International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Punching Shear Behavior of RC Flat Slabs Strengthened with Steel Shear Bolts

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Received 15 March 2018, Accepted 18 May 2018, Available online 22 May 2018, **Vol.8, No.3 (May/June 2018)**

Abstract

This paper aims to determine the efficiency of using steel Shear Bolts to strengthen RC slabs in punching shear at interior columns. The Shear Bolts used in this study consists of a vertical rod and anchored from both ends using a washer and nut system. Shear Bolts are installed in holes, drilled in concentric perimeters around column, after casting and just before testing. In this Work, an experimental research program was described in which seven half-scale models representing interior slab column connections were tested. Seven square specimens (2000 x 2000 x 150 mm) were divided into two groups. The first group deals with three specimens with square column 150 x 150 mm; one specimen without strengthening as a control specimen and the other two specimens strengthened with shear bolts with different strengthened length around the column. The second group deals with four specimens with rectangular column 150 x 300 mm; one Specimen without strengthening and the other three specimens strengthened with Shear Bolts with different strengthened length and arrangements around the column. All Specimens were loaded until failure. The ultimate load, deformation, punching perimeter, strain in flexural reinforcing bars, strains in Shear Bolts, and the failure mechanisms of each specimen were generated and analyzed. The load-deflection curves are presented which show how Shear Bolts increases punching shear capacity and post failure ductility of slab-column connections.

Keywords: *Punching shear, Flat Slabs, Punching Shear RFT., Shear Bolts, Slab-Column Connections, Strengthening and Ductility.*

1. Introduction

Flat slabs used a lot in multi stories structures because of such advantages as: flat ceiling, low formwork, and reduce story height. The critical element of this system is the slab to column connection because of the concentration of the punching shear stress. Punching shear stress may cause a slab sudden failure at the column zone Figure 1.

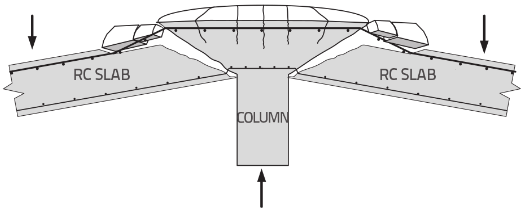

Figure 1: Punching Failure of Slab at Column Zone.

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DOI: https://doi.org/10.14741/ijcet/v.8.3.20

The punching shear capacity and ductility can be increased by using transverse shear reinforcement at slab column connection zone according to different design codes. Transverse shear reinforcement has many types; Bent bars, closed stirrups, open stirrups, continuous stirrups, inclined stirrups, shear hoops, stud rails, and double headed studs as shown in Figure 2.

According to the past version of Egyptian code ECP 203-2007, flat slab structures have been built without any shear reinforcement and shear strength of slab depends only on concrete strength. In the new version of Egyptian code ECP203-2017, the stirrups punching shear reinforcement was added. For that reason, several researchers around the world not only in Egypt have investigated different strengthening methods for interior slab-column connections against punching shear failure.

The subject of punching shear has been studied by various researchers (Kinnunen and Nylander 1960, Shehata 1989, Braestrup et al 1976, Alexander and Simmonds 1987, 1992). Their models established qualitative descriptions of punching phenomenon in slabs. Previous testing by various researchers have also been carried out to study punching shear in slabs at slab-column connections (Dilger and Ghali 1981, Ghali, Sargious and Huizer 1974, Marzouk and Hussein 1991, Elgabry and Ghali 1990, El-Salakawy et al 2003, Rankin and Long 1987).

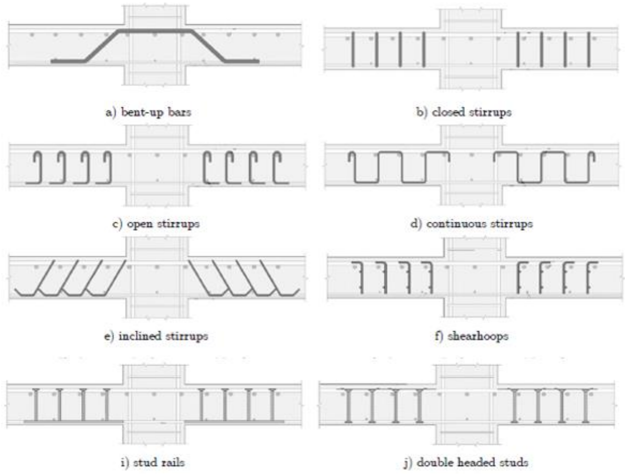


Figure 2: Different Types of Shear Reinforcement in Flat Slabs

El-Salakawy et al. 2003, Adetifa and Polak 2005, Bu and Polak 2009; developed a steel shear bolts consisting of a steel shaft with a steel head on one end and a washer and a nut on the other threaded end. They used it as a transverse shear reinforcement that are installed after casting slabs, and tested its efficiency in increasing slab punching load and ductility. Their studies shown that Shear bolts are effective in preventing punching shear failure for slab-column connection, also the use of shear bolts as transverse reinforcement allowed the slab-column connection to attain flexural capacity and increased the ductility of the connection.

M.A.Polak 2005, Investigated the punching strength and ductility of reinforced concrete slab column connection subjected to cyclic load and strengthened with steel shear bolts. The study has been shown that shear bolts reinforcement in flat reinforced concrete slabs can substantially increase the strength and ductility of the slab-column connection. Post-peak ductility of the slab-column connection which failed by punching through the shear bolts showed substantial ductility after punching took place. This result is especially important for abnormal loading scenarios, where large rotations of the slab-column connections can result in brittle punching failure of slabs without transverse reinforcement, thus perhaps triggering progressive collapse of the surrounding structure. Shear bolts may well serve to dwarf such devastating failure if appropriately retrofitted into existing flat slab structures.

Miguel Fernandez et al 2010, investigated the shear strengthening of existing slabs with an innovative system consisting of inclined bonded bars post-installed within the slab Figure 3.

