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Research Paper

Pilot Experimental Tests on Punching Shear Strength of Flat Plates Reinforced with Stirrups Punching Shear Reinforcement

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ABSTRACT

Flat plates are favor structure systems usually used in parking garages and high-rise buildings due to its simplicity for construction. However, flat plates have some inherent structural problems, due to high shear stress surrounding the supporting columns which cause a catastrophic brittle type of failure called "Punching Shear Failure". Several solutions are used to avoid punching shear failure, including the use of drop panels or punching shear reinforcement. The latter is being a more sophisticated solution from the structural ductility, the architectural and the economical point of view. This study aims at investigating the effect of stirrups as shear reinforcement in enhancing the punching strength of interior slab-column connections. A total of four full-scale interior slab-column connections were tested up to failure. All slabs had a side length of 1700 mm and 160 mm thickness with 200 mm x 200 mm square column. The test parameters were the presence of shear reinforcement and stirrups concentration around the supporting column. The test results showed that the distribution of stirrups over the critical punching shear zone was an efficient solution to enhance not only the punching shear capacity but also the ductility of the connection. Furthermore, the concentrating of stirrups shear reinforcement in the vicinity of the column for the tested slabs increases the punching shear capacity by 13 % compared to the uniform distribution at same amount of shear reinforcement.

1 Introduction

Flat plates are a common form of construction, strongly favoured because of the lack of drop beams which results in a speed of construction time. The flat ceiling also helps with the installation of air-conditioning, electrical wiring, etc. The main disadvantage of the flat plate system is that of the concentration of shear stresses resulting from the transfer of shearing forces or shearing forces combined with unbalanced moments between columns and slabs joints. This area is, therefore, a region of weakness [1-3]. The slabs can suffer a rather sudden and catastrophic brittle type of failure called "Punching Shear Failure" where the column punches through the slab. This particularly occurs when no shear reinforcement is used around the punching shear zone. The optimum design of flat plates is often compromised by their

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ability to resist punching stresses at columns, or other support locations. The shear resistance of flat plates can be increased by providing drop panels, column capitals or punching shear reinforcement. Using drop panels or column capitals may be impractical for architectural reasons. They often necessitate using of suspended ceilings and thereby increasing floor-to-floor height. They are also too costly to build because of the lack of flying formworks. It should be mentioned that the punching shear strength is increased by using drop panels or column capitals but the ductility of the connection is significantly decreased. In contrast, using the shear reinforcement over the critical punching shear zone in flat plates provides an effective solution not only for ductility of the connection but also for the punching shear strength.

The punching shear design is a critical issue for reinforced concrete flat plates in order to produce a safe design. Punching shear design limits and shear reinforcement details around the punching shear zone considerably differ among the European and American design codes [4-9]. On the other hand, the Egyptian design code for buildings [8] does not permit using shear reinforcement in flat plates systems. Therefore, this study presents a part of an investigation which has been conducted at Helwan University to examine the efficiency of closed stirrups as shear reinforcement in flat slab-column connections using locally available materials and similar manufacturing process as commonly used in Egypt to provide some design recommendations for the Egyptian design code of practice [8].

2 Experimental work

A total of four full-scale interior slab-column connections measuring 1700mm x1700mm x160mm (thickness) were tested under concentric punching shear tests. The average effective depth is 130 mm with a central square column dimensions of 200 mm x 200 mm. The bottom (main flexural reinforcement) and top mats had 14 deformed bars of 16 mm and 10 mm diameters with an equal spacing distribution of 130 mm in both directions, respectively. Figure 1 shows the reinforcement details of test specimens.

