonstrated the positive effect of both shear studs and continuous stirrups on the punching shear strength and deformation capacity of slab–column connection. The same conclusion was achieved by (Pilakoutas et al, 2003) for inclined shear band reinforcement. The shear strength is proportional to the flexural reinforcement ratio; in contrast, the rotation capacity is inversely proportional to the

flexural reinforcement (Kinnunen et al, 1960). This study explored the possibility of enhancing the punching shear strength by introducing horizontal mesh reinforcement at the middle of the depth of slab–column connection zone. This reinforcement arrangement is easy to apply and economic in comparison with the other reinforcement types. (Kueres et al, 2017) evaluated the punching shear design provisions according to Eurocode 2 by means of comparisons with test results.

To verify the changes in the current design provisions, the new design method was evaluated using large databanks for flat slabs and column bases without and with shear reinforcement as well as systematic test series. The evaluation of the large databanks indicates a well-balanced level of safety of the proposed design method for all investigated types of members. (Mabrouk et al, 2017) asses the contribution of horizontal flexural reinforcement and vertical shear reinforcement on the punching behavior of reinforced concrete flat slabs. The result from this study showed that the failure of all the tested specimens was a brittle punching failure, adding vertical shear reinforcement in the form of stirrups improved the punching capacity of the slabs, increasing the width of stirrups caused a slight increase in the punching strength, also as the flexural reinforcement ratio was increased, the punching capacity was increased. Finally the current Egyptian code is more conservative than the ACI code in estimating the punching shear capacity.

Self-compacting concrete (SCC) is one of the new types of concrete that possesses High flow-ability, passing ability and stability. It is a highly workable concrete that can flow through congested reinforcing under its own weight and sufficiently fill voids without tending to segregation or excessive bleeding and without the need for Vibration to consolidate it (Okamura et al.1999;Yahia et al.1999)and . In addition, self-compacting concrete should maintain its flow-ability for a reasonably long time [ozawa et al, 1995; Okamura et al. (1995)].

The provisions for calculating the ultimate punching shear capacity recommended by different building codes are reviewed in the following:

- In the Egyptian Code of Practice, ECP-203 [13], the critical shear perimeter is located at a distance 0.5d from the column face, it does not account for the flexural reinforcement effect and the concrete strength is limited to 40 MPa. Besides, it does not take into consideration the contribution of punching shear reinforcement.
- According to the ACI 318-11 [14], the critical perimeter is assumed at 0.5d from the perimeter of the loaded area.
- The critical section adopted by the British Standard, BS-8110 [15], lies at 1.5d from the column face. If shear reinforcement is considered, then it should be provided on at least two perimeters within the punching zone. The first perimeter of reinforcement should be located at approximately 0.5d from the face of the loaded area and should contain not less than 40% of the calculated area of reinforcement. The spacing of perimeters of reinforcement should not exceed 0.75d and the spacing of the shear reinforcement around any perimeter should not exceed 1.5d. The shear reinforcement should be anchored round at least one layer of tension reinforcement. The shear stress should then be checked on successive perimeters at 0.75d intervals until a perimeter is reached which does not require shear reinforcement.
- The critical section adopted by the Eurocode 2, EC2 [16], lies at 2d from the column face, In case of shear reinforcement, a control perimeter set at a distance of 1.5d from the outer most perimeter of shear reinforcement

The main objective of the current work is to compare the punching shear strength of six flat slabs; one made from self-compact concrete, and the remaining made with normal strength concrete, four of these normal slabs were Resisting by bent bar at different location from the column face and one without Resisting to be used as a control slab.

