Behavior of Flat Slabs using Ultra High Strength Concrete under the Effect of Eccentric Punching Shear

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Abstract

This paper is to investigate the behavior of the punching shear strength for ultra high strength concrete (UHSC) flat slabs subjected to eccentric loading with and without shear reinforcement. Also study the application efficiency of using UHSC for strengthening normal strength concrete (NSC) flat slab to punching shear under centric loading by adding a layer of UHSC as a drop panel. In this study, An experimental program included four half scale specimens (1400x1400x120) mm. All specimens have identical in reinforcement distribution with edge column location. One specimen is casted as a control specimen with NSC and two others specimen are caste with UHSC with and without shear reinforcement. The fourth specimen is casted as a NSC and then strengthened by adding UHSC drop panel with thickness 90 mm. The ultimate load, failure mode, cracking, deflections, strain in both shear studs and flexure steel bars and the ductility of the tested specimens were recorded and discussed. A finite element program (ANSYS ®12) was applied to model the tested specimens to predict the behavior and compatibility between experimental and theoretical investigations to display the difference in behavior considering cracking and failure loads as well as deformations and strains. The models results give an acceptable agreement with the experimental results.

Keywords: Punching shear, Flat Slabs, Shear reinforcement, Ultra high strength concrete, Strengthening, Ductility, finite element.

1. Introduction

Flat slab is an ideal structural system for architects and contractors. Flat slabs are beamless reinforced concrete slabs supported directly by columns with reinforcement in two orthogonal directions. The flat slab system is widely popular used structural system for its easy formwork, wiring and ducting work easy, architectural flexibility, more clear space, speed construction. One of the major problems with flat slab is it susceptibility to the punching shear failure of the portion of slab column connection. when the slab column connection is subjected to heavy vertical loading, cracks will occur inside the slab in the vicinity of the column which can arise brittle punching shear failure due to the concentration of high bending moments and shear forces. This failure type is disastrous due to its brittle nature without warning. The shear strength is proportional to the flexural reinforcement ratio; in contrast, the rotation capacity is inversely

proportional to the flexural reinforcement (Kinnunen and Nylander) [1]. The improvement punching shear strength of flat slab has been studied by various researches by provide a different punching shear reinforcement same as bent bars (Tassinari) [2], inclined shear band (Pilakoutas) [3], separated and continuous stirrups (Ruiz and Mattoni) [4], mid-thickness rebar mesh (Salah El Metwally) [5], shear heads (Corley and Hawkins) [6], shear studs (Lips and Muttoni) [7]. These researches intended to all shear reinforcement improved the punching shear strength and ductility, the most method effective for increase the punching shear strength was achieved by using shear studs (Hong Guan and Yew-Chaye Loo) [8]. Using high strength concert without and with shear reinforcement has a significant effect for increase the punching shear strength due to significant high its mechanical properties (Marzouk, Hussein) [9], (Mansour Abd EL Halim) [10]. Ultra High strength concrete (UHSC) is a new advanced of concrete that has been developed late in the 20th century. UHSC provides compressive strength up to 200 MPa. UHSC is a high-strength material created by combining Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water and steel fibers with steam curing system with reduce the pores to the lowest possible ratio by choosing the optimum contents and optimization of the whole grain size distribution of the materials in matrix and on the positive interaction between quartz and silica fume to assure a suitable homogeneous matrix (Enas Kattab) [11]. Some times after the construction of some building finished, the strengthening of existing slab column connections in flat slabs may be required in many case such as extra loads are required due to changing the use of the building, opening are constructed beside columns for ducts or new stair, detecting errors in the design or mistakes during construction. Traditional methods used to enhance punching shear resistance such as increase thickness by adding reinforced concrete layers as a drop panel, steel plates and built-up section at slab column connection (Said Ali Taher) [12], (H. Alam.) [13], Another method by using fiber reinforced polymers has a significant effect for improve the punching shear capacity for slabs central column or with edge column location (Mohamed Makhlouf) [14], (Khaled El Sayed) [15].
This paper explore the effect of using UHSC without and with shear reinforcement and its application using UHSC for strengthening NSC slab under the Effect of eccentric punching shear.

2. Research Program

2.1. Geometry

An experimental program included four half scale specimens. Three specimens with edge column location is be designed to evaluate the behavior of UHSC punching shear under eccentric loading, one specimen (S1) was casted as a control specimen with NSC and the others two specimens (S2, S3) were casted as a UHSC without and with shear reinforcement (shear studs) . The fourth specimen is casted as a NSC and then strengthened by adding UHSC drop panel with thickness 90 mm. All the specimens have a constant slab 1400 mm square and 120 mm thick as shown in figure (1.a & 1.b). All specimens were identical in the distribution of bottom bars (Ø16 @ 100) and top bars (Ø10 @ 200) as shown in figure (2.a & 2.b), For strengthened specimen S4, the reinforcements of the drop panel were 12 mm diameter deformed bars as a two U shaped with epoxy in each side of the slab and dowels 12 mm in each face of stub column as shown in figure (2.a & 2.b). The clear cover for reinforcement was about 15mm with. All specimens detail are listed in Table (1) .

2.2. Material Properties

Two concrete mix were designed with using a different in constituent, content and properties of materials due to the high variation in the required target concrete strength. Table (2.a) presents the concrete mix proportions of the NSC specimens with a cube compressive strength 35 N/mm2. Table (2.b) presents the concrete mix proportions of the UHSC specimens with a cube compressive strength 120 N/mm2. Material properties were measured from standard tests.

