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Improving Punching Shear in Flat Slab by Replacing Punching Shear Reinforcement by Ultrahigh Performance Concrete

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ABSTRACT

Extensive studies have focussed on the issue of the failure of punching shear in flat slabs and ways to strengthen it internally, externally and the importance of this structure (flat slab), and the danger of punching shear failure in the areas of connection of the column - slab. Therefore, this study was based on strengthening the bearing capacity of the flat slab to failure of punching shear with high-performance concrete (UHPC); because it is expensive, so it is not feasible to use it for the whole slab. Therefore, the aim of the study was to replace reinforcement punching shear with UHPC and to determine its optimal use in the shear area. Six samples of flat slabs reinforced with maximum flexural steel loaded with a column in the middle, four forms of UHPC casting instead of shear reinforcement and at two different depths were used. The results showed an improvement in the punching shear strength of the sample cast with UHPC instead of punching shear reinforcement (ACI 318-19) and with all thickness of the slab, it to arrived twice compared to reference sample (NSC) with reinforced flexural steel only. This is the perfect application for the UHPC. It was also noted that casting UHPC with half the thickness of the slab does not give good results compared to those casting with all thicknesses, despite doubling the distance of the UHPC from all faces of the column; but it changes the failure pattern and keeps it away from the danger areas near the unwanted columns.

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1. INTRODUCTION

Flat slab is structure supported by a column without beam. It is a widely used for its many benefits, including: reducing the construction cost in order to reduce the amount of materials used in construction and reduce the work of molds and faster construction and ease the work of flexural reinforcement, reducing the height of the building and thus reducing the loads, ease of setting up of services, reduction in finishing material and flexibility in the arrangement of partitions [1].

There are downsides to use flat slab which are: high shear stresses at slab-column connections may cause punching shear failure, increase in the vertical deflections and the structure has a relatively lesser stiffness under lateral loading [2].

Punching shear failure is considered unwanted failure and defined by Moe [3] as the failure of a concrete slab directly under a concentrated load that occurs when a concrete plug is pushed out of the slab. The pushed-out plug takes the shape of a cone with a top area at least equal to the loading area.

Therefore, many researchers have used methods to strengthening the failure of the punching shear and increase the punching shear capacity in flat plat slabs including an shear stirrups, or use of column heads, drop panels, increased thickness [4, 5], shear heads [6, 7], or shear studs [8, 9]. It is also possible to external strengthening and restore resistance of steel bolts [10, 11], steel bars [12], steel plates [13], fiber reinforced polymer (FRP) sheets or strips [14-17], the combination of FRP sheets and steelbolts [18], FRP strips as through-depth shear stirrups [19, 20]. The normal and hybrid concrete specimens are shown in Figure 1.

Ultra-high-performance concrete (UHPC) is cementitious material is a special and modern type of

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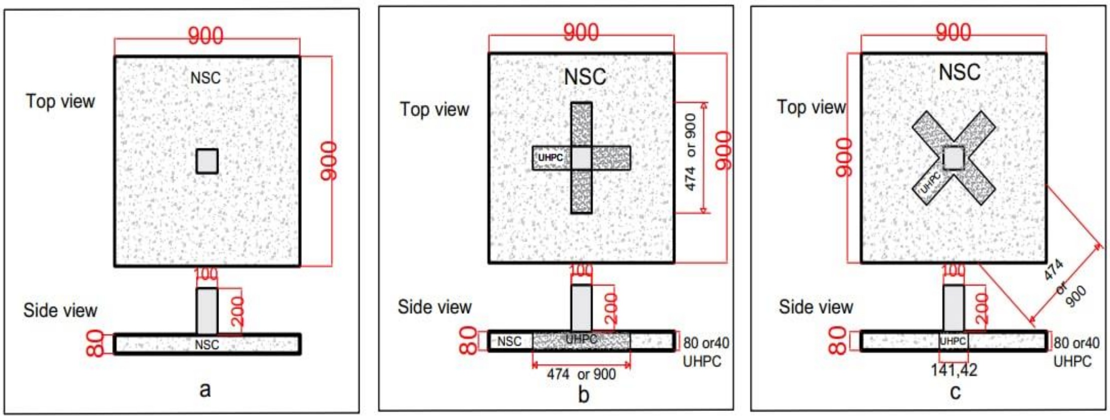


Figure 1. Specimen layout:**(a)** normal concrete NSC or Sh.R.N **(b)** hybrid concrete 187-PF or 400-PC **(c)** hybrid concrete 187-XF or 400-XC (Note: all dimensions in (mm))

concrete, its components differ slightly from one country to another according to the availability of its ingredients and the method of production and maturation [21] amazing mechanical properties, high energy absorption, ductility, permeability and durability. Steel fiber added to improve durability and tensile strength [22].

