CFRP Strengthening Of Concrete Slabs With And Without Openings

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Abstract: This paper presents an experimental investigation of reinforced concrete slabs with openings and strengthened with (CFRP) sheets, all slabs tested under uniformly distributed load with simply supports on the four edges by using high strength concrete. The experimental work includes testing of sixteen reinforced concrete slab specimens with dimensions (1050x1050) mm and (80) mm depth, as well as a series of tests carried out on construction materials. These slabs were arranged in group (1 to 6), where specimen group (1) is slab without openings and without strengthening, all other remaining groups contained three specimens with opening in the middle strip, one specimen was unstrengthened and the others were strengthened with CFRP sheets using two different schemes. The experimental work also includes studying the existence of a square opening in the center of slab (group (2)) and comparing the division of one square opening into two square opening, so the total area of them was equal to the area of one square opening in group (2). These opening were placed within the middle strip of slab, group (3) was central converging opening (center of the middle strip) and group (4) was central diverging opening (on the side of the middle strip), but group (5) and (6) are represented slabs with two opening in the middle strip converging and diverging respectively. Experimental results showed that the presence of the openings, the unstrengthened specimens showed a decrease in ultimate load capacity between (20.3% - 29.6 %) with respect to the control solid slab especially slabs with two converging opening showed a significant decrease in ultimate load capacity. On the other hand, the test results clearly demonstrated that the use of CFRP depends on the strengthening scheme which leads to a significant improvements by (33.3% - 87.5%) in the cracking load and (26.2% - 55.1%) in the ultimate load compared with unstrengthened slab with opening. The experimental tests also showed the slab specimen with two diagonal diverging opening and strengthening with CFRP by second scheme leading to the best results in cracking load by (36.4%) and ultimate load (21.8%) as compared with the control solid slab.

Index Terms: Reinforced Concrete Two-way slab, High Strength Concrete, One central Opening, Two Opening in the Middle Strip, uniformly distributed load, CFRP Sheets.

1 INTRODUCTION

Reinforced concrete structures are largely employed in engineering practice in a variety of situations and applications. Reinforced concrete slabs are among the most common types of structural elements. The slab may provide the lower support floor or upper support roof in any space: e.g., in-situ, precast or composite with a great variety of structural forms: e.g., one way, two ways, beamless and waffle slabs. Slabs are used to provide a flat and helpful surface in construction of reinforced concrete. It is broud, flat plate, with surfaces top and bottom parallel or nearly so. It may be supported by masonry, reinforced concrete beams or walls, structural steel members, columns or continuously by the ground. Reinforced concrete slabs are relatively thin flat structural elements that has the main function to sustain loading acting normal to their plane. However, in addition to this loading, design procedures must take into account environmental effects, such as temperature, and the ability of the slabs to resist load components acting parallel to their plane. Slabs are used as floors and roofs of buildings, as walls in tanks and bridges to transmit relatively heavy concentrated loadings [1].

2 Concrete Slab with Opening

Suspended RC solid slab has been widely used for the multi-storey building and large openings are required by lift, stairways and elevator shafts. Meanwhile, small openings are wanted in the slab to pass the mechanical and electrical services such as plumbing, heating and ventilating risers. The influence of small openings in the structural is not often considered in view of the ability of the structure to redistribute stresses. However, the large openings, the static system may be changed when it needs to remove a significant amount of concrete and reinforcement bar. This may lead to decrease in ability of the structure to resistance the applied loads and the structural requirements [2]. It frequently happens that structures need to be revamped because of numerous components, or instances. These instances are needed for openings to be created. In some cases the need for openings in slabs becomes amongst the most widely problems encountered in the structural engineering when dealing with reinforced concrete slabs, placing new staircases, elevators, additional skylights plumbing, fire protection pipes, heat and ventilation ducts, air conditioning, and utilities (telephones, electricity and wiring ducts), also architectural aspects are often required through the existing floor slabs. Depending on the character of improving, the location of the opening could be either in the negative or positive moment regions of the slab leading to create problems that problems can't be addressed to utilize the same way [3]. In the design of concrete slabs with openings, the building codes propose instructions that are not supported by the underlying theories. Slabs with small holes are traditionally designed using the strip method. For larger holes the strip method is often used, but this method is not accurate and underestimates, in some cases, the load capacity of the structure. Due to lack of accurate calculation method, the size of an opening and the magnitude of allowable load are limited by codes. Considering the relatively low price of steel nowadays, it is hard to find economical aspects in possible improvements in this area. However, knowing the stress distribution in such structures would constitute a background to invent new ways to reinforce and make the design more flexible.

3 HIGH-STRENGTH CONCRETE

The term "High-Strength Concrete" is generally used for

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concrete with compressive strength for (150*300mm) cylindrical specimens of 41 MPa or greater (ACI Committee 363) [4]. HSC is generally a late improvement in the technology of concrete made possible by reducing water admixtures and high-strength cementitious materials (Price, 2003). In recent years, there has been rapid growth in the use of HSC. Moreover, the strength level of high strength concrete, which is commercially available, is being increased [6]. leading to design smaller cross sections. This allowing longer spans, more usable area and in turn reduces the dead weight of buildings [6]. Although HSC provides advantages in terms of performance and economy of construction, a major drawback remains the brittle behavior of the material in some structural applications especially in earthquake resistant structures. Since ductility and strength of concrete are inversely proportional, high strength concrete is significantly more brittle than the normal strength concrete [7]. HSC has been used in many structural applications such as in prestressed concrete beams, bridges, and high rise structures and in the repair of structures (ACI Committee 363) [4]. Many major concrete codes from around the world are based on research conducted on structural members made of normal strength concrete where compressive strength is less than 41 MPa. Recently, some codes have included provisions for the design of high-strength concretes members [8].

4 Objective of the Study

The objectives of the present work are:

1. Experimental study and comparison of the performance of reinforced concrete two-way slabs without opening, with one central opening and two openings having equal the area of one opening and different location in the middle strips under uniform static loading.
2. Investigating the effect of strengthening on RC slab with openings by using CFRP sheets attached to tension faces, and also the effect of the provided length of CFRP sheets.

5 Materials Used to Fabricate the Specimens

The materials used in this investigation are commercially available materials, which include cement, fine aggregates, coarse aggregates, superplasticizer (Viscocrete 4100) and reinforcing bars are used in designing and casting of reinforced concrete two-way slab, while CFRP sheets and epoxy resin are used for strengthening of these slabs. The specifications and properties of these materials are as under:

5.1 Cement

Ordinary Portland cement manufactured by (Tasloja-Keresta) produced in Iraq used throughout this study which confirmed to the Iraqi Specification No.5/ 1984 [9].

5.2 Fine Aggregate (Sand)

Natural sand from Al-Najaf region in Iraq was utilized as fine aggregate. The fine aggregate was sieved at sieve size (4.75mm) to separate the aggregate particle of diameter greater than 4.75mm. The grading test results conform to Iraqi standard No.45/1984 [10].

5.3 Coarse Aggregate (Gravel)

Natural crushed gravel of maximum size 20 mm obtained from Al-Nebai region was used throughout the experimental work. Its grading satisfied the limits of Iraqi standard No.45/1984 [10] for graded gravel.

5.4 Superplasticizer (SP)

Sika Viscocrete 4100 (conforms to the requirement of (ASTM C494-1990)) [11] Type (GF & BSEN 934-2) was used throughout this study with nominal dosage of (0.64 litter per 100 kg of binder) as recommended by technical data sheet.

5.5 Steel Reinforcement

Deformed steel bars (Φ 6mm) in diameter were used as reinforcement to test slab specimens obtained from Turkish production. The tensile test was performed using the testing machine in the Material Laboratory of the Material Engineering Department at AL-Kufa University. The universal testing machine used was capable of recording the load-displacement curve using a computer system until failure of the specimen. Static yield stress and ultimate strength are summarized in Table (1).

