

Experimental and Numerical Investigation on The Punching Behavior of High Strength R.C Flat Slab Under Repeated Load

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Abstract

In this paper, the punching behavior of square simply supported reinforced concrete flat slabs was experimentally and numerically investigated. Four models of reinforced concrete flat slabs were constructed and tested. The test variables were type of concrete and load (four models): High Strength Concrete flat slabs under monotonic load or repeated load (two models) and Normal Strength Concrete flat slabs under monotonic load or repeated load (two models). The results showed that the punching shear strength of flat slab models increased up to 60% with the use of HSC. While, repeated load reduces the punching shear strength of flat slab models by about (34.4%-10%); it depends on the level of loading, number of cycles and type of concrete. Three-dimensional (3D) nonlinear finite element (NFE) analysis has been carried out to conduct the numerical investigation of the general behavior of HSC and NSC flat slab models. The ABAQUS model succeeded to an acceptable degree in predicting the structural behavior of the analyzed flat slabs with average of differences of about 5% between the predicted and experimental ultimate load.

Keywords: Flat Slabs, Punching Behavior, High Strength Concrete, Repeated Load, Finite Element.

الخلاصة

تقدم هذه الدراسة تقصيا عمليا و تحليليا لسلوك ثقب السقوف المستوية الخرسانية المسلحة مربعة الشكل والمسندة بإسناد بسيط . تضمنت الدراسة انشاء وفحص اربعة نماذج للسقوف المستوية الخرسانية المسلحة. وتضمنت المتغيرات العملية نوع الخرسانة والحمل (اربع نماذج) : نماذج سقوف مستوية ذو خرسانه عالية المقاومة تحت تأثير حمل تزايدى او تكرارى (نموذجان) ونماذج سقوف مستوية ذو خرسانه اعتيادية المقاومة تحت تأثير حمل تزايدى او تكرارى (نموذجان) . أظهرت النتائج بان مقاومه قص الثاقب لنماذج السقوف المستوية ازدادت الى حد 60% عند استخدام خرسانه عالية المقاومة . بينما قلل الحمل التكرارى مقاومه قص الثاقب لنماذج السقوف المستوية بحوالي (34.4% - 10%)، اعتمادا على مستوى التحميل، عدد مرات التحميل ونوع الخرسانة . التقصي التحليلي قداماً نموذجاً لاخطي ابالاعتماد على عناصر ثلاثية الأبعاد ملائمة لتحليل نماذج السقوف المستوية المصبوبة باستخدام خرسانة عالية المقاومة وخرسانة اعتيادية المقاومة . ان التحليل النظري المتبع في هذه الدراسة نجح الى درجة مقبولة في تنبأ السلوك الانشائي للسقوف المستوية التي تم تحليلها وبمعدل فروقات بحدود (5%) بين الحمل الأقصى المتوقع والعملي .

الكلمات المفتاحية : السقوف المستوية ، سلوك الثقب، خرسانه عالية المقاومة ، حمل تكرارى ، العناصر المحددة.

1. Introduction

High strength concrete (HSC) is defined by American Concrete Institute (ACI committee 363R, 1997) as "concrete that has a specified average compressive strength of (41MPa) or more at 28 days". HSC has been widely used in the construction industry due to the increasing requirements and economical consideration for structures. The construction of multistoried buildings is increasing day to day due to increase of land cost. In advent of construction technology the use flat slabs are increasing in the building construction. Flat slabs are easy to build and have through their smaller depth, economical and architectural advantages compared to slab with beams. The undesirable suddenness and catastrophic nature of punching failure are of concern to structural engineers (Yogendran *et.al.*, 2007). Thus, it is significant to investigate the efficiency of the use of high strength concrete to improve the punching shear strength of flat slabs under monotonic or repeated load. Several

research studies reported in the literature on improving the punching behavior of flat slabs. Three studies are presented in this section.

(Osman *et.al.* 2000) analyzed six high strength light weight slabs under concentrated loads. Four slabs were constructed of high strength lightweight concrete of compressive strength higher than 70 MPa, with the steel ratio ranging from 0.5% to 2.0 %. the two references specimens were constructed with normal strength concrete and light weight aggregates and had steel reinforcement ratios of 1% and 0.5 %. The results included the ultimate loads, deflections, modes of failure, crack patterns, ductility, concrete strain, and steel strains. The analysis results were compared with other test data on high strength and normal strength normal weight concrete slabs and code predictions for slab strength. Generally, a reduction factor of 0.85 is advised for lightweight aggregates by the ACI code. A similar reduction of 0.8 is suggested by the BS 8110 code. These reduction factors are conservative when used for high strength concrete. A reduction factor of 0.95 is more acceptable for high strength lightweight concrete, and of 0.85 for normal strength lightweight. The results briefed that the change of reinforcement has a more serious effect on general behavior of high strength lightweight concrete slabs compared with normal strength and high strength concrete slabs.

(Faria *et.al.* 2011) presented parametric analysis regarding geometrical and material parameters affecting punching shear of flat slab with orthogonal mesh and square columns. To do this, they used 3D finite element analysis using ATENA program. It was found that the compressive strength, fracture energy and reinforcement ratio are the most effective parameters on punching shear strength. They believed that the tensile strength and modulus of elasticity do not affect the punching load, they are only important regarding punching behavior in terms of cracking and stiffness.