2.1 Material properties

The materials used in fabricating the test specimens were locally available materials. The manufacturing process was similar to the one used in Egypt. The Coarse aggregate used in this investigation was crushed dolomite of size number 2 from Suez Mountain. The maximum nominal size was nearly 20 mm diameter. Also, natural siliceous sand and Ordinary Portland cement were used as fine aggregate and as binding material, respectively. Ordinary drinking water was used for mixing and curing. All materials used in the manufacturing process met the requirements as specified in the Egyptian Standard Specifications (E.S.S) [8]. The target concrete compressive strength was 30 MPa. Twelve concrete cubes were tested using MTS compression testing machine to determine the concrete compressive strength after 28 days. The average concrete compressive strength for all groups after 28 days was 35.5 MPa, except for slab S1-3 f_{cu} was 25.5 MPa. Deformed high tensile steel reinforcements of 10 and 16 mm diameters were used as top and bottom mats in all specimens while mild steel reinforcement of 8 mm in diameter was used as closed stirrups shear reinforcements. Table 1 shows the yield and ultimate tensile strength of steel reinforcements.

Table 1- Mechanical properties of steel reinforcements

Nominal diameter (mm)	Grade	Actual Area (mm^2)	Unit weight N/m	Yield strength MPa	Ultimate strength MPa	Elongation %
Y8	24/35	50	3.85	280	388	27%
Y10	36/52	78	6.02	515.4	666.2	16%
Y16	36/52	201	15.6	408.5	685.6	14%

2.2 Specimens Details

Slab S1-1 was a control slab without shear reinforcement while S1-2, S1-3, and S1-4 were enhanced with closed stirrups shear reinforcement 8 mm in diameter. For S1-2, an equal spacing distribution between shear reinforcement (stirrups) equal to d/2 (≈6.50 cm) was used. The first stirrups line was located at distance d/2 (≈6.50 cm) from the column face and extending to a distance equal to 3.5d (≈45.5 cm), where d is the slab effective depth. S1-3 was identical specimen as S1-2 but the concrete compressive strength was different (= 25 MPa). Slab S1-4 had the same amount of shear reinforcement as in slab S1-2 but different stirrups distribution was used. The first stirrups line was located at distance d/2 (≈6.50 cm) from the column face. Thereafter, the stirrups were concentrated in punching shear zone with an equal spacing of 0.35d (≈4.5 cm) between stirrups for a distance of 1.0d (≈13 cm) then the spacing between stirrups was increased to 0.7d (≈8.50 cm) and extended for a distance 2.0 d (≈25.50 cm). The overall distance of distribution was equal to 3.5d (≈45 cm) from the column face which is the same distance as for S1-2 and S1-3. Figure 1 and 2 show fabrication and the details of specimens.