Table (1) *Properties of steel bars*

Dia. (mm)	*Dia. Equiv.*	*Weight (g/m)*	*As (mm^2)*	*fy (MPa)*	*fu (MPa)*	*Elong. (%)*
6	*5.89*	*212.5*	*27.244*	*550*	*620*	*1.9*

5.6 CFRP Properties

The kind of Carbon Fiber Fabric Sheet used in this study is (SikaWrap- 230C). When tension load is applied on CFRP fiber, they do not exhibit any plastic conduct (yielding) before rupture. The tensile conduct of CFRP fibers is characterized as a linearly elastic stress-strain relationship up to failure. Table (2) shows the properties of the CFRP taken from manufacturer's specification (Technical Data Sheet of Sika 2005) (Sika, 2005).

Table (1) *Properties of carbon fiber fabric laminate (Sika, 2005)*

Fiber orientation Deg.	Weight g/m^2	Thick. mm	Tensile strength MPa	Tensile E-modulus MPa	Elong. %
0º	230	0.131	4300	238000	1.8

5.7 Epoxy Resin

Impregnating resin of type Sikadur-330, comprising of two parts (Resin part A + Hardener part B), was utilized for the glued of CFRP sheet. Table (3) shows the properties of the bonding epoxy taken from manufacturer's specification (Technical Data Sheet of Sika 2005).

Table (3) *Properties of the epoxy resin (Sika, 2005)*

Properties	Sikadur®-330
Tensile strengths , MPa	30 MPa
Bond Strengths	Concrete fracture on sandblasted substrate: > 1 day
E-modulus , MPa	4500
Elongation at break , %	0.9%
Open time , minute	30 minutes at +35°C
Full cure , days	7 days at +10°C
Mixing ratio	Part A : part B = 4 : 1 by weight

6 Reinforced Concrete Slab Specimens

Sixteen slab specimens of (1050×1050×80mm) were casted. The slabs were designed in accordance with (ACI-318, 2011) [12]. The reinforcement was designed to ensure that the section is failed with tensile flexural mode of failure. The main reinforcement consisted of (9 Ø 6mm) in two directions with steel ratio of (ρ=0.42%) as shown in Figure (1).

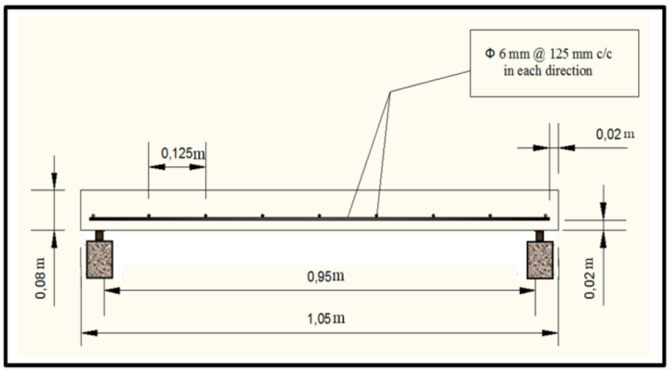


Figure (1) *Details of reinforcement of the slab specimens*

7 Location of Openings

(200×200mm) and (140×140) dimension of openings in all specimens were chosen according to (ACI-318, 2011) [12], for slab with L1≥L2 openings of any dimension allowed in the area common to intersecting middle strips (ACI-318, 2011) [12]. All openings were made in the middle strip as shown in Figure (2).

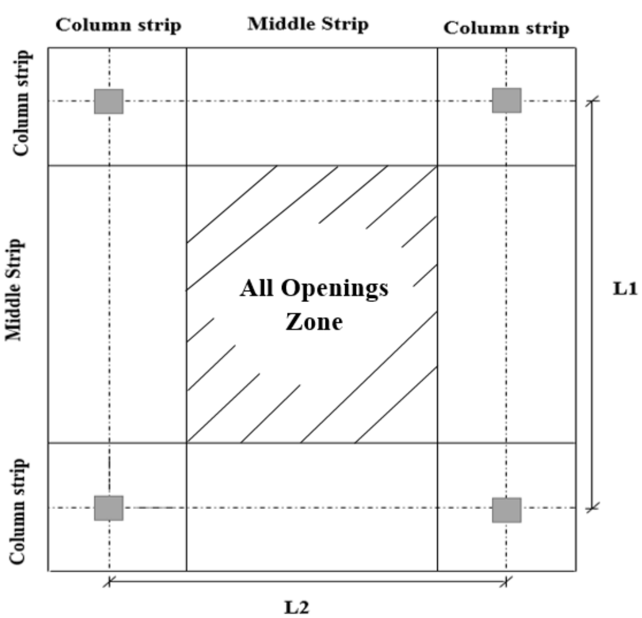


Figure (2) *Location of opening in the two-way slab*

8 Specimens Description

In this work, five control RC slabs without strengthening, and eleven slabs strengthened by CFRP sheet were tested. The considered parameters in this study investigate the behavior of high strength concrete slabs with one square central opening and with two square openings having area equivalent to the one opening which have a different locations in the middle strip furthermore, the openings were strengthened with CFRP strips using two schemes: First scheme, including an installed CFRP strips around the opening on the tension zone of the slab that had a width of (65) mm, (0.131) mm thickness, and its length longer than the opening length of (260) mm, (130) mm from each side. Moreover, the installed inclined strip (450) had a length (260) mm, a width (65) mm, and a thickness (0.131) mm which provided at each corner of opening. The second scheme was same in details to the first scheme, but the length of sheets were provided along of the surrounding of openings equal to clear span of specimen (950 mm).

In present study, all slab specimens were divided into six group as shown in Figure (3):

1- S1: One slab without opening and without strengthening (control solid slab).

2- (S2, S2.1, and S2.2): Three slabs with one central opening (200×200mm). The details of these groups are:

S2: without strengthening and was considered as a control slab for comparison for these group.

S2.1: strengthening by first scheme.

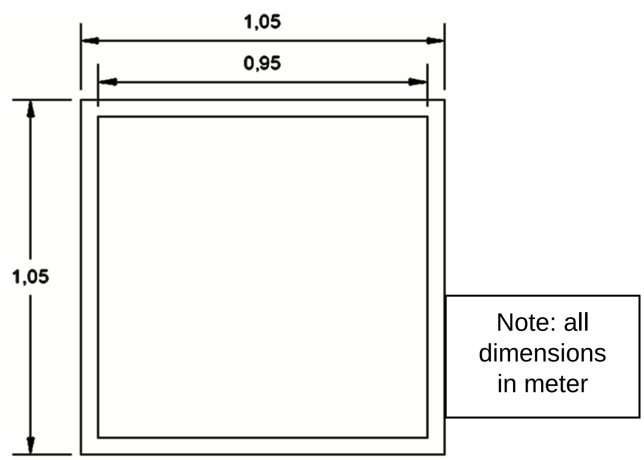
S2.2: strengthening by second scheme.

3- (S3, S3.1, and S3.2): Three slabs with two central converging opening (140×140mm). The details of these group are as same as the above.

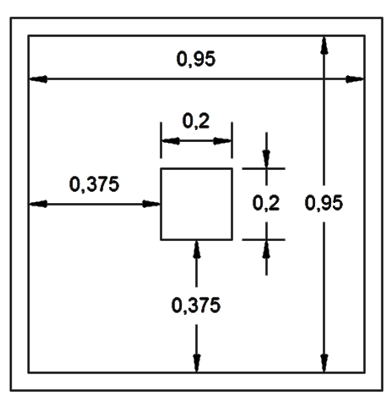
4- (S4, S4.1, and S4.2): Three slabs with two central diverging opening (140×140 mm).

5- (S5, S5.1, and S5.2): Three slabs with two diagonal converging opening (140×140mm).