By reviewing the literature and applications used UHPC and after studying their engineering properties, it was found that the tensile strength of this type of concrete is good and equal to (2.5-3) of the tensile strength of ordinary concrete. This may be due to its high resistance to compression, as the proportionality is direct between the resistance to pressure and tensile strength, in addition to the presence of steel fiber. For these reasons, the idea for this study was formed. There are many applications for high performance concrete (UHPC) such as on-site casting or as an injected material in bridge decks [23], bridge connections [24], strengthening of existing structure [25] and thin slab [26]. There are researchers who used ultra-high performance concrete (UHPC) to strengthen the slab as partial or total use and with different parametric study such as: Harris [27] made an experimental study of (12) unreinforced flat slab model, it was made of a material (UHPC) with different thicknesses and dimensions of the loading plate, and after tests, it was found that the punching shear failure in slab of thickness (51mm) and the shear-flexure failure in slabs thickness 64 and 74 mm; it finally ended the punching shear capacity can be anticipated using updated equations from ACI318-2 instead of the effective depth, the slab thickness is used.

Joh et al. [28] examined five unreinforced flat slabs made of (UHPC) with fixed ends, with investigated variables casting and curing methods. Equations were used by Harris [27] and Graddy et al. [29] to compare the capacities of the slabs that failed in the punching shear to the expected value. whilst the expected strength was compared to Park et al. [30] values of the slabs that failed in flexure. The formula introduced by Graddy et al. [29] overestimated the results while the results were very close to Harris's [27].

Moreillon [31] the researcher studied many variables as fibre volume ratio, reinforcement arrangement, reinforcement ratio and thickness of slabs. the punching shear and flexural strength, they increase by increasing the percentage of fiber steel for the same reinforcement and thickness of the slab, and the strain decreases at the maximum load by increasing the fiber content, reinforcing steel has a greater effect with thicker plates. The researcher concluded a model for calculating the punching shear for plates (UHPC).

Aaleti et al. [32] used waffle bridge deck thickness 200mm, a 150 mm by 200 mm steel plate was used to apply the load to the deck cell between the ribs. Punching shear failure seen at an angle 45, the shear ability obtained by 2.3 is approximately from what can be calculated from the ACI code proposed from Harris [27].

Zohrevand et al. [33] conducted a practical study of hybrid flat plates (NSC/UHPC) with full or half depth and slabs (UHPC) complete with different reinforcement ratio for two groups (1.8% and 0.6%). In slabs with reinforcement ratio (1.8%) that failed to shear the punching as well as the slab full UHPC, as for the slabs with the reinforcement ratio (0.6%) it failed with a composite shear-flexural failure. The hybrid slabs with full UHPC depth had a failure load of 70% (at 1.8%) and 45–66% at (0.6%) more than the reference slab.

Few studies have dealt with on punching shear in flat slab with UHPC, and because it is an expensive material, it is used with normal concrete as a hybrid concrete and what distinguishes this study is that no one searched for the replaceing punching shear reinforcement by ultrahigh performance concrete and obtaining the optimal and economical use (UHPC) in the areas where the column contacts the slab.

2. MATERIAL PROPERTIES

It is necessary to know the physical and chemical properties and the source of all materials used in the composition of concrete, for both types normal and ultra-high performance concrete.

2. 1. Cement Portland limestone cement (CEM II/A-L- 42.5 R) was the type of cement used in this study. Manufactured in Iraq known as (Karasta) and obtained from the local markets, respect to (IQS No. 5/1984) limitations [34].

2. 2. Fine Aggregate (Sand) Natural local sand correspond to the limits of Iraq specification (IQS No.45/1984) [35], used in NSC.

2. 3. Coarse Aggregate (Gravel) Local material maximum size of 14 mm of which correspond to the Iraqi specifications No.45/1984 [35], used in NSC.

2. 4. Fine Aggregate (Extra Fine) Natural fine aggregate imparted was used as natural sand in UHPC just fine sand that was sieved by (600 µm sieve) [35], used in UHPC.

2. 5. Silica Fume Produce from MASTER BUILDERS SOLUTIONS company MBCC Group Silica fume is an extremely fine powder was used in UHPC [36].

2. 6. Steel Fiber Micro steel fibers (type WSF0213) available in the market were used in this research to produce UHPC This sort of steel fibers was made by a company in Jiangxi Province. It is utilized in the present study with length 13mm and aspect ratio (Lf/Df) = 65 and volume fraction (Vf =1.5%).

2. 7. Admixtures (Super Plasticizer) A Super plasticizer used throughout this study for UHPC was "Sika ViscoCrete 5930-L", ViscoCrete 5930-L was made by Sika Company, ASTM C494 05 [37].

2. 8. Mixing Water Tap water has been used for casting and curing all the slab specimens.

2. 9. Reinforcing Steel In this paper, deformed steel bars of two different diameters were used, the ultimate and yielding strength of the diameter (6 and 10 mm) bar were determined by testing method [38]. Table 1 summarized the reinforcing steel ultimate and yielding strength.