(Venkata *et. al.* 2012) tested three of HSC slab specimens those were cast with (60 MPa) grade concrete (mix proportion is 1:1.53:2.2). The water cement ratio 0.32 was adopted and the percentage of silica fume was 7.5% in the mix as replacement of cement. The slab size was cast square with geometry of (1100x1100x50mm). To give good workability for HSC, super plasticizer was added with dosage of 7.5% by weight of cement. To compare the performance of HSC, the normal strength concrete slab specimens were also cast and tested. For normal strength concrete (NSC) (25 MPa) grade of concrete (mix proportion is 1:1.32:2.56) was adopted with water cement ratio of 0.46. In both slabs, nominal reinforcement was adopted with 6mm steel at 105mm center to center are placed in both directions. The load has been applied monotonically. The experimental results observed were that the punching shear carrying capacity of the HSC slabs is much higher than the NSC slab specimens and the increase in ultimate punching shear strength of HSC slabs over NSC slab is 58.70%. Moreover, the stiffness of HSC slabs is in the order of higher magnitude than that of NSC slabs. There is no available work found on the use of high strength concrete in R.C flat slabs under repeated load.

2. Experimental Program

2.1 Details of Test Models

This study is limited to interior flat slab (slab-column connections) and does not include edge and corner connections. It is believed that interior slab-column connections are more critical in punching shear than edge and corner connections in a properly designed multibay flat plate structure with approximately equal reinforcement ratios at all connections (**Gardner and Shao, 1996**).

The experimental program of this study consisted of testing four flat slab reinforced concrete square models. Two of these slabs were tested under monotonic load (ML) and the others were tested under repeated load (RL). All models have the same dimensions and reinforcements; 900×900 mm (overall dimensions), 800 mm (span length), 100 mm (overall depth), 20 mm (clear cover in bottom and sides of slab), 150×150 mm (square column), 300 mm (height of column stubs), 20 mm (clear cover in top and sides of column) as shown in Fig.1.

All flat slab models were reinforced with a high amount of flexural reinforcement ($\rho = 2.24\%$). Columns were also reinforced with more steel ($\rho = 5\%$) and closer stirrup spacing ($s = 75$ mm). In this way, the control models would fail in punching shear. However, these flat slab models differed in other details as follows:-

1. **NSC-ML:** Normal Strength Concrete flat slab model was tested under Monotonic Load.
2. **NSC-RL:** Normal Strength Concrete flat slab model was tested under Repeated Load.
3. **HSC-ML:** High Strength Concrete flat slab model was tested under Monotonic Load.
4. **HSC-RL:** High Strength Concrete flat slab model was tested under Repeated Load.

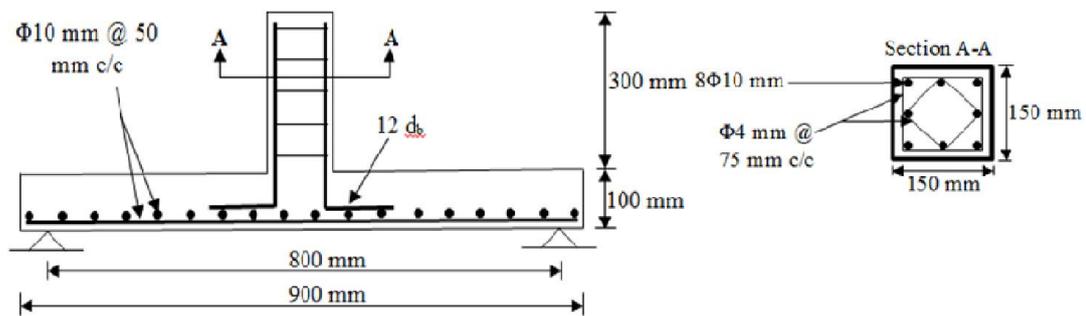


Fig.1:- Details of flat slab models (NSC-ML, NSC-RL, HSC-ML and HSC-RL).

2.2 Properties of Materials

The steel reinforcing bars were in two sizes. The average yield stresses were 422 MPa for the bars size ϕ 10 mm and 510 MPa for the bars size ϕ 4 mm. Tensile test of steel bars were performed according to ASTM A496-02 (ASTM, 2002). The materials (fine aggregate, coarse aggregate, cement and silica fume) used in preparing the concrete were tested according to the standard specifications. To produce HSC with silica fume a high range water reducer was used. It was based on polycarboxylic ether and had the trade mark "Glenium 54". (Glenium 54) produced by (BASF) company. The normal dosage for (Glenium 54) as specified by the producer is (0.5 - 2.5) liter per (100 kg) of cement. The dosage used by the present investigation was (1.9 liter/100kg of cement). The average compressive strength of cylinders f'_c and cubes f_{cu} for NSC at 28 days are 28.50 MPa and 35 MPa, respectively, whereas the average compressive strength of cylinders and cubes for HSC at 28 days are 70.78 MPa and 82.10 MPa, respectively. The compressive strength test of concrete cylinders and cubes were carried out in accordance with ASTM C39/C39M-05 (ASTM, 2005) and BS1881- part 116:2000 (BS, 2000).

2.3 NSC Mix Design

The normal strength concrete (NSC) is designed according to American method of mix proportions selection (**ACI Committee 211.1, 2002**). The mix proportion of NSC are given in Table 1.

Table 1:- The mix proportion of normal strength concrete.

Cement kg/m ³	Sand kg/m ³	Gravel kg/m ³	Water kg/m ³	W/C Ratio
351	861	906	200	0.57

2.4 HSC Mix Design

The high strength concrete (HSC) is designed according to American method of mix proportions selection (**ACI Committee 211.4R, 2008**) and (**Hameed, 2010**). The mix proportion are given in Table 2.

Table 2:- The mix proportion of high strength concrete.

