Behavior of Flat Slabs Using Ultra High Strength Concrete under the Effect of Centric 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 centric 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 six half scale specimens (1400x1400x120) mm which divide into two phases. First phase consisting of three specimens with central column location is be designed to evaluate the behavior of UHSC punching shear under centric loading. Second phase consisting of three specimens with central column location is be designed to evaluate the efficiency of using UHSC drop panel for strengthening NSC slab under the effect of centric punching shear load. 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 result give an acceptable agreement with the experimental results.

Index Terms— Punching shear, Flat Slabs, Shear reinforcement, Ultra high strength concrete, Normal strength concrete, Strengthening, Ductility.

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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 ma-

trix (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 cases such as extra loads are required due to changing the use of the building, opening is 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 explores the effect of using UHSC without and with shear reinforcement and its application using UHSC for strengthening normal strength concrete (NSC) flat slab.

2. Experimental Program

2.1. Matrix of Tested Prisms

An experimental program included six half scale specimens which divide into two phases. First phase consisting of three specimens with central column location is be designed to evaluate the behavior of UHSC punching shear under centric loads, one specimen (S1) was casted as a control specimen with NSC and the others two specimens (S2, S3) were casted with UHSC without and with shear reinforcement (shear studs). Second phase consisting of three specimens (S4, S5, S6) was casted with NSC and then strengthened by a different UHSC drop panel thickness of 60, 90 and 120 mm, respectively. 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 specimens, 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 is 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 longitudinal reinforcement and shear reinforcement. 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 concentric punching test. The specimens were positioned on top of a strong structural concrete floor. Four 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 setup was carefully leveled and aligned to prevent any source of errors due to the lateral eccentricity for concentric case. The specimens were tested using single concentric load testing condition using 1000 KN capacity hydraulic jack as shown in figure (4). For all specimens were simply supported along four sides for central column. 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). The vertical LVDTs with 100 mm amplitude and 0.01 mm accuracy were used to measure the deflections during all stages of loading. Electrical strain gauges 10 mm length,119.8 ± 0.2 Ohms' resistance, and gauge factor 2.11±1% were used to measure strain in steel flexure reinforcement and shear reinforcement.

Table 1: Test Specimens Details

Spec-imen No.	Concrete Strength		Type of Shear	Strengthening Drop Panel	
	Type	Fcu N/mm²	RFT.	Fcu N/mm²	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/m³)	375	1088	725	170	3.5

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

Material	Cement	Silica Fume	Dolomite (D5)	Sand	Quartz	Steel Fiber	Water	Admixture
Mix Proportion (Kg/m3)	800	160	660	330	330	75	154	35.6
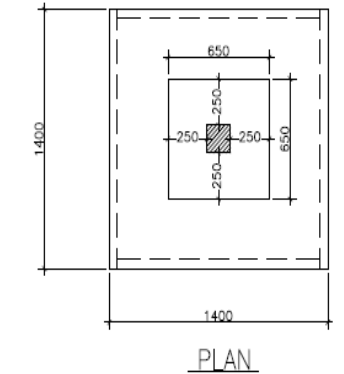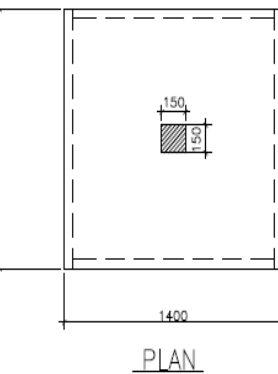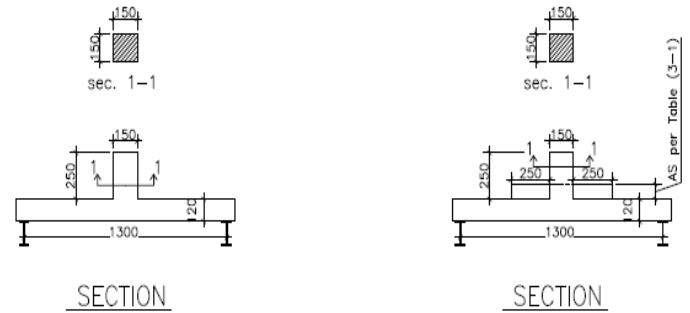
Figure (1.a): Concrete Dimension of S1, S2 and S3
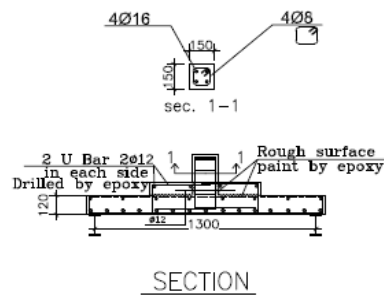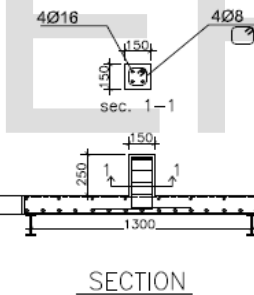
Figure (1.b): Concrete Dimension of S4, S5 and S6