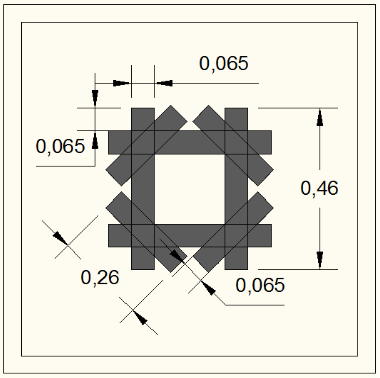
6- (S6, S6.1, and S6.2): Three slabs with two diagonal diverging opening (140×140 mm).



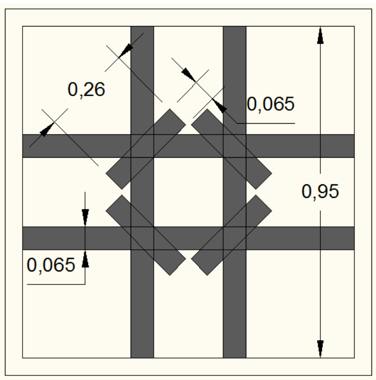
1) *Bottom view of control slab (S1)*



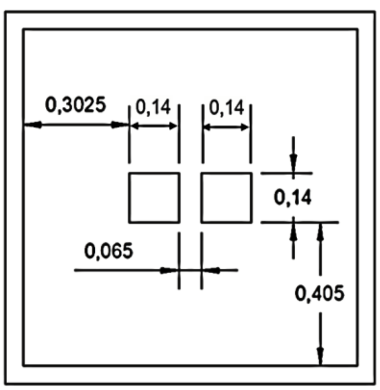
2) *Bottom view of slab (S2)*



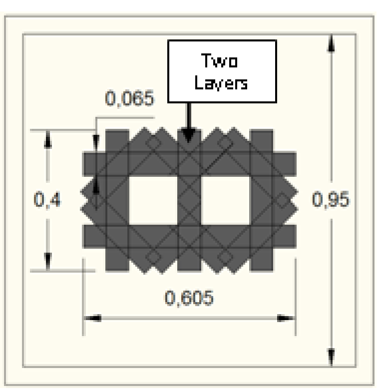
***3)** Bottom view of slab (S2.1) (First Scheme)*
***Figure (3)** Schematic representation of specimens*



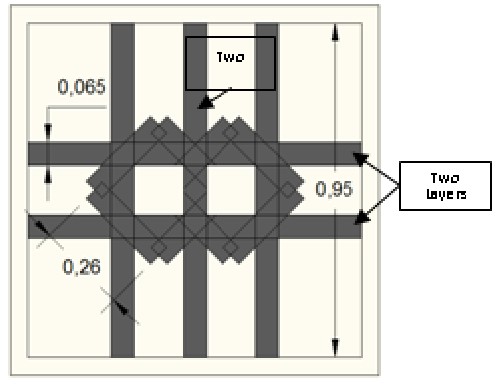
***4)** Bottom view of slab (S2.2) (Second Scheme)*



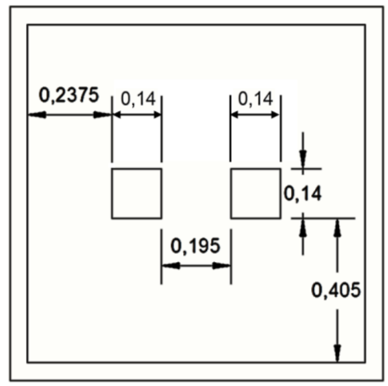
***5)** Bottom view of slab (S3)*



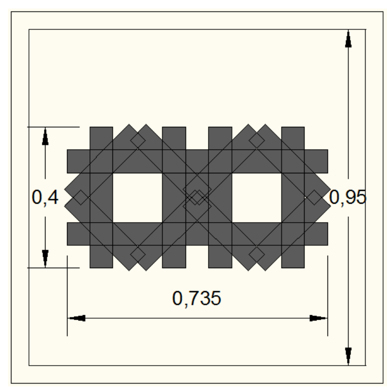
***6)** Bottom view of S3.1 (First Scheme)*



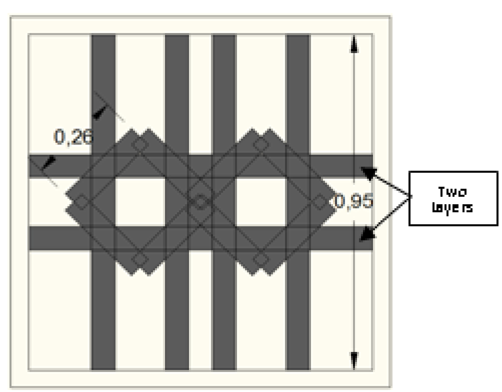
***7)** Bottom view of slab (S3.2) (Second Scheme)*
***Figure (3)** Schematic representation of specimens*



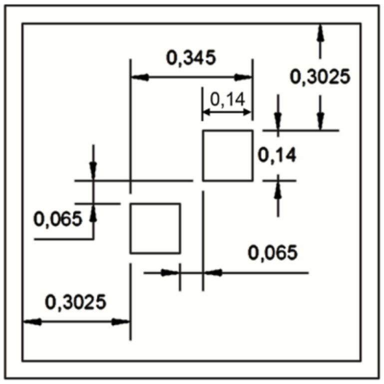
***8)** Bottom view of slab (S4)*



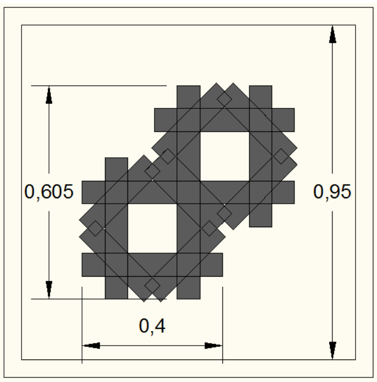
***9)** Bottom view of slab (S4.1) (First Scheme)*



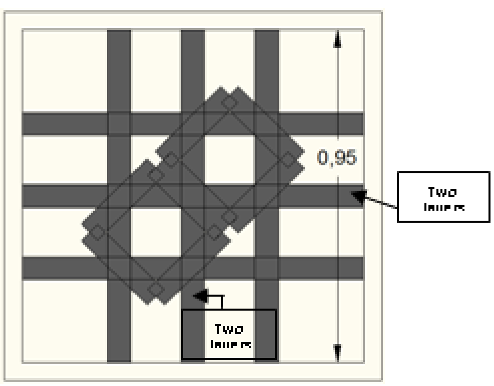
***10)** Bottom view of slab (S4.2) (Second Scheme)*



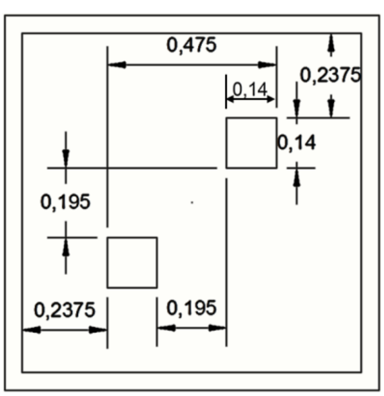
11) *Bottom view of slab (S5)*
Figure (3) *Schematic representation of specimens*



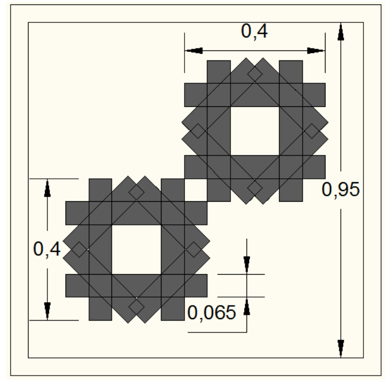
12) *Bottom view of slab (S5.1) (First Scheme)*



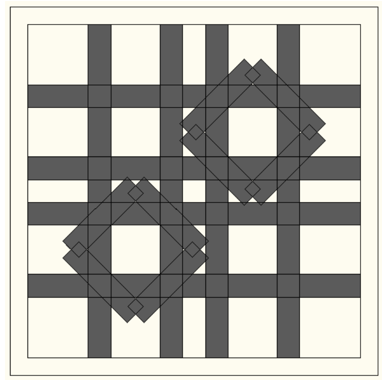
13) *Bottom view of slab (S5.2) (Second Scheme)*



14) *Bottom view of slab (S6)*



15) *Bottom view of slab (S6.1) (First Scheme)*
Figure (3) *Schematic representation of specimens*



16) *Bottom view of S6.2 (Second Scheme)*
Figure (3) *Schematic representation of specimens*

9 Mix Design and Proportion

Low water/cement ratio, high cement content and superplasticizer are necessary to achieve high strength concrete (HSC). Several trial mixes have been made through the earlier stage of the present work. The trial mixes were tested at ages of (3, 7 and 28 day) until the proper mix was achieved which give an adequate strength and workability. The high strength concrete mix was designed to give average cube compressive strength of (73.2 MPa) at 28 day. The details of the mixture are shown in Table (4).