Cement kg/m ³	Silica fume (kg/m ³)	Sand kg/m ³	Gravel kg/m ³	Water kg/m ³	w/cm Ratio	HRWR/Glenium54 (L/m ³)
442	78	739	1067	130	0.25	8.4

2.5 NSC and HSC Mixing Procedure

NSC was mixed according to **ASTM C 192/C 192M-05 (ASTM, 2005)**. Coarse aggregate was added in the pan mixer and about 20% of the mixing water was used. After a few revolutions, fine aggregate was added and about 20% of the mixing water. Then, the mixer was operated for few seconds. Cement and the remaining water were then added. The concrete was mixed for three min. then by three min. break, then by two min.

HSC was mixed according to **ACI 363R-97 (ACI363R, 1997)**. The HSC mixing procedure is stated as follows:-

1. Mix silica and cement in dry condition.
2. Place half quantity of coarse and fine aggregate in mixer.
3. Add all the (Portland cement+silica).
4. Add Rest of fine and gravel.
5. Add all water in mixer.
6. Mix for three minutes.
7. Add the Glenium54.
8. Mix for three minutes.

2.6 Test Procedure

All models were tested in a universal testing machine with capacity of 600 kN under monotonic or repeated loads up to ultimate load. These models were tested under concentrated loading and simply supported along all four edges.

The top surface of the column stub for all models was grinded by using an electrical grinder to get a clean suitable surface and was provided with rubber plates to make the column's surface flat and to avoid non-uniform stress distribution.

In this study two types of load were used one of two types monotonic load and other repeated load. The monotonic load was applied gradually up to failure. While, the repeated load was applied cyclic up to failure. All cycles consist of two steps, first step was loaded up to selected level from ultimate load of control model was tested under monotonic load and second step was unloaded to zero.

The selected levels of load are (0.2P, 0.4P, 0.6P, 0.8P, 0.85P, 0.9P, 0.95P, P, 1.05P, 1.1P, up to failure of model), where P is the estimated ultimate load of control model. Each level of load consists of three cycles, as shown in Fig.2.

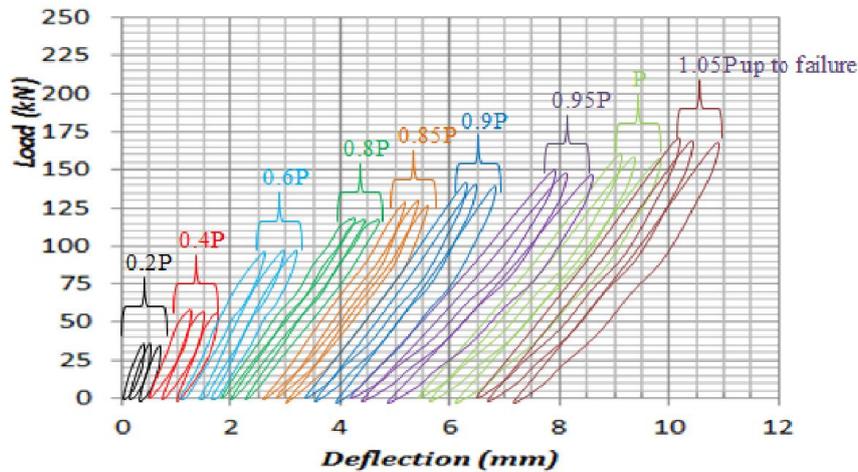


Fig.2:- Explanatory load-deflection curve of model was tested under repeated load.

The strain of concrete were measured by an extensometer of accuracy (0.002 mm). Two pairs of demec discs were used to monitor the strain of concrete at selected levels of loading at several points around the critical section in tension face for all reinforced concrete models.

The deflections were measured by a Linear Variable Differential Transducers (LVDT). Four vertical LVDT were used; one at the center point of the model; two at center of each orthogonal direction for the one quarter of model and one at the center of the diagonal direction for the same quarter of model. The load was applied in stages with 5 kN for monotonic or repeated load test. The first cracking load and its location were recorded. At each load increment, observations of crack development on the concrete models were traced by pencil. For each model, maximum crack width and its location were also measured.

The deflections and strains were measured for each step. The loading was continued until ultimate load. The failure of models was declared when no further increase of the loading readings was recorded with noticeable large deflection in addition to large flexure and shear cracking.

After test completion, the slab-column connection was removed carefully from the test-rig. Fig.3 shows a slab-column connection model that tested in the laboratory of Babylon University.



Fig.3:- Test setup.

3. Experimental Results and Discussion

The results of test were discussed considering the ultimate load, the load-deflection curve, deflected shape, cracking behavior, failure mode and concrete strain around the critical section in tension face of model. Most of the data has been transferred to graphical form for ease of interpretation.

3.1 Ultimate Load and Deflection

Four LVDT were placed one at the center, two at (200 mm) from the center of slab in both directions and one at the quarter of diagonal direction to measure the deflection. The recorded ultimate load and deflection for flat slab models are presented in Table 3.

Table 3:- Deflection at ultimate load for each flat slab model.

Slab-column connection models symbol	Ultimate load P_u kN	Deflection, mm				
		Center	1/4th Point			Average of X and Z directions
			Diagonal	X-Direction	Z-Direction	
NSC-ML	168	6.13	2.37	2.87	2.77	2.82
NSC-RL	125	8.16	2.86	3.34	3.42	3.38
HSC-ML	220	6.51	2.14	2.62	2.72	2.67
HSC-RL	200	7.53	2.32	2.99	2.73	2.86

HSC flat slab model tested under monotonic load (HSC-ML) showed higher ultimate punching load when compared with the NSC flat slab model tested under monotonic load (NSC-ML) by about 31% and the deflection at the maximum punching load is slightly higher (6.2%). The structural behavior of these flat slab models are represented here by their load versus central deflection as shown in Fig.4.