Figure (2.a): Reinforcement Details of S1and S2

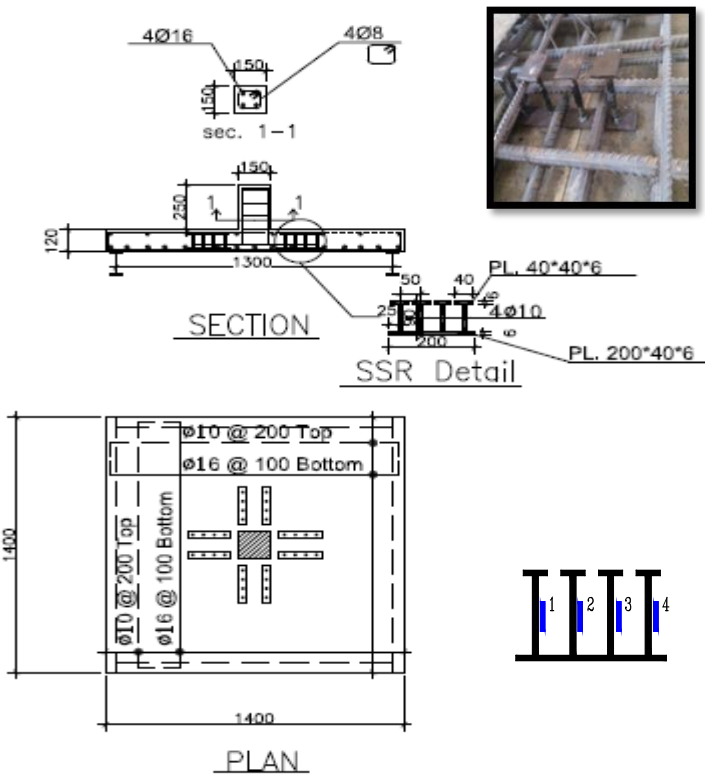Figure (2.b): Reinforcement Details of or S4, S5 and S6
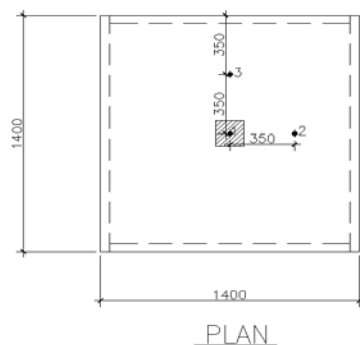
Figure (3): Reinforcement Details of S3

3. Experimental Results

A total of six slab panels were tested under centric loading. Table (3) presents 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, S4, S5 and S6 are shown in figures (6 to 11). 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, it was observed that the column penetrated the slab on the compression side (top) of the slab with extensive spilling of tension concrete cover especially for S1 and S6 specimens were noticed. The crack pattern of all strengthened NSC specimens S4, S5 and S6 were 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 98, 250, 275, 305, 423 and 471 KN for S1, S2, S3, S4, S5 and S6, respectively. the first crack for control specimen S1 was started visible at about one third of failure load. While the first crack for S2, S3, S4, S5 and S6 was started visible at about from 44% to 58% of failure load. This behavior is related to the significant higher stiffness for both of UHSC and the strengthened NSC specimens than of control NSC specimen.