Experimental Work

Test specimens

Table 1. Details of the test specimens

Group	Specimen Code	Fcu (MPa)	Conditions	Bottom RFT	Top RFT	Bent Bar
(A)	S025	25	Control	6 Ø 10	8 Ø 10	-
(B)	S040	40	Self-compact concrete	6 Ø 10	8 Ø 10	-
(C)	ABBS1	25	Resisting by bent bar started at 0.5 d from the column face	6 Ø 10	8 Ø 10	4 Ø 10
	ABBS2	25	Resisting by bent bar started at 1.0 d from the column face	6 Ø 10	8 Ø 10	4 Ø 10
	ABBS3	25	Resisting by bent bar started at 1.5 d from the column face	6 Ø 10	8 Ø 10	4 Ø 10
(D)	ABBS4	25	Resisting by bent bar in which the middle of it was at 0.5 d from the column face	6 Ø 10	8 Ø 10	4 Ø 10

An experimental program were consisting of six square flat slab specimens. One specimen was cast with self-compact concrete and the others specimens were cast with normal strength concrete (the control specimen and four specimens resisting against the shear punching). The specimens ABBS1, ABBS2 and ABBS3 were resisting by bent bar started at 0.5 d, 1.0 d and 1.5 d, respectively from the column face in two directions, the remaining specimen ABBS4 was resisting by bent bar in which the middle of it was at 0.5 d from the column face. Where d is the distance between the column face and bent bar.

The details of test specimens are indicated in Table 1 and in Figs. 1&2. All the test specimen consisted of square flat slabs 1200 mm length and 140 mm thick with 200 mm square reinforced concrete column stubs extending 200 mm above the slabs. The column stub was cast monolithically with the slab. All the slabs were identical in dimensions. The reinforcement was distributed uniformly throughout the width of the slab as shown in Figs. 1 &2.
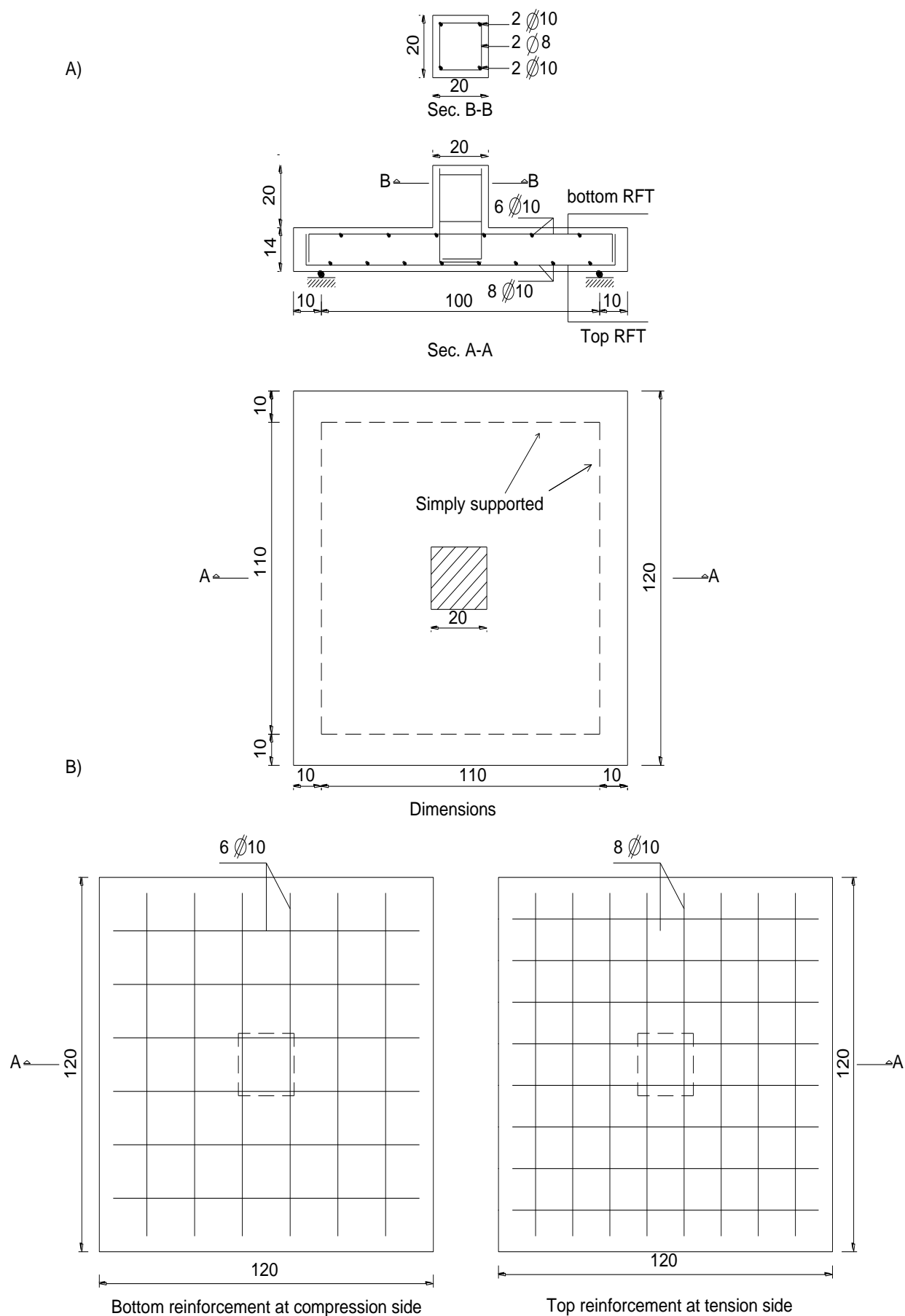
A)