The results of an experimental program, as well as a series of theoretical works grounded on the critical shear crack theory, indicated that the shear failure of slabs reinforced with this system can develop by crushing concrete struts, punching within the shear reinforced zone, and punching outside the shear reinforced zone. For slabs with low flexural reinforcement ratios, the development of a plastic mechanism is also possible if sufficient shear reinforcement is provided.

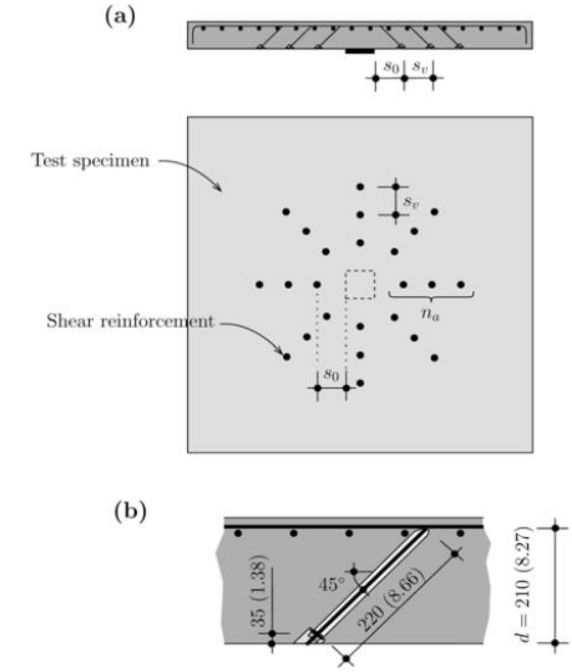


Figure 3: Layout of Inclined Shear Bolts: (a) Cross Section and Plan View; and (b) Dimensions of Shear Reinforcement (Dimensions in mm [in.]).

Hames S.Askar 2015, investigated the efficiency of repairing damaged flat slabs due to punching using a simple and easy method of pre-stressing added bolts as shear reinforcement. In this study, four punching damage slabs with different parameters were repaired with the addition of pre stressed bolts then tested. Test results indicated that repaired specimens recorded higher punching failure load value compared to their reference specimen indicating that the suggested system of repairing punching damaged slabs is effective and could be used in practice.

This paper concentrates on examining the efficiency of using steel shear bolts to increase punching shear strength and post-peak punching ductility of existing slabs including three main parameters: column rectangularity, arrangement of bolts around columns, and spacing between peripheral rows.

2. Testing Program

2.1 Test Specimens

The test specimens were half-scale models assumed to be equivalent to a slab-column connection in continuous slab system. The dimensions of the specimens are boundaries representing the lines of contra-flexure (approximately 0.4 times the span) in addition to 10cm from every side for the supporting steel frame. The continuous system is a flat slab with span equal to 9.00m in both directions. Specimens' dimensions are 2000 x 2000 x 150 mm with clear span between supporting beams equal to 1800mm in both directions. Two column aspect ratios were chosen; 1:1, and 2:1 with column dimensions equal to 220 x 220 x 220 mm, and 300 x 150 x 150 mm respectively as shown in Figure 4 and Figure 5.

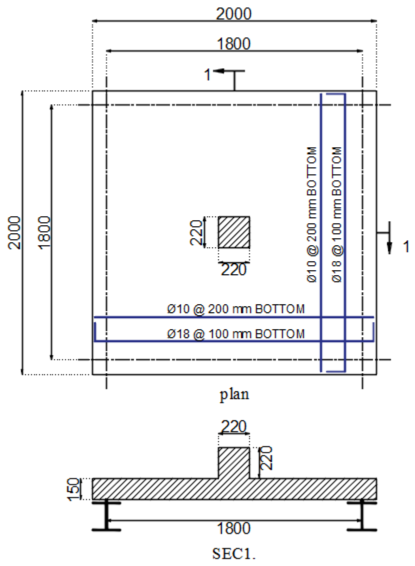


Figure 4: Specimen with Column Aspect Ratio 1:1 (Dimensions in mm)

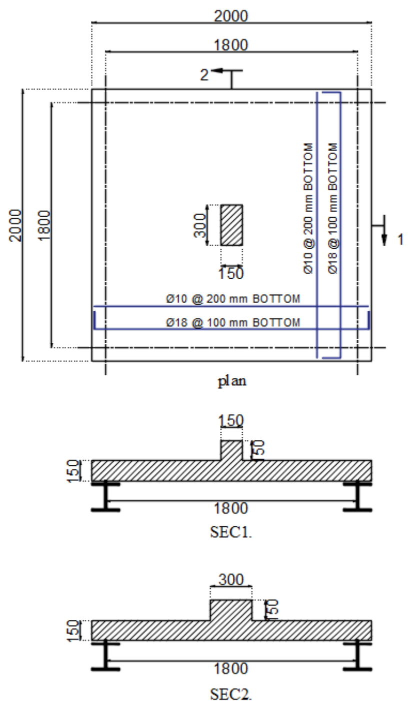


Figure 5: Specimen with Column Aspect Ratio 2:1 (Dimensions in mm)

The clear concrete cover used was 10 mm for bottom and top reinforcement mesh. All specimens were reinforced with bottom longitudinal steel bars Ø18 @ 100 mm in both directions and Ø10 @ 200 in both directions for top reinforcement. Columns longitudinal reinforcement were 4 Ø18 and confined withØ10 @ 100 mm in transverse direction.

Three main parameters were taken into consideration: column rectangularity, arrangement of bolts around columns, and spacing between peripheral rows. Seven specimens divided into two main groups were tested; the first group deal with three specimens with column aspect ratio 1:1, and four specimens in the second group with column aspect ratio was 2:1.