Table (4) *Concrete mix detail*

Parameter		*HSC*
Cement (kg/m^3)		*550*
Water (Liter/m^3)		*140*
HRWRA (Viscocrete) (Liter/m^3)		*3.5*
Coarse Aggregate (kg/m^3)		*1065*
Fine Aggregate (kg/m^3)		*625*
Slump (mm)		*100*
Cube	*3 days*	*49.3*

*(150*150*150)mm compressive strength (MPa)*	*7 days*	*64.7*
	28 days	*73.2*

10 Concrete Casting and Curing

Before mixing, materials (sand and gravel) were weighted and stored in closed plastic containers in the field, whereas cement was weighted during the concrete mixing. The internal surfaces of cube, cylinder and prism were well cleaned and oiled to avoid adhesion with concrete after hardening. After the reinforcement placed in the right position, the slab moulds were placed in the casting site. Coarse and fine aggregate were poured into the mixer followed by 50% of the mixing water. Then cement was added by 25% of mix water. The remaining water mixed with superplasticizer then added gradually to the mix and left to be mixed about 3 min. the concrete was poured in the slab moulds in one layer, and the layer was compacted using a plunger mechanical vibrator (3000 vibration per minute) having a metal rod with diameter of 50 mm for 5 seconds for each insertion. After casting the upper surface of concrete was smoothly finished by using hand trowel and used plastic sheet moulds to cover all specimens. Mixing of concrete and poured it inside the specimens within a temperature (20-25) °C, therefore there is no risk on the soft concrete (IRAQI BUILDING CODE REQUIREMENTS, 1/1987) [13]. After 24 hours of the casting all slab specimens, cubes, cylinders and prisms were removed from their moulds, then burlap sacks were placed over the slabs and specimens to keep them wet until 28 days. As shown in Figure (4).

(a) *Weight and storing materials*

(b)*Mixing and casting process*

(c) *Curing process*
Figure (4) *Casting and curing conditions*

11 Installation of CFRP Strengthening System

The procedure that was used in applying CFRP composite system is summarized below. These steps were followed according to the recommendation of CFRP manufacturer and (ACI committee 440) [14].

11.1 Preparation of Concrete Surface

The most important part of any strengthening application is the bond between the FRP and the surface of concrete to which the FRP is contacted. Right contact ensured that the force carried by the structural member is transferred effectively to the FRP [15]. Before the CFRP sheet was connected to the tension face of the slabs, the surface of the concrete was grinded using an electrical hand grinder to detection the aggregate and to obtain a clean sound surface, and be freed of all contaminants such as dirt and cement dust as shown in Figure (5).

Figure (5) *Concrete surface preparation by electrical grinder*

11.2 CFRP System Application

❖ First of all, the CFRP sheets were cut into the required lengths. Surface preparation of the CFRP followed with a clean to remove any dust or other contaminants before installation.

❖ Two-parts comp. A (white) and comp. B (black) of adhesive (Sikadur-330) were mixed respectively with an electric mixer (here electric low speed drill was used) and mixed in 4: I ratio, until the color was a uniform gray, the adhesive paste then was applied with a special tool on the concrete surface and the adhesive was also applied on the CFRP sheets.

❖ The strips were placed on the concrete, and after the installation of strips, a ribbed roller was rolled in the direction of fibers to correctly seat the sheets by applying enough pressure, so the epoxy was forced out on both sides of the strips.

❖ The epoxy was allowed to cure for at least 7 days before the slabs were tested. After completing the CFRP installation, two days before the testing date, all apparent concrete surface specimens were painted white to detect easily the crack propagation. The steps of installation of CFRP sheets are shown in Figure (6).

Figure (6) *Installation of CFRP sheets*

Figure (6) *Installation of CFRP sheets*

12 Test Setup

After curing the slabs, specimens were transported to the Structural Laboratory of Civil Engineering Department at Kufa University, this is to test them under static loading. All the slab specimens were tested in rigid steel frame with C-section, which was designed as a supporting system. Four 10mm in diameter plain bars were welded on the upper of the square steel base to obtain a simply supported condition for a square shape slab of clear dimension of 950mm. A box of dimensions (1000×1000×100mm), made of steel plate of thickness 2mm and welded the 12mm diameter plain bars on it opened from upper and lower square areas and coated by a sheet of Nylon in the inner surfaces, was used to hold the sand to be placed over the slab as a part of the uniformly distributed load. The sand (100mm) furnishes a good media to distribute the load uniformly coming on the top surface of the sand by the loading base which transmit the load from the hydraulic machine to the layer of sand. Also, wood cube (200*200*85mm) and (140*140*85mm) (length*width*high) was put on the opening to prohibit the sand from fail from the opening. A hydraulic machine with capacity of (2000) kN was used to measure the applied load which transmitted the load to four points using a loading base which consisted of six steel members with I-section of (120×80) mm, four of these members having length (350) mm were parallel and the others (800) mm length welded perpendicularly upon them. The parallel steel members were connected and fixed by welding over a steel plate of (950×950×10) mm. This steel loading base transmitted the load to the 100 mm layer of sand use between the loading base and the slab specimen. The loading system as shown in Figure (7). This method of loading was adopted by [16], [17] and [18].

(7) *Loading arrangement for uniform load test*

13 Tests of Hardened Concrete

13.1 Compressive Strength Test

Test of compressive strength was determined according to (BS. 1881: Part 116: 1989) [19] and (ASTM C39-1993) [20]. Standard cubes of (150×150×150) mm and cylinder specimens (100×200) mm were tested by using a hydraulic compression machine ELE digital of (2000) kN capacity, at a loading rate of 6.8 kN/sec that is available in the Structural Laboratory, Civil Engineering Department at the University of Kufa. The average of three cubes and cylinders were adopted for each test (see Table (5)), all cubes and cylinders were tested at (28, 56) days and at age of slab tests.

Table (5) *Compressive strength and relationships between cubes and cylinders*

Age in days	Compressive strength (MPa)		Relationship between f_{cu} and f'_c
	f_{cu}	f'_c	
28	70.1	60.3	0.86
56	73.9	64.3	0.87
At test of slab specimens (more than 56 days)	74.3	64.8	0.87

3.2 Splitting Tensile Strength

Test of splitting tensile strength was conducted according to (ASTM C496-2004) [21]. The specification of cylinders were (100×200) mm. Two thin plywood strips were put between the specimen and both the lower and the upper bearing blocks of the testing machine, which was a hydraulic compression machine ELE digital of 2000 kN capacity. The test comprised a diametric compressive line load along the length of a cylindrical concrete specimen at a rate of 0.94 kN /sec until the failure occurs. The average of three cylinders was taken at each test (see Table (6)).

