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Original Research

PERFORMANCE OF CONCRETE SLAB REINFORCED BY CFRP BARS AND STRENGTHENED BY DIFFERENT LAYOUT OF CFRP LAMINATES

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Abstract: In recent years, Fiber Reinforced Polymer (FRP) rebar has been adopted to reinforce structural concrete elements such as slabs. FRP strips are also increasingly used to reinforce or strengthen concrete members that require higher carrying capacity or to restore damaged structural elements. Therefore, the reinforcement of concrete structures with this material is increasing but the effect of variables on CFRP-reinforced concrete slabs and externally bonded with CFRP laminates has not been evaluated in detail. This study presents a numerical analysis of the structural performance of concrete slabs reinforced by CFRP bars and strengthened by CFRP laminates using a finite element approach with ANSYS software. Six models with the same geometry (1550x1550x100 mm) were analyzed. Four models were reinforced with CFRP bars and externally strengthened with CFRP laminates, one model was reinforced with CFRP bars without external strength, and one reference model with traditional reinforcing bars (control specimen). Different parameters were adopted, such as amounts of FRP bars and CFRP laminates layout in which some models contained both CFRP bars and CFRP laminates. A uniformly distributed load that was calculated by plastic analysis was applied at the top surface area of each model. The plastic load considers the contribution of the laminated CFRP strips that increased the strength of the slab. Analysis results in the maximum strength carrying capacity in equivalent CFRP bars exhibit higher strength percentages of 5.07% of load capacity but differed in mode of failure than conventional reinforcements control slab.

Keywords: *Ductility; externally strengthened; finite element; strengthened concrete slab; stiffness*

1. Introduction

The reinforcement for concrete structures is necessary due to the numerous factors that affect a structure over its life. Several factors include damage to the building's structural integrity, the need to upgrade its load-carrying capability, structural alterations, or resolving construction-related issues. Many approaches for reinforcing or repairing reinforced concrete (RC) structural elements have been applied to address these issues in the past. For RC slabs, strengthening options include section expansion, ferrocement cover, external steel plate bonding, external post-tensioning, span-shortening techniques, and the addition of supplemental supports, each of which has advantages and disadvantages depending on the circumstances. [1, 2]. Fiber-reinforced polymer (FRP) rebar and strips have excellent properties non-corrosive and non-conductive with higher tensile strength [3]. Bars have been identified as a potential

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substitute for steel reinforcement due to their nonmetallic, noncorrosive nature, high tensile strength, and lightweight. Carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and aramid fiber-reinforced polymer (AFRP) are the most frequently utilized FRP bars. Apart from replacing steel reinforcement with FRP, it has been suggested that they could be utilized as steel pre-stressing tendons in pre-stressed concrete structures (ACI 440R 1996) [4]. An appreciable number of bridges, buildings, and other structures worldwide have been strengthened using FRP laminates and strips using the external bonding (EB) technique [5]. Furthermore, externally bonded reinforcement (EBR), comprising materials such as (FRP), is one of the most efficient and popular retrofitting methods for concrete and steel structures [6]. However, it has a significant drawback of debonding, which may occur at less than 50% of CFRP tensile strength capacity, where up to half of its tensile capacity is ineffective, Previous studies have shown that the use of mechanical anchors, fan anchors, and u-wraps, assisted with mitigating debonding and utilizing the maximum capacity of the CFRP [7]. Besides, FRP bars can be adopted in parallel requirements that minimize the construction cost using these advanced composite materials, especially resist corrosion, compared with the traditional reinforcements [8]. A lower modulus of elasticity of FRP bar than that of traditional reinforcement can be detrimental in case of deflections instead of strength carrying capacity control the design. In addition, tensile strength as (stress-strain) behavior of a specified diameter is impacted by the type, volume fraction, and orientation of the reinforcing fibers and the production process [9, 10]. In slabs reinforced by (GFRP) or (CFRP), the ratio of bottom transverse rebar plays an important parameter [11]. Strengthening the concrete slab with CFRP laminates is highly advantageous as long it improves the concrete slab's flexural capacity without affecting the mode of failure [12]. CFRP laminated thickness affects the strength capacity and stress distribution for the overall performance of the concrete slab [13]. The strengthened concrete slab strains less than non-strengthened concrete slabs because of the effect of the encirclement and confinement [14]. The Strengthening increases the slab's capacity to carry more load [15]. The slabs strengthened with CFRP had the highest flexural capacity for the same concrete compressive strength, while the other strengthened slabs with GFRP, basalt fiber-reinforced polymers (BFRP), and polyethylene terephthalate fiber-reinforced polymers (PET-FRP) displayed nearly identical behavior. The effect of concrete compressive strength on the behavior of the strengthened slabs was moderate, although it was more dominant in the CFRP-strengthened slabs [16]. When CFRP laminates were used to strengthen the thin and highly-strength concrete slabs, it was discovered that an increase in the concrete's compressive strength and the width of the FRP layers led to an improvement in the slabs' capacity [17]. Compared to GFRP and steel bars, the use of CFRP bars improves overall performance and offers closer approximations to strength and deflection values [18].