Fig.1 - Fabrication of the test specimens with stirrups shear reinforcement

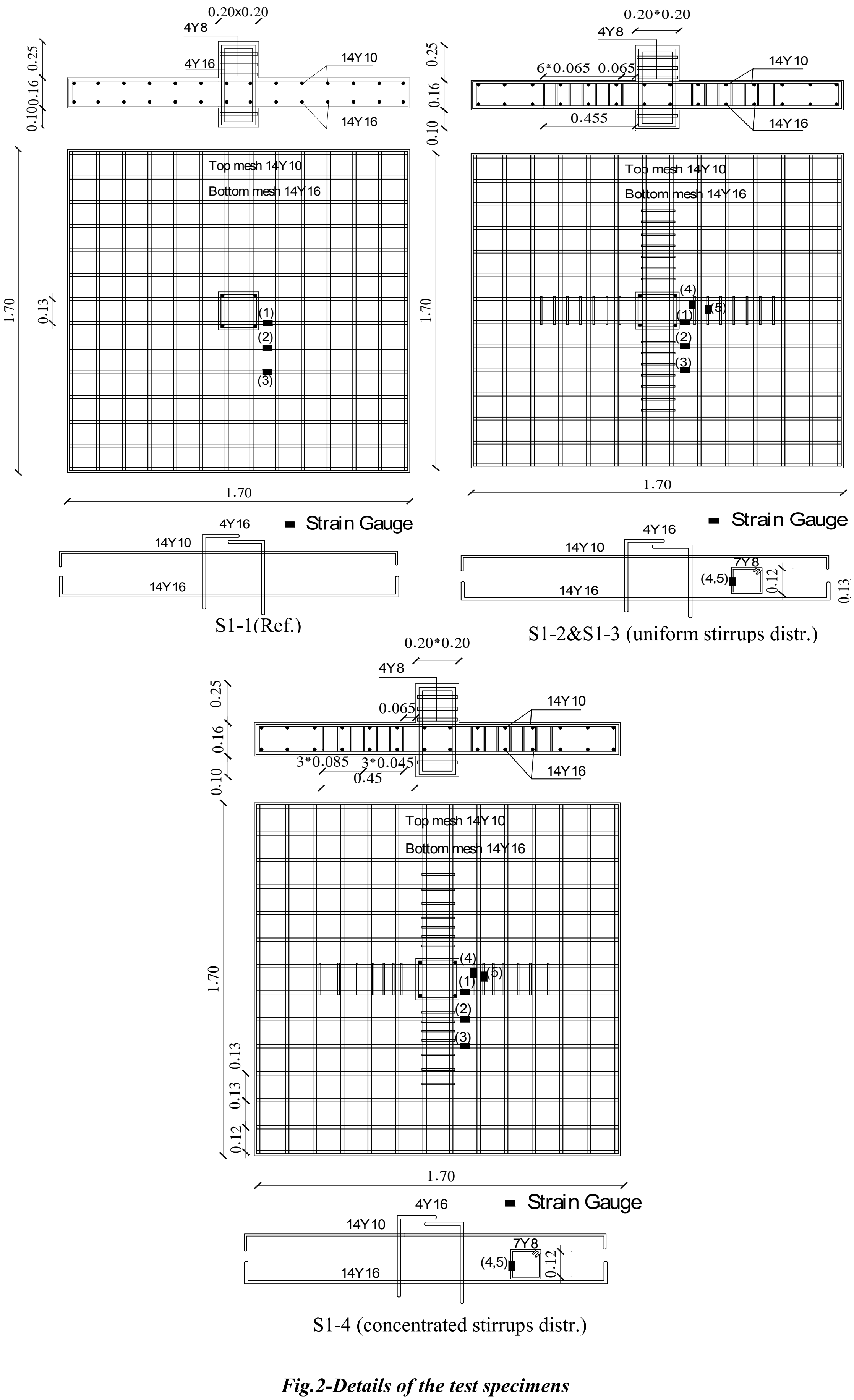


Fig.2-Details of the test specimens

2.3 Test setup and instrumentations

The built supporting frame consists of four beams supported on four columns I.P.E 270 as shown in Figure 3. All slabs were supported on the steel frame along the four sides. A reinforced rubber layer with 2 cm thickness and 5 cm width was placed between the slab and steel beams to ensure uniform stress distribution on the steel frame. A hydraulic jack with 1000 kN capacity was used for load application on all specimens. The jack was connected to a steel column then fixed in a rigid top steel beam of the loading frame. A load cell was attached between the jack and concrete column. The load was incrementally applied under manual controlled loads. The increment of loading was 50 kN up to failure. Deflections for all slabs were measured using three dial gauges located along the centre line of the specimen and one dial gauge located at the center of the column under the slab. The dial gauges were located in both perpendicular directions of the specimen. Electric resistance gauges (5mm length, 120 ohms resistance with gauge factor 2.10) were glued on the steel reinforcements before casting to capture the strains in the steel bars and stirrups. The steel strains were recorded using a digital strain-meter (TC-31K) device and the readings were collected by using data logger at each increment of loading.