Table (6) *Splitting tensile strength*

Age in days	f_c' (MPa)	Splitting Tensile Strength, (f_t) (MPa)		Note
		(Experimental)*	ACI	
28	60.3	4.45	4.58	ACI-363 (0.59 $\sqrt{f_c'}$)
56	64.3	4.61	4.73	
at test of slab specimens (more than 56 days)	64.8	4.62	4.75	

* Each value is an average of three specimens

13.3 Flexural Strength (Modulus of Rupture) Test

Test of flexural strength was determined according to (ASTM C78- 2002)[22] by using Concrete prisms of dimensions (100×100×400) mm. The prisms were casted, demoulded and cured in a similar manner as the cubes. Modulus of rupture tests was performed by using two-point load (simple beam with third-point loading.The capacity of machine was 50kN. The average of three prisms was taken at each test (see Table (7)).

Table (7) Modulus of rupture

Age in days	f_c' (MPa)	Modulus of Rupture (f_r) (MPa)		Note
		(Experimental)	ACI	
28	60.3	6.87	7.3	ACI-363 (0.94 $\sqrt{f_c'}$)
56	64.3	7.06	7.54	
at test of slab specimens (more than 56 days)	64.8	7.12	7.57	

14 Experimental Results and Discussion

14.1 Cracking Patterns

The cracking behavior of each group slab specimen is discussed in the following:

1- Solid slab:

❖ **specimen (S1):**

The first visible cracks were narrow flexural cracks in the mid-span region at a load about (55) kN/m^2. At (70) kN/m^2, new flexural cracks formed and developed diagonally from the mid span of the specimen. Flexural cracks formed and widespread as loading proceeded throughout the slab as shown in Figure (8). Failure of the control test specimen at load (335) kN/m^2 by yielding and cut of steel bar causing decrease in the applied load and a significant increase in the deflection.

Figure (8) *Cracks pattern after failure for slab S1*

The measured cracks may be called service cracks or visible cracks because they are measured when they are visible. Therefore, the cracks may be occurred before this stage of loading.

2- Slabs with one square central opening (200 mm*200 mm) with and without strengthening:

❖ **specimen (S2):**

First crack was observed at corners mouth angle of slab at (40) kN/m^2 as shown in Figure (9a). These cracks appeared due to stress concentration at the corners of opening. As the load increased, these cracks propagated diagonally and widened rapidly toward supports. All slabs failed similarly in flexure. Then, the slab failed by the development of the cracks at the corners at an approximate load (267) kN/m^2, as shown in Figure (9b), which was lower than the control slab (S1) by 20.3 %.

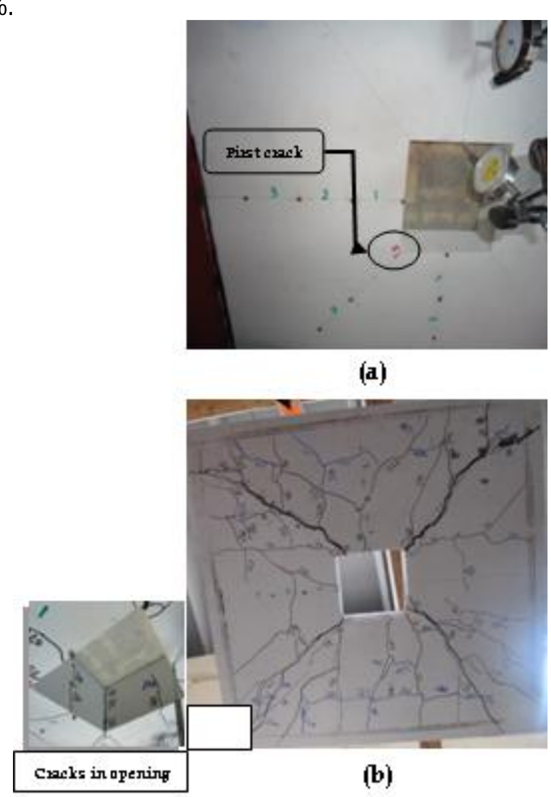


Figure (9) *Cracks pattern for slab S2*
a) First crack b) After failure

❖ **specimen (S2.1):**
The first visible crack at load (60) kN/m^2 at the end of the strip of CFRP, as shown in Figure (10a). At load (80) kN/m^2 new cracks observed in the opening. As the load increased the flexural cracks propagated and widened as loading proceeded diagonally and around the CFRP laminates. Failure mode in this specimen was different when compared with specimen (S2) due to the presence of CFRP around opening. Furthermore, cracks observed inside opening were speared and not concentrated at the corners as the case in specimen (S2). The specimen was failed at an approximate load (339) kN/m^2 by yielding of steel reinforced, which was greater than the slab specimen (S2) and control slab (S1) by (27% and 1.2%) respectively. The strip of CFRP remained without debonding as shown in Figure (10b).

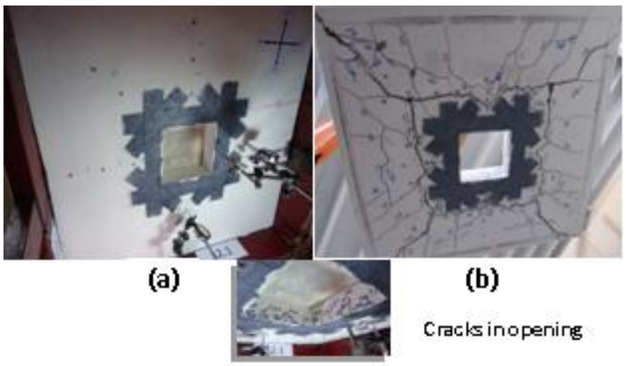


Figure (10) *Cracks pattern for slab S2.1*

❖ **specimen (S2.2):**
First crack was recorded at load (65) kN/m^2. Cracks appeared inside opening was similar to specimen (S2.1). Failure was observed at an approximate load (348) kN/m^2 which was greater than the slab specimen (S2) and control slab (S1) by (30.3% and 3.9%) respectively, as shown in Figure (11), due to CFRP debonding (separation at the interface between the substrate and the adherent material) [ACI Committee 440 (2002)][23] and because of propagation of diagonal flexural cracks at bottom face of the concrete slab. Generally, the crack pattern of these specimen was different from specimens (S2) and (S2.1) due to the presence and length of CFRP sheets which was provided to be equal to clear span of specimen.

Figure (11) *Cracks pattern after failure for slab S2.2*

3- Slabs with two square central converging openings (140 mm*140 mm) with and without strengthening:
❖ **specimen (S3):**
The appearance of flexural cracks was first at (30) kN/m^2 around the corners of the openings as shown in Figure (12a). At load of (60) kN/m^2, new flexure cracks were formed and developed in the middle region due to the high stress concentration at the corners and between openings. Failure was happened at an approximate load (236) kN/m^2 due to the steel yielding as shown in Figure (12b) which was lower than the control slab (S1) by (29.6) %.

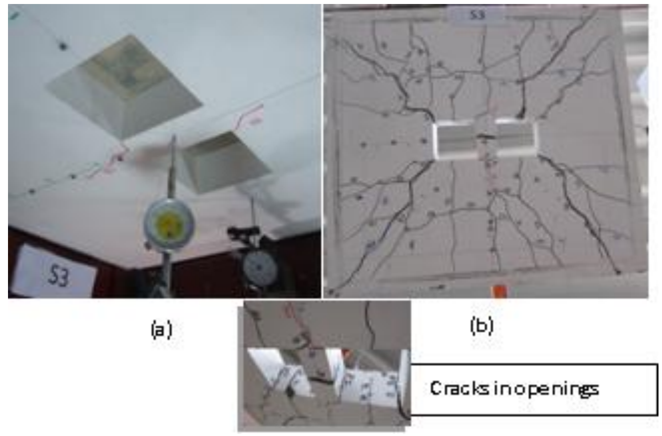


Figure (12) *Cracks pattern for slab S3*

a) First crack **b) After failure**

❖ **specimen (S3.1):**
First crack was recorded at load (40) kN/m^2 beside the CFRP laminates as shown in Figure (13a). At load (70) kN/m^2 new flexural crack observed inside opening, failure mode in this specimen was different when compared with specimen (S3) due to the presence of CFRP around two openings. Furthermore, cracks observed inside openings were speared and not concentrated at the corners. Also, the absence of the crack in middle region between openings was due to the presence of the addition CFRP sheets from inclined strips which was provided around openings. Generally, the behavior of crack to this specimen was same of crack to (S2.1) which was due to the use of same scheme in each specimens. Failure was happened at an approximate load (321) kN/m^2, which was greater than the slab specimen (S3) by (36%) and lower than the control slab (S1) by (4.2%) as shown in Figure (13b) as the flexural cracks increased in intensity and widened diagonally around the CFRP laminates at the tension face.