Ordinary Portland cement is used, water curing was used for NSC while steam curing was used for UHSC specimens.

2.2.1 Reinforcing Steel

The steel used in this research was high tensile steel (40/60) for steel bars and shear studs. It had 460 N/mm2 yield stress. The mild tensile steel (24/35) was used for stirrups.

2.2.2 Shear Reinforcement

The shear reinforcement used in specimen S3 was shear stud reinforcement (SSR) & consisted of vertical studs 10 mm in diameter, spacing 50 mm welded to metal strips mild steel 6 mm thick, 200 mm length and 40 mm width, the vertical studs were welded at the top of each bar with rectangular plates 40x40 mm diameter the total height of SSR was 90 mm and the welding size 4 mm, the detailed of SSR was shown in figure (3).

2.3 Load Set Up & Measuring Devices

All slabs were moved to perform eccentric punching test. The specimens were positioned on top of a strong structural concrete floor. Three steel I-beams were supporting the specimen and steel rods of 22 mm diameter with rubber packing strips were provided along the perimeter of the slab over the line of support. The specimens were tested using 1000 KN capacity hydraulic jack as shown in figure (4). For all specimens were simply supported along three sides and free from the other fourth side at column edge. The vertical displacement of the slab (deflection) was recorded by using linear variable differential transformers (LVDT) which fixed under the bottom side of the slab with special arrangement to ensure proper reading as shown in figure (5). Electrical strain gauges were used to measure strain in steel flexure reinforcement and shear reinforcement.

Table 1: Test Specimens Details

Specimen No.	**Concrete Strength**		**Type of Shear Reinforcement**	**Strengthening Drop Panel**	
	Type	**Fcu N/mm^2**		**Fcu N/mm^2**	**Thickness mm**
S1	NSC	35	----	----	----
S2	UHSC	120	----	----	----
S3	UHSC	120	Shear Studs	----	----
S4	NSC	35	----	120	60
S5	NSC	35	----	120	90
S6	NSC	35	----	120	120

Table (2.a): Mix proportions for NSC specimens

Material	**Cement**	**Dolomite (D10)**	**Sand**	**Water**	**Admixture**
Mix Proportion (Kg/m^3)	375.00	1088.00	725	170	3.5

Table (2.b): Mix proportions for UHSC specimens

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Material	Cement	Silica Fume	Dolomite (D5)	Sand	Quartz	Steel Fiber	Water	Admixture
Mix Proportion (Kg/m3)	800	160	660	330	330	75	154	35.60

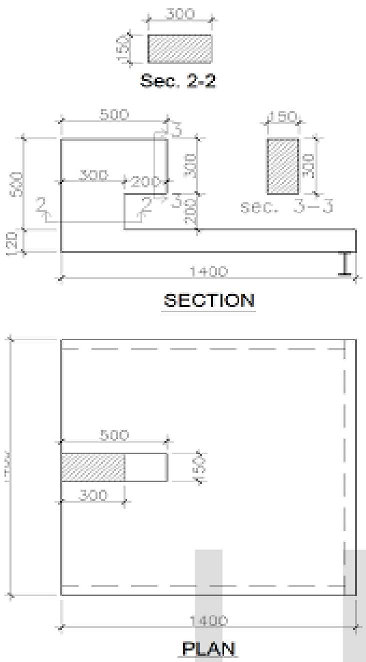


Figure (1.a): Concrete Dimension for S1, S2 and S3

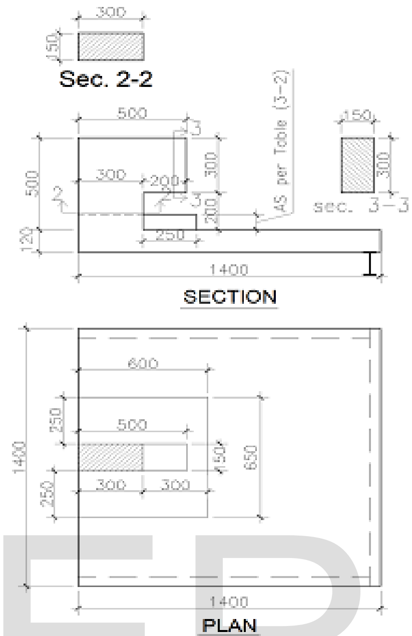
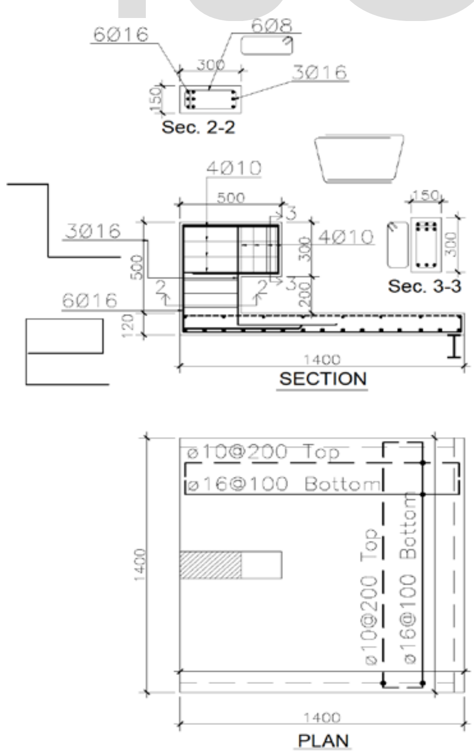