Sec. B-B

Sec. A-A

B)

Dimensions

6 Ø10

8 Ø10

Bottom reinforcement at compression side

Top reinforcement at tension side

Fig. 1. A) Dimensions of slabs, B) Details of reinforcement of reference S025, S040, Dimensions in cm
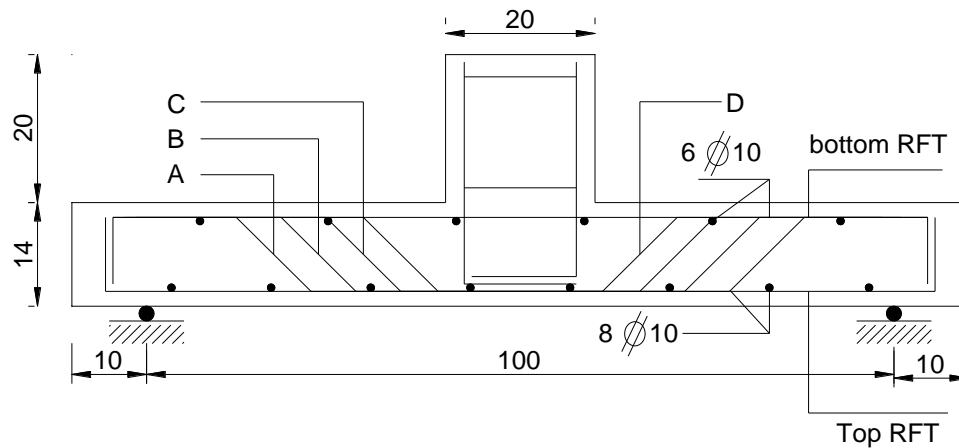
Fig. 2. Typical steel arrangement details of slabs: A) Start of bent bar at 1.5 d from column face, B) Start of bent bar at 1.0 d from column face, C) Start of bent bar at 0.5 d from column face, D) Middle of bent bar at 0.5 d from column face, Dimensions in cm

Properties of Materials

Natural siliceous sand was used as the fine aggregate throughout the current research. The sieve analysis was done on the sand and its result is presented in Table 2. Natural dolomite from Suez zone was used as a coarse aggregate. The dolomite has a nominal maximum size of (20 mm). The particles were smooth in texture with 80 percent of them angular shape. The sieve analysis for the dolomite used is shown in Table 3. Ordinary Portland cement was used and its chemical and physical properties were analyzed according to E.S.S. (2011) for concrete works. Fresh drinking water and free from impurities was used for mixing and curing of the test specimens.

