

BEHAVIOR AND LOAD CAPACITY OF CONCRETE SLAB REINFORCED BY CFRP BAR AND STRENGTHENING BY CFRP LAMINATES

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Abstract

The most common FRP materials used are carbon fiber reinforced polymers (CFRPs), and glass fiber reinforced polymers (GFRPs). The use of CFRPs has grown rapidly in the construction industry, specifically in structural retrofitting, due to their strengthening property of CFRP. CFRPs are moreover high strength, lightweight, noncorrosive, and easy-to-install materials. In the present study, six reinforced concrete slab specimens included two control specimens reinforced by traditional steel reinforcements and the other reinforced by carbon fiber reinforced polymer CFRP bars without strengthening by laminated CFRP strips. The remaining four specimens are interiorly reinforced by CFRP bars and strengthened by CFRP laminates strips with different scheme layouts named Type 1 and Type 2. The specimens were tested under a uniformly distributed load applied at the top surface area of each specimen up to failure. The parameters considered in the present study are the amount of CFRP bars and CFRP laminates layout. Test results indicated that the strength carrying capacity and failure mode of tested specimens differ based on the steel reinforcement type and the presence of CFRP laminates layout.

Keywords:

Ductility;
Energy dissipation;
Simply supported slab;
Two-way slab;
Uniform distributed load.

1 Introduction

Due to its extremely ductile nature until failure, the flexural behavior of a two-way slab has received less attention than punched shear behavior. On the other hand, deflection in slabs can harm non-structural components such as walls, ceiling decorations, and doors, whereas the structural slab can still handle additional loads. As a result, more research is needed to fully comprehend the impacts of flexural failure in two-way slabs [1].

Flexural failure can occur in structural components like beams and slabs. Concrete is strong in compression but weak in tension in general. As a result, concrete fractures under tensile stresses can result in various structural problems. Cracks show the response of concrete to applied loads in both compression and tension. Furthermore, temperature and shrinkage factors in the concrete part may cause further cracks. Highly visible fractures can degrade the structure's aesthetics and cause a considerable loss in the structural member's flexure stiffness [2]. Therefore, the random spread of fractures substantially impacts the slab's flexural stiffness, and crack propagation analysis is challenging due to load transfer in both directions.

For many structural engineering projects, CFRP strengthening has been widely employed in the application of retrofitting ancient structures. A previous study has improved the strength of columns, beams, and one-way slabs [3]. After connecting the CFRP laminates on the side of the tension of the beams and slabs, the concrete beam's and one-way slabs' flexural capacity rises. On the other hand, debonding often occurs in CFRP laminates. In this section, we have highlighted some of the essential research.

CFRP and GFRP Strips were used in this study, where the results showed the effectiveness of CFRP in strengthening the flexural [4]. Using silica-coated GFRP rods, the results were virtually identical to conventional reinforced panels in terms of load-bearing capacity and deflection [5]. FRP

rebar was used as an alternative to steel rebar and compared with traditional reinforcement. The FRP-reinforced slabs showed elastic recovery after unloading and were more susceptible to cracking and deflection than steel RC slabs [6]. Although the slab reinforcement with CFRP stripes effectively strengthened the slab, the failure was the early removal of the CFRP stripes [7]. Used two techniques for strengthened RC slab, near-surface stabilization (NSM) rods and external bounding (EB) by using CFRP Laminate strips. NSM method showed improved bearing capacity and ductile behavior compared to EB CFRP Laminate strips [8]. The slabs were reinforced with different FRP materials (BFRP, GFRP, CFRP), and the slab reinforced with CFRP gave the best results in strength compared to other FRP materials [9]. The slab strengthened with CFRP (strips of fabric) has shown an increase in the static load carrying capacity by a percentage of 25 - 30 % and a decrease in deflection (under ultimate loads) by a percentage of 13 - 23 % [10]. The slab was strengthened with two types of regular CFRP and Pre-saturated laminate slabs. By comparing the two types, the strengthening using Pre-saturated CFRP was more effective than regular CFRP [11]. It used different proportions of the area covered with FRP 25 %, 35 %, and 45 % of CFRP and GFRP to strengthen the slab. Cracks appeared in the slab but did not penetrate the total slab depth [12]. Hybrid concrete slabs were studied and examined, where FRP was used as CFRP, GFRP, and AFRP sheets, and they were connected to the concrete by a glass fiber mesh, as the GFRP gave the best results. In terms of the load-bearing capacity in the optimum design, And it has a lower cost for casting than other models [13]. Using FRP with carbon nanotube-reinforced resins will raise stiffness and ductility by 100 %, and a nearly 13 % increase in the axial and flexural strength of specimens [14]. By employing several types of strengthening on two-way reinforced concrete slabs, it was shown that both carbon fiber laminates and rods considerably raise the cracking strength, as well as the ultimate load capacities and deflection responsiveness [15]. Using the groove approach, the effectiveness and precision of the equations employed in the analysis of RC beams reinforced with CFRP sheets/laminates were examined. Using the moment amplitude equations proposed by ACI 440.2R-17 and other theoretical models the code's safety margin was validated. The majority of the analytical models utilized in this work predicted the bending strength of externally bonded reinforcement (EBR)-enhanced beams more precisely than externally bonded reinforcement on grooves (EBROG)-reinforced beams [16]. Numerical analysis of the interaction of reinforced concrete slabs with subsoil was studied. The researchers found the punching mechanism was affected not only by the mechanical properties of the concrete but also by the properties of the subsoil, and the crack width increases with increased load [17]. When strengthening the thin and high-strength concrete slab with CFRP laminates, it was found that an improvement in the capacity of the slabs occurred with the increase in the compressive strength of concrete and the width of FRP layers [18]. The thin reinforced concrete slabs with high-strength concrete were externally strengthened with carbon fiber-reinforced polymer (CFRP) laminates. It was found that with the increase in the concrete strength, the gain in the flexural capacity of slabs from CFRP reinforcement decreases [19]. The use of CFRP bars enhances the overall performance more than GFRP and steel bars and provides more rapprochements to the strength and deflection values [20]. The slabs were strengthened with CFRP laminates applied according to the near-surface mounted (NSM) technique by using two types of adhesives (flexible and stiff). It proved a clear dependence of the flexural performance of the slab on the adhesive, where using a flexible adhesive produces about 80 percent of the maximum load applied in the case of using stiff adhesives [21]. Strengthening beams with NSM-CFRP strip bands enhanced their performance in terms of failure load, ductility, and flexural strength [22].