Figure (1.b): Concrete Dimension for S4



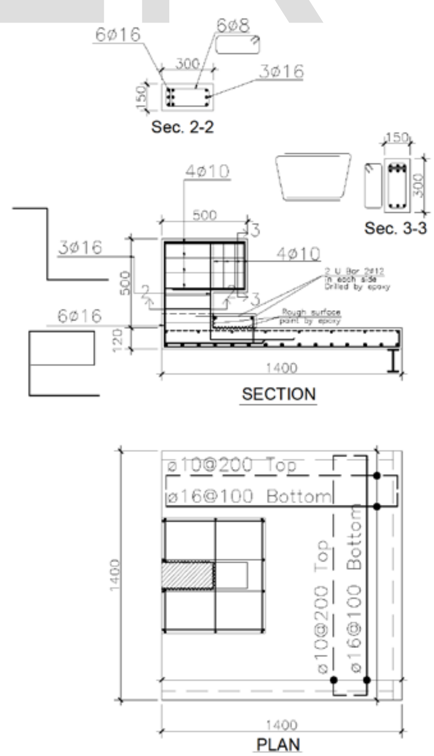
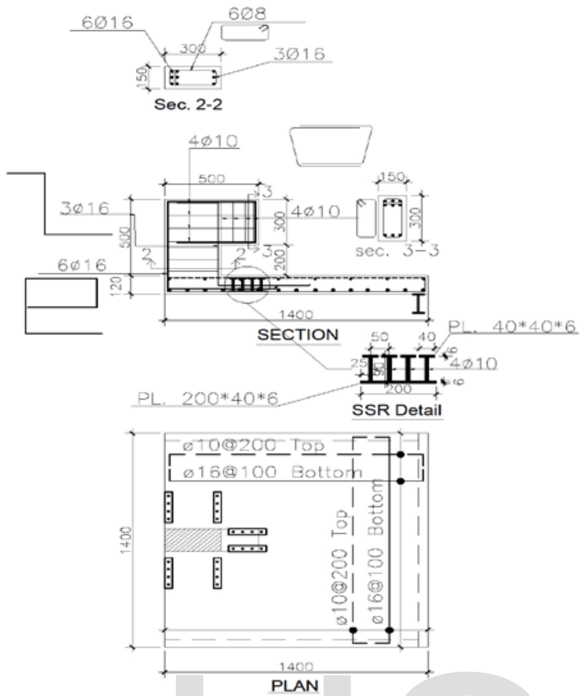


Figure (2.a): Reinforcement Details for S1, S2

Figure (2.b): Reinforcement Details for S4



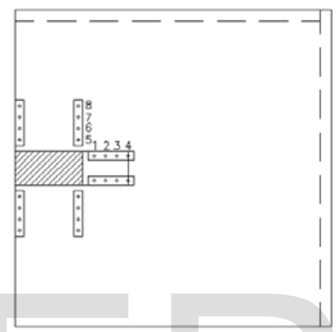


Figure (3): Shear studs Details for S3

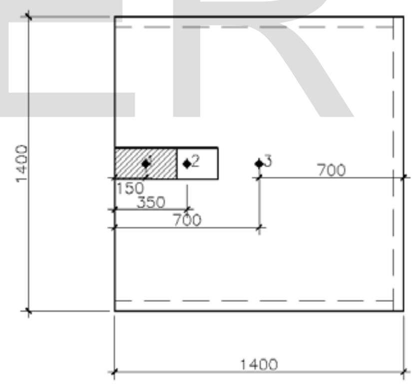


Figure (4): Test set-up

Figure (5): Arrangement of LVDT

3. Experimental Results

A total of six slab panels were tested under centric loading. Table (3) illustrates failure modes of all tested specimens. The following sections provide the experimental results and discussions.

3.1 Failure Mode and Crack Patterns

All specimens were failed in a typical punching shear mode not failed in flexural mode. The crack patterns in all specimens for S1, S2, S3 and S4 are shown in figures (6 to 9). The similar behavior of formation and shape of crack pattern up to failure load is occurred, under loading, the firstly cracks started with vertical cracks on the tension side (bottom) of the slab near to the column edges. As the applied load increased, the width of these cracks became wider and other new cracks were observed running from column edges at tension side towards the slab edges in radial directions. All these cracks were shortly followed by the formation of circumferential cracks occurred at a location farther away from the column stub which form a semi square shape. For all the tested specimens. The crack pattern of all strengthened NSC specimen S4 was not changed the shape of punching failure surface on the tension face but shifted the failure surface away from the column face after the perimeter of drop panel. Table (3) shows The first crack appeared at the corresponding crack load were 62, 131, 146 and 185 KN for S1, S2,S3 and S4, respectively. The first crack for control specimen S1 was started visible at about 37% of failure load. While the first crack for S2, S3 and S4 was started visible at about from 45%, 46.5% and 51% of failure load, respectively. This behavior is related to the significant higher stiffness for both of UHSC and the strengthened NSC specimen than of control NSC specimen.