Table 2. Grading of fine aggregate according to (ASTM C33)

Sieve size (mm)	9.5	4.75	2.36	1.18	0.61	0.31	0.16
% passing (ASTM C33)	100	95-100	80-100	50-85	25-60	5-30	0-10
% passing used dolomite	100	100	96	75	45	20	1

Table 3. Grading of coarse aggregate according to (ASTM C33) and grading of natural dolomite used

Sieve size (mm)	20	12.5	9.5	4.75	2.36
% passing (ASTMC33)	100	90-100	40-70	0-15	0-5
% passing used dolomite	100	96	85	53.2	7.3

For the concrete strength; standard cubes have been tested for strength control. Table 4 shows the average strength of all specimens designated as 25 MPa for normal slab concrete and 40 MPa for self-compact concrete slab. Based on the results of different trail mixes, the concrete mix proportions illustrated in Table 5 were selected to cast the test specimens with

normal strength concrete. The concrete mix proportions illustrated in Table 6 were selected to cast the test specimen with self-compact concrete.

Table 4. Used material properties

Cubes number	F cu (MPa)	Average (MPa)
1	27.32	Normal strength concrete 25
2	26.89	
3	26.49	
4	24.65	
5	39.81	Self-compact concrete 40
6	43.65	
7	42.21	

Table 5. Concrete mix design (normal strength concrete 25 MPa)

Cement	Water	Coarse aggregate	Fine aggregate
300 kg	150 kg	1290 kg	645 kg

Table 6. Concrete mix design (self-compact concrete 40 MPa)

Cement	Water	Coarse aggregate	Fine aggregate	Flyash	ViscoCrete
425 kg	148 kg	838 kg	686 kg	85 kg	17 kg

High tensile steel bars with 10 mm diameters were used as main and secondary reinforcement in the two directions of tested slabs. The concrete columns were reinforced with normal mild steel as stirrups with 8 mm diameters and high tensile steel bars with 10 mm diameters as main reinforcement. Table 7 illustrates mechanical properties of steel reinforcement.

Table 7. Mechanical properties of steel reinforcement

Steel Type	Yield Stress (kg/cm2)	Tensile Strength (kg/cm2)	Elongation %	Modulus of Elasticity (t/cm2)
High Tensile	3675	5350	16.0	2100
Normal Mild	2550	3750	24.30	2050

Preparation of the Test Specimens

Six square wooden forms for slab specimens 120×120×14 cm with stub columns 20×20x20 cm at the center of each slab specimen were prepared. The reinforcement was then placed in their right position in the forms (Fig. 3). Wooden forms for the stub columns were installed at the center of the specimens. A 50 liter capacity mixer was used with a speed of about 50 revolutions per minute. Materials were added in the following sequence: coarse aggregate, sand and cement. The dry constituents were mixed without water for two minutes, then the water was added and the operation continued for an additional three minutes to ensure adequate mixing as shown in Fig. 4. The forms were coated with oil before casting. The concrete mix was charged out from the mixer bowl. A mechanical vibrator was used in placing the concrete around the reinforcing bars together with the hand tamping and rodding to ensure full compaction. The slabs specimens were left in the forms for 24 hours after which the sides of the forms were stripped. The specimens were cured by water sprinkling twice a day for 28 days.

Fig. 3. wooden forms and reinforcement

Fig. 4. Mixing materials

Test set-up

The specimens were tested in Al-Menofia University Reinforced Concrete Lab. The models were tested under concentrated loads at the center of the column stub up to failure. Loads were applied in increments

using a hydraulic jack of 100 ton maximum capacity. Dial gauges of 0.01 mm accuracy and total capacity of 25 mm were used for measuring deflections, first cracking loads and ultimate failure loads were recorded. Propagation of cracks was marked after each load increment up to failure. The description of loading system is shown in Fig. 5, while Fig .6 shows the arrangements of the dial gauges for different specimens.