The First crack load and Failure load increase by almost twice as much if two layers of (CFRP) sheet are used for external reinforcement instead of one layer [19].

Few studies have been done to confirm that CFRP laminates with various layouts that provide the same or more strength capacity, fewer deformations, and a reduced mode of failure can strengthen concrete slabs instead of conventional reinforcing. Yet, early debonding, which greatly reduces the ductility of RC slabs, was the most common reason for failure in CFRP laminates. As a result, anchorage can be employed to lessen CFRP-enhanced early debonding.

2. Aim and Significance of Study

The aim and significance of the present study are to evaluate the structural performance of concrete slabs reinforced by CFRP bars and strengthening by CFRP strips under the effect of static loads. The finite element approach with ANSYS was applied to analyze the models and check out the strength-carrying capacity.

3. Finite Element Analysis

A numerical method as a finite element analysis is adopted to analyze reinforced concrete slab (RCS) models. Three-dimensional modes have been made for the RCS under the effects of uniformly distributed loading. The purpose of the finite element analysis by ANSYS package version 20.00 R1 is to evaluate the structural performance of RCS by applied loading that is analyzed by plastic analysis. The main assumptions that are adopted for all models are that the simulated materials such as concrete, reinforcements, and CFRP behaved as isotropic and homogeneous, plane sections remain plane before and after applied loading (geometrically linear behavior), and full interaction bond between reinforcements and surrounding concrete (no shear friction) and full interaction between CFRP laminates and concrete (no slip at the interface). Different elements are adopted, such as concrete, reinforcements, CFRP bars, CFRP laminates, and supports. The structural concrete slab is modeled with ANSYS capable of checkout the mode of failure. The most important criteria in concrete are cracking and crushing, which occur in tension and compression zones, respectively. The finite element method uses a smeared cracking approach to model the reinforced concrete. In the smeared cracking approach, cracking of the concrete occurs when the principal tensile stress exceeds the modulus of rupture suggested by ACI – 318- 2019 [20]. Discrete is the method that is adopted to simulate the reinforcements of reinforced concrete members model and conventional and CFRP bars. In this method, the reinforcement is modeled as actual representations; the concrete and reinforcement meshes are merged with the same nodes when the reinforcement nodes are joined to the concrete nodes mesh. Full displacement compatibility between reinforcement and concrete is an aspect of the discrete representation. Their disadvantages are the restriction of the mesh and the increase in the total number of elements. Four elements are chosen to represent the reinforced concrete slab models. SOLID65 element is selected to simulate the concrete slab, LINK180 for steel reinforcements, and SHELL181 for CFRP

SOLID185 was used to simulate supports around the model. It is defined as eight nodes, each of which has three degrees of freedom: translations in the x, y, and z directions. The supports were modeled as homogenous structural solid materials. Each selected element type represents and simulates the actual behavior of each material. SOLID65 element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. LINK180 element is adopted to simulate reinforcement. It is a 3D spar element with two nodes, each three degrees of freedom per node, capable of translations in all three directions and an additional capable of plastic deformation. SHELL181 element to simulate the CFRP laminated because this element is suitable for thin or thick shell structural elements. It has four nodes has six degrees of freedom for each node and translations in the three directions with rotations and SOLID185 element for support. Materials model properties for each material such as Poisson's ratio, modulus of elasticity, compressive strength, tensile strength, open and close shear transfer coefficients (for concrete), for steel bar and CFRP laminate only Poisson's ratio and modulus of elasticity for linear analysis are input as required by ANSYS software.

4. Finite Element Models

Six models were built and analyzed, considering different parameters such as support conditions as simply supported for all four edges, main reinforcements distributions and rebar's type (traditional and CFRP bars), and CFRP laminated layouts. Table 1 lists the finite element models and the descriptions for each model.

