CONSTRUCTION
e-ISSN: 2785-8731
VOL. 2, ISSUE 1, 88 – 102
DOI: https://doi.org/10.15282/cons.v2i1.7583

ORIGINAL ARTICLE

Enhancement of the Punching Shear Resistance in the Normal Concrete Flat Slabs using Different Patterns of the Ultra-High Performance Fiber Reinforced Concrete Strips

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ABSTRACT – In the last few years, the flat slab system has become widespread for constructing multi-story buildings in many countries due to its simplicity and fast construction. However, the demand for the strengthening of reinforced concrete is a critical element in existing structures due to design or construction errors, and changes in the building function become a challenging area to develop and extend the durability of structures. In the reinforced concrete structure, flat slabs are the most critical element that requires strengthening because of exhibition punching shear failure. There are many materials and techniques used in the strengthening field. Due to well-known superior mechanical properties in strength and durability, ultra-high-performance fiber-reinforced concrete becomes the early relevant substance in the strengthening field. This study highlights the behavior of ten small-scale specimens of reinforced concrete flat slabs with different concrete grades, strengthened against punching shear by ultra-high performance fiber reinforced concrete strips in different distribution patterns at punching shear critical sections. The strips are jointed to the tensile slab surface through adhesive epoxy material. The outcomes indicated that the ultra-high performance fiber reinforced concrete strengthening strips enhanced the punching shear resistance of the normal strength concrete slabs, up to 53.1%, 16.63%, and 16.5% for different concrete grades examined in the study for flat slabs, which are 20.8, 32.6, and 43.3 MPa, respectively. This improvement in punching shear resistance was obtained by enhancing slab thicknesses and widening the resisting area for punching shear at critical sections. In addition, the strengthening technique transforms the failure's mode of slabs from brittle to ductile.

ARTICLE HISTORY
Received: 02nd Apr 2022
Revised: 18th Apr 2022
Accepted: 22nd Apr 2022

KEYWORDS
Flat slab
Normal strength concrete
Shear resistance
Strengthening Strips
Ultra-high performance fiber reinforced concrete

INTRODUCTION

The Reinforce concrete flat slab system structures have been broadly used worldwide. However, due to overcapacity, aging, and various destructive change in environmental conditions during many years of the structure's service life, these structures are going toward dropping their function in terms of carrying load capacity, stiffness, and durability, rather than sometimes they are used for different other purposes despite their original design function. Therefore, strengthening reinforced concrete flat slab system structures becomes essential to restore their functions and extend their lives to avoid the community charges in demolition and reconstruction [1].

Flat slab strengthening techniques against punching shear are one of the earliest topics investigated by researchers; several techniques have been developed. Currently, strengthening techniques against punching of reinforced concrete flat slabs that are externally applied to increase the ultimate shear capacity of slab-column connections can be obtained through two main approaches; (a) enhancing the capacity directly in shear and (b) enhancing the flexural capacity [2]. These two concepts in the strengthening field are expressed practically as four techniques category; the first is shear strengthening, like installing anchored or head bolts, grids of fans, and stirrups. Second, flexural strengthening can usually be achieved by adding longitudinal reinforcement on the top of the slab. Newly flexural strengthening consists of either gluing FRP strips in orthogonal directions or using a bonded reinforced concrete overlay. The third technique is an enlargement of the support, which could be improved by widening the column, casting a concrete capital, or post-installing a steel capital, and the last technique is post tensioning systems, where various types of pre-stressing systems have been adopted for the strengthening of existing slabs, such techniques considered under both shear strengthening and flexural strengthening categories. Recently, overall strengthening with fiber-reinforced polymers (FRP) in most strengthening techniques categories was used due to not being time-consuming, nor a change in the geometry of the strengthened elements, and increases the load-carrying capacity of the strengthened structures element. FRPs have critical disadvantages for strengthening reinforced concrete slabs, which do not present ductility, and for the right application of the material, experienced and trained staff is required [3].

Furthermore, the bond act performance between this external strengthening material and structures concrete element is still a weak point in the strengthening mechanism of the structures. The cost and difficulty of the previous techniques

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may at times counterbalance the advantages of flat slabs. Therefore, there is an obvious requirement for improved techniques to address punching shear in flat slabs.

Ultra-high-performance concrete (UHPC), as an originated cement-built composite material, has been developed in different countries. Recently studies on ultra-high-performance fiber-reinforced concrete (UHPFRC) have shown great potential for enhancing the punching shear capacity of flat slabs [4]. This different cementitious substance particle in admixtures was optimized to produce maximum packing density, with low water to binder ratio smaller than 0.25 by using a superplasticizer agent and adding steel fibers with volume content of 1-4%, leading to output concrete with high tensile strength grater 7 MPa and compressive strength grater 150 MPa, and high energy dissipation capacity with ductile failure due to fibers [3],[5]. Recent studies indicated that concrete combined with steel fibers subjected to cyclic loading displayed extra load-bearing capacities, cracking resistance, energy dissipation values, and deformation capability compared to non-fibrous concrete [6]. Correspondingly, the strength of UHPFRC could be improved faster throughout heat curing, where shrinkage and creep coefficients are small in that curing process [7].

Moreover, the strength of UHPFRC is superior to normal concrete reinforced with steel or fiber due to low air content and low water permeability that guarantee high durability [8]. Overall, due to these superior mechanical properties, UHPFRC is probable to become appropriate material for strengthening deteriorated RC structures elements, enhancing the flexural or shear capacity and ductility, and improving the permeability and durability of the specific strengthened structure element. Although studies clearly show that UHPFRC flat slabs have considerably higher punching shear strength than their complements from NSC, it may not be economically feasible to construct an entire slab by UHPFRC. Therefore, the researcher's strengthening field attempt to determine the optimal use of UHPFRC within the critical punching shear area [4].

Currently, many researchers focus on the slab-column strengthening of RC flat slabs using the UHPFRC layer [9]. Therefore, the research now in this new technique concentrates on combining the effectiveness of strengthening with cost, ease, and speed of preparation and application, rather than enhancing the RC elements' stiffness, resistance, and durability. Two different partial uses of UHPFRC mechanism techniques as a layer for the strengthening were performed, first sandblasting RC substrate surfaces then casting UHPFRC and second prefabricated UHPFRC element bonded to RC element using an epoxy adhesive. Test results showed that both techniques guaranteed a bond between the RC and UHPFRC layers [10].

Bonding properties and quality between the ordinary concrete and the strengthening materials is one of the most important issues in strengthening processes. Many codes provide several tests to ensure a desirable strong bond, such as ASTM. Several researchers have conducted experimental work and found a perfect bond property between the substrate and adhesive materials, especially for fiber-reinforced cementitious materials used to strengthen and repair structural elements. In this framework, various tests were carried out, such as; the slant-shear test with the inclined bond interface at 55°, 60°, and 70°, pull off, and splitting tensile tests for two different bonds mechanism methods, epoxy-bonded and sandblasted. The outputs present that those normal concrete specimens with rough surfaces made by sandblasting present higher slant shear strength than epoxy-bonded ones. Furthermore, the findings of splitting tensile strength reported a perfect bond between normal concrete and UHPFRC [10].

Similarly, split tensile strength, and slant-shear tests measured the bond strength between the host concrete and ultra-high performance fiber concrete UHPFRC. The results indicated that UHPRFC provides perfect bonding at the early strengthening age and works strongly together with the surface of the normal concrete [11].

Moreover, several experimental works were carried out and found excellent bonding through adhesive material between the host concrete and UHPFRC in different strengthening techniques. This means that UHPFRC bonded very powerfully and efficiently with the normal concrete and adhesive material, and they behave almost monolithic [12]. It was related to this concept, the outputs of the tensile splitting test highlight that the failure commonly happened in normal concrete samples.