(a) ***(b)***

Figure (13) *Cracks pattern for slab S3.1*
a) First crack *b) After failure*

❖ **specimen (S3.2):**
The first visible crack at load (50) kN/m^2, at load (110) kN/m^2

new cracks observed in the opening. Finally debonding failure was occured at an approximate load (351) kN/m^2 due to the widespread and large flexural cracks at bottom tension zone, which was greater than the slab specimen (S3) and control slab (S1) by (48.7% and 4.8%) respectively as shown in Figure (14).

Figure (14) *Cracks pattern after failure for slab S3.2*

4- Slabs with two square central diverging openings (140 mm*140 mm) with and without strengthening:

❖ **specimen (S4):**

First crack occurred at load about (35) kN/m^2 around the corners of the openings as shown in Figure (15a). With an increase load, the flexural cracks increased in intensity and widened between openings and diagonally towards supporting. The specimen was failed at load (260) kN/m^2 due to steel yielding as shown in Figure (15b) which was lower than the control slab (S1) by (22.4) %.

(a) ***(b)***
Figure (15) *Cracks pattern for slab S4*
a) First crack *b) After failure*

specimen (S4.1):

The appearance of flexural crack was first at (50) kN/m^2 at mid span. At load (70) kN/m^2, new flexural crack was formed within the mid span beside of the CFRP laminates. The crack pattern of this specimen has mainly the same behavior of crack propagation of (S2.1) as shown in Figure (16). Failure was happened at an approximate load (328) kN/m^2 due to steel yielding, which was greater than the slab specimen (S4) by (26.2%) and lower than the control slab (S1) by (2.1%).

(a) ***(b)***
Figure (16) *Cracks pattern for slab S4.1*
a) First crack *b) After failure*

❖ **specimen (S4.2):**

The cracks pattern of this slab specimen is shown in Figure (17). First crack was recorded at load (65) kN/m^2 in the mid span. The flexural cracks increased and widened as loading proceeded. Finally debonding failure was occured at load (370) kN/m^2, which was greater than the slab specimen (S4) and control slab (S1) by (42.3% and 10.4%) respectively.

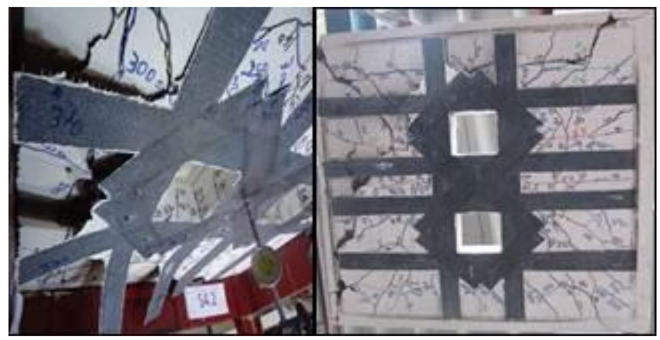
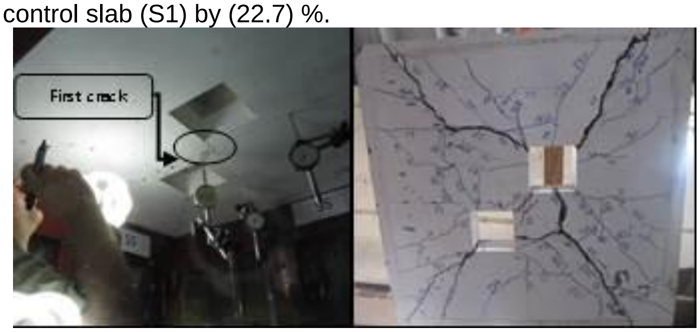


Figure (17) *Cracks pattern after failure for slab S4.2*

5- Slabs with two square diagonal converging openings (140 mm*140 mm) with and without strengthening:

specimen (S5):

First crack observed at corners between openings at an applied load of (30) kN/m^2. These cracks appeared due to stresses concentration at the corners of opening as shown in Figure (18a). As the load increased, new flexural cracks formed and widened along the diagonal of slab. Finally failure happened at an approximate load (259) kN/m^2 due to steel yielding, as shown in Figure (18b) which was lower than the control slab (S1) by (22.7) %.



(a) *(b)*
Figure (18) *Cracks pattern for slab S5*
a) First crack *b) After failure*

❖ **specimen (S5.1):**
The cracks pattern of this slab specimen is shown in Figure (19). First crack was pointed at load (45) kN/m^2 beside of the CFRP laminates. As the load increased, the flexural cracks propagated and widened as loading proceeded diagonally around the CFRP laminates. Failure was happened at an approximate load of (332) kN/m^2 due to steel yielding while the strip of CFRP stayed without debonding, which was greater than the slab specimen (S5) by (28.2%) and lower than the control slab (S1) by (0.9%).

(a) ***(b)***
Figure (19) *Cracks pattern for slab S5.1*
a) First crack *b) After failure*

specimen (S5.2):
First crack observed at an applied load (55) kN/m2 between of the CFRP sheets from the support to the middle span. At load (300) kN/m2, debonding was started at CFRP sheets at the support. Failure was happened at an approximate load (339) kN/m2 by CFRP debonding due to the propagation of diagonal flexural cracks at bottom face of the concrete slab similar to the behavior of specimen (S4.2) as shown in Figure (20), which was greater than the slab specimen (S5) and control slab (S1) by (30.9% and 1.2%) respectively.

Figure (20) *Cracks pattern after failure for slab S5.2*

6- Slabs with two square diagonal diverging openings (140 mm*140 mm) with and without strengthening:
specimen (S6):
First crack noticed at corners between openings at an applied load of (40) kN/m^2. These cracks appeared due to the stresses concentration at the corners of opening as shown in Figure (21a). The crack pattern of this specimen has mainly the same behavior of crack propagation of (S5). As the load increased, new cracks formed and widened along the diagonal of slab. Finally failure was happened at an approximate load (263) kN/m^2 due to the yielding of steel reinforced, as shown in Figure (21b) which was lower than the control slab (S1) by (21.5) %.

(a) ***(b)***
Figure (21) *Cracks pattern for slab S6*
a) First crack *b) After failure*

specimen (S6.1):
First crack was pointed at load (55) kN/m^2 beside of the CFRP laminates. As the load increased, new cracks formed and widened diagonally. Finally debonding failure ocurred at load (350) kN/m^2 due to the widespread and large flexural cracks at bottom tension zone which was different from specimen (S6), as shown in Figure (22). It was greater than the slab specimen (S6) and control slab (S1) by (33.1% and 4.5%) respectively.