Table 1. Models symbols and descriptions

Model symbol	Reinf. type	Spacing (mm)	Strength.
SS-Control	Steel -Bar	Φ10@300	N/A
SC	CFRP -Bar	Φ10@150	N/A
SC1-S1	CFRP -Bar	Φ10@200	Str. -Type1
SC1-S2	CFRP -Bar	Φ10@200	Str. -Type2
SC2-S1	CFRP -Bar	Φ10@300	Str.- Type1
SC2-S2	CFRP-Bar	Φ10@300	Str.-Type2

The cover for each side is 25 mm, and the bottom is 20 mm, with a total model height of 100 mm and plane layout dimensions of 1550x1550 mm. In model SC, the traditional reinforcement was replaced by CFRP bars that used the same diameter but differed in center-to-center spacing. Model SC1-S1 spacing of CFRP bars is 200 mm and strengthening by CFRP laminated-Type1 is shown in Fig. 1(a), also model SC2-S2 same as model SC1-S1 but differs in CFRP laminated-Type2 layout that is shown in Fig. 1(b). Model SC2-S1 is similar to model SS-control but replaces the traditional reinforcement by CFRP bars and strengthened – Type 1. Model SC2-S2 is the same as model SC2-S1 but Strengthened by CFRP laminates-Type 2. Table 2 lists the mechanical properties of concrete, traditional reinforcements, CFRP bars, and laminated CFRP. The stress-strain curves of concrete, steel bar, and CFRP bar are shown in Figs. 2-4 respectively. Model SS-control represents the control model that is reinforced by traditional reinforcements.

The SS model was designed according to ACI 318-19 [19], and the other models were designed according to ACI 440.15.1R [21].

Table 2. Materials mechanical properties

Concrete			Traditional reinforcement			
f'c (MPa)	Ec (MPa)	V	Fy (MPa)	fu (MPa)	Es	v
21	21500	0.2	565	782	204700	0.3
βo	βc					
0.2	0.7					
CFRP bar*			**CFRP laminate****			
fu (MPa)	Ef (MPa)	V	Thick. (mm)	f_{fu} (MPa)	Ef (MPa)	v
2172	124000	0.3	1.4	3044	158000	0.3