Using a thin layer of UHPFRC as an external tensile strengthening for reinforced concrete flat slabs at punching shear critical section enhances the effect of slab thickness against punching and contributes effectively to the composite's bending and shear capacity slab. Zohrevand et al.[4] reported that the partial use of UHPFRC within the critical punching shear area of the RC slabs improves the shear capacity and significantly influences cracking patterns in the punching shear area compared to the reference RC slab. Based on the presented facts, this investigation attempt to develop an easy and practical model for strengthening flat slab against punching shear by using precast thin UHPFRC strips at critical section and evaluate the behavior and contribution effect on punching shear resistance of composite slab.

SIGNIFICANCE OF THE STUDY

The strengthening application of slab-column connections of flat slabs is considered the hardest type of strengthening practice. This experimental study investigated the punching behavior of interior slab-column connections of reinforced normal strength concrete (NSC) flat slabs strengthened with UHPFRC strips through adhesive material at the critical section of punching shear.

The present study evaluates the performance of strengthening different grades of reinforced normal strength concrete slab substrate by UHPFRC strips, jointed together in different distribution patterns at critical sections of punching with adhesive epoxy resin in the interface area. In addition, they are quantifying the effect of the different distribution patterns of UHPFRC strips used for strengthening different grades of slab specimen's substrate for punching at the crack and ultimate loads.

EXPERIMENTAL PROGRAM

The experimental program was organized for strengthening different grade of NSC flat slabs substrate by UHPFRC strips against punching shear as follow:

Methodology

The research attempt to investigate a new technique for strengthening different grade of NSC flat slab specimens against punching shear by using an unconventional material which is UHPFRC strips with different distribution pattern at critical location section, that composites through epoxy adhesive material,

The mixing design of normal strength concrete adopted in this study ensures obtaining three concrete grades for specimens of 21 MPa, 31 MPa, and 41 MPa at 28 days. Correspondingly, the mix design of UHPFC was adopted to produce strips for strengthening purposes with dimensions of 10 mm thickness and 20 mm width.

From a designed flat plate concrete slab structure with similar grid column lines of 5400 mm in both directions, the column dimension is 300×300 mm, and the thickness of the slab is 200 mm. Twelve one-four scale slabs were built, as tabulated in Table 1. The specimens represent interior slab-column connections, which are simply supported along its four edges, representing that portion of the slab within the negative bending moment region and inside the lines of contra flexure, which is approximately equal to 0.422 times the span between columns, based on Ali, B. A. [13]. The present simulated specimen produced in this case after scaling is a simple support square slab with a side length equal to 620 mm, to be tested at 570 mm c/c of supports in both directions, a total thickness is 50 mm, and loaded by bearing steel plate with dimension 75×75 mm serve like the central column. All the slabs were provided with two-way flexural reinforcement consisting of plain 5 mm bars in diameter, placed at the tension face with a clear cover of 8 mm below the mesh, as shown in Figure 1.

Table 1. Characteristics of slab specimens and strips parameters.

Parameters	Concrete grades		
	Slab specimens concrete grade, 21 MPa	Slab specimens concrete grade, 31 MPa	Slab specimens concrete grade, 41 MPa
Control slab without strengthening	GCF1	GCF2	GCF3
Strip pattern 1, fixed at critical section *d*	G3F1	G3F2	G3F3
Strip pattern 2, fixed at critical section 1.5 *d*	G3F1*	G3F2*	G3F3*
Strip pattern 3, geometric sun vector shape around 0.5 *d*	G3F1**	G3F2**	G3F3**

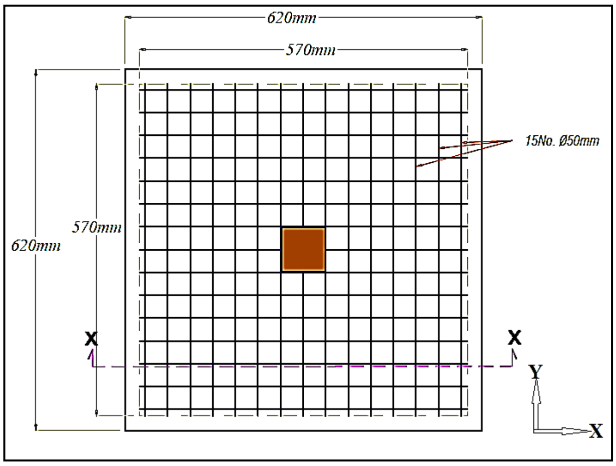


Figure 1. Flexural reinforcement of slab specimens.

Materials

Reinforced normal strength concrete slab specimens

Different grades of normal strength concrete were used in this study which are 21, 31, and 41 MPa for substrate slab specimens; all of the mixes contain Type-I ordinary Portland cement, river sand with fineness modulus of 2.4, coarse aggregate with a maximum size of 9.5mm, and different water-cement ratio based on to target concrete grades. The slump value of fresh concrete was between 150-and 180 mm. The mix proportion of the normal strength concrete slab specimens is shown in Table 2. Standard cylinders have been taken from NSC mixes for 28 days to ensure desired compression strength.

Table 2. Mix proportion for different grades of normal strength concrete.

Concrete type	Target strength, MPa	w/c	Mix proportion cement: fine aggregate: coarse aggregate
NSC	21	0.67	1: 2.1: 2.32
NSC	31	0.56	1: 1.6: 1.93
NSC	41	0.49	1: 1.23: 1.61

Ultra-high performance fiber reinforced concrete strips

The mix design of UHPFRC strips achieved by improving concreting techniques and materials and having a very low water-binder ratio contains Type-I ordinary Portland cement, densified silica fume, well-graded sieved, and dried fine sand, copper-coated micro steel fibers, and poly-carboxylate based superplasticizer. The physical properties of straight copper-coated micro steel fibers are shown in Table 3. It has an aspect ratio of 40, as shown in Figure 2. To prevent the growth and interconnectivity of micro-cracks by absorbing the tensile stresses included fiber with 2 % by volume [3]. The standard cylinder has been taken from the UHPFRC mix to ensure mechanical properties at 28 days. The mixed proportions of the UHPFRC strengthening material are displayed in Table 4.

Table 3. Straight coated copper micro steel fibers properties.

Fiber type	Diameter mm	Length mm	Aspect ratio	Tensile Strength, MPa	Elastic Modulus, GPa
High strength coated copper micro steel fibers	0.20	8	40	≥2859	45-50

Figure 2. Straight copper-coated micro steel fibers.

Table 4. Mix proportions for ultra-high performance fiber reinforced concrete.

Concrete type	Strength target MPa	Mix proportion					
		w/b	Cement	Silica fume	Plasticizer	Silica sand	copper coated micro steel fibers % by volume [14]
UHPFRC	≥150	0.24	1	0.25	0.0187	0.45	2

Adhesive material

Adhesives can consist of various materials or come in several forms; the more popular adhesives are polymers, composites, grouts, mortars, and glues. The evidence regarding bond strength between a substrate (reinforced normal strength concrete slab specimens) and strengthening material (UHPFRC strips) reported in the literature indicate that the important property ensuring the effectiveness of any concrete strengthening is the bond strength between the existing concrete substrate and the strengthening material [14]. Besides the degree of surface preparation roughness of the substrate, the bond strength is governed by the mechanical properties of the NSC substrate and strengthening material, especially the tensile strength that controls crack development at the interface [15].