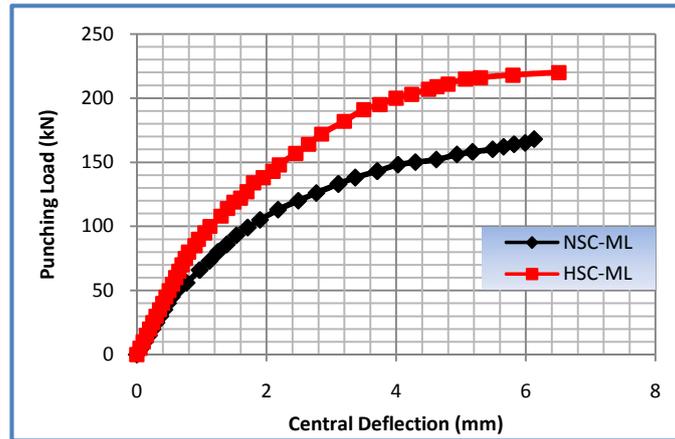


Fig.4:- Effect of replacement of NSC by HSC on load-central deflection for flat slab models tested under ML.

HSC flat slab model tested under repeated load (HSC-RL) showed more significantly higher ultimate load when compared with the NSC flat slab model tested under repeated load (NSC-RL) by about 60% and the deflection at the maximum punching load is slightly lower (7.72%).

The structural behavior of these flat slab models are represented here by their load versus central deflection as shown in Fig.5.

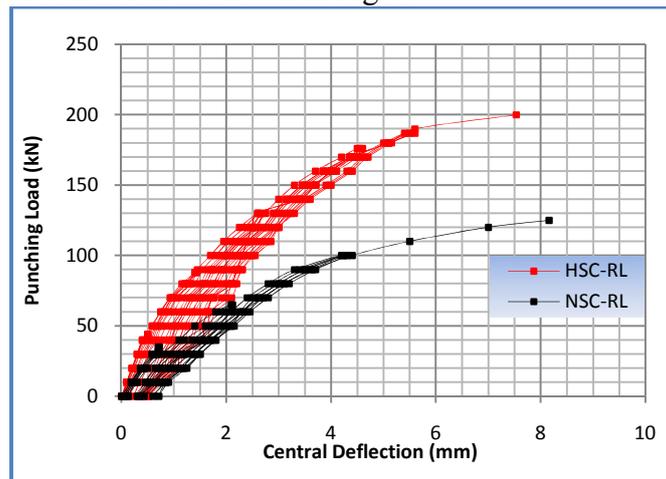


Fig.5:- Effect of replacement of NSC by HSC on load-central deflection for flat slab models tested under RL.

Therefore, it is concluded that the use of high strength concrete improves the punching shear resistance allowing higher forces to be transferred through the flat slab. The stiffness of HSC flat slabs is in the order of higher magnitude than that of NSC flat slabs. The NSC flat slab model tested under monotonic load (NSC-ML) showed higher ultimate load when compared with the NSC flat slab model tested under repeated load (NSC-RL) by about 34.4% and the deflection at the maximum punching load is lower by (24.88%). The structural behavior of these flat slab models are represented here by their load versus central deflection as shown in Fig.6.

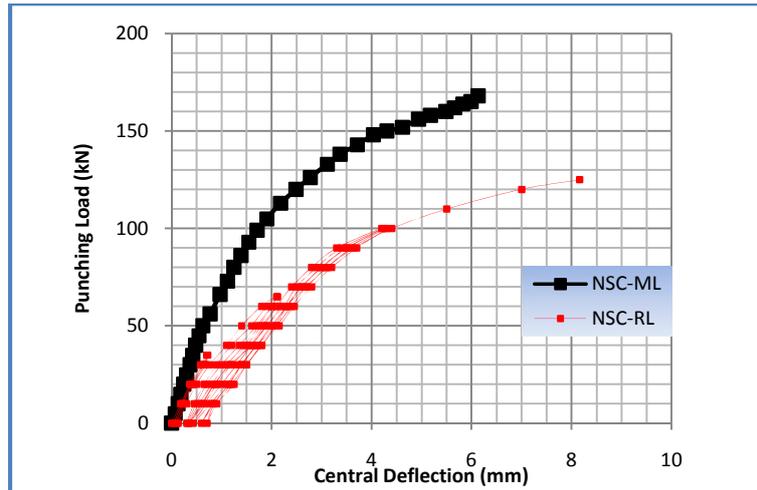


Fig.6:- Effect of replacement of pattern of load on load-central deflection for NSC flat slab models.

While the HSC flat slab model tested under monotonic load (HSC-ML) showed somewhat higher ultimate load when compared with the HSC flat slab model tested under repeated load (HSC-RL) by about 10% and the deflection at the maximum punching load is lower (13.55%).

The structural behavior of these flat slab models are represented here by their load versus central deflection as shown in Fig.7.

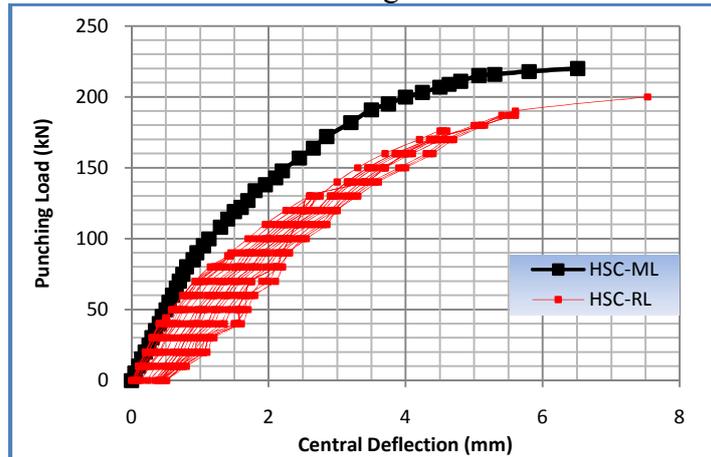


Fig.7:- Effect of replacement of pattern of load on load-central deflection for HSC flat slab models.