There are limited studies related to ensuring that the conventional reinforcement of concrete slabs can be replaced by CFRP bars and strengthened by CFRP laminates with different layouts that give the same or more strength capacity, fewer deformations, and a mode of failure. However, the most common cause of failure in CFRP laminates was early debonding, which significantly reduces the ductility of RC slabs. Therefore, anchorage can be used to mitigate early debonding of CFRP strengthened. Therefore, the fundamental goal of the present study is to experimentally investigate the effects of flexural strengthening of two-way slabs reinforced with CFRP bars and strengthened with CFRP laminates.

2 Experimental work

In the present study, the strengthening and flexural behavior of two-way RC slabs were evaluated under uniformly distributed load up to failure. For comparison purposes, the first and second specimens were considered the control slab specimen. The classification of the remaining four slabs

was based on the reinforcement ratio and strengthening. Structural test results of RC slabs reinforced by different amounts of FRP bars and strengthened by CFRP laminate will be discussed and evaluated based on the behavior and strength of each tested specimen.

3 Specimen descriptions

A total of six slab specimens represent the experimental tests adopted to investigate the behavior and strength of the RC slab. Table 1 lists the specimens marks for all tested specimens in which all tested specimens have the same geometry concrete slab of 1550 x 1550 x 100 mm and are simply supported for all edges. All slabs were cast using ready-mix concrete with mix design as listed in Table 2. Specimen SS-control represented the control specimen reinforced by traditional reinforcement with a deformed bar 10 mm in diameter with the center to center spacing of 300 mm for each direction and placed at the specimen bottom with a 20 mm cover without strengthening by CFRP laminate. Model SC is designed to bear the same strength capacity as SS but is reinforced by FRP bars instated from traditional reinforcements. Specimen SC1-S1 reduced the amount of FRP reinforcement of Specimen SC and replaced the reminder reinforcement by CFRP laminate layout Type 1, while specimen SC1-S2 strengthened by CFRP laminate layout Type 2. specimens SC2-S1 and SC2-S2 represent the same as specimen SS but replaced the traditional reinforcement bar by FRP bar (same diameter and amount) but strengthened by layouts Type 1 and 2 respectively (see Table 4, and 5), and additional transverse layers of CFRP laminates were attached to the CFRP's ends using anchor bolts with diameter 6mm to better the end anchorage of the CFRP laminate to the concrete surface. Fig. 2 shows details of the CFRP laminate layout of Type 1 and 2 and anchorage. Specimen SS was designed according to ACI 318-19 [23], and other Specimens were designed according to ACI 440.15.1R [24]. For this study, a CFRP unidirectional carbon fiber laminate was utilized as the FRP material. Table 6 shows the mechanical properties of CFRP. The glue utilized was Sikadur-32LP, a two-component epoxy impregnating A and B resin. The mechanical properties of the epoxy are shown in Table 7.

Table 1: Specimen descriptions.

Specimen marks	Reinforcement type	Spacing [mm]	Strengthening (CFRP laminates)
SS-Control	Traditional reinforcement	$\Phi 10@300$	N/A
SC	CFRP-Bar	$\Phi 10@150$	N/A
SC1-S1	CFRP-Bar	$\Phi 10@200$	Type1
SC1-S2	CFRP-Bar	$\Phi 10@200$	Type2
SC2-S1	CFRP-Bar	$\Phi 10@300$	Type1
SC2-S2	CFRP-Bar	$\Phi 10@300$	Type2

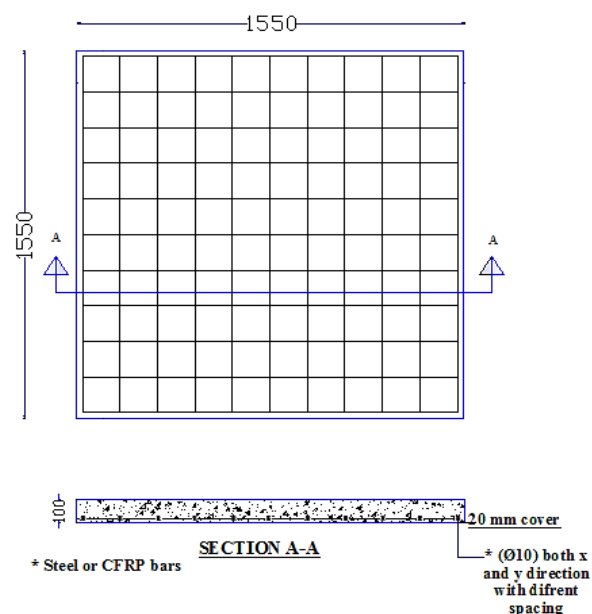


Fig. 1: Details and dimensions of the test specimens (all dimensions in mm).