TYTAN FIX JET 20 adhesive was used for jointing normal strength concrete slab specimens with UHPFRC strips in the investigation. Based on ASTM C1583[16]. Pull-off test implements for checking the bond between two parts by preparing three NSC slab specimens with dimensions 50×500×500 mm for three different grades of concrete 21, 31, and 41 MPa with preparing UHPFRC strips with dimensions 10×150×500 mm.

After 28 days curing process, each set of strips with a thickness of 10 mm combined with one of the different grades of concrete slabs by adhesion epoxy, as shown in Figure 3(a) and kept until the end of adhesion curing time. Then the operation of three cores on each combined slab-strip made and penetrated to the depth from NSC slab surface equal to the thickness of each strip above them, with 50 mm diameter in order to combine instrument dolly 50 mm diameter with the top surface of strips using the same adhesive material, as shown in Figure 3(b). The last stage is implanted after the adhesive curing period by applying direct tension force on the dolly to pull- off the substance, as shown in Figure 3(c). The result shows that the adhesive agent is acceptable for the study since de-bonding does not occur in the adhesive layer despite detachment and separation from the surface of NSC slab specimens occur in all grades, which ensures that no de-bonding occurs in the testing process, as shown in Figure 3(d).

Figure 3. Pull-off test phases.

SPECIMEN PREPARATION

The mold of normal strength reinforced concrete slabs was prepared by plywood with dimensions (620×620×50) mm for the three grades of concrete. For each grade such as 21 MPa, four specimens were prepared, one of them for control and denoted as GCF1, and remain three specimens denoted like G3F1 for strengthening strips pattern one, G3F1* for strengthening strips pattern two, and G3F1** for strengthening strips pattern three, similarly for other grades 31 MPa (F2) and 41MPa (F3). The fresh NSC was placed in the molds with a flexural reinforcement mesh and vibrated for 30 seconds on external electric vibrated with surface finishing to be left to set for 24 hours. After that, the NSC specimens were removed from molds and cured for 28 days; then, surface preparations were performed for the strengthening process with UHPFRC strips.

The strip's molds were prepared by plywood with dimensions of 10 mm thickness, 20 mm width, and different lengths based on the distribution pattern on critical location, which is the square pattern at distance 1d, 1.5 d, and geometric sun vector shape around 0.5d from the face of the column, as shown in Figure 4. The fresh mix of UHPFRC was placed in the strip molds and left to set in its molds for 16 hours. After that, the UHPFRC strips specimens were removed from molds and cured in the steam room for five days at a temperature of 55°C; they moved from the steam room and were cured in a water tank for 28 days. Finally, at the end of 28 days, the specimens were pulled out from the water tank for surface preparations.

Both NSC specimen slabs and UHPFRC strips, after 28 days of curing time left, dried at laboratory temperature for one day with the cleaning by removing the debris and dust on the substrate contacting the surface of all specimens. For the next day, the bonding process started by applying one layer of adhesive epoxy "TYTAN JET FIX 20" on each surface of specimens and strips to be bonded together according to the different distribution patterns and left for three days curing time for the epoxy setting in temperature of between 25 - 31°C to be completed for testing, as shown in Figure 4.

Figure 4. Strengthened NSC slab specimens by different distribution patterns of UHPFRC strips.

Test set-up

The normal strength concrete slabs were tested using the loading frame of a flexure test machine with a 15 tons capacity jack for loading that was associated with a loading cell for measuring the load, as shown in Figure 6. The NSC slab specimens were loaded using steel bearing plate head with dimension 75×75 mm as a representation of the column head from the design procedure after scaling, as shown in Figure 5.

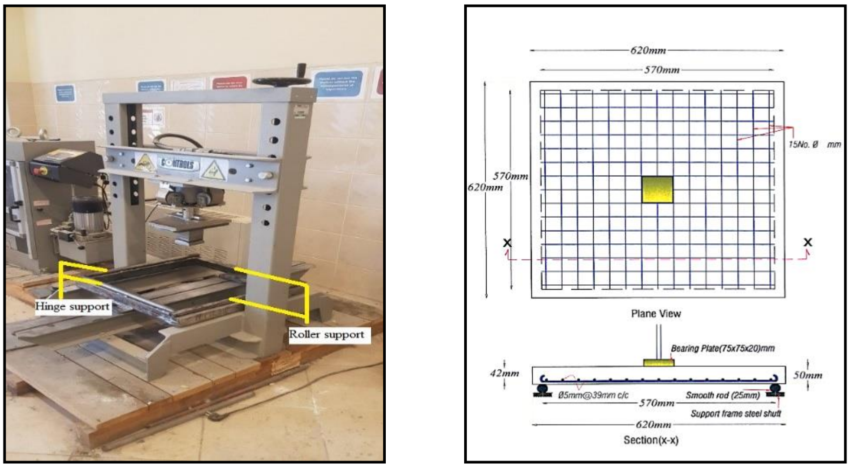


Figure 5. Loading set-up of the NSC strengthened slabs.

Ultra-high performance fiber reinforced concrete strips

Test measurements and instrumentations used for the loading arrangement for testing different grades of normal strength concrete slab specimens under pure punching shear loading associated with rotation angle, deflection, concrete strain, and the strain in reinforcements as follow:

1. Load measurements:

   The slabs were held and slowly set on the frame supports, as shown in Figure 7. The spacing between the fixed supports concerning the dimensions of the slabs is adjusted with the center of slabs setting dimension. The slabs were loaded using the machine's jack that serves as column head load at the slab center through load cells until failure under pure punching shear load.

2. The angle of rotation measurement:

   The slab specimen angle of rotation was measured during a loading test from the support relative to the center of slabs by fixing a digital inclinometer on the slab surface, and the data was recorded through the high-quality HD camera fixed in front of the testing machine of the slabs, as shown in Figure 7.

3. Deflection measurements:

   The slab specimen deflection was measured during a loading test by Linear Variable Displacement Transducers (LVDT), with 150 mm capacity, its box body fixed at the position of the slabs center parallel to the loading column head jack, was recorded the displacement occurred at the center of specimen surface vertically during the loading test, as shown in Figure 6.

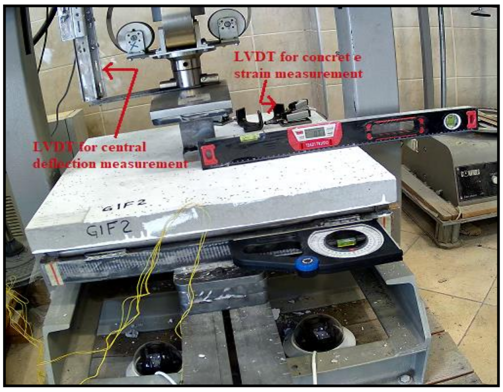


Figure 6. Loading set-up of flat slab strengthened specimens for punching shear test.

4. Reinforcement steel strain measurements:

   Electrical metal-foil sensing grid strain gauges were used for measuring strain occurring in the longitudinal reinforcements and fixed on the internal top surface of the central longitudinal reinforcement bars in one direction at three various positions at distances *0.5d*, *1d*, and *1.5d*, from the face of column location where *d* is the effective depth of slab specimen which is 42 mm.

5. Concrete strain measurements:

   The compression surface of slab specimens was prepared by drawing three lines at 0º, 45º, and 135º degrees at one of the slab corners [14], which intersection between lines positioned at 300 mm from support. The areas on the drawn lines were ground with sandpaper and cleaned with a gauze sponge. Then, the three LVDTs with 50 mm displacement measurement capacity were bonded to the prepared compression face by M200 superglue to make a strain rosette and denoting LVDT1, LVDT2, and LVDT3, in order to measure the slab concrete surface strain occurring during loading test, as shown in Figure 7.