The increase in compressive strength of concrete from 28.5 MPa to 70.78 MPa, led to decrease the effect of repeated load on punching shear strength from 34.4% to 10%. It also, led to decrease in residual deflection from 0.71 mm to 0.51mm. The experimental results, show that the repeated load (RL) increases the flat slab rotation, decreases the bond properties between concrete and steel reinforcement and thus reduces the punching shear strength compared to a monotonically loaded flat slab.

3.2 Deflected Shape

The 70% of the ultimate load of control model (HSC-RL) was considered as a service load for all flat slab model and the corresponding deflected shape along the X or Z-axis was drawn. The effect of replacement of Normal Strength Concrete (NSC) by High Strength Concrete (HSC) on the deflection characteristics at the average of 70% of ultimate load for HSC-RL as service load (140 kN) for all flat slab models is shown in Fig.8.

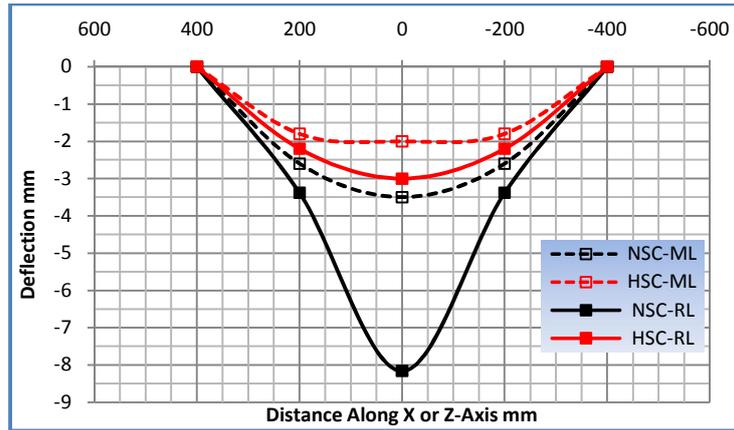


Fig.8:- Effect of replacement of NSC by HSC on the deflected shape along X or Z-axis at 140 kN for flat slab models tested under ML and RL.

The curves show that failure is brittle for HSC flat slab model tested under monotonic load, less brittle for HSC flat slab model tested under repeated load and ductile in NSC flat slab model tested under repeated load. This means, that NSC flat slab model is more ductile from HSC flat slab model under both monotonic and repeated load.

The increase in the compressive strength of concrete by about 148.35% decreases the deflection at 140 kN by about 63.23% when comparing the central deflection for HSC-RL and NSC-RL as noted in Fig.7. The HSC-ML showed about 42.85% and 30.77% lesser central and mid side deflections; respectively than NSC-ML due to the increase in the compressive strength of concrete. The effect of changing pattern of load (repeated instead of monotonic) punching load on the deflection characteristics at the average of 70% of ultimate load for HSC-RL as service load (140 kN) for all flat slab models is shown in Fig.8.

At load 140 kN, the HSC flat slab model tested under RL exhibited higher deflections at center and mid side of flat slab model by about 50% and 22.22%; respectively when compared with HSC-ML flat slab model. At service load (140 kN), the maximum deflection for all flat slab models within the limit of deflection of ACI 318-14 (ACI 318, 2014) which is equal to 4.44mm except NSC-RL model which exceed the limit of deflection.

3.3 Cracking Behavior and Failure Mode

Table 4 list the first cracking load and its percentage of the ultimate failure load, the max. width of crack where the service load equal 70% of ultimate load, maximum crack width at failure for flat slab models tested under ML or RL and failure mode, respectively.

Table 4:- Results of cracks for all flat slab models tested under ML and RL.

Flat slab model symbol	Ultimate load P_u (kN)	1 st Crack in tension face		P_{cr}/P_u %	Crack width at 70% P_u w_s (mm)	Max. crack width in tension face at failure w_m (mm)	Failure mode
		Load P_{cr} (kN)	Crack width w_{cr} (mm)				
NSC-ML	168	50	0.048	29.76	0.29	2.74	punching shear
NSC-RL	125	34	0.075	27.20	0.41	3.86	punching shear
HSC-ML	220	83	0.031	37.73	0.19	2.05	punching shear
HSC-RL	200	72	0.043	36.00	0.25	2.73	punching shear

The distance between the failure surface and the column face in tension and compression faces of all flat slab models and the angle of diagonal cracks of the punching cone are presented in Table 5.