Table 2: Mix proportions for 1 m³ of concrete.

Cement [kg/m ³]	Sand [kg/m ³]	Gravel [kg/m ³]	Water [l/m ³]	W/C
350	1200	1050	147	0.42

Table 3: Characteristics of concrete.

f_c^* [MPa]	E_c [MPa]	f_t [MPa]	f_r [MPa]
21	21500	2.93	3.17

* f_c tested at 28-day.

Table 4: Characteristics of steel reinforcement.

Nominal diameter [mm]	Nominal area [mm ²]	f_y [MPa]	f_u [MPa]	E_s [GPa]
10	78.5	565	782	204.7

Table 5: Properties of CFRP* bars.

Nominal diameter [mm]	Nominal area [mm ²]	Ultimate tensile load [kN]	f_{fu} [MPa]	E_f [MPa]
10	71.26	154	2172	124000

*Supplied by the manufacturer.

Table 6: Properties of CFRP laminate (Model HM-1.4T)*.

Width [mm]	Thickness [mm]	Tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break
50	1.4	3044	158000	0.0177

*Provided by the manufacturer.

Table 7: Properties of resin remarks of sikadur-32LP*.

Density [kg/l]	Tensile strength [MPa]	Elastic modulus [MPa]	Mixing ratio
1.4 ± 0.1	20	2600	Part A (resin): part B (hardener) = 2: 1 by weight

*Provided by the manufacturer.

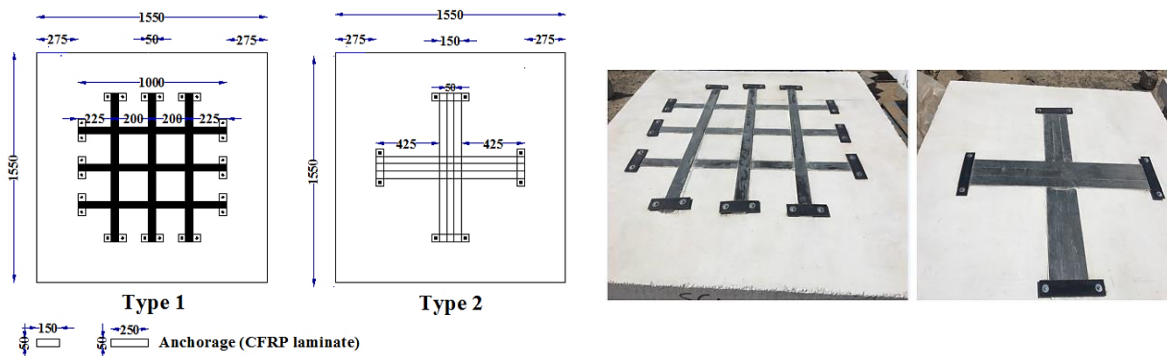


Fig. 2: Details of CFRP laminate layout of type 1 and 2 and anchorage (all dimensions in mm).

4 Test setup and procedure

All slabs were tested using a steel frame that was particularly designed for the specimens' tests of this study. The sides of the frame were made of steel section with a depth of 150 mm and flange width of 80 mm and equipped with steel plate stiffeners welded to the web of the section at 1560 mm spacing, and a supporting steel frame fixed from the top of the I-section cap with a depth of 80 mm and width of 24 mm. The slabs were simply supported four all sides, sitting on a steel frame with a span of 1400 mm between supports. The uniform load was provided based on using a thick wood plate with dimensions of 1500 x 1500 mm, and a thickness of 23 mm on the slab, and put the sand between and over these plates was distributed uniformly over the overall surface area of the slab.

The uniformly distributed load was applied using a hydraulic jack 500-ton capacity was put on the top surface of the loading frame that transfers the load from the hydraulic jack to the rubbers and then to the tested slab specimens. The test was started with the application of a load of 50 kN and increased gradually with load control and recorded the corresponding central deflection up to failure

for each Specimen by using a dial gauge, and crack width by using a concrete crack microscope with metric scale 0 – 1.8 mm. The data was recorded and captured by a device National Instruments NI PXIe-1062Q series multi-function device. Fig. 3 and Fig. 4 show details test setup and UDL application for slab specimens.

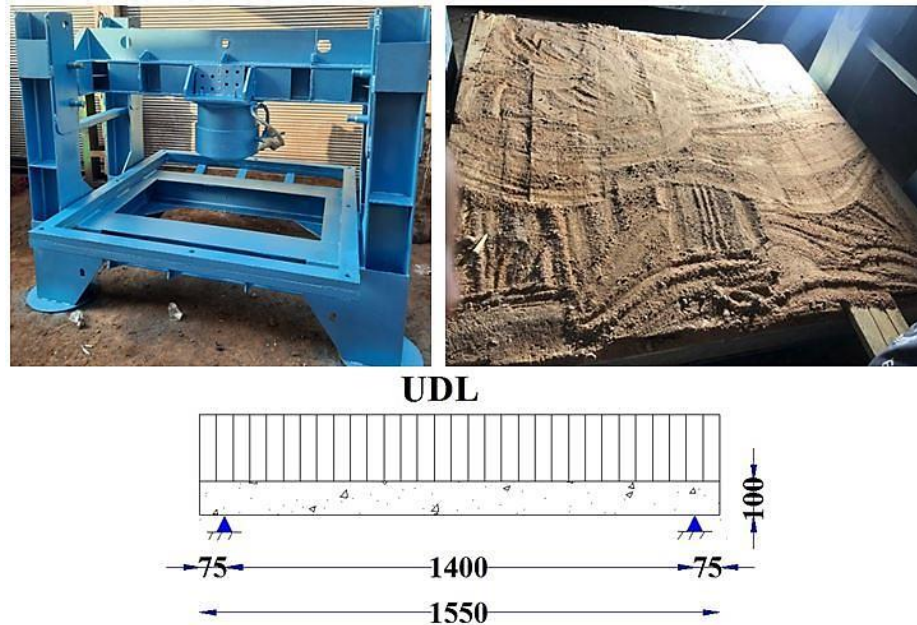


Fig. 3: Steel frame and UDL application for slab specimens.