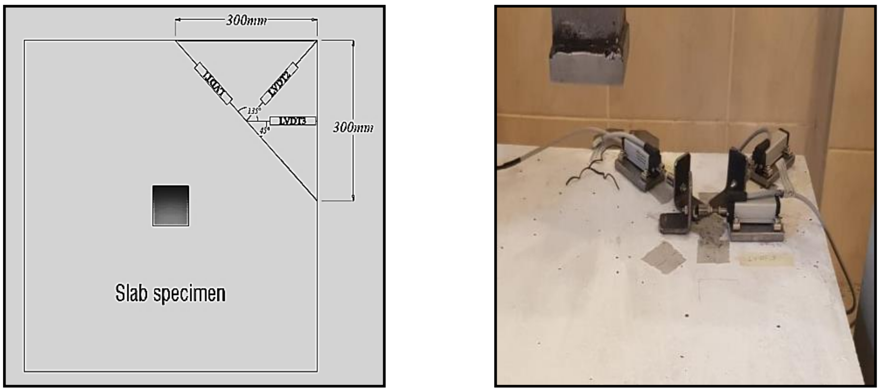


Figure 7. LVDT's rosette set-up for measurement of slab specimens' plain strain.

Testing procedure

The slabs were placed horizontally and centered on the supports, and then the first readings of strain gauges and instruments were recorded. The vertical load was gradually applied by bearing head column juke with a constant 0.05 MPa/s. At each loading stage, the deflection at the center of the slabs, rotation at the supports, LVDT's measurement of concrete strain on the compression face, and strains of reinforced steel bars were recorded and sought for the appearance of any cracks. The positions and extensions of the first visible and other consequent cracks were marked during loading. When the failure was achieved, the failure load was recorded, and the loading was stopped at that moment, which showed a drop in load reading associated with increasing LVDT reading. Some photographs of the final crack patterns were taken. The whole testing process of each specimen was recorded through four full HD digital cameras, where two of them fixed under-slab specimens for observation and detection of the first crack and one of them fixed next to the testing machine to record the testing process and the last fixed on the machine load cell and data analog for recording reading process.

EXPERIMENTAL RESULTS

A quantity of data was collected from the tests. The load is considered the most suitable relation between the data. Therefore, the experimental load-support rotation, load-mid-span deflection, load-reinforcements strain, and load-concretes strain relationships were organized for all tests. The experimental relationships are presented and investigated to identify the effects of parameters and behavior of specimens at the critical area of punching shear under loading.

Mechanical properties of concretes

The mechanical properties of different grades of normal strength concrete used for slab specimens and ultra-high performance fiber reinforced concrete used for strengthening strips, such as compressive strength, tensile strength, and modulus of elasticity, used for casting reinforced concrete slab specimens and punching shear strengthening strips were investigated.

Mechanical properties of normal strength slab concrete

The mix proportions designed to obtain three grades of concrete, 21, 31, and 41 MPa, were used to cast thirty slab specimens strengthened with UHRFC strips in three groups, each containing four slab specimens. The mechanical properties of normal strength concrete were determined for all groups, and the result summary of these properties is presented in Table 5.

Table 5. Mechanical properties of normal strength concrete used for slab specimens.

Slab group	Target grade of NSC, MPa	Cylinder compressive strength, MPa	Splitting tensile strength, MPa	Flexural strength, MPa	Modulus of elasticity by ACI eq., GPA
GCF1	21	20.8	2.07	3.8	21.44
GCF2	31	32.6	2.31	4.35	26.84
GCF3	41	43.3	3.02	5.18	30.93

Mechanical properties of ultra-high performance fiber reinforced concrete

The mix proportions were designed during the trial mix period for the ultra-high-performance fiber-reinforced concrete strips with an aspect ratio of fibers 40 (AR-40), to be used for producing strips for strengthening normal strength concrete slab specimens, From the same mix proportions of UHPFRC of strips, cube sample of (200×200×200) mm was taken and used for determining the static modulus of elasticity by ultrasonic pulse velocity test based on ASTM C 597 [17], as shown in Table 6.

Table 6. Mechanical properties of UHPFRC strengthening strips.

Concrete type	Cylinder compressive strength, MPa	Splitting tensile strength, MPa	Flexural strength, MPa	Modulus of elasticity by UPV test, GPA
UHPFRC	173.24	13.77	13.83	51.23

Punching loads of the strengthened flat slabs

As shown in Figure 8, the outcomes of test results clearly show a significant increase in cracks load for all grades of NSC slab specimens strengthened with UHPFRC strips compared to the controls slab specimen. The results indicate an increasing crack load of 99%, 138%, and 135% for Pattern one, Pattern two, and Pattern three recorded for concrete grades 20.8 MPa, respectively. Similarly, 12.56%, 13.2%, 28.9%, and 12.4%, 14.6%, 17.9% increasing crack load recorded for concrete grades 32.6, 43.3 MPa, respectively, which means that the strengthening with UHPFRC strips enhances the energy absorption capacity of slab specimens respect to load increasing before cracking.

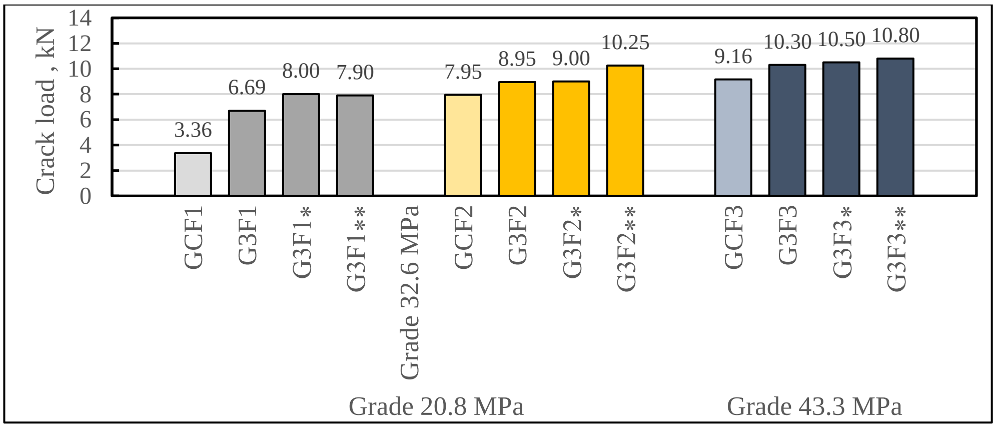


Figure 8. The effect of strips distribution pattern on the punching shear resistance of slab specimens at crack load.

The ultimate strength of slab specimens at failure was improved compared to the non-strengthened control specimens due to the strengthening with UHPFRC strips. The ultimate load capacity improved, as shown in Figure 9. Ultimate load increases around 5.75%, 53.1%, and 24.72% for Pattern one, Pattern two, and Pattern three for concrete grades 20.8 MPa. Similarly, 7.9%, 16.6%, 14.5%, and 3.8%, 16.5%, 7% increasing crack loads were recorded for concrete grades 32.6, 43.3 MPa, respectively; these results mean that the strengthening with UHPFRC strips in different distribution patterns improve ultimate strength capacity of slab specimens respect to load increasing before failure due to presenting more flexible behavior lead to exhibited significant growth in ultimate strength at the failure in all different grade of concrete strength.