Figure (4): Test Set-up

Figure (5): Arrangement of LVDT

Table 3: Test Results

Spec- imen No.	First crack		Ultimate		$\frac{Pu(specimen)}{Pu(control)}$	Ductility $\frac{\Delta u}{\Delta cr}$
	Load (Pcr) (KN)	Deflection (Δcr) (mm)	Load (Pu) (KN)	Deflection (Δu) (mm)		
S1	98	1.75	303	5	1.0	2.86
S2	250	4.9	567	10.6	1.87	2.16
S3	275	4.6	627	11.9	2.07	2.59
S4	305	2.1	650	6.4	2.15	3.05
S5	423	2.14	778	7	2.57	3.27
S6	471	2.23	812	7.61	2.68	3.41

Tension side   Compression side
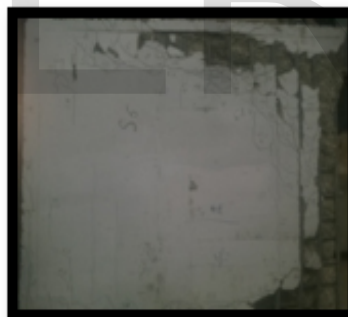Figure (9): Crack Pattern of Slab S4

Tension side   Compression side
Figure (10): Crack Pattern of Slab S5

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 (11): Crack Pattern of Slab S6

Tension side   Compression side
Figure (8): Crack Pattern of Slab S3

3.2 Load Deflection Behavior

Figure (12&13) show the load deflection curve of all specimens under centric 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 defor- mations curves with a different column deformation started more or less straight linear until the ultimate

load was attained. It can be shown from table (3) and figure (12) the failure punching load were increased from 303 KN for S1 to 567 KN for S2 with an increase of 87%. Also, the central deflection with corresponding to ultimate load increased from 5 mm for S1 to 10.6 mm for S2 with an increase of 112%. When using UHSC specimen with shear reinforcement (shear studs) at S3 specimen, the ultimate punching load increased to 627 KN with an increase of 107% compared to control NSC specimen S1 and also, it led to additional 11% increase in the ultimate punching load compared with UHSC specimen without shear studs (S2). On the other hand, whereas the central deflection increased from 5 mm for S1 to 11.9 mm for S3 with an increase of 138% and with an increase of 12.2% 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, S5 and S6 on the punching shear capacity and compared with control NSC slab S1. The ultimate punching load were 650 KN for S4, 778 KN for S5 and 812 KN for S6 with an increase of 114.5%,156.7% and 168%, respectively, compared to control NSC slab S1. The central deflection was recorded 6.4 mm for S4, 7 mm for S5 and 7.61 mm for S6 with an increase of 28%, 40% and 52.2%, respectively, 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 central deflection 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 for group A. 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 or with shear reinforcement (shear studs) showed a reduction of the ductility by 24% for S2 and 9.4% for S3, respectively, compared with NSC slab S1. For the strengthened slabs S4, S5 and S6, the ductility increased by 6.6% for S4, 14.3% for S5 and 19.2% for S6, respectively, 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 all strengthened NSC slabs by using UHSC drop panel led to 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 (14) shows the relationship between load and strain in shear reinforcement (shear studs) curve for S3 specimen under centric load. It can be noticed that the recorded strain result is mainly same in both direction due to symmetry of geometrical. The values strains of first row of shear studs 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. All recorded strains shear stud's reinforcement was lower than the value of yield strain for used shear studs (0.0023). Figure (15) shows the relationship between load and strain in flexure steel (bottom) bars curve for all specimens under centric 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.
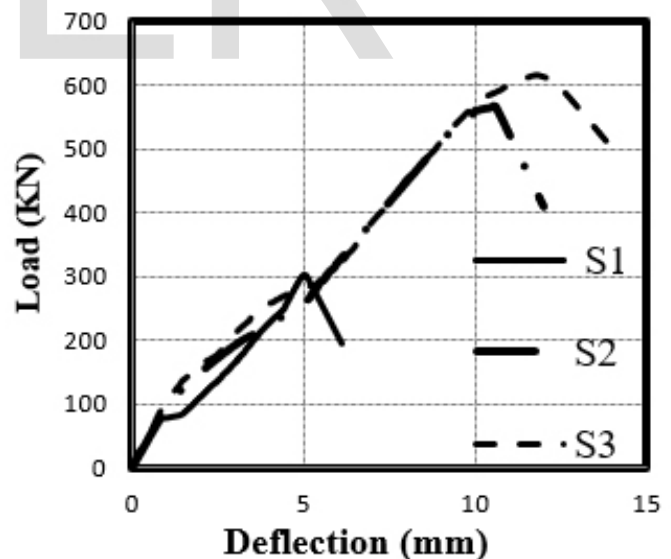