In group A, first specimen (S0) casted and tested without strengthening as a control specimen and the other two specimens (SC3X8–d1, and SC3X8–d2) were strengthened with eight rows of shear bolts, each row had 3 bolts with constant distance from column face to first peripheral row equal to 0.5 d and distance between peripheral rows was equal to 0.5 d, and ¾ d for second and third specimens as shown in Table 1.

Also for group B, the first three specimens (R0, RC3X8–d1, and SC3X8–d2) are as before in-group A. In addition to that, last specimen (Srad3X8-d2) was strengthened with a radial arrangement of shear bolts at distance 0.5 d from column face to the first peripheral row and ¾ d between peripheral rows as shown in Table 1. The five strengthened specimens constructed are shown in Figure 6 and control specimens are shown in Figure 4, and Figure 5.

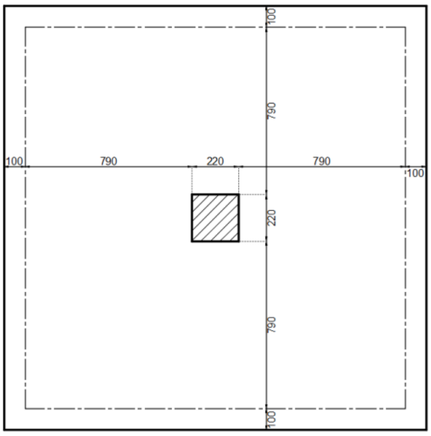
Table 1: General Description of Test Specimens

Group	Specimen	Column Aspect Ratio	Column Dimensions (mm)	S0	Si
A	S0	1	220 x 220	----------	----------
	SC3X8-d1	1	220 x 220	0.5 d	0.5 d
	SC3X8-d2	1	220 x 220	0.5 d	3/4 d
B	R0	2	300 x 150	----------	----------
	RC3X8-d1	2	300 x 150	0.5 d	0.5 d
	RC3X8-d2	2	300 x 150	0.5 d	3/4 d
	Rrad3X8-d2	2	300 x 150	0.5 d	3/4 d

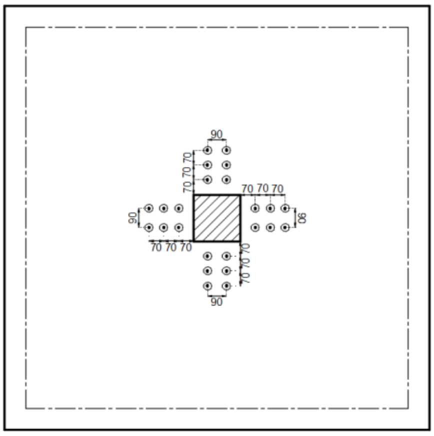
2.2 Shear Reinforcement

Five slabs were strengthened with post installed shear bolts. Used shear bolts consists of a reinforcement steel bar with 10 mm diameter and threaded ends for the nuts that hold bar in place as shown in Figure 7.

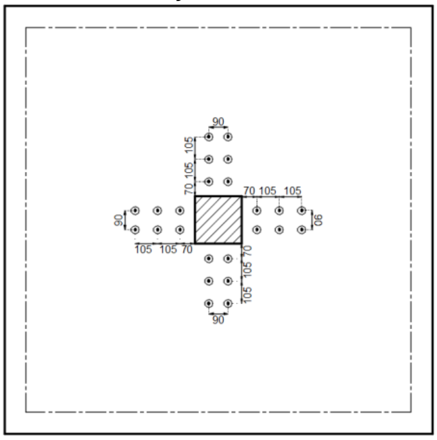
Nonstandard circular washer was used at the threaded ends as anchor plates for the shear bolts. They work similar to other reinforcing methods in use by preventing the propagation and widening of inclined shear crack as shown in Figure 8.