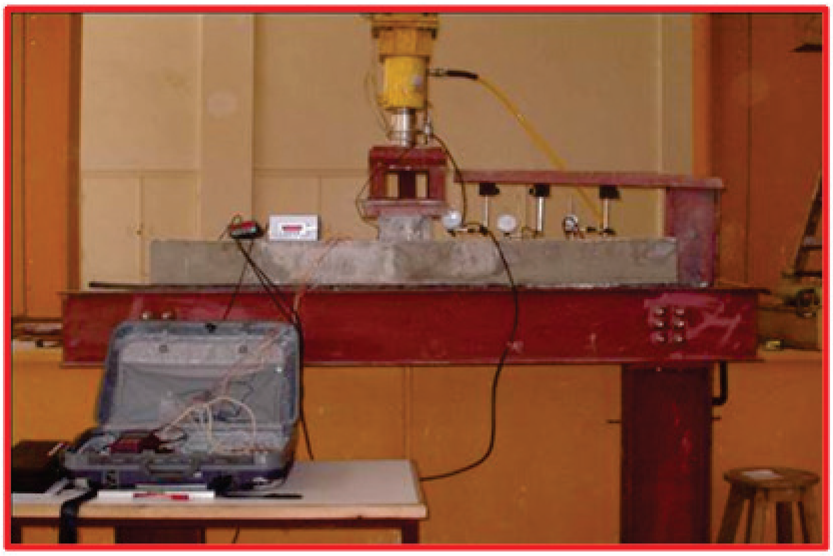


Fig.3- Test setup

3 Test results

3.1 Mode of Failure

All specimens failed in a typical punching shear mode. Slabs without shear reinforcement failed in a brittle and sudden manner while specimens provided with shear reinforcement failed inside the shear reinforced zone in a ductile mode. Table 2 shows the ultimate loads carrying capacities and deflections of each specimen as well as loads at first cracking and cracking to ultimate loads and deflection ratios. Figure 4 shows the punching shear failure surface in the slab tension side.

Table 2- Test results

Slab	Cracking case		Ultimate case		Crack/Ultimate (%)		Measured ductility (mm)
	Pcr (kN)	Deflection (mm)	Pu (kN)	Deflection (mm)	Load (%)	Deflection (%)	
S1-1	126.8	4.38	366.8	13.3	34.6	33.4	9.07
S1-2	160.0	-	470.2	-	34.0	-	-
S1-3	119.9	3.91	412.7	13.8	29.1	28.3	9.12
S1-4	150.0	4.29	530.0	14.1	28.3	30.5	9.90