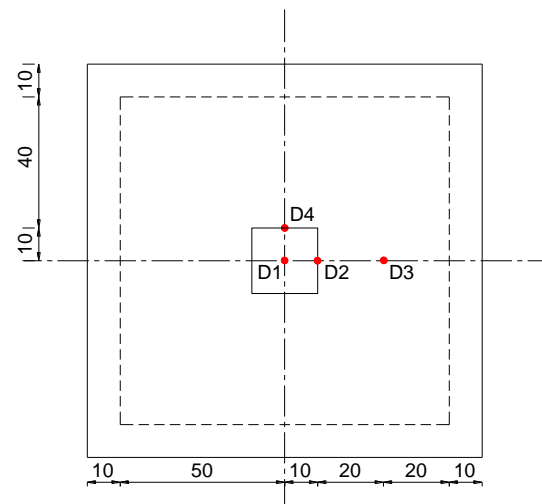

Fig. 5. Description of the loading system

Fig. 6. Arrangements of dial gauges for different specimens, Dimensions in cm

Results and Discussions

The behavior of the test specimens in terms of load-deflection relationship and mode of failure are illustrated and discussed in the current sections. Load-deflection curves for all specimens are presented in Fig. 7. Table 8 shows the experimental results of all the tested slabs in the terms of ultimate and first crack load, the deflection at the failure and at the first crack load, ductility ratio and energy absorption. The ductility ratio was calculated as ratio of the mid span deflection at the ultimate load to that at the first cracking load. The energy absorption was obtained by calculating the area under the load-deflection curve for each slab. Fig. 8 shows the ultimate and the first crack loads for all tested slabs. The average ductility ratio and energy absorption for all tested slabs are shown in Fig. 9.
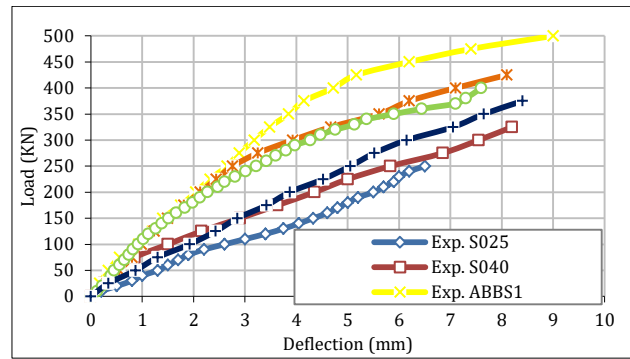
Fig.7. Load-deflection curves of all test specimens at D1

Table 8 Experimental results

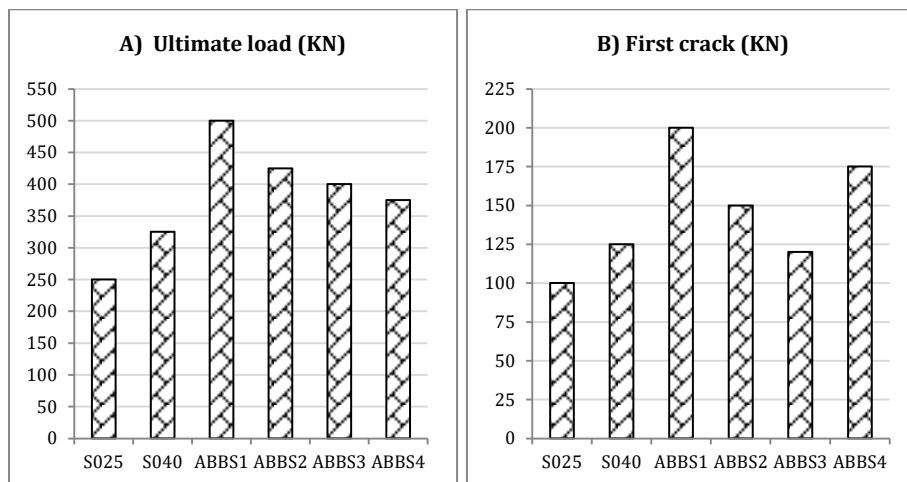| Slab code	Load (KN)		Deflection at Ultimate Load (mm)	Deflection at First Crack (mm)	Ductility Ratio	Energy Absorption (KN.mm)
	Ultimate	**First Crack**				
S025	250	100	6.50	2.6	2.50	78.12
S040	325	125	8.20	2.15	3.81	1528.00
ABBS1	500	200	9.0	2.04	4.41	3027.50
ABBS2	425	150	8.10	1.49	5.44	2209.50
ABBS3	400	120	7.60	1.12	6.79	1917.40
ABBS4	375	175	8.40	3.42	2.46	1721.50