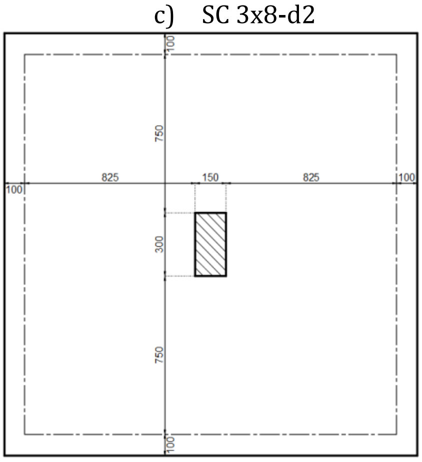
a) S0



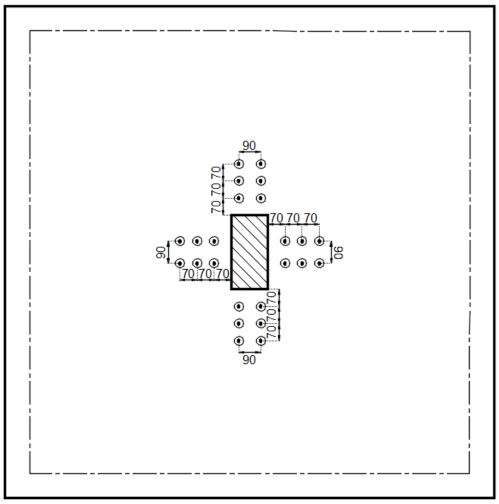
b) SC 3x8-d1



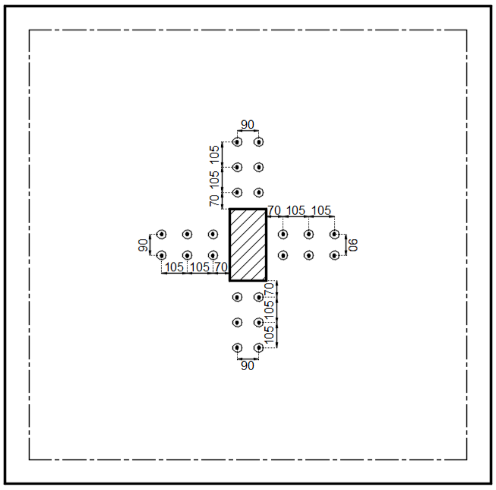
c) SC 3x8-d2



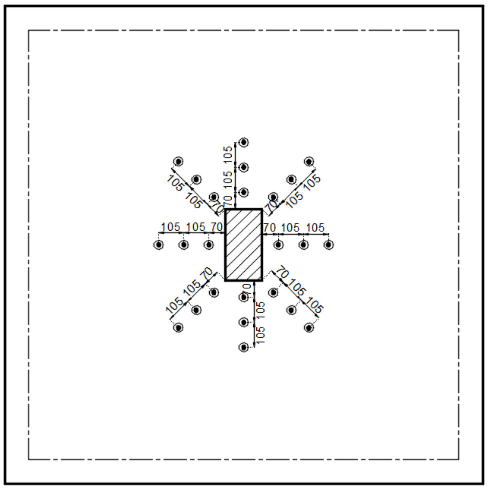
d) R0



e) RC 3x8-d1



f) RC 3x8-d2



g) Rrad 3X8-d2

Figure 6: Tested Specimens

Shear bolts were installed in hole drilled in the slab after casting and just before testing. The holes were drilled perpendicular to the slab plane using 16mm diamond coring bits then cleaned from boring dust and filled with epoxy material with entering the bar in hole as shown in Figure 9.

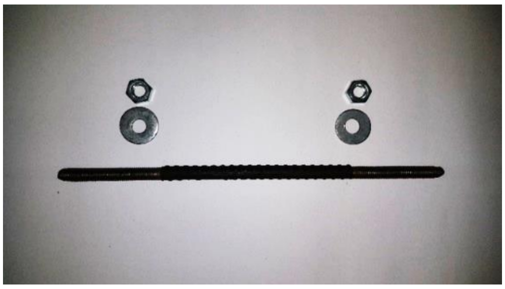


Figure 7: Typical Shear Bolt

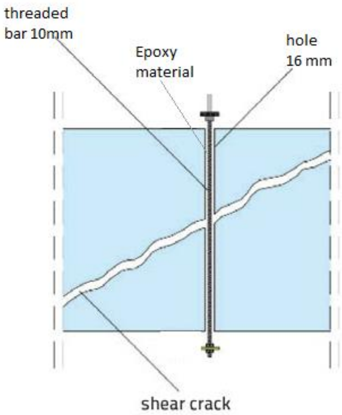


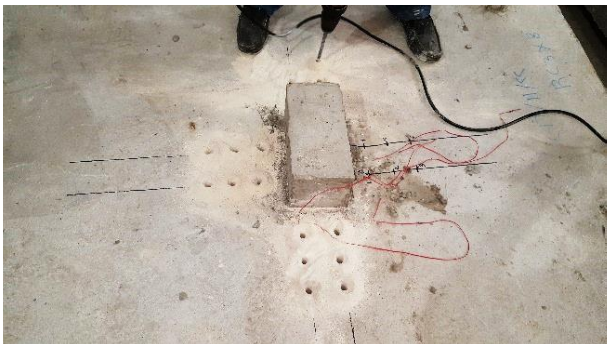
Figure 8: Shear Crack

2.3 Materials

Ordinary locally available concrete constituent materials had used to manufacture the test specimens. All specimens were made from one concrete mix with the proportion shown in Table 2. Material properties were measured from standard tests. The 28-day concrete compressive cube strength fcu=25 Mpa. While the yield strength of the longitudinal reinforcement and shear bolts was found to be 455 Mpa.

Table 2: Mix Design Proportion (Average Strength= 25 MPa)

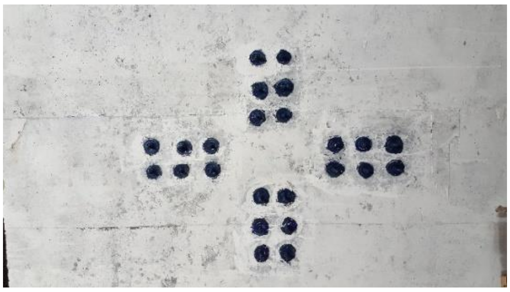
Material	Dolomite	Sand	Cement	Water
Mix Proportion (Kg/m^3)	898	863	384	230



(a)Boring in Slab

(b) Cleaning Holes

(c) Filling Holes with Epoxy Material and Entering Bolt in It



(d) Final View for Strengthened Specimen

Figure 9: Installing Shear Bolt Stages.

2.4 Specimens Measuring Devices

Five LVDT with accuracy of 0.01mm were used to measure the axial deformation. The axial deformation was measured at lower mid span of flat slab specimens, at L/8 and L/4 from mid span in two main directions as shown in Figure 10. Before casting the specimens, Electrical strain gauges with 10 mm length, 119.8±0.2 Ohms' resistance, and gauge factor 2.11±1% were used to measure the longitudinal strain of steel rebar at column face of flat slab specimen and for shear bolts. The strain gauges fixed on rebar in the two main directions at column face as shown in Strain Gauges in Steel Shear Bolts Figure 11. The strain gauges were connected to a strain meter device with accuracy of 1× 10-6, and covered by a waterproof coating to protect them from water and damage during casting. In addition, the strains are recorded automatically using a data acquisition system.

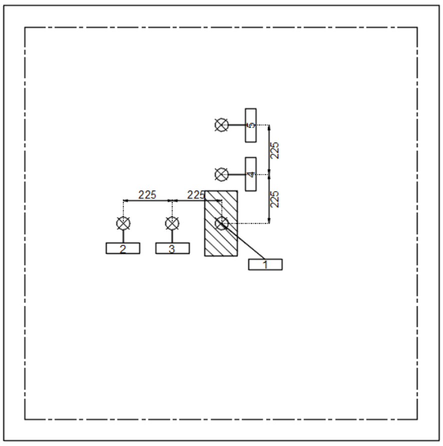


Figure 10: Position of LVDT on a Typical Specimen (Dimensions in mm)

a) Strain Gauges in Bottom Mesh

b) Strain Gauges in Steel Shear Bolts

Figure 11: Locations of Strain Gauges Fixed on Rebars In The Two Main Directions and for Shear Bolts

3. Experimental Test Results

Experimental test results and discussion includes; ultimate load versus max. deflection, load displacement curve, strain in steel rebar, strain in shear bolts, and failure pattern for each specimen will be described in this section.