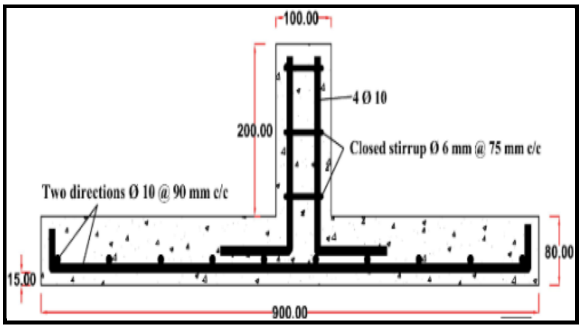
TABLE 1. Result of Reinforcing Steel

ϕ (mm)	Fy (MPa)	Fu (MPa)
6	420	448
10	545	626.45

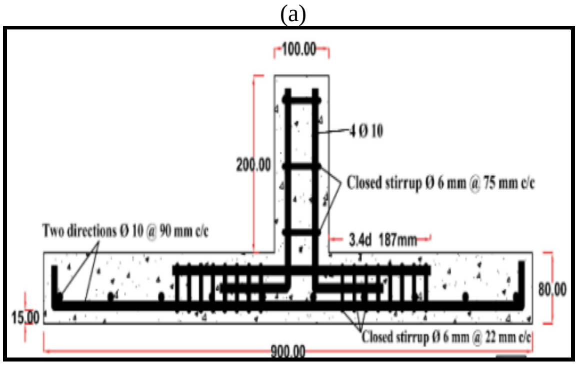
3. EXPERIMENTAL WORK

Six specimen, each of them designed as square flat slabs with dimensions (900 * 900 mm) and thickness (80 mm) and a square column in the center of the slab with dimensions (100 * 100 mm) and height (200 mm) and the column is reinforced with 4 Ø 10mm according to ACI-318M-19 code chapters 10, 10.6 and 10.7 [39] and three bars shear reinforcement (stirrups) Ø 6mm as show in Figure 2. The flexural reinforcing factor was installed for each slab and according to ACI-318M-19 code chapters 8, 8.6 and 8.7 [39], and we used the largest percentage (ρmax) for the purpose of studying the punching shear failure. The cover in all directions equal 15mm according to ACI-318M-19 term 20.5.1 [39] and effective depth 55mm. This study included three parameters (Investigated variables): (1) shape of UHPC (2) depth of UHPC, and (3) the presence or absence of reinforcement of the punching shear. Two slabs was made entirely from NSC one of which contains the reinforcement of the punching shear Figure 1a. The rest of the models of hybrid concrete in different shapes for UHPC Figures 1(b) and 1(c). Reinforcement steel of flexural and punching shear is shown in Figure 2.

The first specimen name NSC (normal strength concrete), the two specimen name Sh.RN (normal strength concrete with reinforcement shear punching)



(a)



(b)

Figure 2. (a) Reinforcement Steel of Flexural (b) Reinforcement Steel of Flexural and Punching Shear

designed according Figure R8.7.6(d) in ACI-318M-19 code [38] Figure 3. The third specimen name 187-PF(187 equal 3.4d) [39], where P: plus shape UHPC F:full depth, 4th specimen 187-XF(X: multiplication sign shape of UHPC F: full depth), 5th specimen name 400-PC (Arm length plus shape same amount of UHPC used in the third model for the half thickness of the slab in the face of compression), 6th specimen name 400-XC (the same 5th model rotated at angle 45).

All samples were reinforced with the above-mentioned details shown in Figure 2(a). One model had reinforcement with punching shear, the details of which are shown in Figure 2(b). This model was poured and thefirst model was cast with ordinary concrete as a reference for comparison. Since UHPC is an expensive material, this study relied on strengthening the punching shear by replacing the same area of the shear reinforcement steel, which is in plus shape of the length of each arm equal to 3.4d Figure 2(b) and equal to 187 mm because the effective depth is 55 mm and the same shape UHPC was rotated at an angle of 45 in the fourth model. As for the model Fifth, the same amount of UHPC in the third model was used to half the thickness of the slab in the compression face of slab, and the sixth model was rotated the fifth model at an angle of 45. The UHPC was not placed in the tension face because it does not give the desired results as mentioned in literature [40].