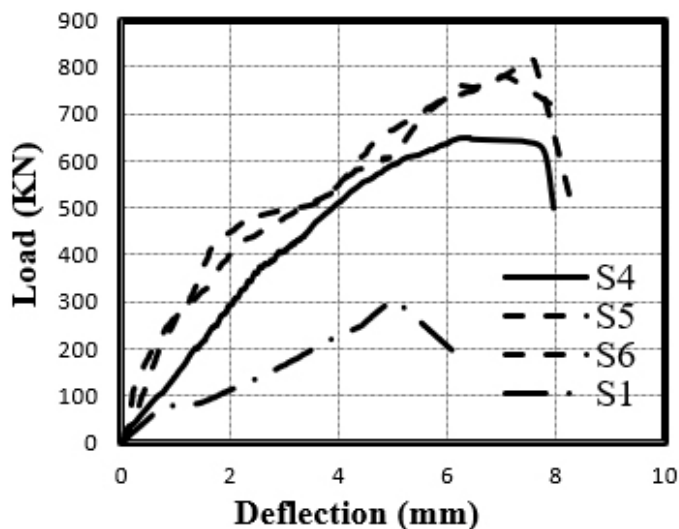Figure (12): Load Deflection Curves for Slabs S1, S2 and S3

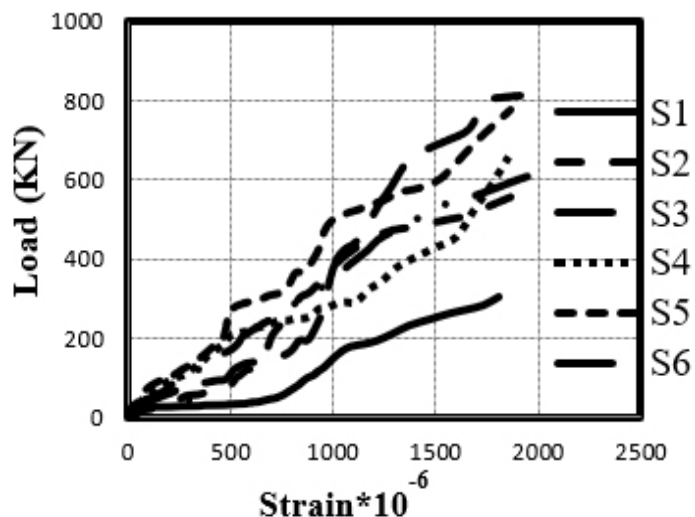Figure (13): Load Deflection Curves
for Slabs S1, S4, S5 and S6