3.1 Load Displacement Curves

For specimens in group (A) which have column aspect ratio equal to (1); the load displacement curve for all LVDTs locations at the bottom surface of specimens where drawn on the same graph as shown in Figure 12, Figure 13, and Figure 14. Figure 15 shows the central deflection for specimens.

Based on group (A); strengthened specimens with column aspect ratio equal to (1) using steel shear bolts showed a great improvement in ductility compared to the unstrengthened specimen as shown in Table 1. Also there was increment more than 40% in punching shear capacity. The value of Ultimate load of specimen SC3X8-d1 increased by 48% compared to specimen S0, while specimen Sc3X8-d2 increased by 36%. Thus, increase the distance between peripheral rows of shear bolts from ½ d to ¾ d decreased specimen capacity by 8% while the ductility decreased by 14%.

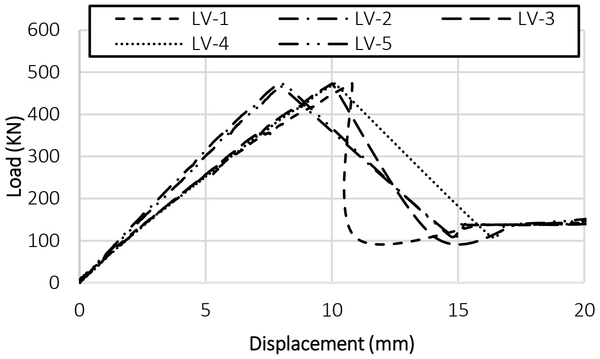


Figure 12 Load Displacement Curve for Specimen (S0)

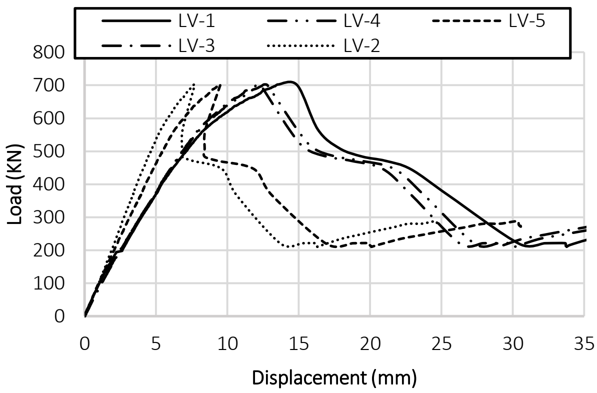


Figure 13: Load Displacement Curve for Specimen SC3X8-d1

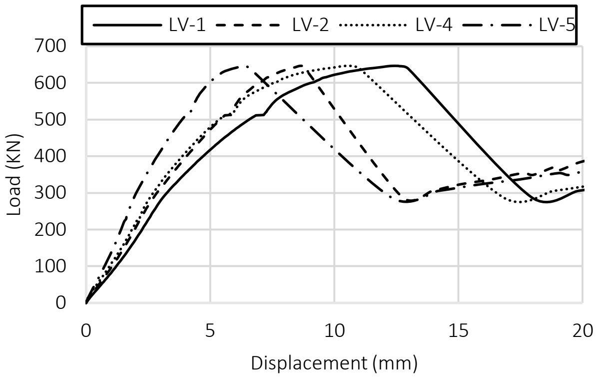


Figure 14: Load Displacement Curve for Specimen SC3X8-d2

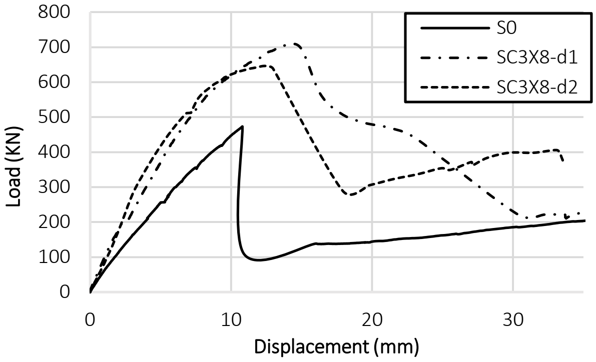


Figure 15: Group (A) Central Deflection

For group (B) specimens which have column aspect ratio equal to (2) the load displacement curve for all LVDTs locations at the bottom surface of specimens where drawn on the same graph as shown in Figure 16, Figure 17, Figure 18, and Figure 19. Figure 20 shows the central deflection for group (B) specimens.

Based on group (B); improvement of strengthened specimens ductility was great as shown in Table 1 In Addition, there was increment more than 40% in punching shear capacity. The value of Ultimate load of specimen RC3X8-d1 increased by 42% compared to specimen R0, while specimen SC3X8-d2 increased by 43%. Thus increase the distance between peripheral rows of shear bolts from ½ d to ¾ d with the same arrangement decreased specimen capacity by 1% while the ductility decreased by 17%. Specimen Rrad3X8-d2 has a radial arrangement with same distance between peripheral rows of RC3X8-d2, in spite of that results showed great decrement in ductility equal to 32% compared to Specimen RC3X8-d2 and the load decreased by 10% compared to RC3X8-d2. Which mean that the radial arrangement in slabs supported on columns with aspect ratio greater than (1) is not efficient and the Cartesian arrangement is more preferable. Table 3 shows the results summary for Ultimate load, Maximum Displacement, Displacement at yield of rebar, Ductility, and mode of failure. The load at which the first yielding occurs is an indicator of the stiffness of the specimen. Further, the strain at first yielding is an indicator of the ductility of the specimen being tested as shown in Table 3.