Fig. 4: Test setup.

5 Experimental results and discussion

5.1 General observation and mode of failure

The load was applied as uniform at the top zone of the slab specimen and increased progressively while the slab was observed to bend (flexural) under the effect of the applied load until the first break appeared in the slab; the slab behaved elastically during the early stages of the test.

Based on the test results of RC slab specimens up to failure, the different failure mode was presented, relying on reinforced materials such as traditional reinforcements and CFRP bars with and without strengthening by CFRP laminate and layout. In general, flexural failure occurred in most specimens without spalling of concrete cover and debonding of CFRP laminate Except for a specimen SC1-S2 in which a Demolition of CFRP beside one at the end and specimen SC2-S2 in which a debonding of CFRP Without separation of the anchorage.

5.1.1 Specimen SS

At load 220 kN, the first crack appeared in the constant moment region. Cracks spread along the slab in the tension zone, at the failure stage, the mode of failure is flexural, in which the specimen is deflected toward the center of the specimen line in two directions. The flexural failure occurred and deflected shape appearance at the failure stage due to the presence of traditional reinforcements in the tension zone in both directions. This mode of failure occurred due to the under-reinforcement design of the control specimen and the reinforcement reach yield before the concrete crush.

5.1.2 Specimen SC

This control specimen is reinforced by CFRP bars without CFRP laminate strengthening. Early in the test, the slab exhibited an elastic behavior in which the first crack occurred with a load of 123 kN. The cracks rapidly enlarged and spread after an increase in applied load. The failure mode that occurred in Specimen SC was concrete crush at the failure stage with flexural FRP bars in two directions with crack concentrations on all edges. Also, the specimen bends and deflects toward the center of the specimen line in two directions. This specimen reminded stiff and gave a strength capacity higher than the SS specimen. This specimen has sufficient deformability before failure, and the concrete crushing and FRP bars rupture.

5.1.3 Specimen SC1-S1

Increase in spacing (reduce in the amount of reinforcements CFRP bars) and used strengthening by laminated CFRP in the tension zone of RC slab in this specimen. The first crack was observed at load 100 kN. Strength capacity is less as compared with the SC specimen. Most cracks start from the edge, and the presence of laminated CFRP leads to connecting the cracked part of the concrete slab. No rupture and debonding in CFRP laminate failure occurred only flexural. The mode of failure combined was flexural and shear at support.

5.1.4 Specimen SC1-S2

The First crack appeared at load 125 kN, Cracks propagations and intensity in this specimen were more than specimen SC1-S1 due to CFRP laminate layout. No rupture or debonding was observed in the contact area. Little cracks appear in the region of strengthening by CFRP laminate because they worked as bridges to connect the cracks part of the specimen due to applied load but still, the failure mode is flexural.

5.1.5 Specimen SC2-S1

In this sample, the first crack was seen at load 88 kN. A shear failure occurred at the supports without CFRP laminate debonding or failure with cracks propagated around the CFRP laminate strengthening zone. The shear failure occurred due to reducing in the reinforcement of FRP bars so that the transfer load at the strengthening edges of the specimen become more lead to produce more cracks so that it spalling at this zone surrounded the CFRP laminate, the mode of failure combined was flexural and (shear at support).

5.1.6 Specimen SC2-S2

The first crack was observed at load 76 kN. Cracks spread in the tensile zone of the slab, with fewer cracks inside the CFRP laminate, with debonding of CFRP Without separation of the anchorage or laminate failure with cracks propagated around the CFRP laminate strengthening zone. The shear failure same as specimen SC2-S1 in which the cracks increased towards the supported edges. The mode of failure combined was flexural and shear-tension.