Table 3: Test Results

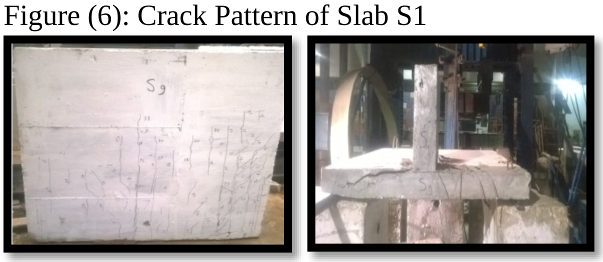
Specimen No.	**First crack**		**Ultimate**		**Pu(specimen) / Pu(control)**	**Ductility Δu / Δ cr**
	Load (Pcr) (KN)	**Deflection (Δcr) (mm)**	**Load (Pu) (KN)**	**Deflection (Δu) (mm)**		
S1	62	1.85	168	7.5	1.00	4.05
S2	131	3.5	289	12.8	1.72	3.66
S3	146	3.51	314	13.81	1.87	3.93
S4	185	2.0	365	8.35	2.17	4.18

Tension side Compression side

Figure (6): Crack Pattern of Slab S1

Tension side Compression side

Figure (7): Crack Pattern of Slab S2



Tension side Compression side

Figure (8): Crack Pattern of Slab S3

Tension side Compression side

Figure (9): Crack Pattern of Slab S4

3.2 Load Deflection Behavior

Figure (10&11) show the load deflection curve of all specimens under eccentric loading were exhibited to three stages of behavior. The three stages of loading are marked by the significant slop change of the load deflection curve. The first stage namely first crack load which start from zero loading till the cracking load. The second stage namely service load which begin from cracking load till the formation of slab folding mechanism. The third stage namely ultimate load which the slab undergoes large plastic deformations curves with a different column deformations started more or less straight linear until the ultimate load was attained. It can be shown from table

(3) and figure (10) the failure punching load were increased from 168 KN for S1 to 289 KN for S2 with an increase of 72%. Also the maximum deflection under column with corresponding to ultimate load increased from 7.5 mm for S1 to 12.8 mm for S2 with an increase of 70.7%. When using UHSC specimen with shear reinforcement (shear studs) at S3 specimen, the ultimate punching load increased to 314 KN with an increase of 87% compared to control NSC specimen S1 and also, it led to additional 9% increase in the ultimate punching load compared with UHSC specimen without shear studs (S2). On the other hand whereas the maximum deflection under column increased from 7.5 mm for S1 to 13.81 mm for S3 with an increase of 84% and with an increase of 8% compared with UHSC specimen S2 without shear reinforcement. From table (3) and figure (13) show the effect of using UHSC slab as a drop panel for strengthening the NSC slab S4 on the punching shear capacity and compared with control NSC slab S1. The ultimate punching load were 365 KN for S4 with an increase of 117% compared to control NSC slab S1. The maximum deflection under column was recorded 8.35 mm for S4 with an increase of 11% compared to control NSC slab S1. From the above mentioned results, we can conclude that the increasing compressive strength by using UHSC led to significantly increase of the punching shear capacity. Also providing shear reinforcement as a shear studs to UHSC slab improve the punching shear capacity. For all strengthened NSC slabs with using UHSC drop panel with different thickness were significantly increase of the punching shear capacity especially at S5 slab with a depth of 90mm drop panel. Also the maximum deflection under column has significantly increase when using UHSC without or with shear reinforcement in contrast has a less increase of the deflection for all strengthened slab compared to the control NSC slab due to its high stiffens.

3.3 Ductility

Table (3) shows the ductility of all specimens. The term deflection ductility refers to the ratio of the ultimate deflection at peak load to the corresponding crack deflection at the first yield. The ductility of using UHSC slab without and with shear reinforcement (shear studs) showed a reduction of the ductility by 10% for S2 and 3% for S3, respectively, compared with NSC slab S1. For the strengthened slab S4 the ductility increased by 3% for S4 compared with NSC slab S1. From the previous results show that the using UHSC has a significantly reduction for the ductility while the using shear reinforcement are improved the ductility of UHSC slab. For the strengthened NSC slabs by using UHSC drop panel led to slightly improvement of the ductility.

3.4 Load Shear Reinforcement and Flexure Steel Bar Strain Behavior

The value of strain which makes steel rebar reaches to the yielding for both main flexure steel bars and shear studs, is 0.0023. Figure (12) shows the relationship between load and strain in shear reinforcement (shear studs) curve for S3 specimen under eccentric load It can be noticed that the recorded strain result are not the same in both direction due to the specimen with edge column was un symmetrical of geometry. The value of first row shear studs strain for S9 are higher the others row due to its located at critical distance from face of column. The recorded results indicated that the stains in shear studs are inversely proportional with the distance from face of column. Also all the recorded shear strain for all rows (1, 2, 3, 4) at direction x were higher the corresponding strains for rows (5, 6, 7, 8) at direction y. All recorded strains in shear studs reinforcement were lower than the value of yield strain for used shear studs (0.0023). Figure (13) shows the relationship between load and strain in flexure steel (bottom) bars curve for all specimens under eccentric load. All the values of the maximum strain in steel bottom reinforcement for all specimens were recorded not reached to the yield value of used steel (0.0023). This indicated that the all specimens were failed in pure punching shear failure not in flexural failure.