Fig. 8. A) Ultimate load for all tested slabs, B) First crack load for all tested slabs
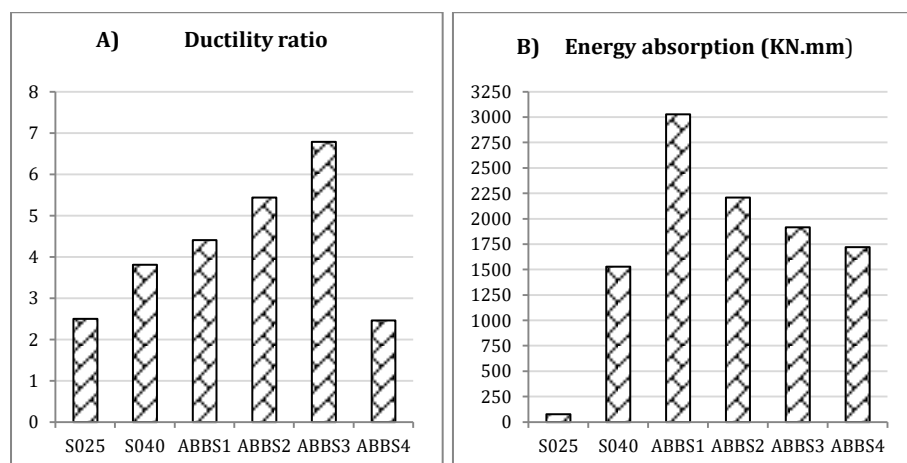

Fig. 9. A) The average ductility ratio for all tested slabs, B) Energy absorption for all tested slabs

Effect of Resisting of concrete

Fig. 10 shows the comparison between load-deflection curves at the center (D1) of the control slab S025 and specimen S040, and at the midpoint (D3) between the center of slab and the support. The ultimate load and the first crack load for self-compact concrete (S040) was higher than the control slab (S025) by 30% and 25%, respectively.
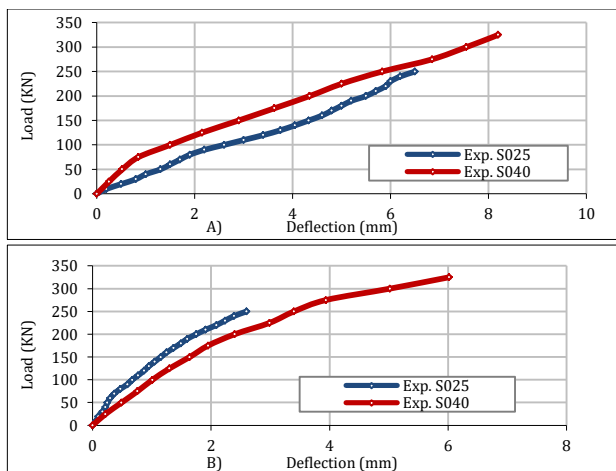

Fig. 10. Comparison between load-deflection curves of the specimens S025 and S040, A) load-deflection at D1, B) load-deflection at D3