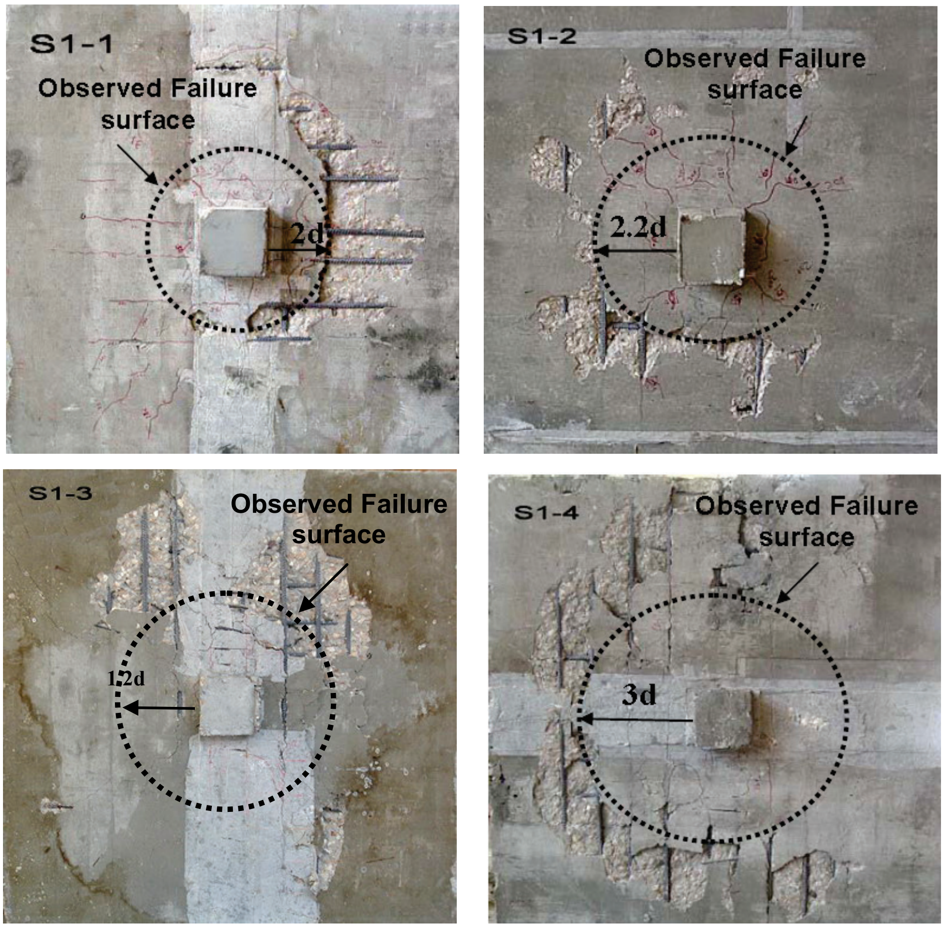


Figure 4- Punching shear failure surface in the slabs tension side

3.2 Load-deflection relationships

Figure 5 shows the load–deflection relationships using the LVDTs located at center the column. All specimens showed similar load–deflection responses up to the sudden punching shear failure. It should be mentioned that the presence of the shear reinforcement in the punching shear zone enhanced the ductility of the connection which turns to a more ductile behavior. The ductility was computed at deflection of 70 % of the ultimate loads. Table 2 shows the measured ductility of different specimens.

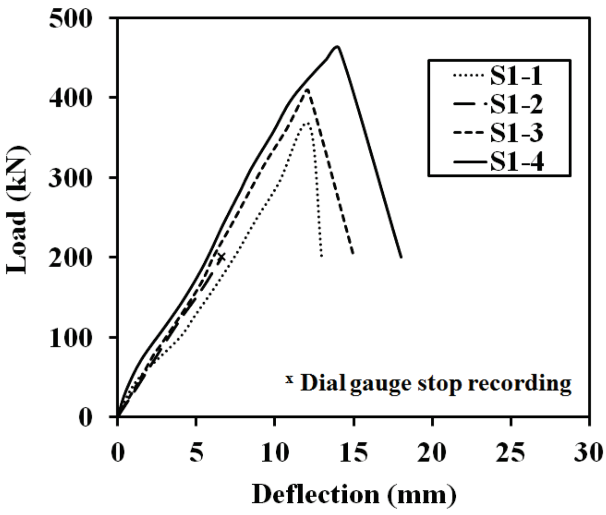
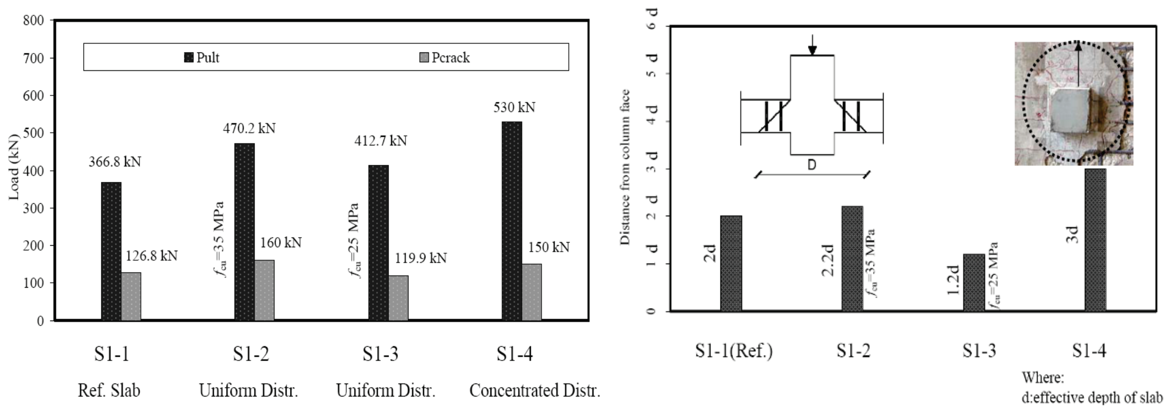