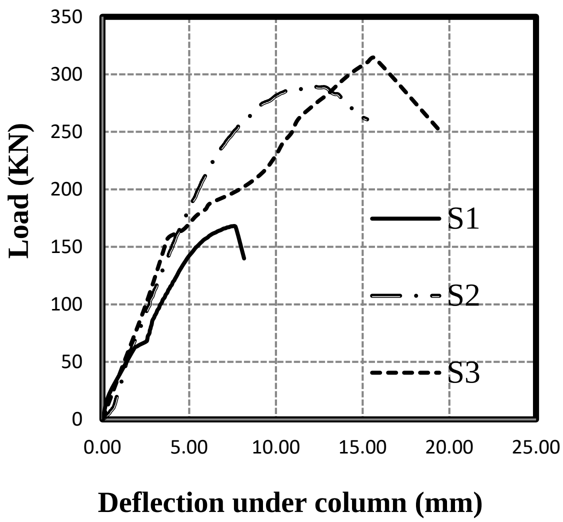


Figure (10): Load Deflection Curves for Slabs S1, S2 and S3

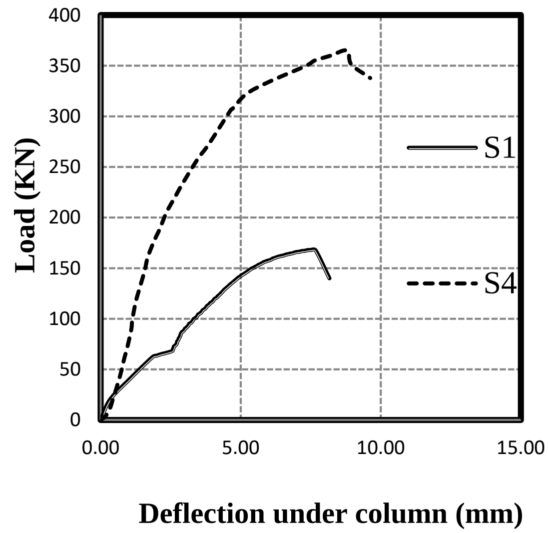


Figure (11): Load Deflection Curves for Slabs S4

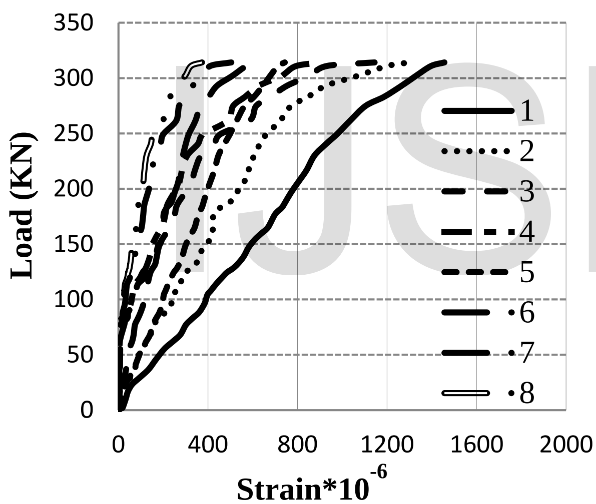


Figure (12): Load-Strain Curve in Shear Reinforcement for S3

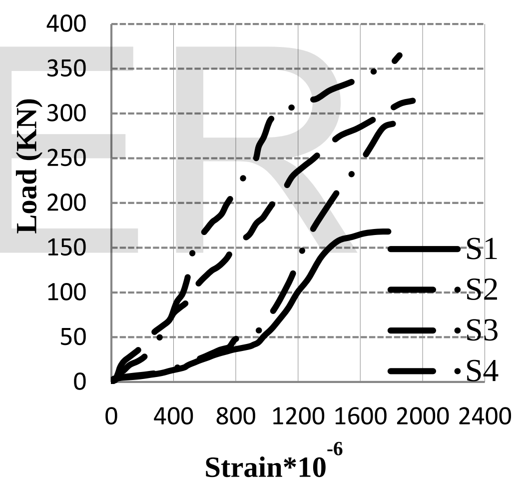


Figure (13): Load-Strain Curve in Bottom Steel for Slab S1, S2, S3 and S4

4. Finite Element Analysis

Finite element method (FEM) is a process which finite degrees of freedom can be approximated to be an assemblage of element each with a specified number of unknowns. In recent years, the use of finite element analysis has increased due to progressing knowledge and capabilities of computer software and hardware. It has now become the choice method to analyze concrete structural components. The use of computer software to model these elements is much faster, and extremely cost-effective.

Finite element model was developed to simulate four specimens, S1 through S4, from linear through nonlinear response and up to failure, using the software package ANSYS®12. Comparisons were done with respect to load-deflection relationship below loaded point of the slab, failure loads, and cracks patterns at failure. Modeling simplifications and assumptions developed during this research are presented below.

4.1 Element Types

Concrete Element (Solid 65), Reinforcement Element (Link 180), Shear reinforcement element (Beam 188). Figures (14&15) showed finite element mesh and details of reinforcement for specimens with and without strengthening.

4.2 Comparison of Result

Table (4) showed the comparison between the models results with the experimental results. Figures (16 to18) showed crack pattern at failure, strain contour in bottom longitudinal steel bars and shear studs for specimens with and without strengthening. Figures (19 and 22) showed the comparison between the experimental results and FE results of load-deflection curve of models. Figures (23) showed comparison between the experimental results and FE results in strain shear studs of model S3.

Table 4: Comparison Between The Models Results With The Experimental Results

Specimen No.	**Exp. Results**		**ANSYS Results**		**Pu (Exp.) / Pu(ANSYS)**	**Δu (Exp.) / Δu(ANSYS)**
	Load (Pu) (KN)	**Deflection (Δ u) (mm)**	**Load (Pu) (KN)**	**Deflection (Δ u) (mm)**		
S1	168	7.50	157.00	7.38	1.07	1.02
S2	289	12.80	248.20	11.75	1.16	1.09
S3	314	13.81	287.00	12.20	1.09	1.13
S4	365	8.35	321.00	7.55	1.14	1.11