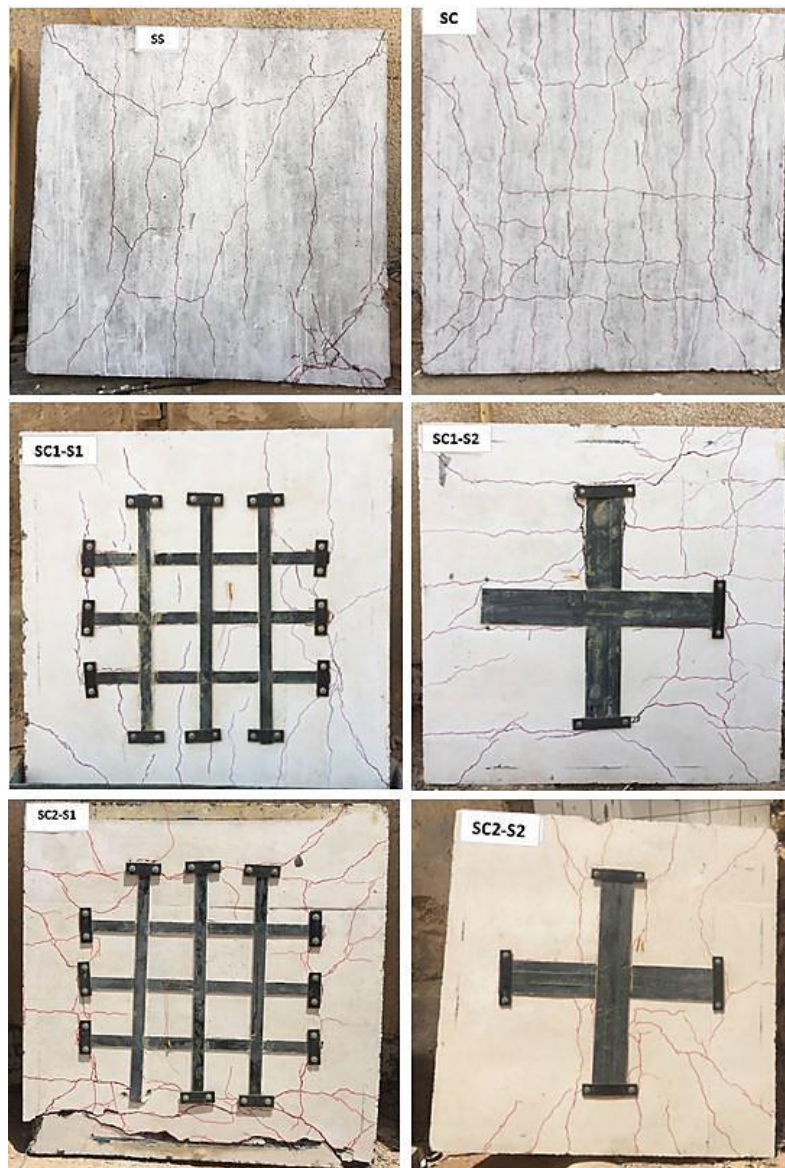


Fig. 5: Crack propagations and intensity for all tested specimens.

5.2 Load-deflection behavior

Table 8 lists the test results of all tested specimens with adopted parameters first crack load, deflection at first crack, maximum load, maximum deflection, failure load, and the corresponding deflection at failure load are lists.

Table 8: Test results for all specimens.

Specimen mark	P_{cr} [kN]	Δ_{cr} [mm]	P_m [kN]	Δ_m [mm]	P_F kN]	Δ_F [mm]
SS-Control	220	9.81	750	17.05	720	20.46
SC	123	3.5	788	19.00	765	23.56
SC1-S1	100	5.69	475	10.90	405	13.41
SC1-S2	125	6.23	675	16.54	628	21.17
SC2-S1	88	7.32	500	16.95	440	22.21
SC2-S2	76	2.72	550	15.70	502	19.63

Figs. 6 - 11 show the load-deflection behavior and comparisons of tested specimens. In general, all specimens started with linear behavior up to the point of inflection, representing nearly the load that caused the first crack. This point differs from specimen to specimen and depends on various

criteria, such as the specimen's strength capacity, reinforcement, and presence of CFRP laminate strengthening. Specimen SC gave a strong carrying capacity of 788 kN more than the SS specimen 750 kN due to reducing bars spacing and the ductility of the FRP bar compared with traditional reinforcement. Table 9 lists the comparisons for tested specimens with control specimen SS as a load capacity.

Table 9: Load capacity comparison with control specimen SS.

Specimen mark	Maximum load P_m [kN]	% Increase [+] and decrease [-]
SS-Control	750.00	---
SC	788.00	+ 5.07
SC1-S1	475.00	- 36.67
SC1-S2	675.00	- 10.00
SC2-S1	500.00	- 33.33
SC2-S2	550.00	- 26.67

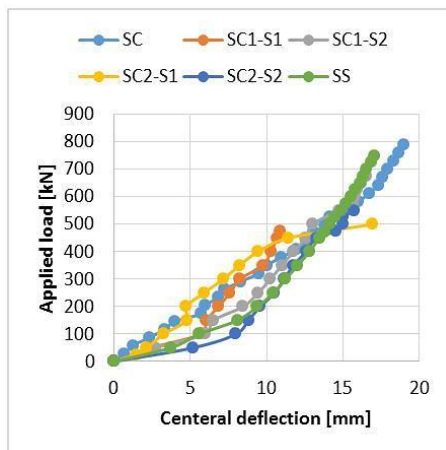


Fig. 6: Load-deflection variation for all tested specimens.

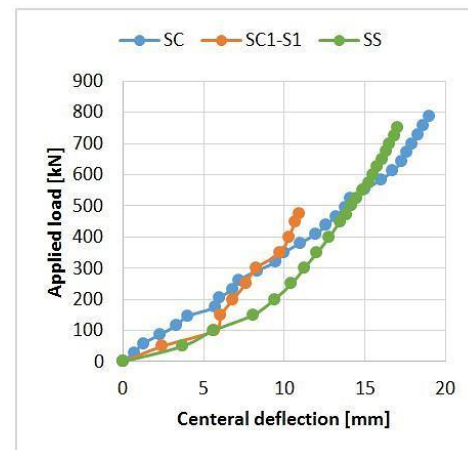


Fig. 7: Load-deflection variation for SC, SC1-S1, and SS specimens.

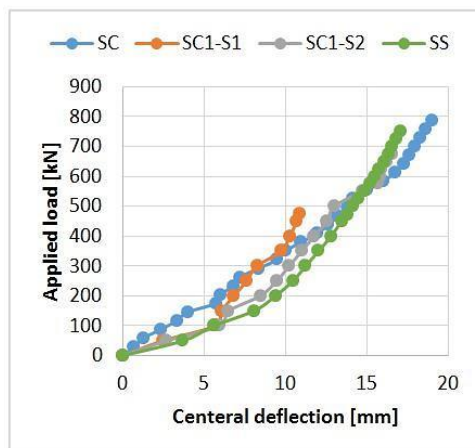


Fig. 8: Load-deflection variation for SC, SC1-S1, SC1-S2, and SS specimens.