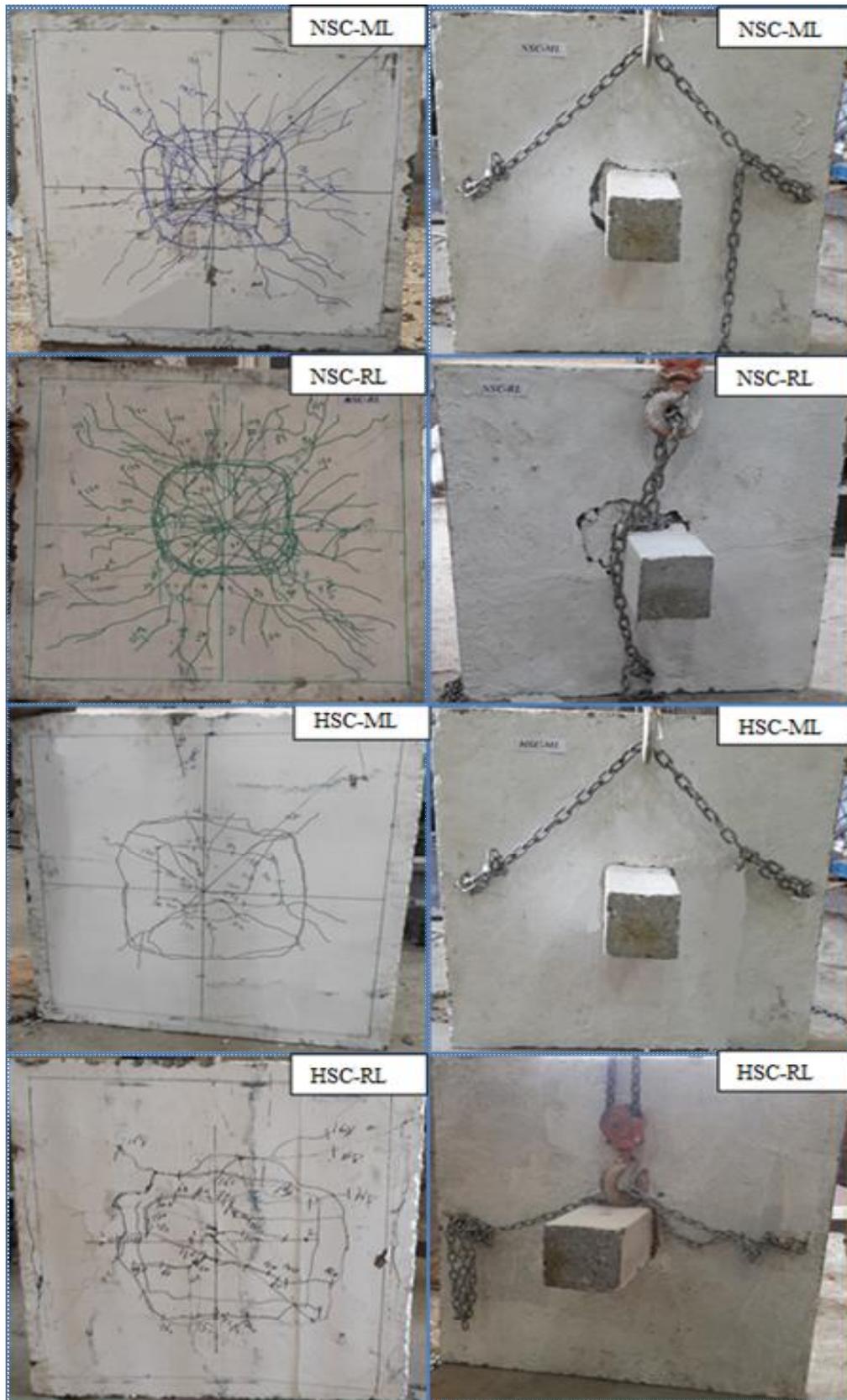
Table 5:- The distance between the failure surface and the column face and the angle of diagonal cracks of the punching cone for all flat slab models.

Flat slab model symbol	Distance between the failure surface and the column face (mm)		Angle of diagonal cracks of the punching cone
	In tension face	In compression face	
NSC-ML	d*	0	55°
NSC-RL	d	0	55°
HSC-ML	1.5d	0	43.6°
HSC-RL	1.5d	0	43.6°

d* = The average effective depth of slab = 70 mm.

From Table 5 and Fig.9, it is concluded that the diameter of the punching cone for HSC flat slabs is larger than that of NSC flat slabs and the location of critical shear crack at the tension surface is far away from the face of the column. The angle of punching cone of HSC flat slabs is less than that of NSC flat slabs. Also, using the HSC decreases the number of cracks.

The repeated load did not change the location of failure surface and angle of diagonal cracks of the punching cone but it increases number of cracks. The number of radial cracks in NSC-RL and HSC-RL models are more than that of NSC-ML and HSC-ML models, respectively.



Tension face **Compression face**
Fig.9:- Cracks patterns at failure for the tested flat slab models.

3.4 First Crack Load

As expected from mechanical properties of each concrete type, HSC-ML and HSC-RL give higher value in first cracking load by about 66% and 111.76%, respectively, in comparison with NSC-ML and NSC-RL. This is due to higher modulus of rupture (f_r) of HSC than that of NSC by about 185.48%. HSC-ML and NSC-ML give higher value in first cracking load by about 15.28% and 47.00%, respectively, in comparison with HSC-RL and NSC-RL. This is due to the decrease in the bond properties between concrete and steel reinforcement due to the repeated load. Therefore, the first crack load appeared in tension face of flat slab model tested under RL before these flat slab model tested under ML due to high tensile stresses resulting from repeated load that produced high tensile strain which led to the occurred cracking.

3.5 Crack Width

From Table 4 the HSC-ML model gives lower first crack width and maximum crack width at service and failure load by about 35.42%, 34.48% and 25.18%, respectively in comparison with NSC-ML. While, the HSC-RL model gives lower first crack width and maximum crack width at service and failure load by about 42.67%, 39% and 29.27%; respectively in comparison with NSC-RL. Fig.10 shows the relation between load and maximum crack width for these four flat slab models at all stages of loading.