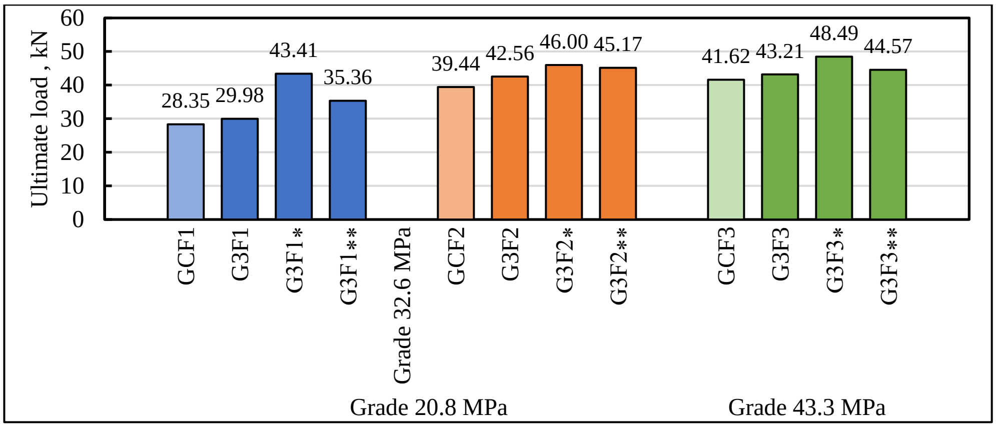


Figure 9. The effect of strips distribution pattern on the punching shear resistance of slab specimens at ultimate load.

Load-deflection relationship in the tested slabs

The deflection was measured at the center of the tested slab specimens by LVDT. The load-deflection relationship was nearly linear, and the deflection was almost insignificant as the slabs preserve a relatively high stiffness before concrete section cracking. After the first crack appeared, the load-deflection relation largely depended on the reinforcement and the strips distribution pattern for strengthening punching shear.

The distribution of UHPRFC strips in different patterns for strengthening covered different areas of the critical section of punching shear and influenced deflection. Figure 10 shows that deflection curves of tested slabs with concrete strength of 20.8 MPa, strengthened by different strips distribution patterns, that all pattern has a good effect on a deflection with developed load up to failure, especially Pattern three means more flexible actions and punching resistance while the slab specimens with strengths of 32.6 MPa and 43.3 MPa do not show the same behavior, as shown in Figures 11 and 12. It notes that ultimate load at failure increases without improving deflection compared with the control slab specimen. Therefore, the type of patterns slightly affects deflection when the compressive strength of concrete grade rises.

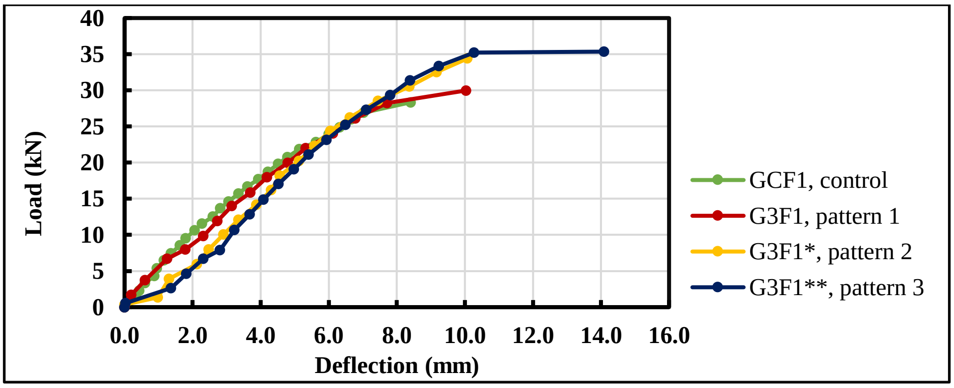


Figure 10. The effect of distribution strips pattern on the deflection of flat reinforced concrete slab specimens G3 in GCF1 set, with concrete grade 20.8 MPa.

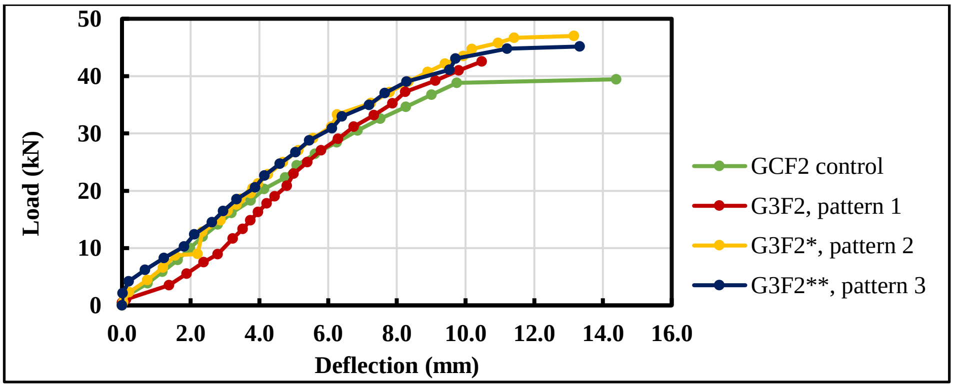


Figure 11. The effect of distribution strips pattern on the deflection of flat reinforced concrete slab specimens G3 in GCF2 set, with concrete grade 32.6 MPa.

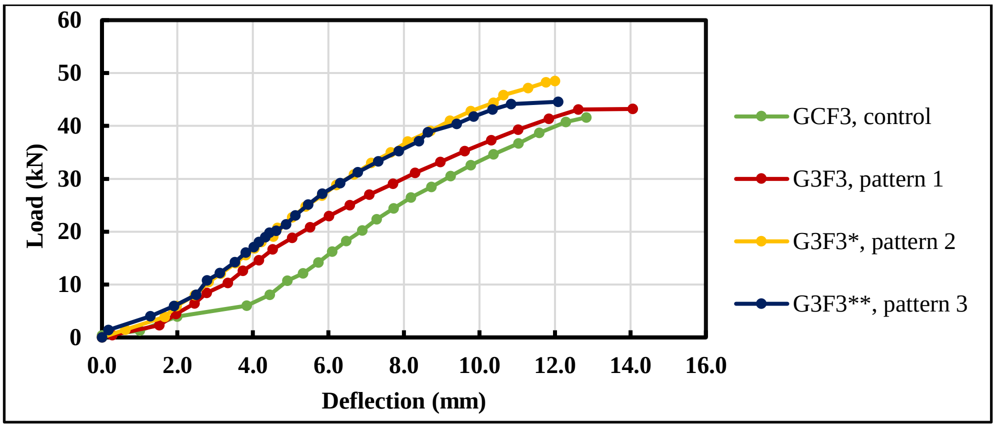


Figure 12. The effect of distribution strips pattern on the deflection of flat reinforced concrete slab specimens G3 in GCF3set, with concrete grade 43.3 MPa.

Support rotation

Figure 13 shows that strengthened slabs using UHPFRC strips increase the angle of support rotation compared with the control specimen, this increase of angle rotation varies according to the type of strips distribution patterns, where an increasing amount of 109%, 507 %, 664% at crack load, and 99%, 75 %, 20% at ultimate load for pattern 1, pattern 2 and pattern 3 recorded respectively. From these results understood that type of strips pattern influence effectively on the deformation capacity of the strengthened slab specimens.