Figure (15): Load-Strain Curve in Bottom
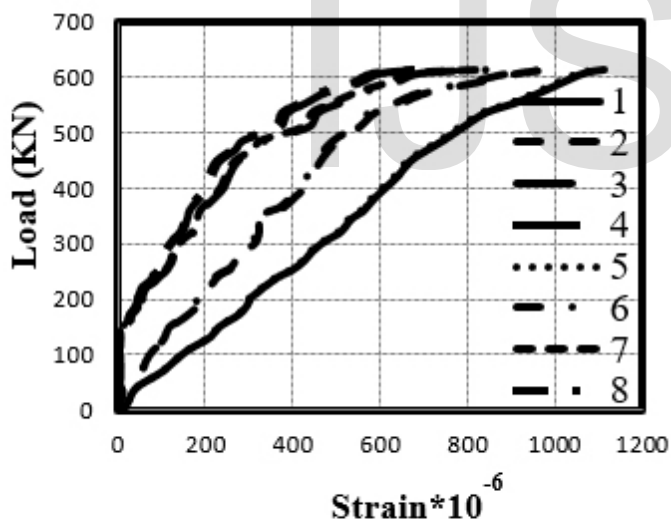Steel for slab S1, S2, S3, S4, S5 and S6

Figure (14): Load-Strain Curve in Shear
Reinforcement for S3

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 six specimens, S1 through S6, from linear through non-linear 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 (16&17) 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 (18 to 20) showed crack pattern at failure, strain contour in bottom longitudinal steel bars and shear studs for specimens with and without strengthening. Figures (21 and 22) showed the comparison between the experimental results and FE re-

sults 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

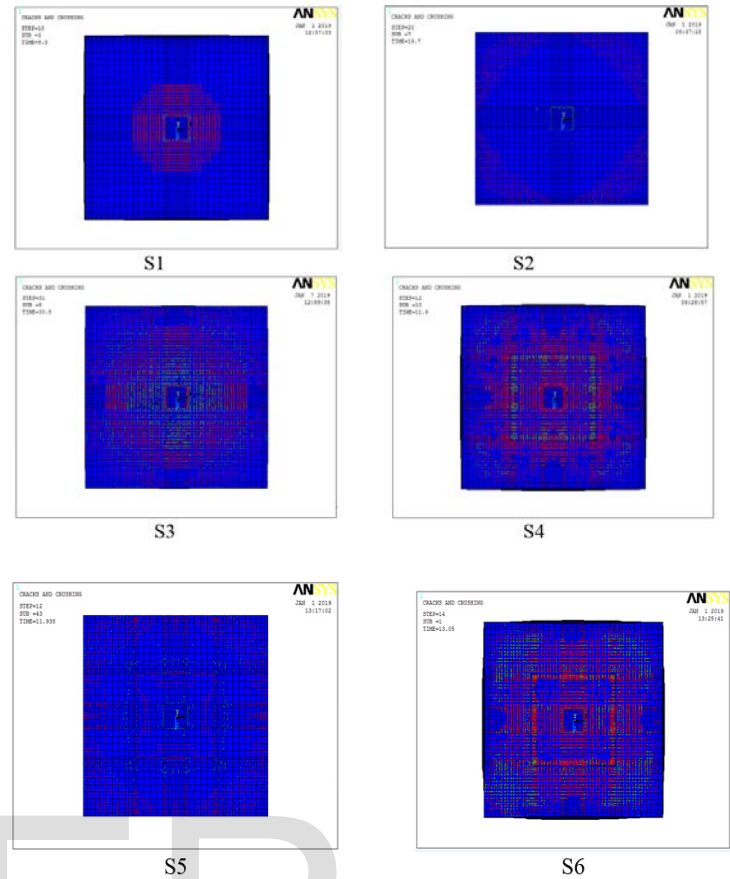| Spec-imen No.	Experimental Results		ANSYS Results		ANSYS Results	Δu (Exp.) Δu (ANSYS)
	Load (Pu) (KN)	Deflection (Δu) (mm)	Load (Pu) (KN)	Deflection (Δu) (mm)		
S1	303	5	282	4.60	1.07	1.09
S2	567	10.6	548	10.20	1.03	1.04
S3	627	11.9	619	11.85	0.99	1.00
S4	650	6.4	688	5.99	0.94	1.07
S5	778	7	799	6.00	0.97	1.17
S6	812	7.61	829	6.77	0.98	1.12