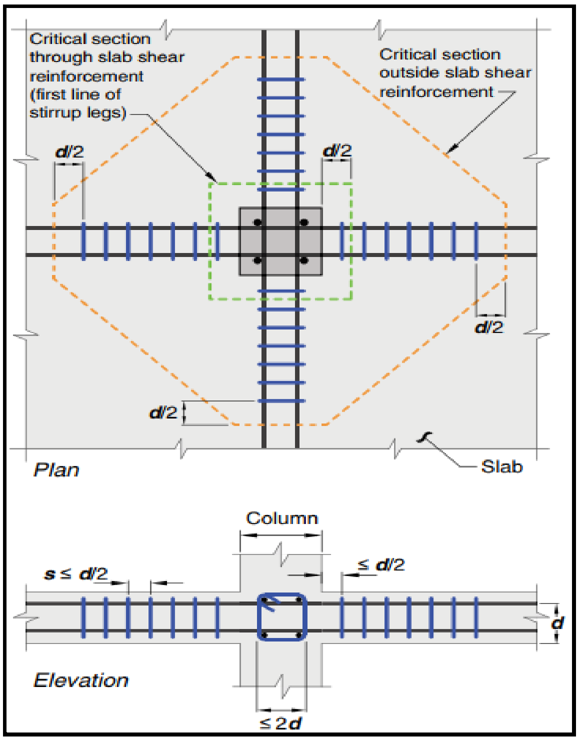


Figure 3. Reinforcement steel of punching shear according ACI318-19 code [38]

3. 1. Specimen Preparation and Casting The molds were prepared from plywood of the necessary dimensions, and a pre-prepared reinforcing steel mesh was placed and covered from the mold with plastic spacers. Table 2 summarized the components and proportions NSC and is designed according to ACI-211.1 the aim of the concrete strength (f'c) for all slabs was (23 MPa) at age of 28 days. Table 3 states the components and proportions UHPC and were designed according to ACI PRC-239-18: Ultra-High Performance Concrete [41], as well as we made experimental mixtures to reach the compressive strength of 122Mpa at age of 28 days, these numbers were taken from an average of three cylinders for each mixture, (100*200mm) for UHPC and (150*300mm) for NSC.

Mixing Procedure of NSC by electrical horizontal mixer rotary drum of (0.09 m³), while UHPC was mixed by manually controlled electric mixer used as in Figure 4. A work plan has been developed for casting UHPC and NSC in the hybrid samples at the same time and the steel mold of UHPC is withdrawn and compacted at the same time also to prevent cold joints as in Figure 4. the columns were casted the next day used NSC.

TABLE 2. Details of Mix Proportions

W/C =0.58	Cement	Coarse Aggregate	Fine Aggregates	Water
Weight (kg)	368	900	850	213

TABLE 3. Trail Mixes Proportion of UHPC

No. of Mix	1	2	3 (Selected)
Cement (kg/m^3)	975	1000	1000
Fine sand (kg/m^3)	1050	1050	1050
Micro silica fume (kg/m^3)	230	245	255
Steel fiber % by volume	2	2	2
water/(cement+silicafume)	0.19	0.17	0.155
Superplasticizer % by weight of cementitious material	4.25	4.5	5
***fc'* (28 days) MPa**	85.63	105	122

3. 2. Test Setup and Procedure The specimen were prepared and cleaned after the end of the curing stage after 28 days and paint it white to make it easier to notice cracks during and after testing. A simple support for the slab was used, represented by a pre-prepared steel frame, and it was placed in test device with a capacity of (600 kN). The protocol loading that was used to load the slabs is to transfer the axial load from the column to the slab after placing a cap over the column to prevent local failures, we placed the load sensor (load cell) and placed a bearing plates between them as shown in Figure 5.