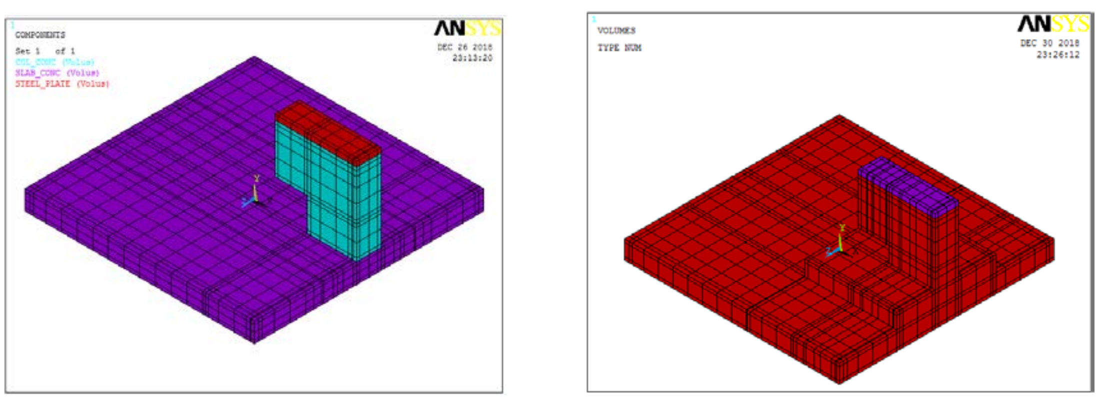


Figure (14): Finite Element Mesh Used for Specimens With and Without Strengthening

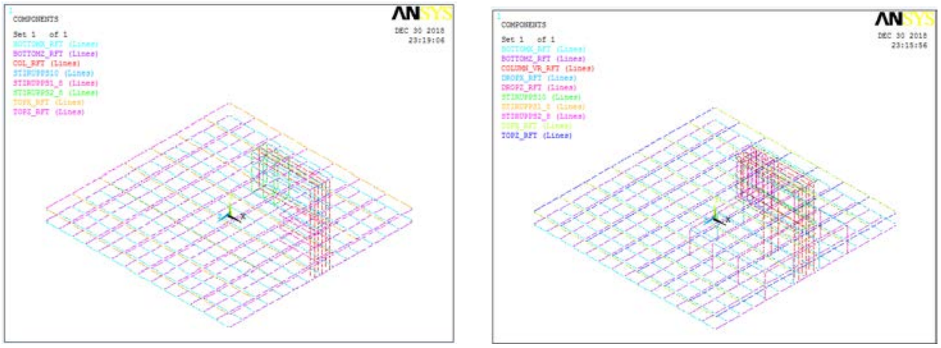
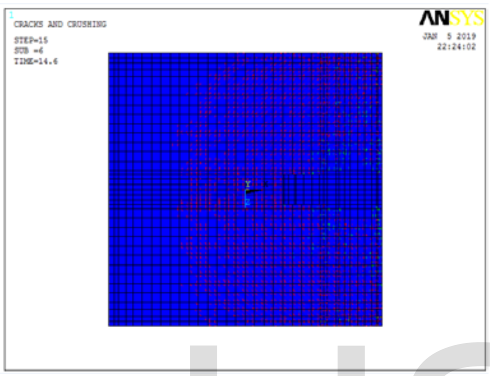
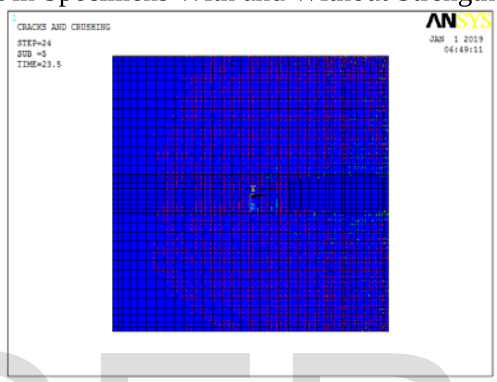


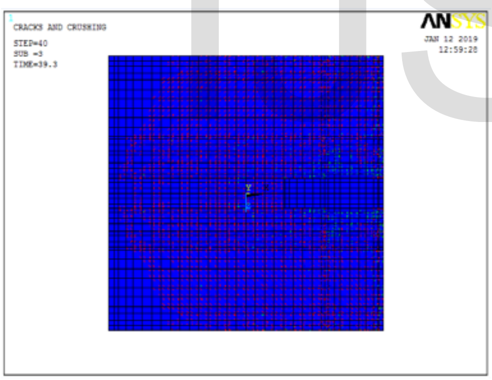
Figure (15): Details of Steel Reinforcement in Specimens With and Without Strengthening