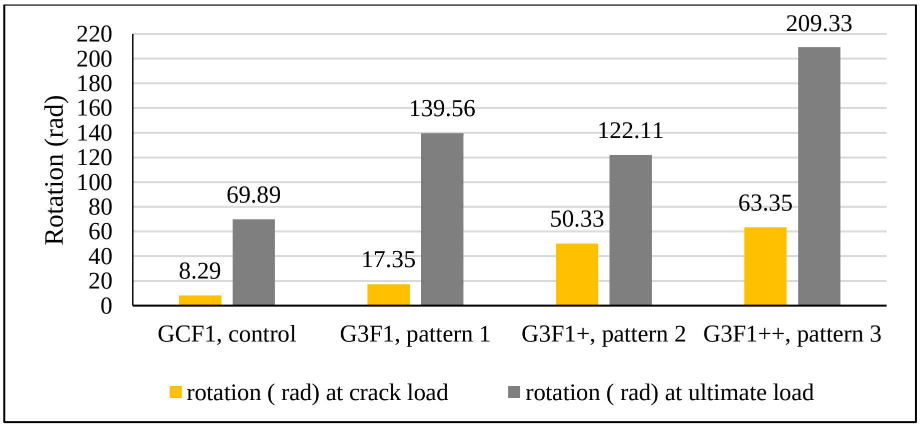


Figure 13. The effect of strips distribution pattern on the support rotation for concrete grade 20.8 MPa at the crack and ultimate load, set G3 of GCF1.

Slab specimen under label GCF2, set G3, the rotation angle data of this set, as shown in Figure 14, indicate that each pattern increases the rotation angle compared with the control specimen; the displayed results show the moderate effect on strengthened slabs deformation capacity when compressive strength increase because of a slight increase of rotation angle about (81%) at crack load and about (51%) at ultimate load were recorded.

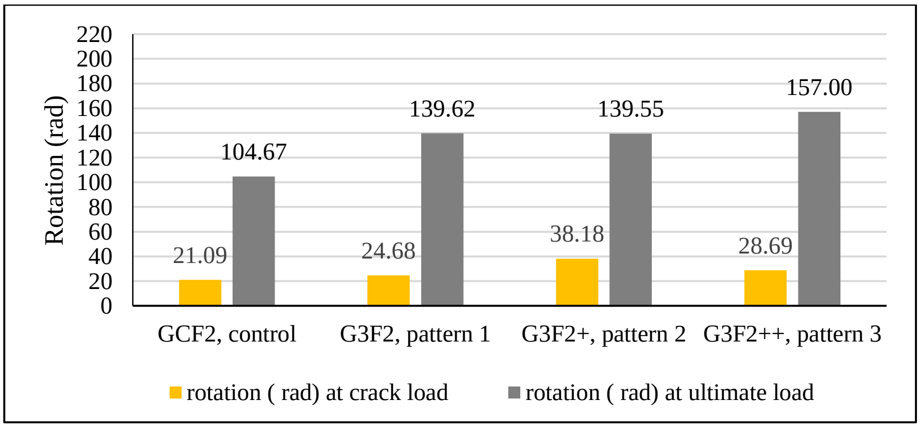


Figure 14. The effect of strips distribution pattern on the support rotation for concrete grade 32.6 MPa at the crack and ultimate load, set G3 of GCF2.

Figure 15 detected that patterns two and three of UHPFRC strips have no remarkable effect on the angle of rotation at the crack load stage compared with the control specimen, while distribution pattern one has a little positive effect. All the Patterns that detect positive effects at the ultimate load stage were important; increasing the rotation angle detected, especially distribution pattern 1, means more increase in deformation capacity of slab specimens while increased changes occur in the compressive strength of slab specimens.

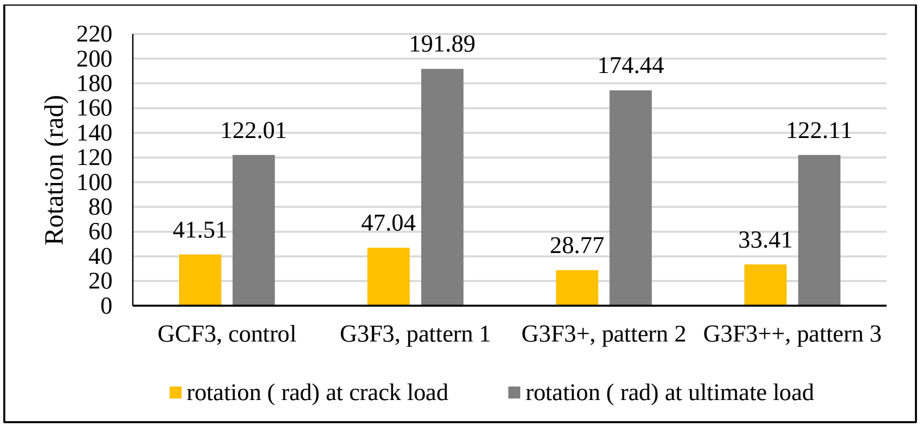


Figure 15. The effect of strips distribution pattern on the support rotation for concrete grade 43.3 MPa at the crack and ultimate load, set G3 of GCF3.

Strain in steel reinforcement

Strain gauges were fixed on the surface of the flexural reinforcement at three locations distance from the face of the column, which are 0.5 d, 1 d, and 1.5 d, as indicators for the value of strain in refinement at a different position in reinforced concrete slabs, as shown in Figure 16.

Figure 16. Location of strain gauges on reinforcement of slab specimens.

The experimental load-strain relationship for teste slab specimens was accomplished, and three sample cases are displayed in Figures 17 - 19 for all types of concrete strengths (20.8 MPa, 32.6 MPa, and 43.3 MPa) strengthened with different distribution patterns of UHPFRC strips. Generally, in nearly all slabs, the reinforcement strain curves change in slope at a specific location; this can be considered the first cracking load. After creating the first crack, the rate of strain increase when the loading increase at the same rate. It is noted that when the slab specimen's compressive strength increases, the strain decreases. The strain profile of the slabs developed at different load levels compared with control slabs. In all cases, their role is perceived in the strain relationships in transferring the amount of strain from the critical section for punching far away from the column.

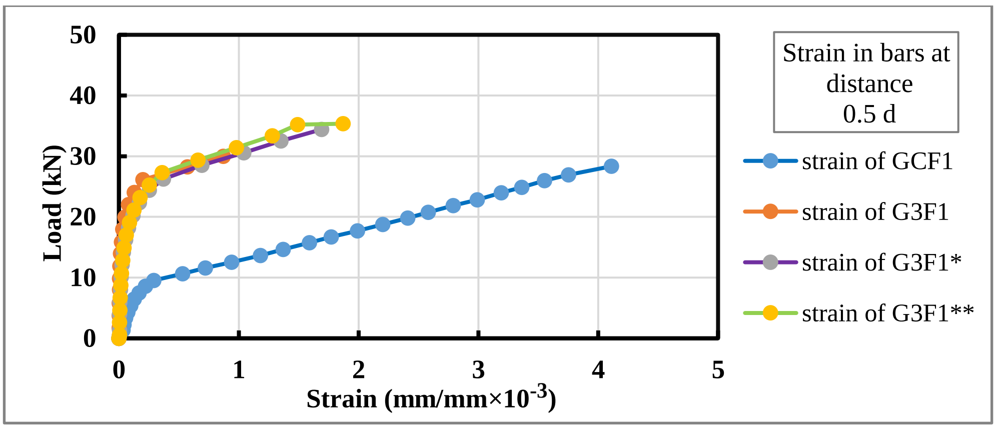


Figure 17. Load versus strain in reinforcement located at a distance 0.5 d from column face, for different strip distribution pattern G3 of GCF1, compressive strength 20.8 MPa.