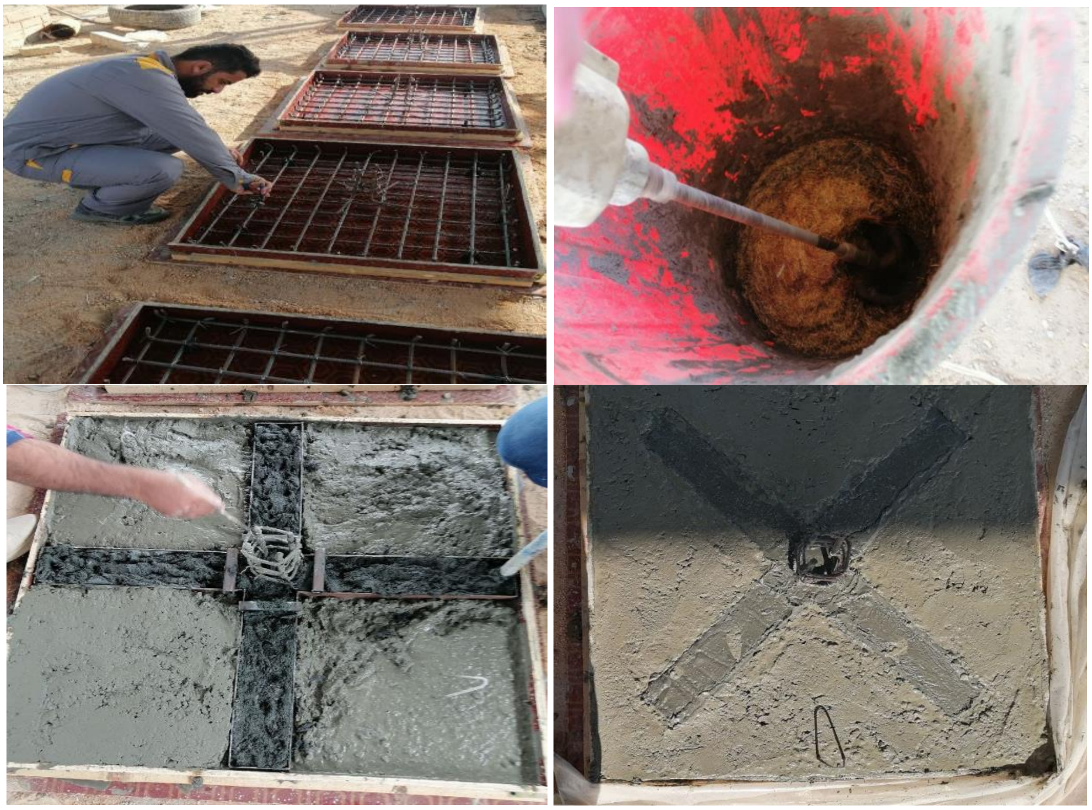


Figure 4. Specimen Preparation and Casting

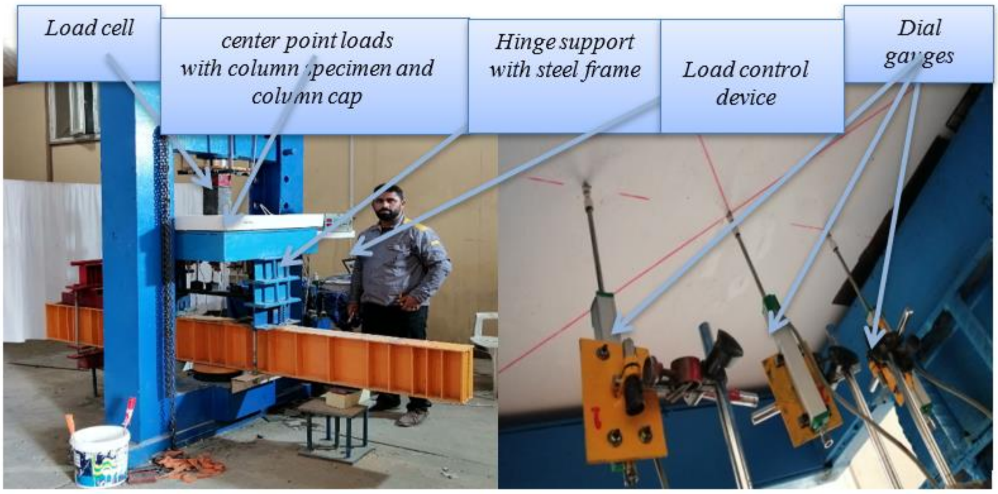


Figure 5. Test setup

We followed a constant load rate for all models, and dial cauges a number of three, one in the middle and two with the average distance between the center and the edge on each side, as shown in Figure 5. After preparing all the test instruments, we started loading and recording data (load, deflection, cracks pattren , and cracks location) and indicating the development of cracks.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4. 1. Estimating Punching Shear Capacity

The punching shear of slabs can be calculated based on ACI 318-19 as in Equation (1). It should be noted that this model has limitations on compressive strength which should not exceed 69 MPa. This limitation is ignored in this study since this model is applied for UHPC slabs which have fc significantly larger than 69 MPa.

$$Vc = 0.33\lambda s\,\sqrt{fc, u} * b_o d$$
$$\lambda s = \sqrt{\frac{2}{1+0.004d}} \leq 1 \qquad (1)$$

where fc,u: compressive strength for NSC or UHPC bo: critical punching perimeter at a distance of d/2 from the column face and λs: size effect modification factor. Kadhim et al. [42] proposed Equation (2). model to calculate the perimeter of failure. It is established that the failure of the punching shear occurs outside UHPC and this applies to our study except in slab 400-XC where the failure occurred during UHPC.

$$b_o = \max\binom{4(c=d)}{4L} \qquad (2)$$

After estimating the shear capacity with the modified model of the code as in the Table 4 and after comparing with the practical estimation, we notice that the percentage of difference is good for the references slabs. As for 187-PF and 187-XF, the percentage difference is greater, and this may be due to combined shear-flexural behavior. As for samples 400-PC and 400-XC it cannot be guessed according to Kadhim et al. [42] because of the failure within the region of UHPC or because of the failure of the flexural.