*, ** Supplied by the manufacturer

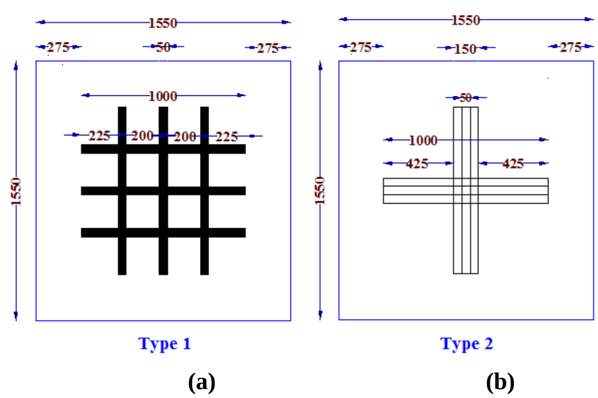


Figure 1. CFRP laminates layout- (a) Type 1, (b) Type 2

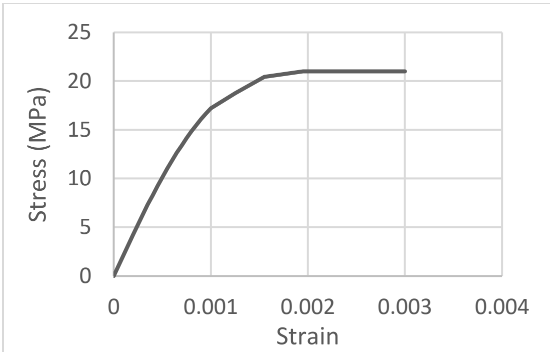


Figure 2. Stress-strain curve concrete of compression

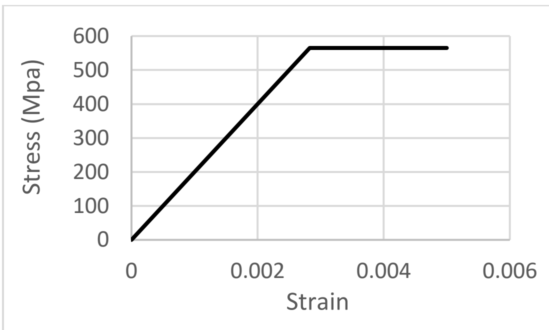


Figure 3. Stress-strain steel bar curve

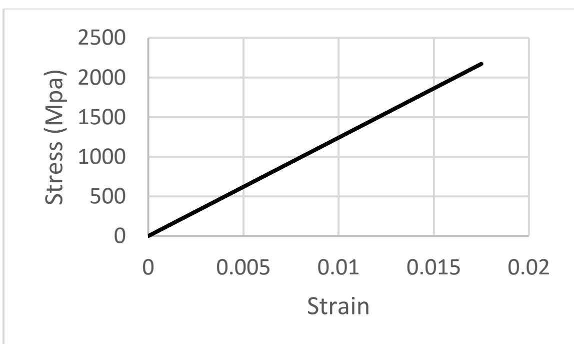


Figure 4. Stress-strain CFRP bar curve

The total number of elements is 15376, and the element size is 25 mm as cubic (62 elements in x direction, 62 elements in the z-direction, and four elements in the y direction). The support conditions along the four edges are simply supported. The uniformly distributed loads were applied at the top face load per unit area of each model as pressure plastic loads. The three-dimensional control model with supports at the bottom (red color) as shown in Fig. 5. Figs 6 to 10 shows reinforcement distribution and CFRP laminates layout.