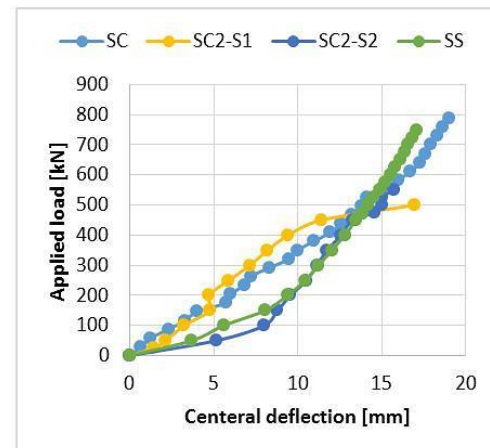


Fig. 9: Load-deflection variation for SC, SC2-S1, SC2-S2, and SS specimens.

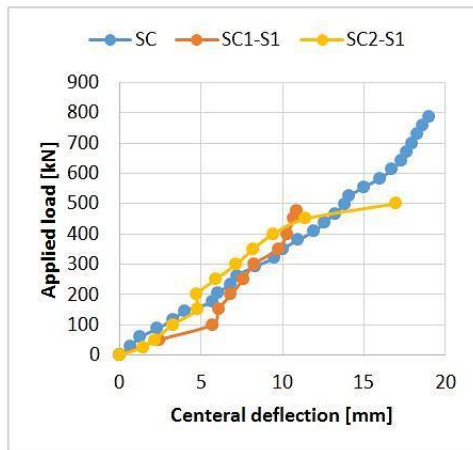


Fig. 10: Load-deflection variation for SC, SC1-S1, and SC2-S1 specimens.

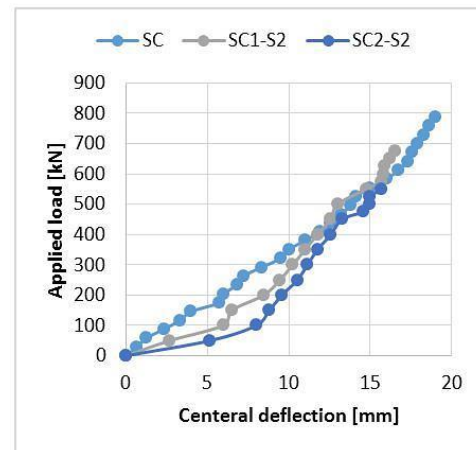


Fig. 11: Load-deflection variation for SC, SC1-S2, and SC2-S2 specimens.

5.3 Ductility and stiffness

Concrete ductility is the capacity of a concrete slab to bear or resist significant deflection before failing. The ductility of a concrete slab is very important and critical because it gives indications and provides quality and signs of collapse or failure so that it prevents the total collapse of a concrete member, which means the concrete slab can undergo more deformations (large deformations) without fail. Concrete is a brittle material, so the presence of CFRP laminate enhances the concrete property. All specimens' ductility U was calculated by dividing the deflection at the failure load Δ_F by the deflection at the maximum load Δ_m as follows:

$$U = \frac{\Delta_F}{\Delta_m} \quad (1)$$

Obtained load-deflection curves that recorded measurements experimentally at the midpoint for each tested specimen. The applied load vs. deflection at the slab's midpoint are shown in the Figures mentioned above for all specimens. The stiffness k_s is defined as the ratio of the ultimate load P_u to ultimate load deflection Δ_u as follows:

$$k_s = \frac{P_u}{\Delta_u} \quad (2)$$

Table 10 lists the ductility, ductility index, and stiffness for all tested specimens. Figs. 12 - 14 show the ductility, ductility index, and stiffness variations for tested specimens.

Table 10: Ductility, ductility index, and stiffness of all tested slab specimens.

Specimen mark	Ductility U	Ductility index UI	Stiffness k_s [kN/mm]
SS-Control	1.2	2.97	43.99
SC	1.24	2.77	41.47
SC1-S1	1.23	2.87	43.58
SC1-S2	1.28	2.85	40.81
SC2-S1	1.31	2.88	29.50
SC2-S2	1.25	2.83	35.03

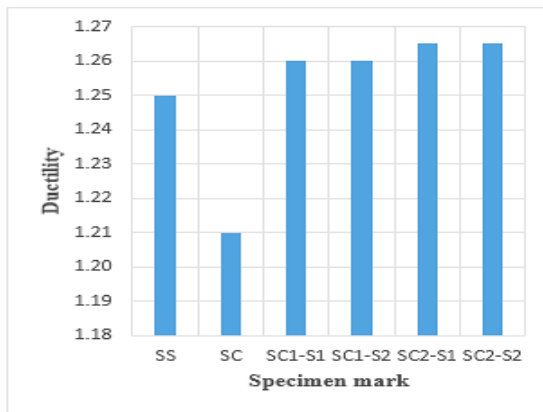


Fig. 12: Ductility of all tested specimens.

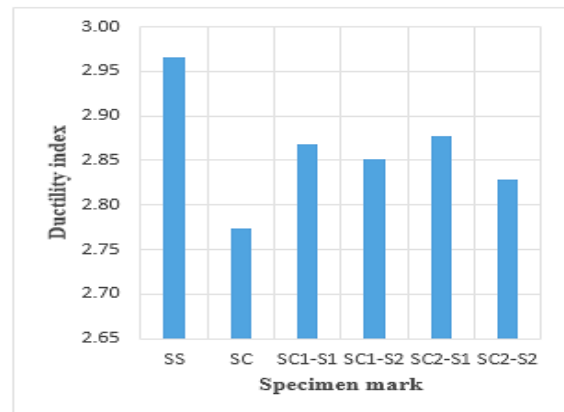


Fig. 13: Ductility index of all tested specimens.