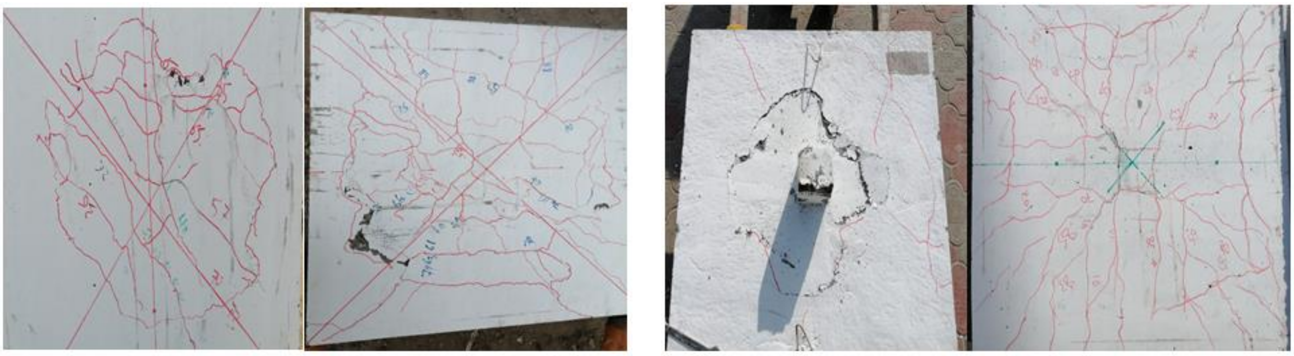
From the foregoing, we conclude that the code equation is very conservative, and we also recommend suggesting a new mathematical model or an modify to the code equation in order to be inclusive of all forms UHPC and not just for regular shapes.

4. 2. Failure Modes All models were designed to fail in punching shear, so we used the largest percentage of flexure reinforcement, general description of the evolution of cracks, at early stages of loading, all tested flat slabs were free from cracks and responded in an elastic manner at low load levels. The deflection was proportion to the applied loads. Subsequently, with increasing load, more cracks were developed and we noticed that in the sample consisting of ordinary concrete NSC (pure punching). We note that the first crack appeared at distance d/2 from the face of the column and with the continuation of the loading, the diagonal cracks appeared, the cracks developed and their width increased, and then the oceanic dredgers appear. As for Sh.RN the failure of punching shear occurs earlier compared to the flexural failure whose features are not complete in this model, the failure of the punching shear in this model proves what the code predicts at a distance d/2 from the end of the punching shear reinforcement. In the two models made of normal concrete, we notice the delay in the appearance of the first crack compared to the rest of the models made of hybrid concrete, where (for NSC 31% of the ultimate load) and (for Sh RN 35% of the ultimate load).

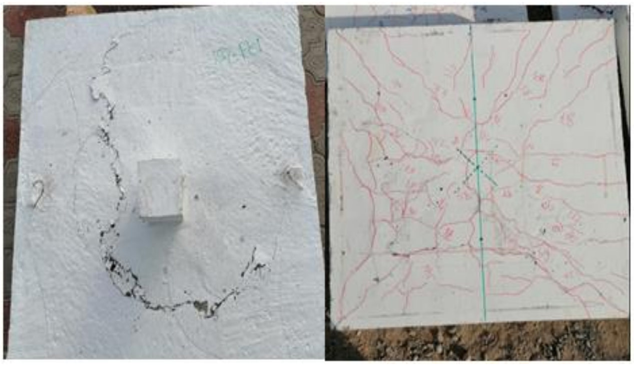
In the 187-PF model, it occurs Punching failure and the diagonal cracks where the first crack appeared in the connection NSC & UHPC and parallel to the first crack, cracks began to appear with the progression of the load and other cracks perpendicular to the previous one, and then the cracks developed and became diagonal towards the corners of the slab, and the last crack appeard in the tension face in the Figure 6(c).

In the 187-XF model, it occurs punching failure and the diagonal cracks too, great similarity between this slab and the previous sample to a large extent in the development of the cracks and the value of the first crack (25% and 26% compared to the the ultimate load and perhaps the only difference in the ultimate load.

In samples strengthen punching shear according to code distance (Sh.RN,187-PF &187-XC), failure occurs at a distance of approximately d/2 from the ends. a circular or redial crack occurs away from the column in the tension face of the slab in the two models (187-XC & 400-PC). Isolation occurs between NSC & UHPC in 400-PC and we can say that this form of UHPC strengthening made the slab fail with flexural failure (diagonal cracks or yield lines) in this model. In all the hybrid models in the face of tension, we notice the crack almost at the limits of the UHPC region , except in the 400-XC model, the failure occurs at a distance equal to the column side in all UHPC directions, as shown in Figure 6.