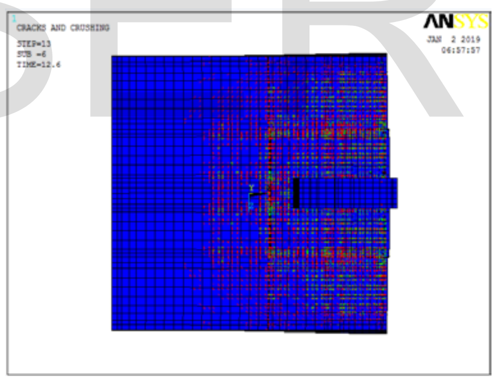
S1



S2



S3



S4

Figure (16): Crack Pattern for Models

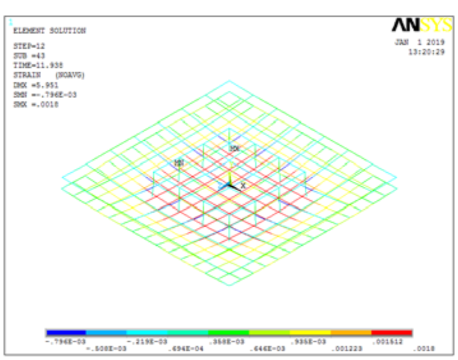


Figure (17): Strain Contours in Bottom Bars

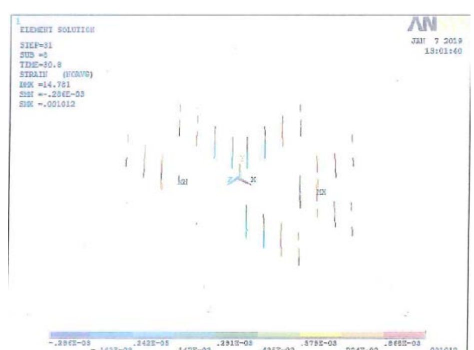


Figure (18): Strain Contours in Shear Studs

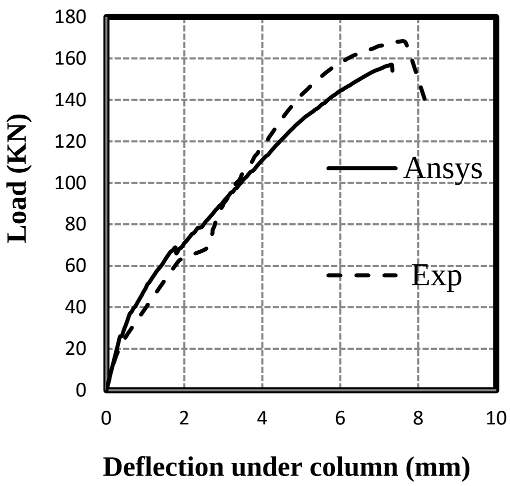


Figure (19): Experimental VS. FE Results of Load-Deflection of S1

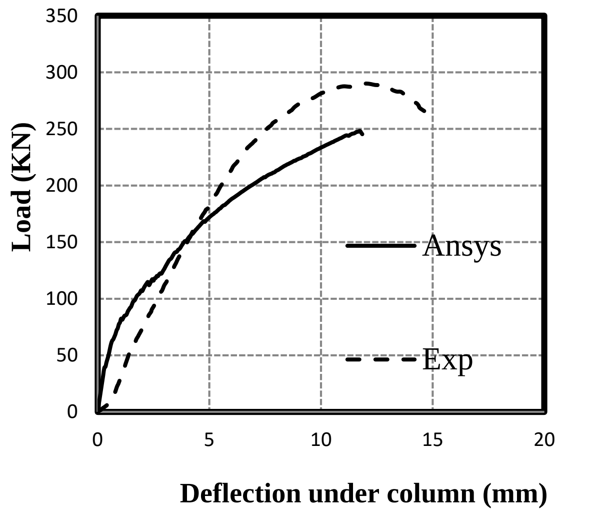


Figure (20): Experimental VS. FE Results of Load-Deflection for S2

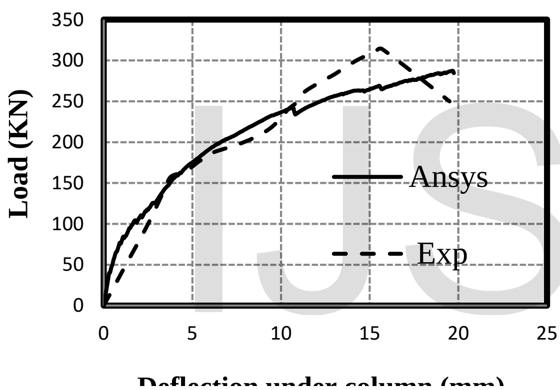


Figure (21): Experimental VS. FE Results of Load-Deflection of S3

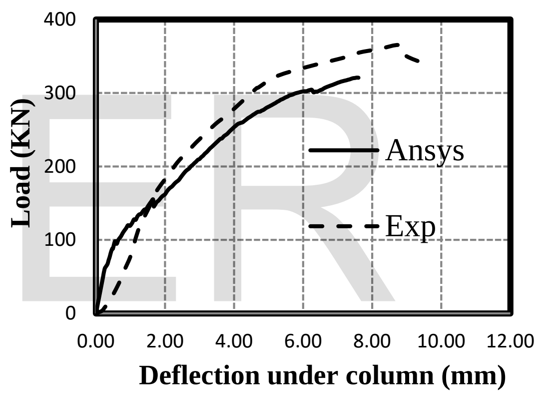


Figure (22): Experimental VS. FE Results of Load-Deflection for S4

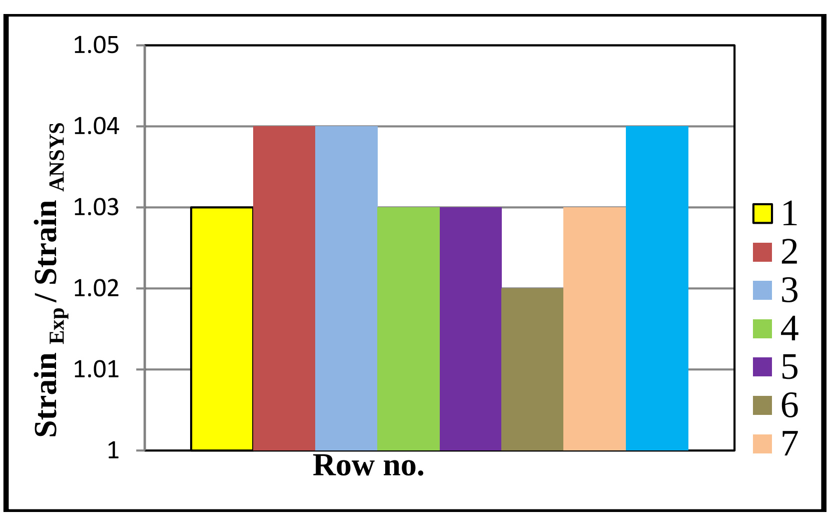


Figure (23): Experimental VS. FE Results in Strain Shear Studs for S3

5. CONCLUSIONS

Based on the results obtained from experimental, the following main conclusions can be drawn:

1 – Using UHSC has significant effect in increasing the punching shear strength capacity. For the UHSC specimens were subject to punching shear under eccentric loading, the ultimate load was increased by 72% compared to the NSC specimens.