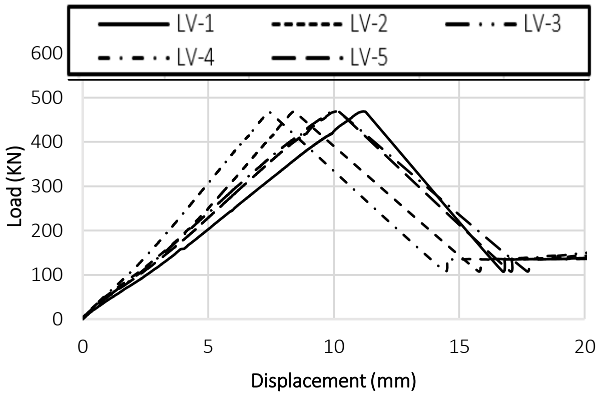


Figure 16: Load Displacement Curve for Specimen R0

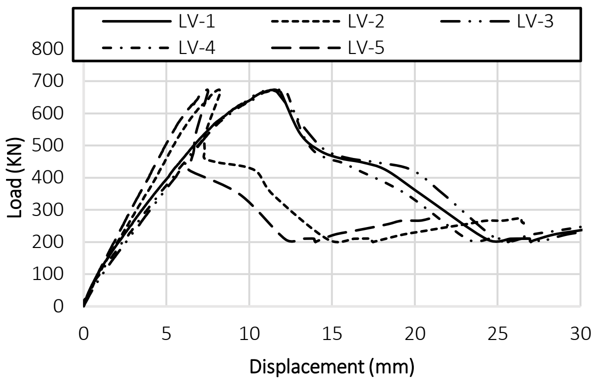


Figure 17: Load Displacement Curve for Specimen RC3X8-d1

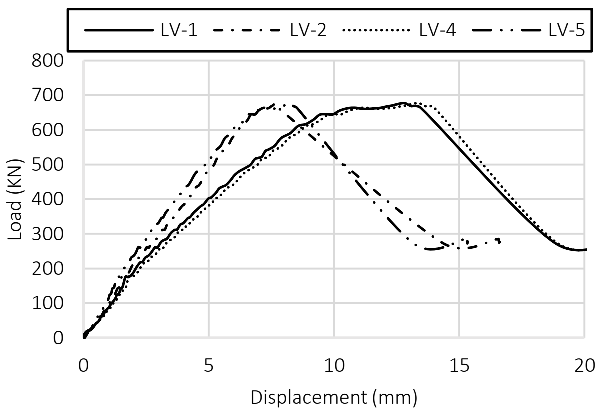


Figure 18: Load Displacement Curve for Specimen RC3X8-d2

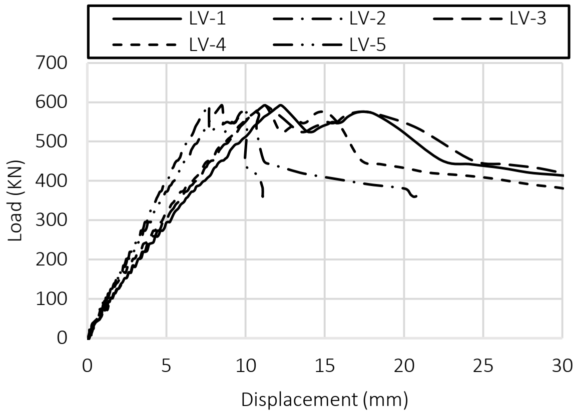


Figure 19 Load Displacement Curve for Specimen Rrad3X8-d2

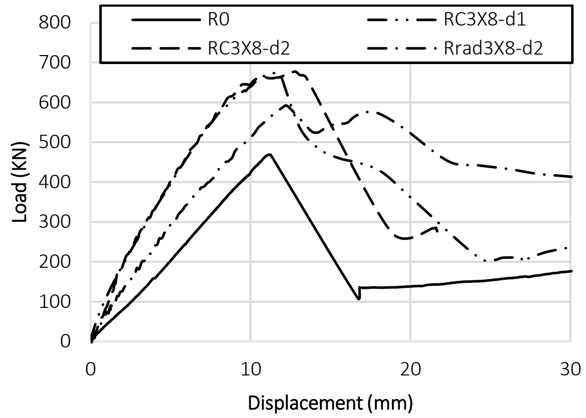


Figure 20 Group (B) Central Deflection

Table 3: Displacement, Ductility, and Mode of Failure

Group	Specimen	Ultimate Load (KN)	Max. Strain (bottom Mesh Rebar)	Displacement at Yield Δ_y (mm)	Ultimate Displacement Δ_u (mm)	Displcement Ductility= Δ_u/Δ_y (mm/mm)	Mode of Failure
A	S0	473	0.002	7.60	10.81	1.42	Pure Punching
	SC3X8-d1	702	0.015	8.00	13.56	2.12	Flexural Punching
	SC3X8-d2	646	0.022	8.50	12.39	1.81	Flexural Punching
B	R0	468	0.002	8.02	11.27	1.40	Pure Punching
	RC3X8-d1	670	0.012	7.25	11.99	2.01	Flexural Punching
	RC3X8-d2	663	0.013	8.10	14.02	1.74	Flexural Punching
	Rrad3X8-d2	591	0.003	9.00	12.28	1.36	Flexural Punching

3.2 Strain in Steel Rebar

The strains in the longitudinal reinforcement bars were been measured and recorded. This observation indicated that if the strain in steel rebars reached to the yield strain value or not which helps in specify the type of failure whether pure punching failure, pure flexural failure, or combination between flexural and punching failure. The value of strain, which makes steel rebar reaches to yielding, is 0.0025.

For specimens in group (A); the values of longitudinal strain in steel rebar at column face and at distance ½ d from column face were observed as shown in Figure 21, and Figure 22. The strains in longitudinal reinforcement showed some variation in the location at which first yield occurs.