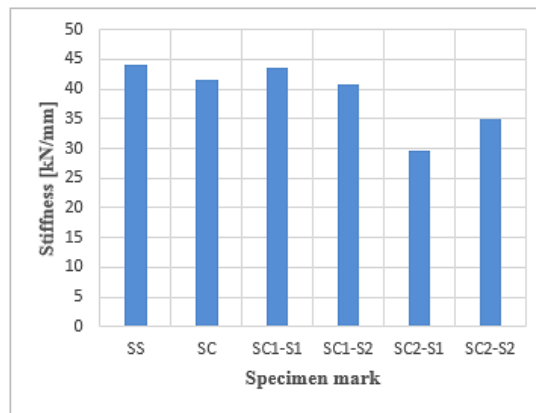


Fig. 14: Stiffness of all tested specimens.

5.4 Energy dissipation

The energy absorption of each specimen is the zone under the load-deflection curve [25]. The resistance of plain concrete against applied load is less due to low energy dissipation and low resistance in tensile strength. The energy absorption can be adopted to assess the post-cracking behavior of concrete at the deflection at mid-span. Table 11 lists the energy absorption for all tested specimens. A decrease in energy dissipation reduces the effect of applied load (absorb), and the load spreads over a large area so that the pressure produced from external load becomes less, which produces little damage. Fig. 15 shows the energy dissipation for all tested specimens. Specimen SC1-S1 gave smaller energy dissipation, so this specimen is the best solution.

Table 11: Energy dissipation of all tested specimens.

Specimen mark	Energy dissipation ED [kN·mm]	Energy dissipation ED [kN·m]
SS-Control	4163	4.163
SC	6545	6.545
SC1-S1	1795	1.795
SC1-S2	4237	4.237
SC2-S1	5191	5.191
SC2-S2	2953	2.953

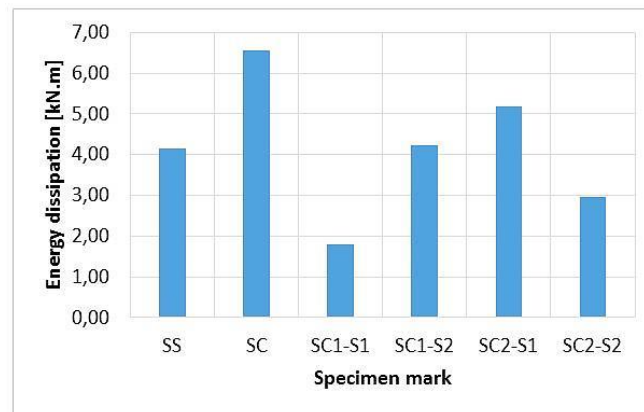


Fig. 15: Energy dissipation of all tested specimens.

5.5 Crack width

Under flexural loadings, such as reinforced concrete slabs under uniform distributed loading, the crack width relies on the amount of applied load, reinforcement, and concrete compressive strength. The permissible width of a crack under flexural loadings in concrete is limited to 0.2 mm, and the maximum crack width is 0.4 mm based on ACI-318-2019 [17]. The important parameter that plays an important in reducing the crack widths can be by using suitable reinforcement to distribute the cracks over the cross-section and tensile reinforcement with crack reinforcement so that many smaller cracks are present instead of fewer, wider cracks. The lower stiffness of CFRP and more flexibility lead to developed more deflection and wider crack width [ACI440-1R-15]. The limited crack widths range in the case of concrete members reinforced by FRP is 0.4-0.7 mm [ACI440-1R-15].

Fig. 16 shows the load-crack width variation for all tested specimens for each applied load step. Specimen SS gave less crack width because the reinforcement amount was enough to minimize the crack width. Specimen SC shows resistance to developing cracks due to more reinforcements than other specimens and is equivalent to specimen SS. CFRP layout Type 2 is better in the results of crack width but more than the control specimen SS.

Fig. 17 shows the load-crack width variation for all tested specimens. These variations based on the load caused a crack width of 0.4 mm. The crack width depends on the load resistance of the tested specimen. The load also caused a crack width of 0.4 mm; specimen SC1-S2 was 571 kN while specimen SS and SC were 450 and 350 kN respectively.

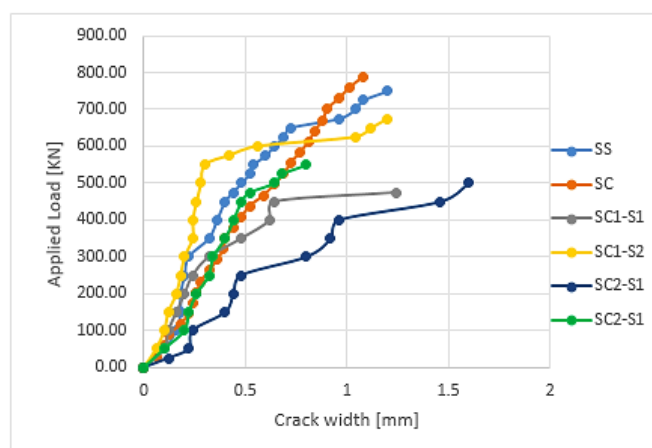


Fig. 16: Load-crack width variation at each load step for all specimens.