Effect of bent bars position

Fig. 11 illustrates comparison between load-deflection curves at D1 and D3 for control slab (S025) and Group C (ABBS1, ABBS2 and ABBS3). The results shows that the ABBS1 has the highest ultimate load and it was double load of the control slab, the ABBS2 was higher than the control slab by about 70% for ultimate load and by about 50% for first crack load, the lowest load for experimental groups was associated with ABBS3, it was 60% and 20% higher than the control slab for ultimate load and the first crack load, respectively.
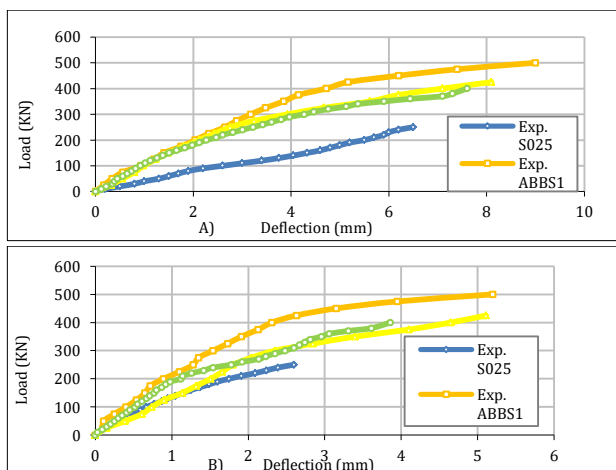

Fig. 11. Comparison between load-deflection curves of the specimens S025 and all specimens of Group D: A) load-deflection at D1 and B) load-deflection at D3

Effect of start and middle of bent bar at 0.5 d

Comparison between load-deflection curves at D1 and D3 for the specimen ABBS1 and ABBS4 in which the specimens was resisting at 0.5 d by bent bar at start and at the middle from the column face in two directions; respectively was shown in Fig. 12. The results show that ABBS4 has higher ultimate and first crack loads (375 KN and 175 KN) than control group (250 kN and 100 kN), but it is lower than that for ABBS1 (500 kN and 200 kN).
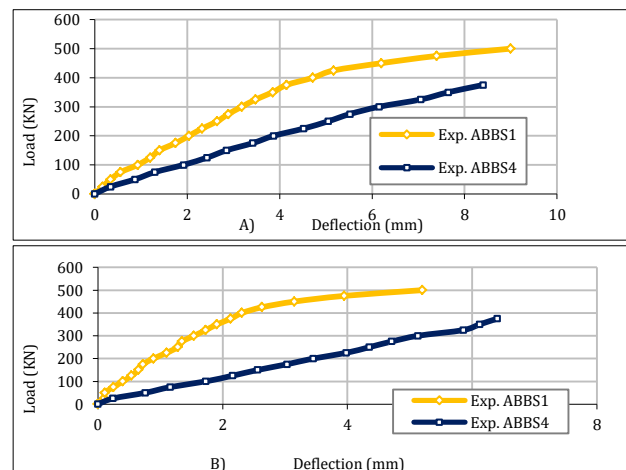

Fig. 12. Comparison between load-deflection curves of the specimens ABBS1 and ABBS4; A) load-deflection at D1, B) load-deflection at D3

Cracks observation

For all the specimens, surface cracks on the tension side of reinforcement, had been observed and marked during the test. The initial crack development in all specimens followed a similar pattern. Diagonal cracks were getting wider and tangential cracks had been developed. Fig. 13 shows the crack pattern in the tension side for all specimens. For the compression side, cracks had been developed around the column in all specimens.

Fig. 13. The crack pattern (propagation) in tension side for all specimens

Fig. 13 The crack pattern (propagation) in tension side for all specimens, continue

Conclusions

The main goal of the current research is examining the punching shear resistance of flat slab by using self-compact concrete and using additional modalities of bent bar reinforcement, to compare between different codes in order of identifying the suitable code for determining the position of critical section of punching shear. From the experimental results, the following conclusions could be drawn as below:-

1) The increase of strength concrete lead to increase of ultimate load of slab, and this explain the high resistance of punching shear strength of self-compact concrete.
2) The critical parameter of punching shear lay at 0.5 d from the column face, so the Egyptian code is one of the best international code for determining the critical section of punching shear.
3) Resisting of slab at position more or less than 0.5 d leads to reduce of punishing shear resistance of slab.
4) Flat slabs resisting by bent steel bars have the highest punching shear resistance comparing to its corresponding slabs resisting by added straight bars.

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