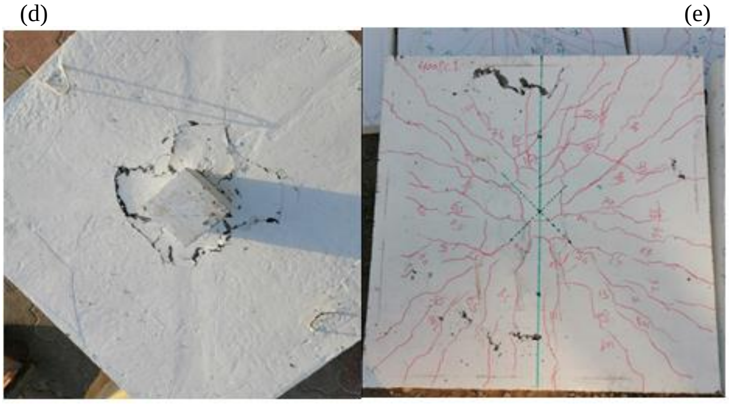


Tension face (a) | Tension face (b) | Compression face | Tension face (c)



Compression face Tension face Compression face Tension face

(d) (e)



Compression face Tension face

(f)

Figure 6. Failure Mode For All Specimens (a) NSC (b) Sh.RN (c) 187-PF (d) Specimen 187-XF (e) 400-PC (f) 400-XC

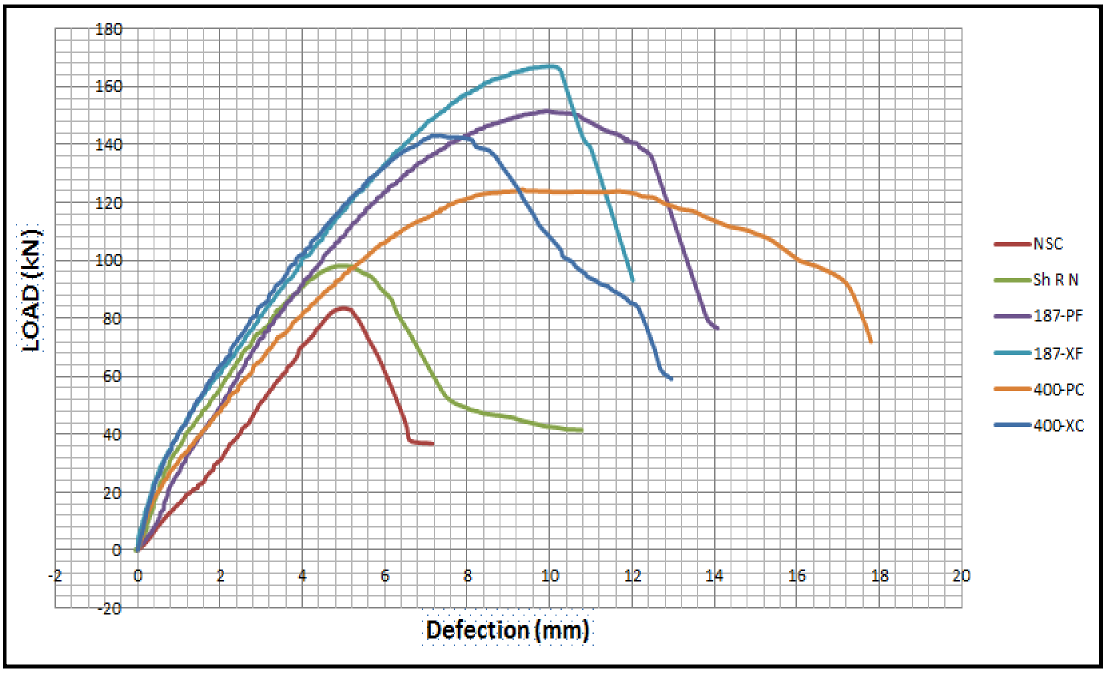


Figure 7. Load-Center Deflaction Curves of Specimens

TABLE 4. Result of Specimen

Specimen	First crack (KN)	Ultimate load (KN)	Ultimate deflection mm	Shear capacity (kN) ACI 318-19	Vexp./Vnum.	Failure type
NSC	26	83.5	4.98	58.45	1.42	P
Sh RN	35	98	5.03	72.24	1.35	P
187-PF	38	151.5	9.94	90.9	1.66	P+F
187-XF	44	167	9.94	103.54	1.61	P+F
400-PC	30	124	8.34	----	----	F
400-XC	36	143	7.31	----	----	P+F

where p: punching failure F: Flexure failure

4. 3. Load-Deflection Response

Generally, there was insignificant deflection at the first stage of loading representing the uncrack stage, however, the deflection increased after the formation of the first flexural crack in the slab.

All curves were drawn in one figure for ease of observation of the results and comparison between them in terms of ultimate load, deflection and area under the curve, from Figure7 (load-deflection curves) and Table 4 we observe the failure of the brittle and sudden punching shear for the model without the shear reinforcement

The models with UHPC total depth of slab gave a high punching shear bearing capacity that reached twice the resistance of the reference model and 70% of the model containing the punching shear reinforcement. The models with UHPC half thickness of the slab gave not high results to strength shear in 70% of the normal concrete model, but it change of failure pattern and contains energy absorbed after failure(post punching capacity) and which increase by increasing ratio steel fiber in UHPC.

The improvement of punching resistance after being proven by this practical study was compatible and supported by a theoretical study in the finite element method using the (ABAQUS) program by Kadhim et al. [42] and Sousa et al. [43] as shown in Figures 8 and 9.