For specimens in group (B); which have column aspect ratio equal to 2, the values of longitudinal strain in steel rebar were measured for both long and short column dimension directions. The measured strain showed that the short column dimension direction rebars had strain value greater than other in long column dimension direction. Figure 23 and Figure 24 show the measured strain for group (B) specimens at column face and at distance d/2 from column face.

As shown in figures from Figure 21 to Figure 24 the longitudinal reinforcement for un-strengthened specimens S0, and R0 didn't reach to the yield; which mean that the mode of failure for these specimens is pure punching failure.

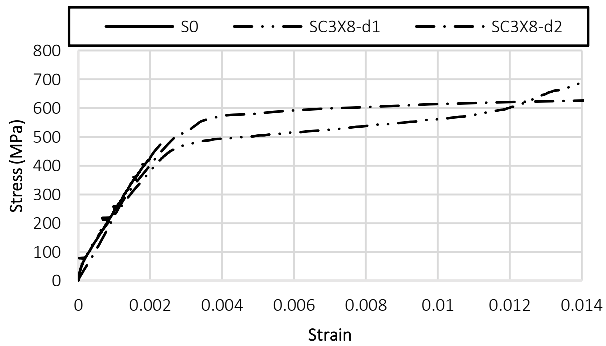


Figure 21: The Relation between Applied Load and Longitudinal Strain in Mid Reinforcement Bar at Column Face for Group (A)

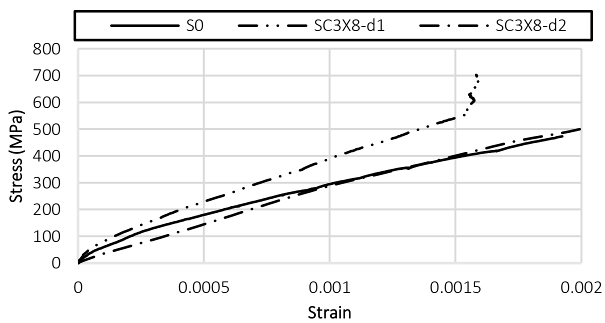


Figure 22: The Relation between Applied Load and Longitudinal Strain in Mid Reinforcement Bar at d/2 from Column Face for Group (A)

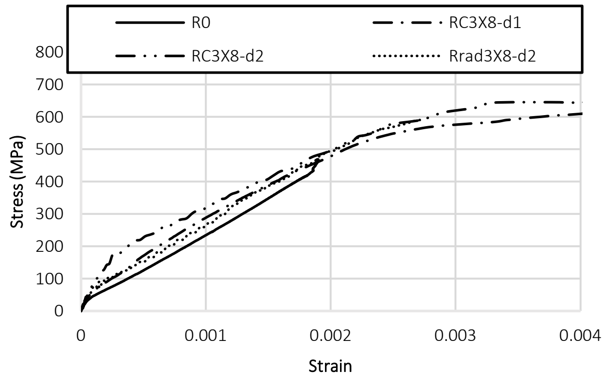


Figure 23: The Relation between Applied Load and Longitudinal Strain in Mid Reinforcement Bar at Column Face for Group (B) in Short Column Dimension Direction

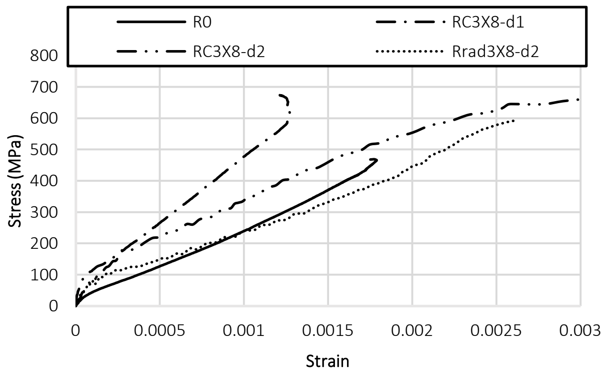


Figure 24: The Relation between Applied Load and Longitudinal Strain in Mid Reinforcement Bar at d/2 from Column Face for Group (B) in Short Column Dimension Direction

3.3Strains on Transverse Reinforcement (Shear Bolts)

For all strengthened specimen, strains were measured for (3) bolts in both direction of specimen; the first at d/2 from column face, the second at ½ d or ¾ d from first bolt, and third bolt at ½ d or ¾ d from second bolt. In all specimens, the first shear bolt strain was greater than other. All measured strains were lower than the value of yield strain for used steel (0.0025) except specimens of group (B).

Figure 25 shows the load strain curve for the first shear bolt in strengthened specimens of group (A), and group (B). For example, to compare the value of strain in shear bolts according to its position from column face;

Figure 26 shows the load strain curve for the three shear bolts of specimen SC3X8-d2. Since individual shear bolts are installed in this method, it may be a divisible to use steel with a bigger cross-section or yield strength on the first peripheral row closer to the column.

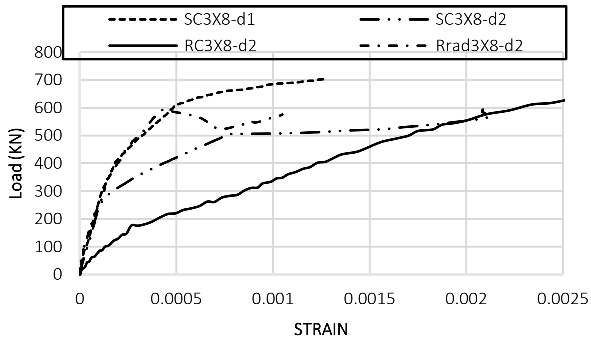


Figure 25: The Load Strain Curve for the First Shear Bolt at d/2 from Column Face