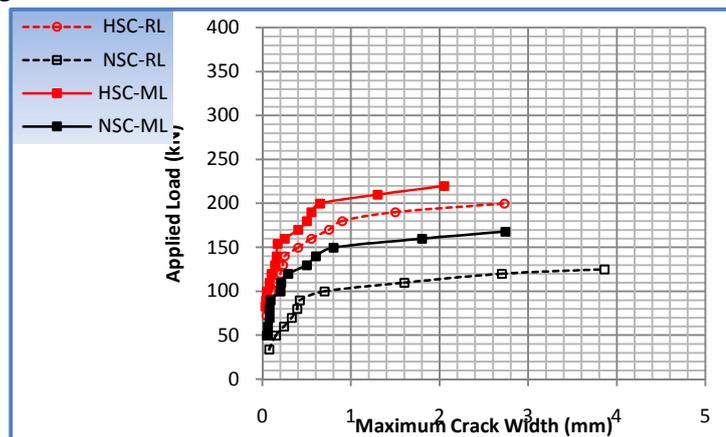


Fig.10:- Effect of concrete type on load-maximum crack width for flat slab models tested under ML or RL.

From Fig.10, NSC-RL and HSC-RL models exhibited higher values of crack width compared to the NSC-ML and HSC-ML models, respectively at the same load level. The maximum cracks width at service load (70% P_u) of NSC-RL and HSC-RL models are more than NSC-ML and HSC-ML models by about 41.38% and 31.57%, respectively. At service load (70% P_u), the maximum crack width for all flat slab models within the limit of crack width of ACI 318M-14 (ACI 318M, 2014) which is equal to 0.41 mm for the steel reinforced concrete.

3.6 Concrete Strain

At service load of HSC-RL (140 kN), The normal concrete strain in tension face of HSC-ML and HSC-RL models are lower than NSC-ML and NSC-RL by about 50% and 20%, respectively. This means, that NSC flat slab model is more concrete strain from HSC flat slab model under both monotonic and repeated load because the low modulus of elasticity of NSC.

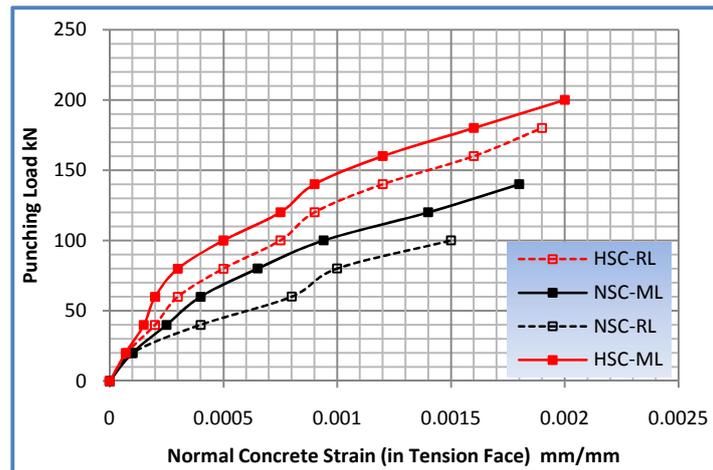


Fig.11:- Effect of type of concrete on load-concrete tensile strain for flat slab models tested under ML or RL.

In order to compare normal concrete strain behavior for flat slab models tested under ML with flat slab models tested under RL, Fig.11 shows the normal concrete strain values for NSC-ML, HSC-ML, NSC-RL and HSC-RL models and the punching load. The normal concrete strain of HSC-ML model at 140kN is less than it is in HSC-RL model by about 25%.

4. Finite Element Modeling

Finite element analysis, as used in structural engineering, determines the overall behavior of a structure by dividing it into a number of single elements, each of which has welldefined mechanical and physical properties. Modeling of the constitutive material properties is an important aspect of any finite element analysis. The constitutive model should correctly describe the behavior of the material under uniaxial and multiaxial states of loading. Finite element modeling and analysis were carried out to simulate the behavior of the four tested flat slabs from linear through non-linear response and upto failure, using the ABAQUS (Version 6, copyright 2013) computer program. The choice of the proper element type is very important in the finite element analysis. The chosen element type depends upon the geometry of the structure and the number of independent space coordinates necessary to describe the problem. Each component of flat slab should be modeled by the proper element type and then each type of element should be provided by the properties according to the material of that component. In the present study, three-dimensional model was used to analyze flat slab. The concrete was divided in its length, width and depth into brick elements (Solidelements) (C3D8R, 8-node linear brick, reduced integration). Element type (Trusselements) (T3D2, two-node linear displacement, Truss elements) is used to model steel reinforcement. These truss elements are embedded into continuum elements to model the bond strength between reinforcement and concrete.

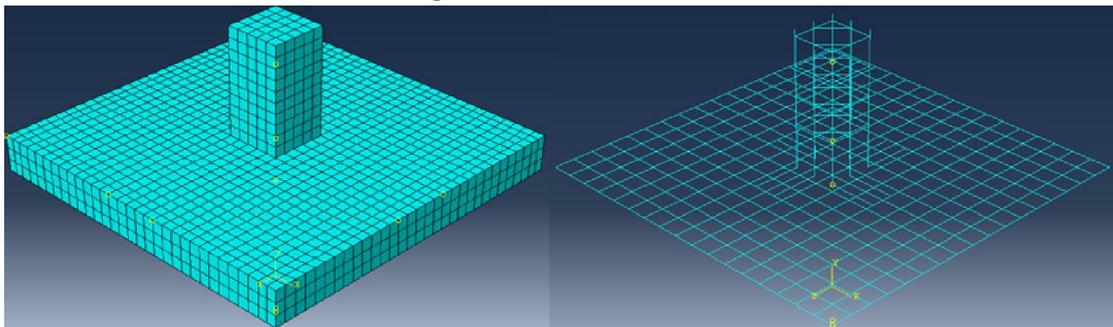


Fig.12:-Geometry of the numerical model.