2 – Using UHSC has significant effect in increasing the initial cracking load. For the UHSC specimens were subject to punching shear under eccentric loading, the ultimate load was increased by 111% compared to the NSC specimens. This behavior is related to the tensile strength and modulus of elasticity of UHSC greater than the NSC specimen.

3 – Using UHSC has inverse effect in the ductility, For the UHSC specimens were subject to punching shear under eccentric loading, the ductility was decreased by 10% compared to the NSC specimens. This behavior led to the rupture is more brittle when comparing with the NSC specimen.

4– The UHSC specimen S3 containing shear reinforcement (shear studs) gave higher punching shear capacity with 9% than the UHSC specimen S2 without shear reinforcement, also the UHSC specimen S3 containing shear reinforcement improved the ductility with 7.4% compare with the UHSC specimen S2 without shear reinforcement, it concluded the providing shear reinforcement to the UHSC slabs had a slightly effect for increasing the punching shear capacity.

5– The final shape of the punching cone is completed after the column stub starts to penetrate through the slab.

6 – Crack pattern of all UHSC specimens with shear reinforcement were not changed the shape of punching failure on the tension face but shifted the failure surface away from the column face.

7– For the NSC specimens were strengthened by using UHSC as drop panel with a thickness 90 mm, a significant increasing of the punching shear strength capacity and also the ductility was increased with a slight increasing of the deflection when comparing to the NSC specimens. This behavior is due to the bigger in perimeter of loading and high stiffness of whole section .

8 – Crack pattern of the strengthened NSC specimens by UHSC drop panel was not changed the shape of punching failure surface on the tension face but shifted the failure surface away from the column face after the perimeter of drop panel .

9 – Based on the experimental work observations, For edge UHSC specimens, the critical shear perimeter is proposed to be taken at 2.5d from the face of the column, and can be defined as:

$b_o = 4c + 2.5 \pi d$.

10 – A numerical model using FEM (ANSYS ®12) is presented. The simulated models gave a good agreement prediction with a test results. For both of UHSC slabs (with and without shear reinforcement) and the strengthened NSC slab by UHSC drop panel, the difference in the results of the punching shear capacity between the experimental results and the predicted values were range from 7% to 16%. The others variables which observed at the experimental program (maximum deflection under the column, maximum strain in the flexure steel and maximum strain in the shear studs gave a good agreement with prediction values of the simulated models.

REFERENCES

[1] S. Kinnunen, H. Nylander, Punching of concrete slabs without shear reinforcement, Transactions of the Royal Institute of Technology, No. 158, Stockholm, Sweden, 1960.

[2] L. Tassinari, S. Lips, A. Muttoni, M.F. Ruiz, Applications of bent-up bars as shear and integrity reinforcement in R/C slabs, Session 2B-5: construction Technology, 2011.

[3] K. Pilakoutas, X. Li, Alternative shear reinforcement for reinforced concrete flat slabs, J. Struct. Eng. 129 (9) (2003) 1164–1172.

[4] F.M. Ruiz, A. Muttoni, Performance and design of punching shear reinforcing systems, 3rd Fib International Congress,2010.

[5] Salah E.E. El-Metwally, Effect of mid-thickness rebar mesh on the behavior

and punching shear strength of interior slab–column connection, HBRC Journal, 2016.
[6] Corley, W. G. and Hawkins, N. M., “Shear head Reinforcement for Slabs.”, ACI Journal, Vol. 65, No. 10, October, 1968, pp. 811-824.
[7] S. Lips, A. Muttoni, Experimental investigation of reinforced concrete slabs with punching shear reinforcement, in: 8th Fib PhD Symposium, Lyngby, Denmark, 2010.
[8] Guan, Hong and Loo, Yew-Chaye, Canadian Journal of Civil Engineering, 2013
[9] Marzouk, H.; Hussein, A. Experimental Investigation on the Behaviors of High-Strength Concrete Slabs, ACI Structural Journal, Vol. 88, No. 6, pp. 701-713,(1991).
[10] Mansour Abd EL-Halim, Punching Shear Performance Of High And Ultra–High Reinforced Concrete Slab-Column connections, Ph.D. Ain Shams University 2017.
[11] Enas khattab, production of ultra high strength concrete using local materials and its application in axially loaded columns, Ph.D.- Ain Shams University 2010.
[12] Said AMT. Strengthening of R.C. slab column connection to resist punching shear. Ph.D. Thesis, Faculty of Engineering, Cairo University; 1998.
[13] H. Alam, Strengthening Of R.C. Slab-Edge Column Connection To Resist Punching Shear, Arab Structural Engineer Conf. , 2003 .
[14] Mohamed Hussein Makhlouf, Strengthening and repair of normal strength concrete slab and high strength concrete column connections under eccentric loading, Benha University, 2013.
[15] Khaled Mohamed El Sayed, Repair and Strengthening of R.C Flat Slab Connection with Edge Columns against Punching Shear, Benha University, 2016.