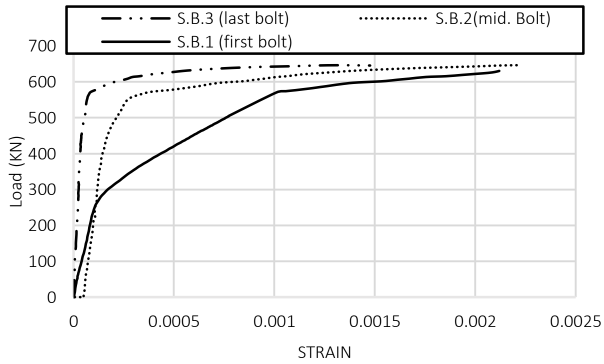


Figure 26: The Load Strain Curve for Shear Bolts in Specimen SC3X8-d2

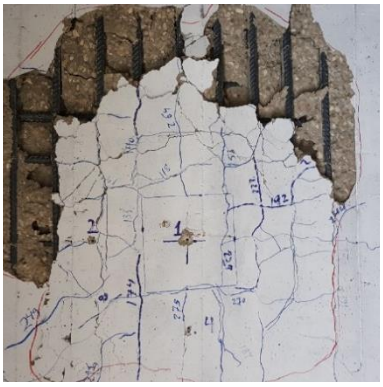
3.4 Failure Pattern

For group (A) specimens; Mode of failure of specimen S0 was brittle science the failure mode in concrete due to punching shear as shown in Figure 27. Figure: 28, and Figure 29 shows the crack pattern and mode of failure at the top and bottom of strengthened specimens SC3X8-d1, and SC3X8-d2 respectively, which give better performance more than un-strengthened specimen S0. It could be observed in strengthened specimens SC3X8-d1, and SC3X8-d2 that the punching shear perimeter increased to be start from last peripheral row at top.

For group (B) specimens with column aspect ratio equal to (2); the unstrengthened specimen R0 has a brittle punching failure accompanied by some flexural cracks as shown in Figure 30. Strengthened specimens RC3X8-d1, and RC3X8-d2; the punching shear perimeter increased to be out of the last peripheral row as shown in Figure 31, and Figure 32. While specimen Rrad3X8-d2 that has a radial arrangement and the same distance between peripheral rows as RC3X8-d2, had a mode of failure worse than RC3X8-d2 as shown in Figure 33.

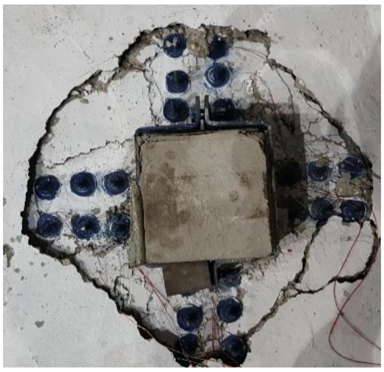
The first crack in all strengthened specimens starts at the last peripheral rows on top specimen while in Rrad3X8-d2 the cracks started from column face and the last crack ends at the last peripheral row as shown in figures from Figure 27 to Figure 33.

a) Top view



b) Bottom view

Figure 27: Crack Pattern and Mode of Failure for Specimen S0

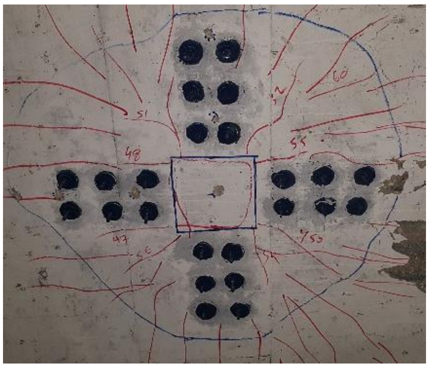


a) Top view

b) Bottom view

Figure: 28 Crack Pattern and Mode of Failure for Specimen SC3x8-d1

a) Top view



b) Bottom view

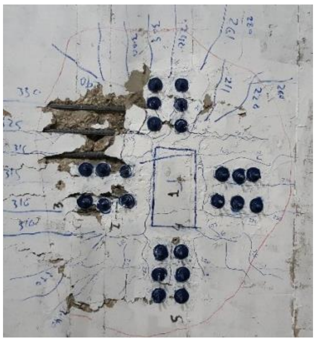
Figure 29: Crack Pattern and Mode of Failure for Specimen SC3X8-d2

a) Top view

b) Bottom view

Figure 30: Crack Pattern and Mode of Failure for R0

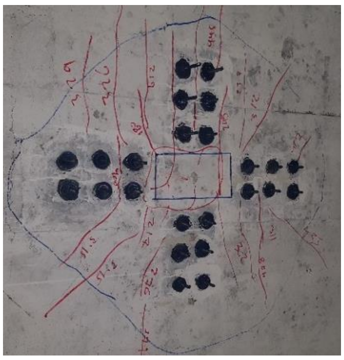
a) Top view



b) Bottom view

Figure 31: Crack Pattern and Mode of Failure for Specimen RC3x8-d1

a) Top view



b) Bottom view

Figure 32: Crack Pattern and Mode of Failure for Specimen RC3X8-d2

a) Top view

b) Bottom view

Figure 33: Crack Pattern and Mode of Failure for Specimen Rrad3x8-d2.

Conclusions

Using steel bolts as a shear reinforcement in strengthening slabs against punching failure is effective in preventing sudden punching shear failure in flat slabs at column zone (slab column connection), which mean that the failure of flat slabs strengthened with steel shear bolts becomes semi brittle failure instead of pure brittle failure. Also the use of shear bolts has a good efficient in enhancing the ultimate punching shear capacity and ductility of slabs.

Shear bolts with Cartesian and radial arrangement, and column aspect ratios (1), and (2) were studied. Results showed that the use of radial arrangement with column aspect ratio more than 1 in not preferable and Cartesian arrangement recommended instead.

Also spacing between peripheral row ½ d, and ¾ d were studied. Slabs with distance between peripheral rows ½ d is more ductile than other with distance ¾ d.

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