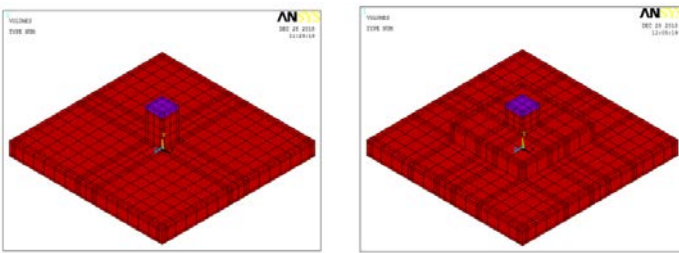Figure (18): Crack Pattern for Models

Figure (16): Finite Element Mesh Used for Specimens with and without Strengthening
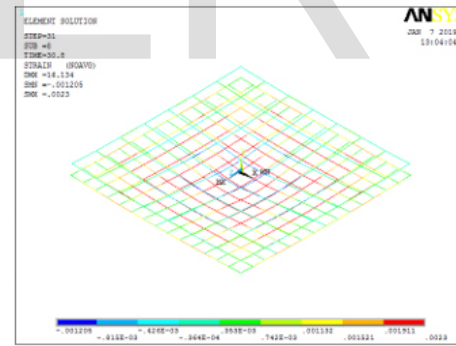

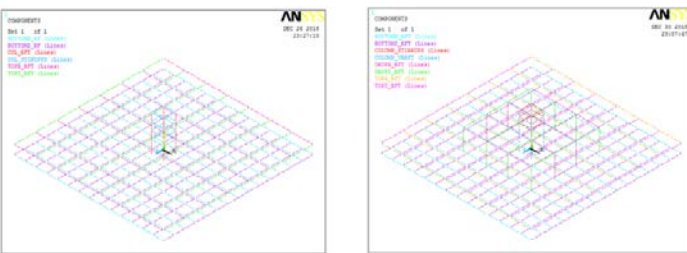Figure (19): Strain Contours in Bottom Longitudinal Steel Bars of Models

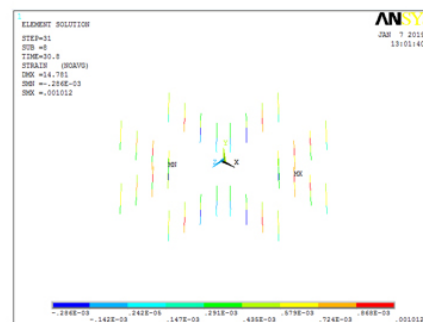Figure (17): Details of Steel Reinforcement in Specimens with and without Strengthening

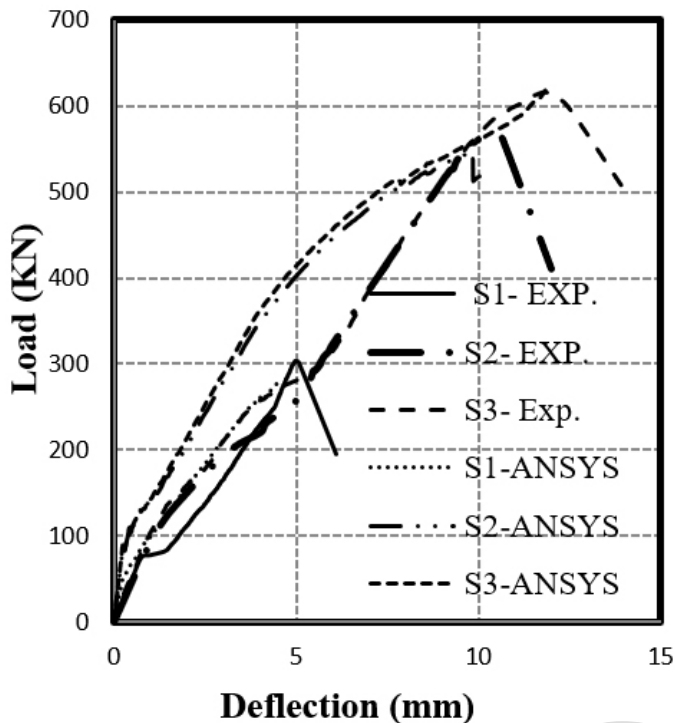Figure (20): Strain Contours in Shear Studs