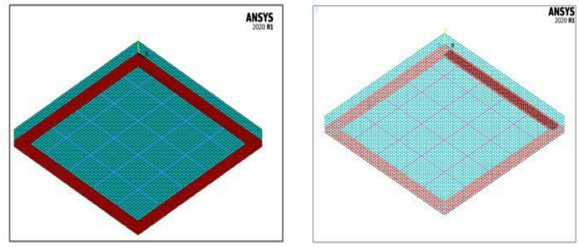


Figure 5. Three-dimensional and reinforcement distribution of model SS

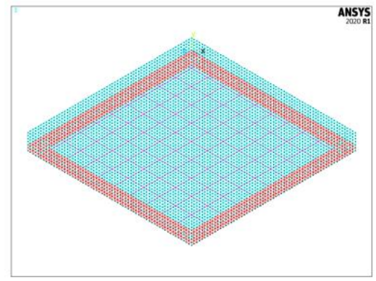


Figure 6. Reinforcement distribution and CFRP laminates layout of model SC

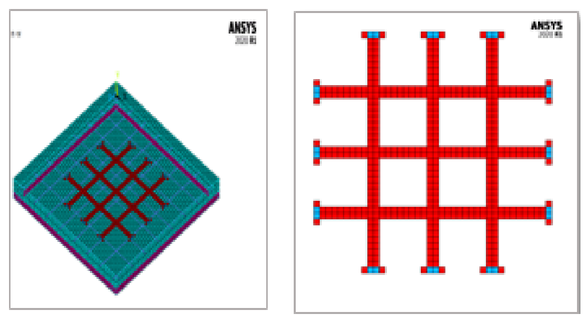


Figure 7. Reinforcement distribution and laminated CFRP layout of model SC1-S1

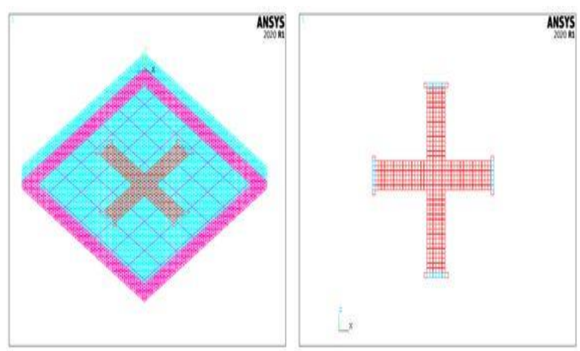


Figure 8. Reinforcement distribution and CFRP layout of model SC1-S2

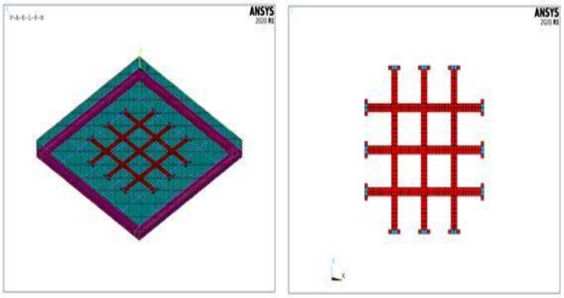


Figure 9. Reinforcement's distribution and CFRP layout of model SC2-S1

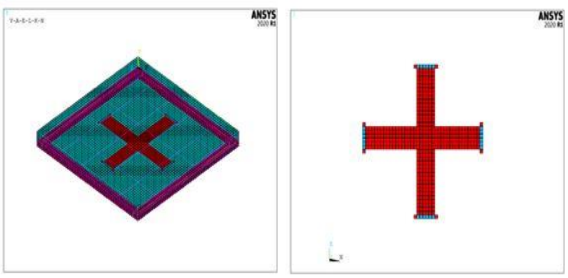
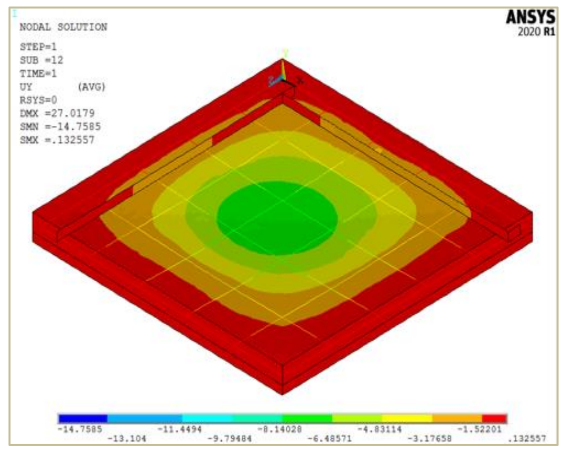


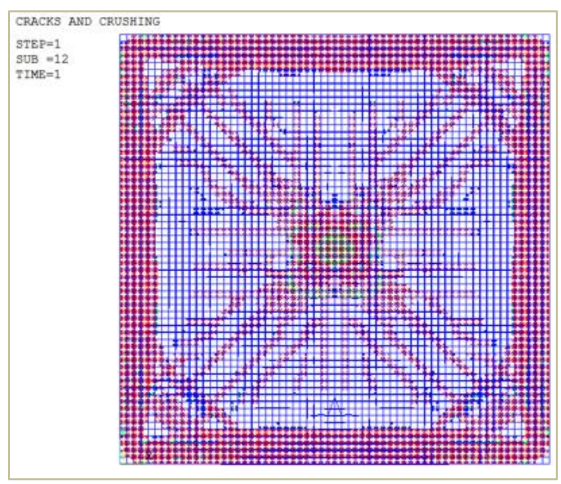
Figure 10. CFRP layout of model SC2-S2-three-dimensions

5. Analysis Results

Numerical analysis results are similar to experimental tests such as load-deflection were investigated. Midspan deflection and cracking patterns for all the simulated specimens are illustrated in Figs. 11 - 16. Maximum deflection for all models occurs in the bottom mid-span of reinforced concrete slab and the maximum strain in concrete at the top of each model. However, most of the results of the deflection were convergent while the model SC1-S1 recorded the minimum deviation. Crack propagations started from the bottom and then raised towards the model edges, in which the crack intensity relies on the amount of reinforcements and presence of CFRP laminates and layout (Type 1 or 2). Table 3 lists the maximum applied load, maximum deflection, stiffness, and ductility for all models. Table 4 lists the load capacity comparison with control model SS for all models. The maximum strength carrying capacity in the model SC, which is nearest to the control model SS, and the weakness model is SC1-S1. All models have crack propagation and intensities more than the control model. No failure occurs in CFRP laminates as debonding due to increased compressive stress at the contact surface between concrete and laminated CFRP.

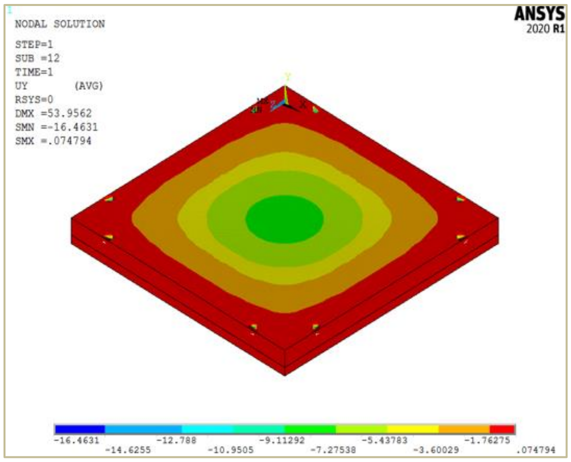


(a) Deflection

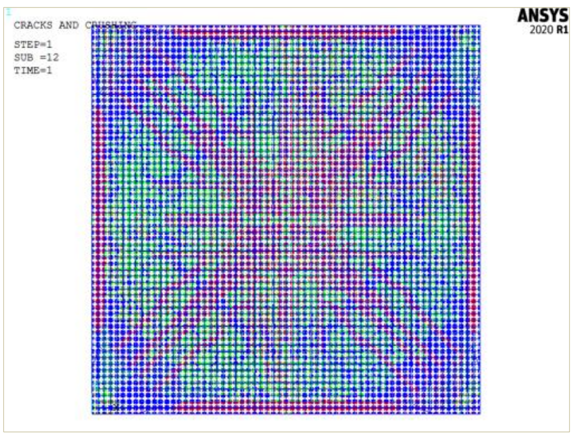


(b) Cracks Propagations

Figure 11. Deflection, and cracks propagations of model SS at final stage analysis