5. Numerical Results

The numerical results of ultimate loads, load-deflection curves and first cracking loads are concerned to compare them with those of experimental work. This comparison was conducted to verify the numerical model. Table 6 shows a comparison between experimental and numerical ultimate loads for the study models. Table 7 shows a comparison between numerical and experimental results of the first cracking load for flat slab models.

Table 6:- Comparison between experimental and numerical ultimate loads for flat slab models.

Flat slab models symbol	Ultimate load P_u kN		Difference ratio %
	Experimental	ABAQUS	
NSC-ML	168	173	2.97
NSC-RL	125	131	4.80
HSC-ML	220	231	5.00
HSC-RL	200	214	7.00

Table 7:- Experimental and numerical first cracking loads for flat slab models.

Flat slab models symbol	1st Cracking load kN		$\frac{P_{cr}num.}{P_{cr}exp.}$
	Experimental $P_{cr}exp.$	Numerical $P_{cr}num.$	
NSC-ML	50	52	1.04
NSC-RL	34	38	1.12
HSC-ML	83	85	1.02
HSC-RL	72	75	1.04

In general, the ultimate loads predicted by the numerical analysis are greater than those of experimental testing. The percentage of difference for the ultimate loads is between (2.97-7) % for all the models as shown in Table 6. The first cracking load obtained from numerical data for all cases showed results higher than the experimental data recorded with average differences not more than 5.58% for all flat slab models. Fig. 13 shows a comparison between experimental and numerical results for the load versus central deflection curves of all flat slab models.

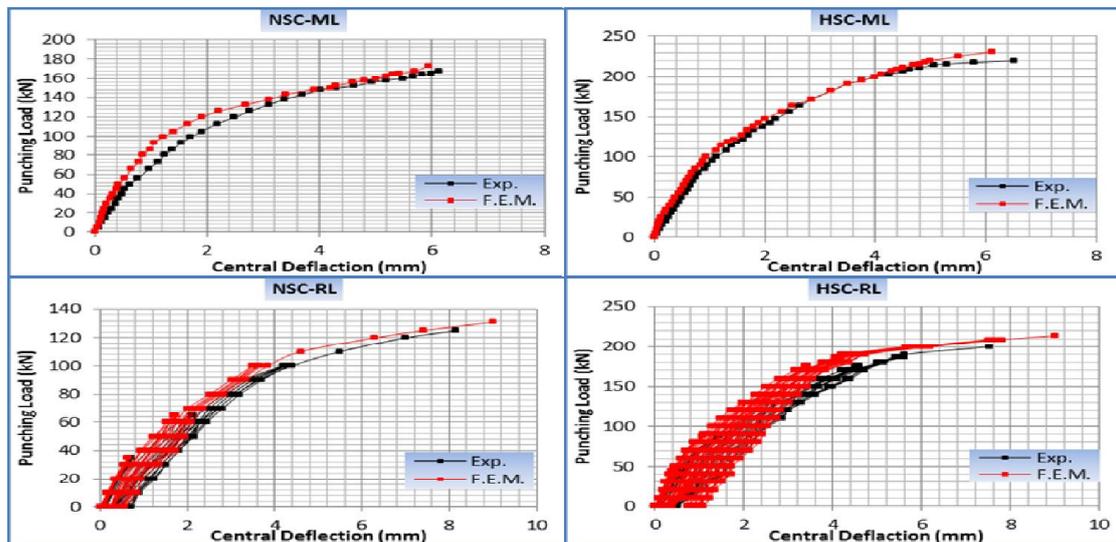


Fig.13:- Load-deflection curves of all flat slab models.

This comparison shows in general that the numerical models are stiffer, and the numerical analysis gives a smaller value for the deflection and a greater value for ultimate load with a little difference in the ultimate load values. This may be caused by the following: 1. The finite element model is based on assumed displacement field that means stiffer behavior than actual one. 2. The concrete of experimental models is not perfectly homogeneous as assumed in the numerical models. 3. Micro-cracks which may have occurred in concrete due to shrinkage reduce the stiffness in some degree. 4. Cracks in plastic behavior of each element are only tested at gauss points which give overestimate of ultimate load and stiffer response.

6. Conclusions

Based on the results of the experimental work and finite element analysis for the tested flat slab models, the following remark points can be concluded:-

1. The results of experimental work exhibited that the punching shear strength of flat slab model significantly increases with the use of HSC, but the rupture is more brittle than that of NSC flat slab model. By comparison with the NSC model, the use of HSC led to an increase the punching shear strength by about 60%.
2. The experimental results exhibited that the repeated load affects the deformation behavior and punching shear strength of flat slab models since it causes the fatigue in flat slab model. Repeated load reduces the punching shear strength of flat slab models about 34.4% for NSC by application of ten cycles and 10% for HSC by application of sixteen cycles associated to a monotonically loaded flat slab models.
3. The diameter of the punching cone for HSC flat slab models is larger than that of NSC flat slab models and the location of critical shear crack at the tension surface is far out from the column face by about 50%. The angle of punching cone of HSC flat slab models is less than that of NSC flat slab models to be from 55° for NSC flat slab models to 43.6° for HSC flat slab models.
4. The 3D FE analysis by ABAQUS program shows that it is possible effectively to simulate the real behavior of flat slab models, with a certain degree of accuracy. One of the most important things in this analysis is the correct choice of the adequate material modelling.
5. The ultimate numerical loads gotten by FE analysis agree well comparing to the corresponding values of experimental tested flat slab models; where the average difference of the ultimate load was less than 5% for all the analyzed models.

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