Figure (21): Experimental VS. FE Results of Load-Deflection Curves for S1, S2, S3
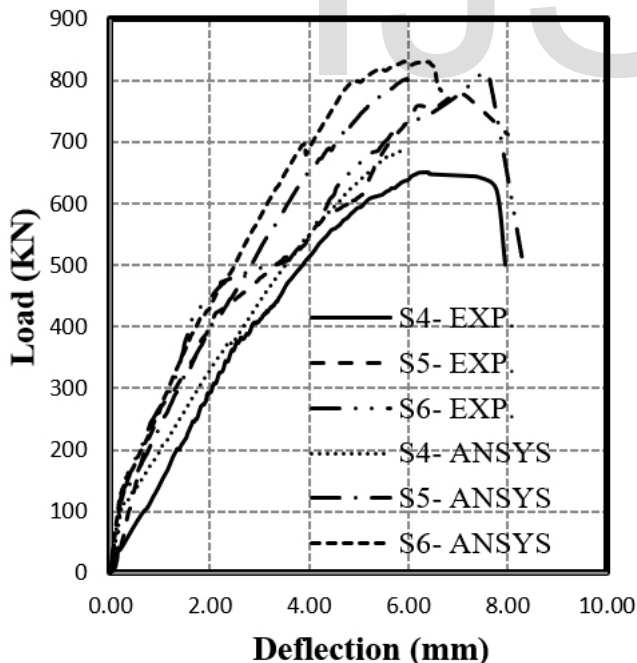

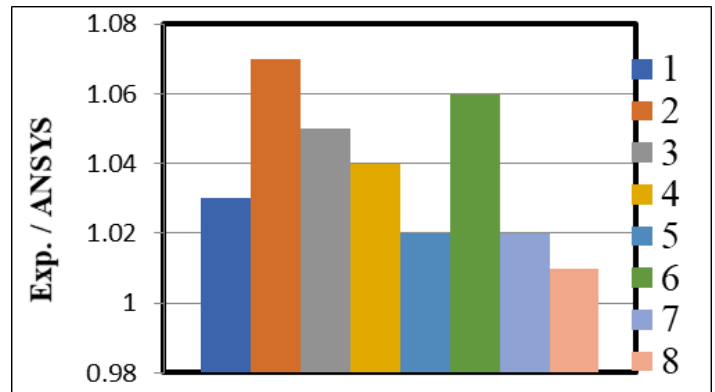Figure (22): Experimental VS. FE Results of Load-Deflection Curves for S4, S5, S6

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 centric loading, the ultimate load was increased by 87% 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 centric loading, the ultimate load was increased by 155% 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 centric loading, the ductility was decreased by 24.5% 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 11% than the UHSC specimen S2 without shear reinforcement, also the UHSC specimen S3 containing shear reinforcement improved the ductility with 20% 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 all NSC specimens were strengthened by using UHSC as drop panel with a different thickness, A sig-

nificant 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 all strengthened NSC specimens by UHSC drop panel were 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 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:

$b_o = 4c + 5 \pi d$ in case of interior column.

10 – A numerical model using FEM (ANSYS ®12) is presented. The simulated models gave a good agreement prediction with a test result. for both of UHSC slabs (with and without shear reinforcement) and the strengthened NSC slabs 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 - 6% to +7%. 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.

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