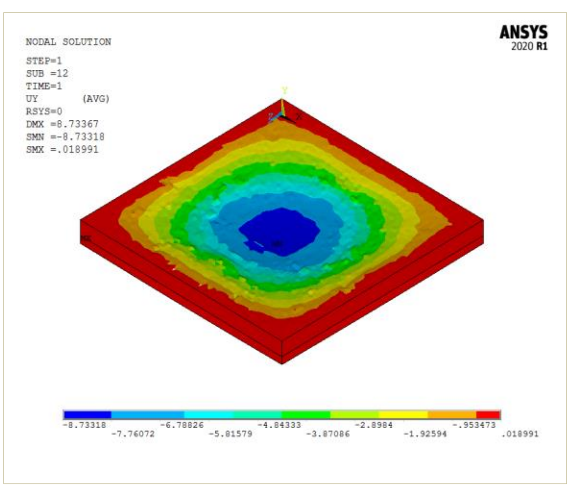


(a) Deflection

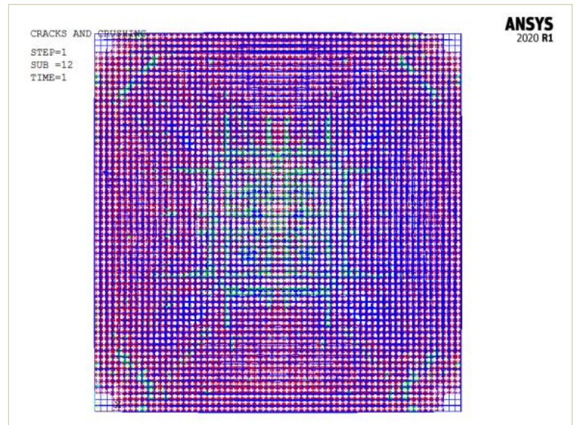


(b) Cracks propagations

Figure 12. Deflection, and cracks propagations of model SC at final stage analysis

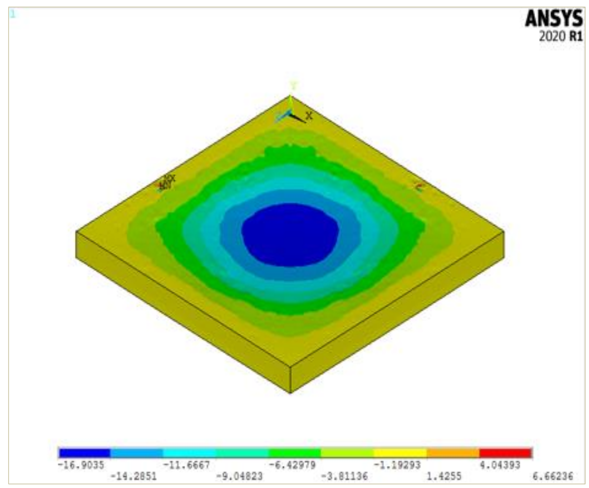


(a) Deflection

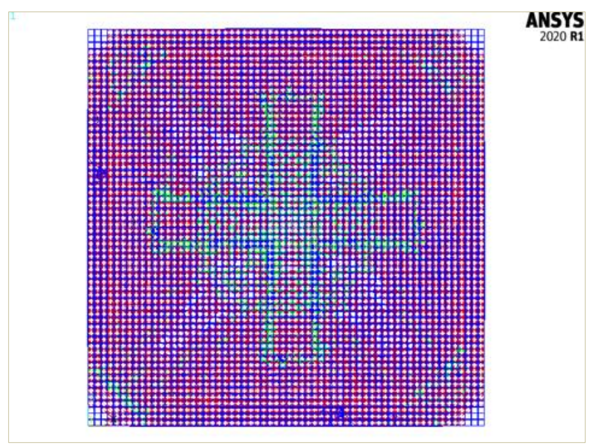


(b) Cracks propagations

Figure13. Deflection, and cracks propagations of model SC 1-S1 at final stage analysis