The two above researchers used an expirmental study for the same as Zohrevand et al. [33] to compare with their theoretical study and they reached theoretical results with a small coefficient of change. They proved that using UHPC is a viable solution to strengthen the flat slab, and this is consistent with the conclusion of present study.

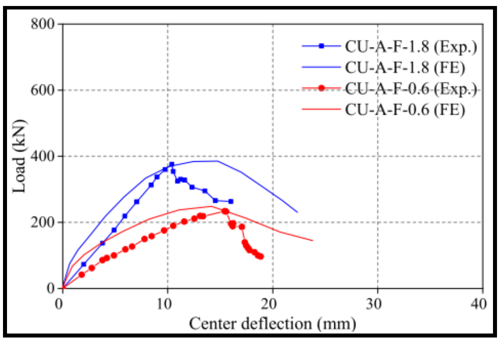


Figure 8. Validation Study: Load- Central Deflection [42]

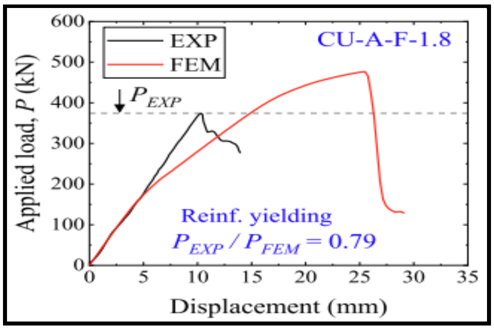


Figure 9. Validation Study: Load- Central Deflection [43]

5.CONCLUSIONS

Six square samples of flat plate slabs with central bearing of a column model consisting of normal concrete, this slab consisting from normal concrete or hybrid concrete (normal and high-performance concrete) to be tested the capacity of punching shear with the stability of the quantity of high-performance concrete with a change in its depth or shape. After the experimental study, the following conclusions were summarized:

1. The models with UHPC total depth of slab gave a high punching shear bearing capacity that reached twice the resistance of the reference model and 70% of the model containing the punching shear reinforcement.
2. The models with UHPC half thickness of the slab gave not high results to strength shear , but it change of failure pattern and contains energy absorbed after failure(post punching capacity).
3. We notice the crack at the limits of the UHPC region, except in the 400-XC model, the failure occurs at a distance equal to the column side in all UHPC directions so there is no need to use it.

4. Post punching capacity is the residual strength of slab may be measured as the load after punching failure at whose the load-deflection response tends to flatten and which increase by increasing ratio steel fiber in UHPC.
5. Hybrid slabs composed of NC and UHPC often fail the punching and flexural compound due to high initial stiffness and ductility of the UHPC.
6. Replacing the reinforcement shear with another strengthening is an important point that designers resort to in areas of rebar engagement.
7. From theoretical punching shear capacities, we conclude that the code equation (ACI318-19) is very conservative, and we also recommend suggesting a new mathematical model or an modify to the code equation in order to be inclusive of all forms UHPC and not just for regular shapes.
8. Since the sample rotated at an angle 45 gave the best results, so this study suggests that the position of the shear reinforcement should be studied at an angle 45 from what the code places.

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Persian Abstract

چکیده

مطالعات گسترده ای بر روی موضوع شکست برش پانچ در دال های مسطح و راه های استحکام بخشی داخلی، خارجی و اهمیت این سازه (دال تخت) و خطر شکست برشی پانچ در نواحی اتصال ستون متمرکز شده است. - دال بنابراین، این مطالعه مبتنی بر تقویت ظرفیت باربری دال تخت در برابر شکست برش پانچ با بتن با کارایی بالا (UHPC) بود. چون گران است، بنابراین استفاده از آن برای کل دال امکان پذیر نیست. بنابراین، هدف از این مطالعه جایگزینی برش پانچ آرماتور با UHPC و تعیین استفاده بهینه از آن در ناحیه برشی بود. شش نمونه دال مسطح تقویت شده با حداکثر فولاد خمشی بارگذاری شده با ستون در وسط، چهار فرم ریخته گری UHPC به جای آرماتور برشی و در دو عمق متفاوت استفاده شد. نتایج نشان داد که مقاومت برشی پانچ نمونه ریختگی با UHPC به جای آرماتور برشی پانچ (ACI 318-19)بهبود یافته و با تمام ضخامت دال، در مقایسه با نمونه مرجع (NSC)با فولاد خمشی مسلح شده، دو برابر شده است. فقط. این برنامه عالی برای UHPC است. همچنین اشاره شد که ریخته‌گری UHPC با نصف ضخامت دال در مقایسه با ریخته‌گری با تمام ضخامت‌ها، علیرغم دوبرابر شدن فاصله UHPC از تمام وجوه ستون، نتایج خوبی را به همراه ندارد. اما الگوی شکست را تغییر می دهد و آن را از مناطق خطرناک نزدیک ستون های ناخواسته دور نگه می دارد.