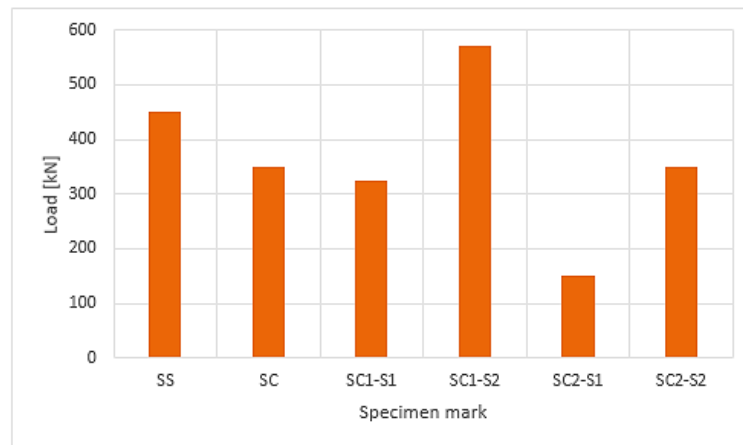


Fig. 17: Load-crack width variation at load cause 0.4 mm for all specimens.

A numerical method as finite element analysis (FEA) by ANSYS package version 20.00 R1 was adopted to check out the deformation of all tested specimens by applying the same experimental tests geometry, applied loadings, and support conditions. Table 12 lists the comparison results of maximum deflection by experimental tests and numerical analysis, where the ratio of FEA differences to the experimental test result ranged between 0.8 – 1.02.

Table 12: Comparisons between test and numerical deflection results

Model mark	Maximum deflection (Exp.) [mm]	Maximum deflection (FEA) [mm]	(FEA / Exp.) deflection
SS- Control	17.05	14.76	0.87
SC	19.00	16.47	0.87
SC1-S1	10.90	8.73	0.80
SC1-S2	16.54	16.90	1.02
SC2-S1	16.95	14.47	0.85
SC2-S2	15.70	14.31	0.91

6 Discussions

In simply supported RC slabs reinforced by traditional reinforcements such as SS specimens, the failure mode occurs as flexural due to the design principle suggested by ACI-318-2019 [41]. The design is based on under-reinforcement due to the yielding in reinforcement (specimen SS). The presence of CFRP bars in specimen SC as equivalent reinforcements of specimen SS (only differ in yielding strength) gave strength capacity higher than specimen SS due to the used same diameter of traditional reinforcement with less spacing and higher yield strength. ACI 440.1R-15 [42] design guideline used the ratio of FRP reinforcement to a balanced reinforcement ratio value ρ_f/ρ_b parameter and thresholds of 1.0 and 1.4 to predict whether FRP bar rupture or concrete crushing will occur first. In case of $\rho_f/\rho_b \geq 1.4$, concrete crushing is the predicted failure mode but in case of $\rho_f/\rho_b \leq 1.0$, FRP rupture is the predicted failure mode.

Cracks intensity and crack propagations differ from one specimen to the other. The specimen has been strengthened by CFRP laminates; the cracks propagations rounded the CFRP laminates with little inside the strengthening scheme because of the presence of CFRP laminates bridging the concrete at the bottom. Cracks intensity for specimen SC is more than other specimens due to their no-yielding strength of CFRP bars so the increase in applied load up to a failure of concrete.

Deflection increase when an increase in the strength capacity of the slab specimen at the ultimate stage and also in the failure stage but become less when compared to the same load of another specimen due to the adopted parameter. CFRP laminates scheme gave approximately the same strength capacity and maximum deflection but less spacing (increase in CFRP bar amount) plays an important parameter to reduce deflection and increase slab strength capacity.

Specimens strengthened by CFRP laminates gave ductility higher than specimens SS and SC due to the presence of CFRP laminates that enhance the strength capacity load but gave lower stiffness due to an increase in deflection at the maximum applied load.

Energy dissipation of specimen SC gave higher than the other specimens because this specimen was reinforced only by CFRP bars which make the RC slab not sufficient enough to absorb the applied load due to the less effectiveness of CFRP bars to bear and resist the applied loads.

7 Conclusions

Experimental of six concrete slabs reinforced by traditional and CFRP bars and strengthened by CFRP laminate were investigated. Based on the test results, below are important points concluded as follows:

- 1) Concrete slab reinforced by traditional reinforcements filed as flexural without cover spalling and normal deflected shape with cracks propagations (under reinforcement).
- 2) The slab specimens behaved elastically during the early stages of the tests.
- 3) The specimen slab reinforced by CFRP bars without strengthening with CFRP laminates exhibited significant elastic when upon unloading, but this was not observed in the steel-RC slab (control slab) because the CFRP reinforcements did not reach their rupture strain at the failure time.
- 4) The presence of CFRP bars in specimen SC as equivalent reinforcements gave higher strength percentages of 5.07 % of load capacity but differ in failure mode as compared with control slab specimen SS.
- 5) Cracks intensity for specimens reinforced by CFRP bars more than other control specimens.
- 6) Increasing in load capacity occurred by 42 % and 10 % for specimens reinforced by CFRP bars and strengthening with CFRP laminates layout 2 when compared with layout 1.
- 7) Specimen reinforced by CFRP bars exhibit an increase in the ductility of 3 % when compared with the control specimen reinforced by traditional reinforcement.
- 8) The energy dissipation of the specimen reinforced by CFRP bars only gave higher than the other specimens, where it exhibit an increase of 57 % when compared with the control specimen.
- 9) The put of the anchorage increased the strength of the CFRP laminates, so debonding did not occur in most specimens.
- 10) Using FRP reinforcing bars enhances the durability of the concrete slabs, specifically against aggressive environments where corrosion of conventional steel bars is the dominant reason for failure.

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