Figure (22) *Cracks pattern after failure for slab S6.1*

❖ **specimen (S6.2):**
The cracks pattern of this slab specimen i00
s shown in Figure (23), First crack was pointed at load (75) kN/m^2 near the support and beside of the CFRP laminates. As the load increased, the flexural cracks propagated and widened as loading proceeded diagonally between the CFRP laminates. Finally, failure happened at an approximate load (408) kN/m^2 due to CFRP debonding near the support (similar to the behavior of specimen S2.2), which was greater than the slab specimen (S6) and control slab (S1) by (55.1% and 21.8%) respectively

Figure (23) *Cracks pattern after failure for slab S6.2*

14.2 Load-Deflection Curves

To measure the deflection of slabs, three dial gage were placed at different locations. For control slab S1, the dial gages were placed at a mid span point, at (10) cm from mid span and at one point of the quarter span. For slab (S2, S2.1 and S2.2), the dial gages were placed at a midpoint close to the opening and two dial gage at quarter span points toward (X and Z) directions. All other slabs, the dial gages were placed at mid span point and two dial gage at quarter span points.The comparison of load deflections curves of (RC) slabs with or without (opening and strengthening) can be shown in Figures (24) to (30). Obviously, it was noticed that the presence of opening causing a reduction in stiffness and an increase in deflection at the same load stage. Furthermore, the presence of CFRP sheets, especially the specimens were strengthened by second scheme, enhanced the behavior of strengthened slabs in comparison to the control specimen (S1) and control slab in the same group by increasing the ultimate load and reducing the ultimate deflection.