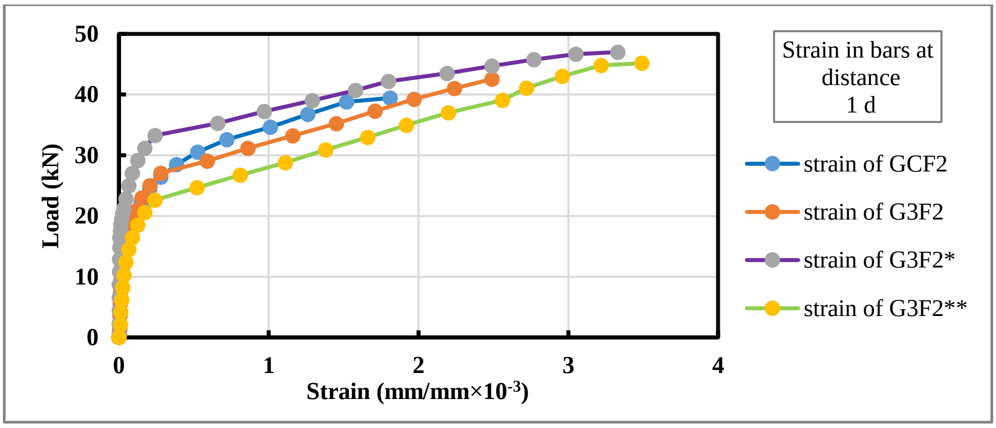


Figure 18. Load versus strain in reinforcement located at a distance 1 d from column face, for different strip distribution pattern G3 of GCF2, compressive strength 32.6 MPa.

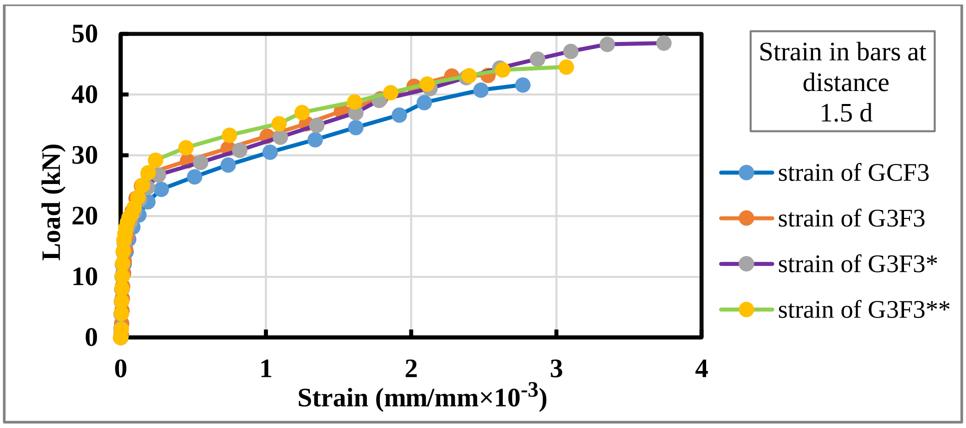


Figure 19. Load versus strain in reinforcement located at a distance 1.5 d from column face, for different strip distribution pattern G3 of GCF3, compressive strength 43.3 MPa.

Strain at concrete surface Different

Figures 20 – 22 show the variation of strain in concrete at the compression face of the flat slab with loads. The maximum shear strain of concrete in the principal plane was measured by three LVDTs placed based on the Strain Rosettes arrangement and set up at 0º, 45º, and 135º degrees concerning the horizontal top surface planes of concrete slab specimens to obtain principal shear strain during the test procedure. Figure 20 shows that all different distribution patterns of strips used in strengthening slab specimens have a significant effect on reducing shear strain in concrete compared to control specimen GCF1, which means absorption enhancement of extra energy for the load increasing, as noticed from the data recorded were the crack load rises to compare to control specimens, which lead to higher punching resistance at ultimate load failure for this grade of concrete strength.

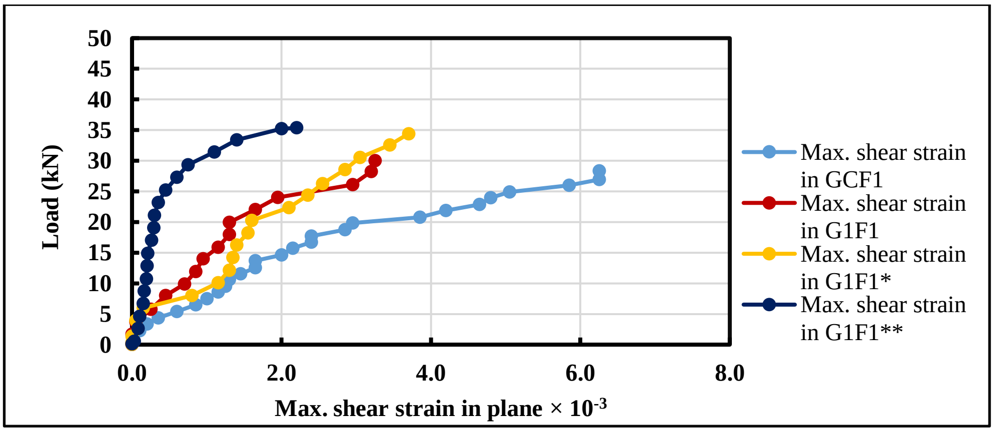


Figure 20. Load versus maximum plane shear strain at compression face of concrete slab specimens G3 of GCF1 set, strips distribution pattern vary, with grade 20.8 MPa.

The strain increasing rate to the increased loading rate from the outcome results remains the same in most slabs and higher than the control specimen's strain for the same load, as shown in Figure 21. While two strengthened slab specimens, which are G3F2 and G3F2*, reduce the amount of concrete shear strain overall points during the loading up to failure concerning the increasing loading rate.

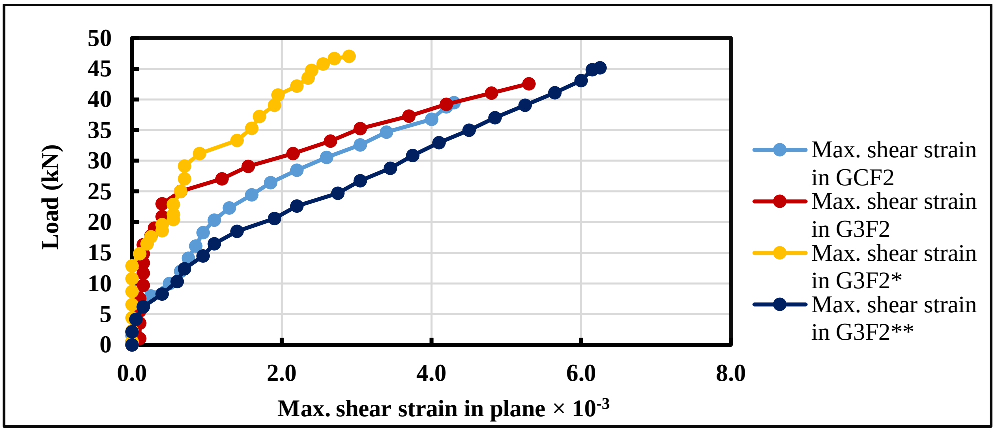


Figure 21. Load versus maximum plane shear strain at compression face of concrete slab specimens G3 of GCF2 set, strips distribution pattern vary, with grade 32.6 MPa.

The high rate of concrete shear strain detected for the GCF3 set, as shown in Figure 22 for increasing load rate, due to the high strength of slab specimens, indicates that strengthening UHPRC strips on energy absorption reduced when the strength of concrete grows up. In contrast, their character for increasing the ultimate load of failure remains according to the figures' relationships.