Figure 5- Load versus deflection responses

3.3 Effect of stirrups concentration

For slabs S1-2, S1-3 and S1-4, the presence of stirrups shear reinforcement around the column increased the ultimate carrying capacities by 28.2, 12.5, 44.5 % compared to the control specimen S1-1, respectively. At the same amount of shear reinforcement, the concentration of stirrups shear reinforcement as in slab S1-4 increased the load carrying capacity by 12.7 and 28.6 % compared to their counterparts S1-2 and S1-3, respectively. Besides, the observed punching failure surface and the ductility of the connection were increased. Thus, it can be concluded that concentration of stirrups shear reinforcement around the column was a more efficient than the uniform distribution of the same amount of shear reinforcement. Figure 6 shows the effect of stirrups concentration on the ultimate load capacities and the observed crack surface after failure.



(a) (b)

Figure 6- a) the effect of stirrups concentration on the ultimate capacity; b) effect of stirrups concentration on punching cone perimeter surface

4 Comparisons with Different Codes

The predicted ultimate capacity (V_{code}) was calculated according to ACI 318 (2015), CSA A2.3 (2014) and BS 8110 (1997) punching shear design equations. All safety factors and partial material factors in the equations were taken to be equal to 1.0. The ratios between ultimate loads from the experimental tests (V_{test}) to the predicted values (V_{code}) are reported in Table 3. It should be noted that no codes consider the effect of the stirrups concentration in calculating the ultimate punching shear stress. Therefore, the average spacing of stirrups distribution (S_{ave}) was used for S1-4. The ACI and CSA design codes showed conservative predictions with average V_{test}/V_{code} of 1.25±0.12 and 1.17±0.12 and COVs of 10% and 10%, respectively. While the BS 8110-97 code was slightly unconservative predictions for the tested slabs with shear reinforcement with an average of V_{test}/V_{code} of 0.94±0.03 and COV of 3%.

Table 3- Comparisons between different codes

Slab	b_o @ 0.5d (mm)	b_o @ 1.5d (mm)	S_{av} (mm)	V_{Test} (kN)	V_{Code} (kN)			$\frac{V_{Test}}{V_{Code}}$		
					ACI 318	CSA A23.3	BS 8110	ACI 318	CSA A23.3	BS 8110
S1-1	1320	2360	----	366.8	324.1	374.4	289.5	1.13	0.98	1.27
S1-2	1320	2360	650	470.2	386.1	411.2	484.4	1.22	1.14	0.97
S1-3	1320	2360	650	412.7	362.3	384	455.4	1.14	1.07	0.91
S1-4	1320	2360	625	530	383.0	406.3	567.3	1.38	1.3	0.93
							Average*	**1.25**	**1.17**	**0.94**
							SD	0.12	0.12	0.03
							COV (%)	0.10	0.10	0.03

Note: d (effective depth) =130mm, fy (φ8) =280MPa, b_o: perimeter length of critical section from the column face (equal to 0.5 d for the ACI and CSA codes and 1.5 d for the BS code); S_{av}: Calculated average spacing between stirrups in rows toward the column direction, Average was calculated for the slabs with shear reinforcement only.

5 Concluding Remarks

On the basis of the experimental tests results, the following concluding remarks can be drawn:

1. The distribution of stirrups shear reinforcement over the critical punching shear zone provided an excellent and efficient solution in increasing not only the ultimate load capacity but also the ductility of the connection. The ultimate capacity increased ranged from 12.5 to 44.5% compared to their control specimen.

2. Concentrating the stirrups shear reinforcement in the vicinity of the column for the tested slabs was more beneficial in increasing the punching shear capacity than uniform distribution at the same amount of shear reinforcement. The ultimate capacity increased by 13 % compared to their counterpart slab with uniform stirrups distribution around the column.

3. The ACI and CSA design codes showed conservative predictions with average V_{test}/V_{code} of 1.25±0.12 and 1.17±0.12 and COVs of 10% and 10%, respectively, while the BS 8110-97 code was slightly unconservative predictions with an average V_{test}/V_{code} of 0.94±0.03 and COV of 3% for the tested slabs with shear reinforcement.

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