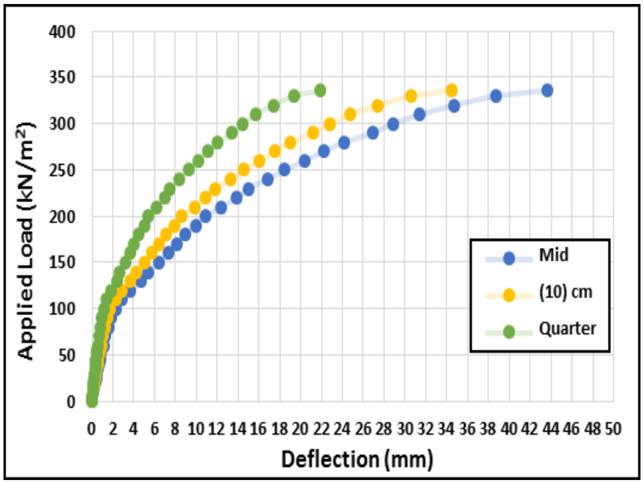


Figure (24) *Load-deflection curve for group (1) (slab S1)*

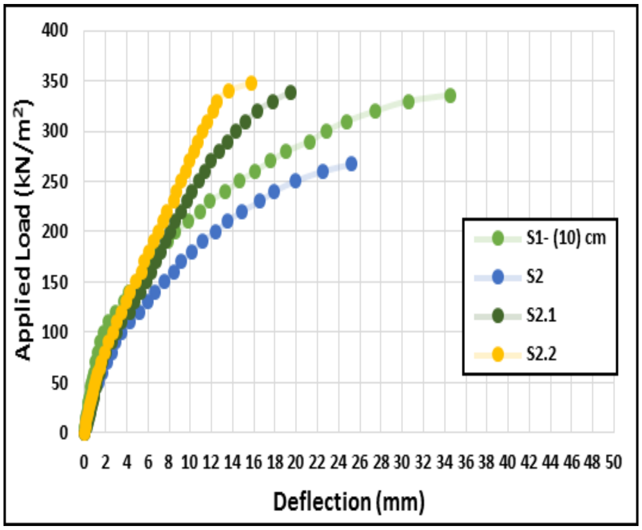


Figure (25) *Load-deflection curve for group (2)*

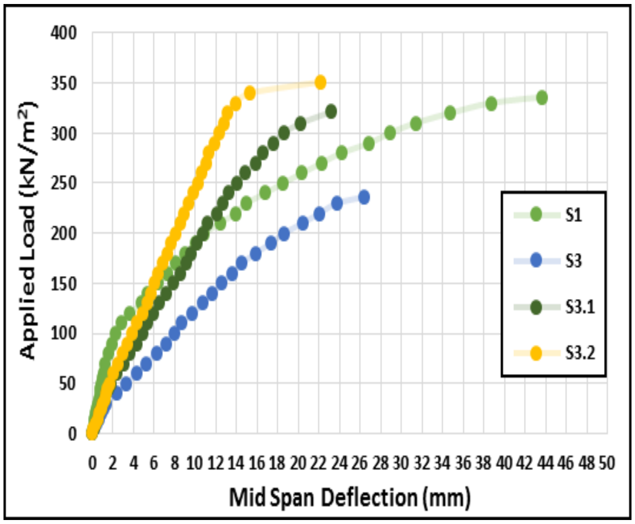


Figure (26) *Load-deflection curve for group (3)*

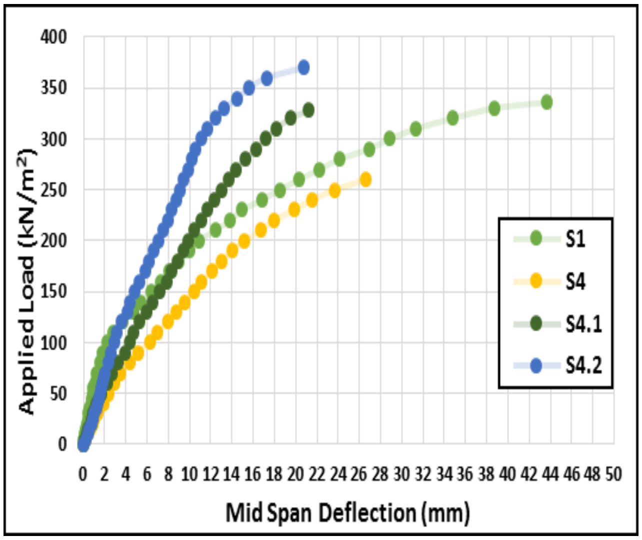


Figure (27) *Load-deflection curve for group (4)*

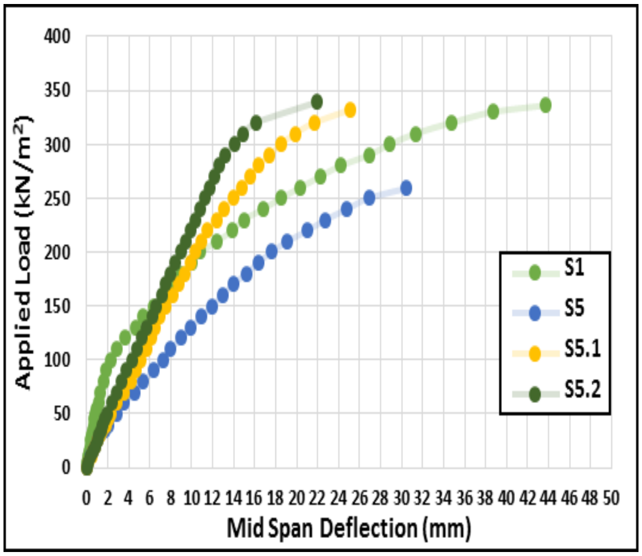


Figure (28) *Load-deflection curve for group (5)*

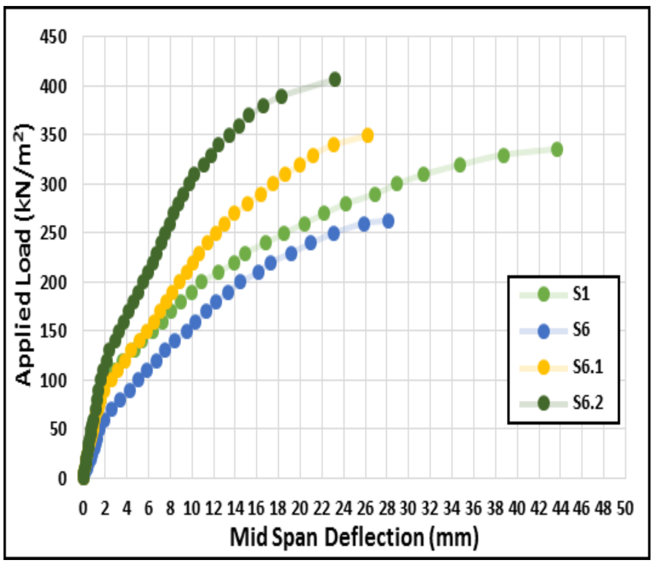


Figure (29) *Load-deflection curve for group (6)*

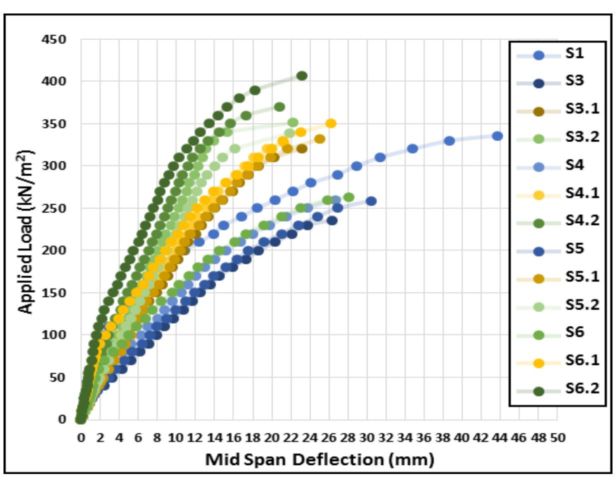


Figure (30) *Load-deflection relationships at the mid span, for slab without openings (S1) and all slabs with two openings with and without strengthening*

14.3 Concrete Cracking

The experimental crack width at the tension zone was measured at each 10 kN/m2 by using crack meter (Direct Measurment Microsope, Range (0 to 2.5) mm, Division (0.02) mm) and using the ruler if the crack width became greater than (2.5) mm. Figures (31) showed the development of inclined crack width for all slab specimens. In general, it was noticed that the presence of opening caused an increase in the crack width as compared to the control solid slab (S1) at the same load stage. In addition, the crack width in strengthening slabs, at the same load stage, were less than in control slab (S1) and control slab in the same group which due to was the strengthening with CFRP system controlled the expanding of the crack width. So the expansion of crack width befited with CFRP stretching.

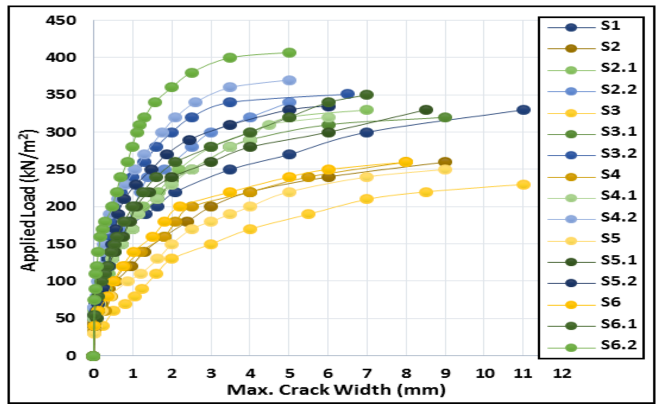


Figure (31) *Crack width for all groups*

14.4 The effects of CFRP Area on First racking Load and Ultimate Load

The area of CFRP had an effect on the results of first cracking load and ultimate load. Figures (32) and (33) showed the relationship between the presence of CFRP by using first scheme and the effect of increase the area of CFRP was glued on the bottom face of the slab specimens by using the second scheme on the first cracking load and the ultimate load respectively.

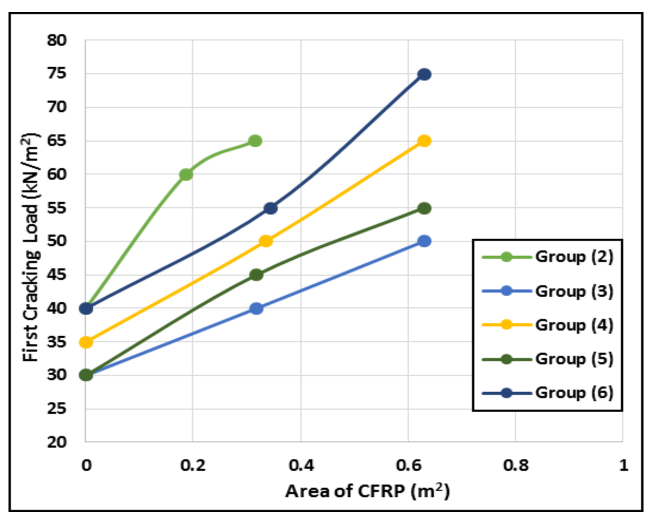


Figure (32) *The effect of CFRP area on first cracking load*

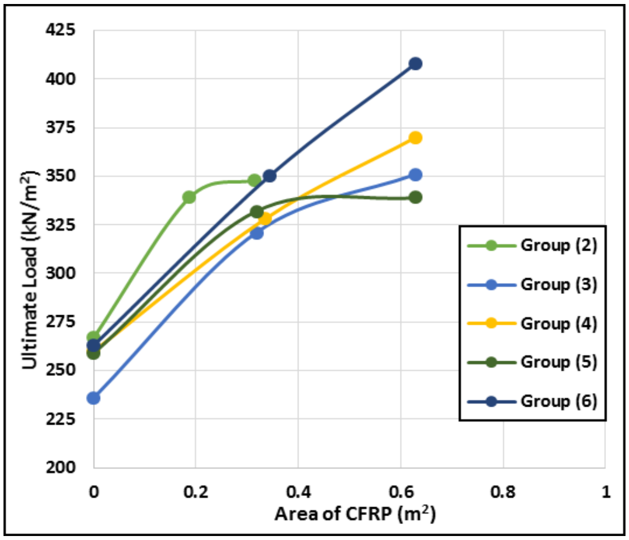


Figure (33) *The effect of CFRP area on ultimate load*

15 Conclusions

1. The presence of openings in slabs showed decrease in stiffness. In this study, all slab with two openings gave the minimum results in the ultimate load ranged between (21.5% - 29.6%) compared with the control solid slab.
2. Using CFRP strips in two way RC slabs with openings had a significant effect on the ultimate strength and deflection of tested slabs. The high modulus of elasticity of CFRP strip was found to be an important factor in decreasing the deflection of RC slabs.
3. Using CFRP strips as external strengthening had a significant effect on crack pattern of the reinforced concrete two-way slabs with opening by delaying the crack appearance and reducing the crack width. The increase in cracking load was about (33.3% - 50%) for slabs strengthening by first scheme and (62.5% - 87.5%) by second scheme compared with the control slab in the same group.
4. RC two way slabs with openings and strengthened with CFRP sheets showed an increase in ultimate load, capacity. This increase was about (26.2% - 36%) for slabs strengthening by first scheme and (30.3% - 55.1%) by second scheme compared with the control slab in the same group.
5. Slabs with openings and strengthening with CFRP sheets by second scheme showed an increase in the stiffness of the slabs at all stages of loading, and consequently reducing the deflection at corresponding loads. The decrease in maximum deflection was about (15.8% - 37.6%) compared with the control slab in same group and (2.2% - 19.3%) compared with the strengthened slab by first scheme.
6. The debonding in slab specimens was sudden and the only indication of incipient failure was few popping sounds as the debonding cracks propagated quickly to the end of the sheet. The clear message of the experimental results was that the premature and brittle nature of debonding failure may reduce the level of safety of the strengthened RC slabs.
7. Slab specimen with two diagonal diverging opening and strengthening with CFRP sheets by second scheme gave the best results for the ultimate load capacity with increase (21.8%) compared with the control solid slab and (55.1 %) compared with the control slab in the same group. In practical terms, it could be used in case of the need for the presence of openings in the slabs.

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