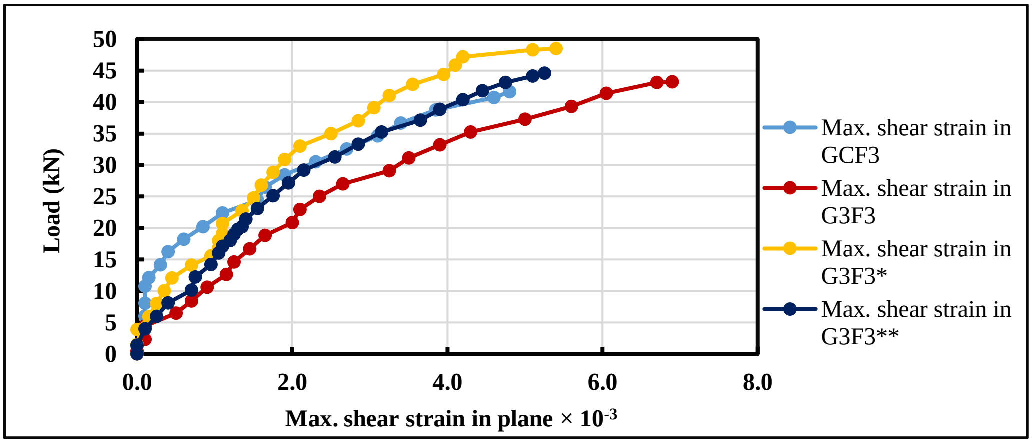


Figure 22. Load versus maximum plane shear strain at compression face of concrete slab specimens G3of GCF3 set, strips distribution pattern vary, with grade 43.3 MPa.

The pattern of cracks and modes of failure

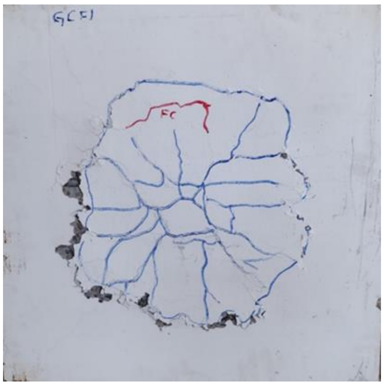
Different the punching shear failure of reinforced concrete flat plates is a brittle form of failure and mystified researchers for a long time due to the complexity of its mechanism that depends on a large number of factors and the difficulty of direct measurements of the internal failure mechanism. Observation from previous punching shear studies cannot provide sufficient experimental evidence for revealing the failure mechanism. The failure mode is usually identified based on structural reactions from experimental observations such as load-deflection response, strain in flexural reinforcement, principal compressive stress and strain in concrete, and crack pattern. Accordingly, the encountered failure modes during the slab tests can be categorized into flexural punching, punching shear, and premature de-bonding. The premature de-bonding failure was also followed by brittle punching failure [18].

The investigation results in an observation indicated that critical shear cracks developed from internal diagonal cracks initiated at mid-height of the slabs and unevenly distributed around the columns. The propagation of the internal diagonal cracks was independent of flexural cracks initiated at the slab tension faces but closely related to the unloading of radial strains of concrete at the slab compression faces. As the load increases after the first crack's formation, more cracks begin to appear and move towards the edge of the slab. In the compression face of the tested slabs, some cracks appear away from the edge of the column. At the moment of punching failure, the critical shear cracks propagated from compression to tension zones, forming a punching failure cone (pyramid). Moreover, the punching shear failure process was progressive; that is, the continuous weakening of the compression zone by the critical shear crack resulted in the shear splitting of the compression zone, which generated the final failure of the connections.

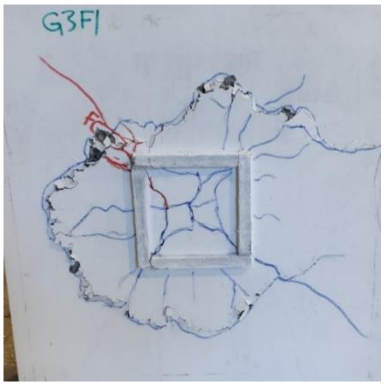
The crack pattern of the tested slab specimens is shown in Figure 25. Which are final tension faces Patterns after the slabs failure; through observation and comparing these patterns, It was realized that the failure mode of the control specimens, which are not strengthened by the UHPFRC strips, regarded as having a punching shear failure type, the first crack formed around the perimeter of the column and extended in both directions toward the center of column and radial toward the corner of the slab with increasing of the load, at the same time gradually the number of small cracks start to develop around the central area of slabs with extending to the outer area in all direction.

The effect using different UHPFRC strips distribution patterns no enlarging in the radius of failure zone were observed as shown in collected Figures 23, except in some cases, the type of strips parameter strengthening enlarge the area of punching far away from 0.5d from the face of column region to outward, this observed in slab specimens G3F1, G3F2*, G3F2**and G3F3**, as shown in Figure 23. As punching shear zone observation displays, distribution pattern 2 has a greater effect on increasing the number of cracks in the punching shear zone than the other distribution pattern.

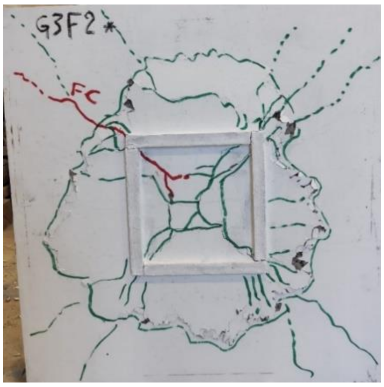
The slab specimens were strengthened by different UHPFRC strips distribution pattern viewed punching shear failure due to the sudden separation of circular crushing around the column at failure load without more extending of cracks toward slab corners, except the slabs G3F2* and G3F3, which appears flexural-shear punching mode failure due to weak contribution of the strips distribution pattern effect used for them to alter the mode to punching shear failure by absorption more load energy applied.



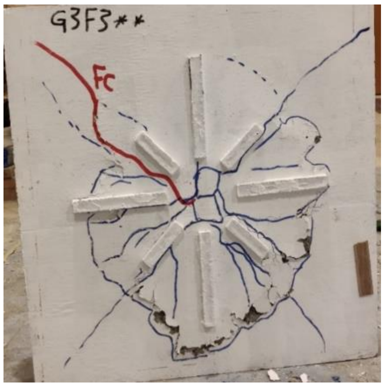
GCF1 tension face, No. of cracks 15



G3F1 tension face, No. of cracks 18



G3F2* tension face, No. of cracks 23



G3F3** tension face, No. of cracks 16

Figure 23. The pattern of crack and mode of failure at tension face of strengthened slab specimens.

CONCLUSIONS

The study outcomes data from the tests of flat slab specimens strengthened by different distribution patterns of ultra-high performance fiber reinforced concrete strips against punching shear and statically analysis of the result obtained from the tests, performed following conclusions drawn below:

a) Pattern two, where the distribution of UHPFRC strips used for strengthening slab specimens is square shape jointed to slabs tension surface at a distance 1.5d from the column face, has an excessive effect on punching shear capacity at the crack and ultimate stage in all concrete slabs grades, where maximum increasing of 138%, 28.9% and 14.6% at crack load and 53.1%, 16.6% and 16.5% at ultimate load record for slabs concrete grade 20.8, 32.6 and 43.3 MPa respectively.

b) Pattern three, where the distribution of UHPFRC strips used for strengthening slab specimens is geometric sun vector shape jointed to slabs tension surface at a distance 0.5d from the column face, has a moderate effect on punching shear capacity at crack stage lone in all concrete slabs grades, where maximum increasing of 135.1%, 28.9% 17.9% recorded for slabs' concrete grades 20.8, 32.6 and 43.3 MPa, respectively—corresponding to ultimate punching shear resistance moderate effect observed.

c) The load-deflection and support rotation relationship of the strengthened slab specimens with the UHPFRC strips clarifies significant flexural behavior increases compared to control slab specimens, which express the transformation of the failure mode from brittle to brittle ductal failure.

d) From observing the failure mode of slab specimens, Pattern two increases the punching area zone far away outside the column, which mentions the growing deformation capacity of slabs before failure.

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