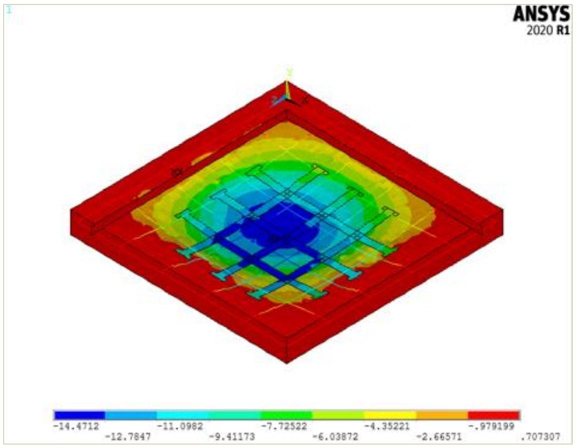


(a) Deflection

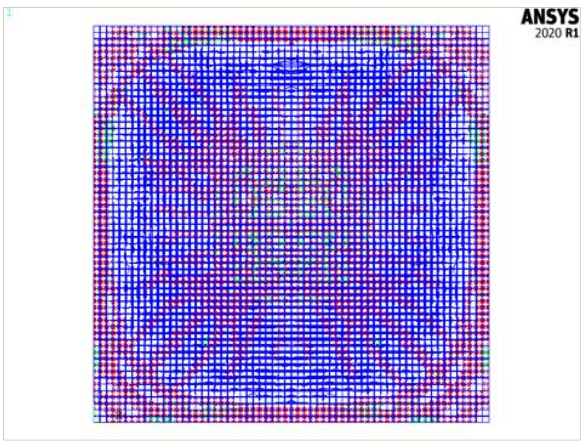


(b) Cracks propagations

Figure14. Deflection and cracks propagations of model SC1-S2 at final stage analysis

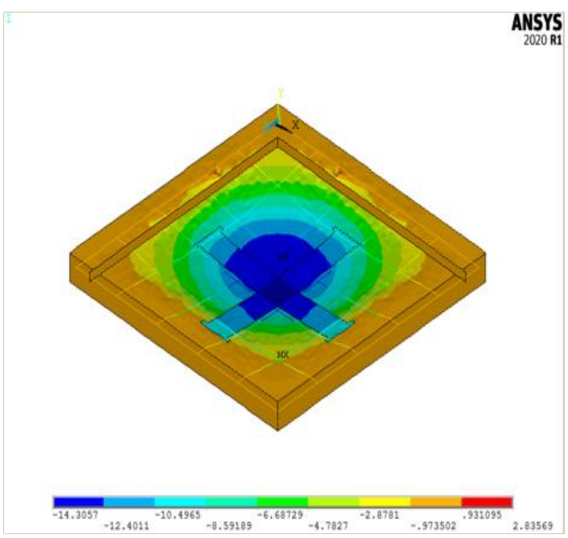


(a) Deflection

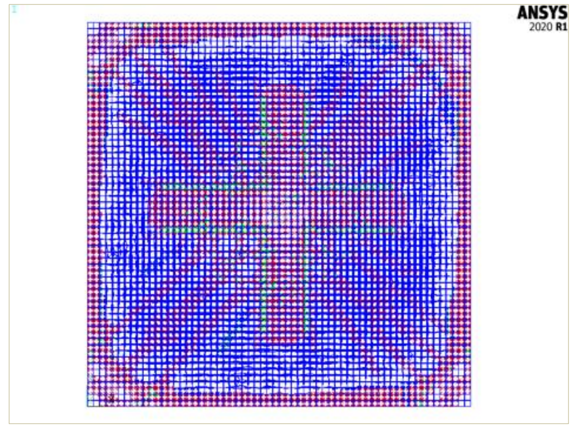


(b) Cracks propagations

Figure15. Deflection, and cracks propagations of model SC2-S1 at final stage analysis



(a) Deflection



(b) Cracks propagations

Figure16. Deflection, and cracks propagations of model SC2-S2 at final stage analysis

Table 3. Maximum applied load, maximum deflection, stiffness, and ductility for all models

Model mark	P_m (kN)	Δ_m (mm)	Stiffness (kN/mm)	Ductility (maximum deflection/ elastic deflection)
SS-Control	750	14.76	50.81	13.92
SC	788	16.47	47.84	7.88
SC1-S1	475	8.73	54.41	2.23
SC1-S2	675	16.90	39.94	5.20
SC2-S1	500	14.47	34.55	7.16
SC2-S2	550	14.31	38.43	5.44

Table 4 presents the worst-case occurrence in model SC1-S1 compared to control model SS followed by SC2-S1, indicating that the strengthening layout Type 2 exhibits performance and strength capacity better than Type 1.

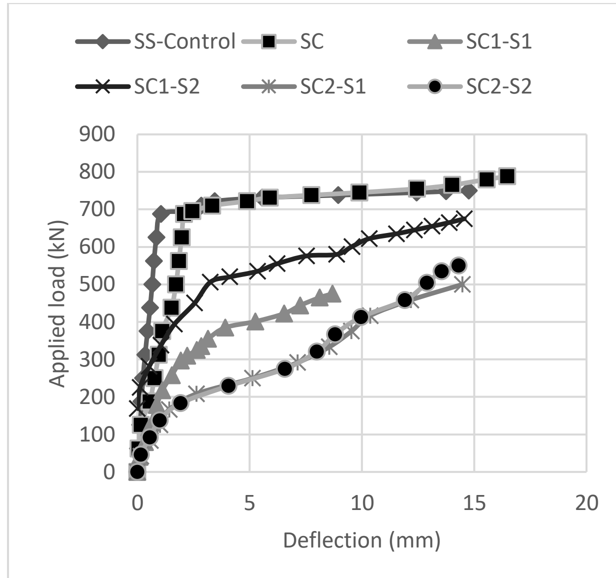
Table 4. Load capacity comparison with control model SS

Model mark	Maximum load (kN)	% Increase (+) and decrease (-)
SS-Control	750	----
SC	788	+5.07
SC1-S1	475	-36.67
SC1-S2	675	-10
SC2-S1	500	- 33.33
SC2-S2	550	- 26.67

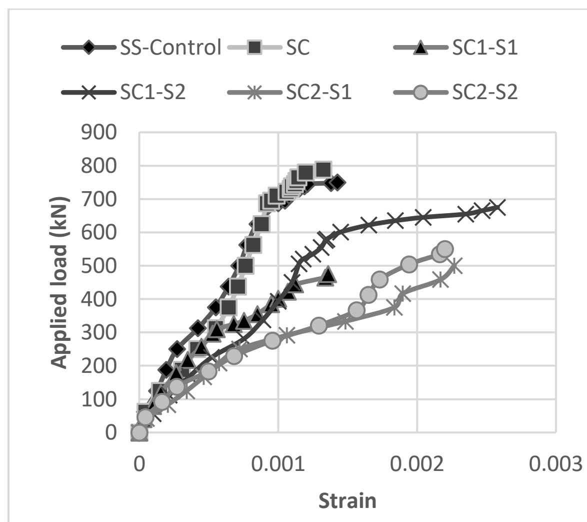
Fig. 17 illustrates the load-deflection and load-strain in concrete performance of all models, respectively. All models do not reach the maximum strain suggested by ACI-318-2019 code (0.0030), in which the maximum strain occurs in model SC1-S2 equal to (0.0026) and minimum in model SC1-S1 equal to (0.00135).

Fig. 18 shows the performance of all models representing stiffness, and ductility (ratio of maximum deflection of deflection in elastic). In general, the performance of reinforced concrete slabs under uniformly distributed monotonic load started as linear with a small applied load up to the inflection point. At this point, the model loses some of its strength resistance. The location of this point depends on the applied load, the amount of reinforcement (traditional or CFRP bar), and the existence of CFRP laminate. As the applied load increases, the deflection increases, which causes the stiffness of the reinforced concrete slab model to decrease. The stiffness of each model is listed in Table 3 in which the maximum stiffness occurs in model SC1-S1 due to having less deflection, but the better model is SS. Ductility is the ability of a reinforced concrete slab to deform without significant resistance loss; type SS has the highest ductility.

The maximum deflection obtained from both numerical analysis and experimental testing is compared in Table 5, where the ratio of the FEA result to the experimental test result varied from 0.80 to 1.02.



(a) Load-deflection

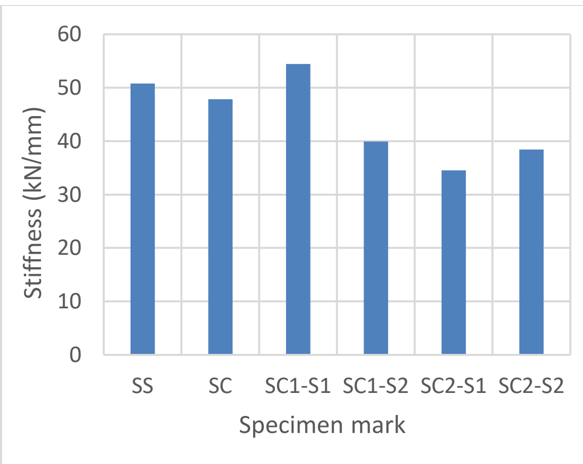


(b) Load-strain

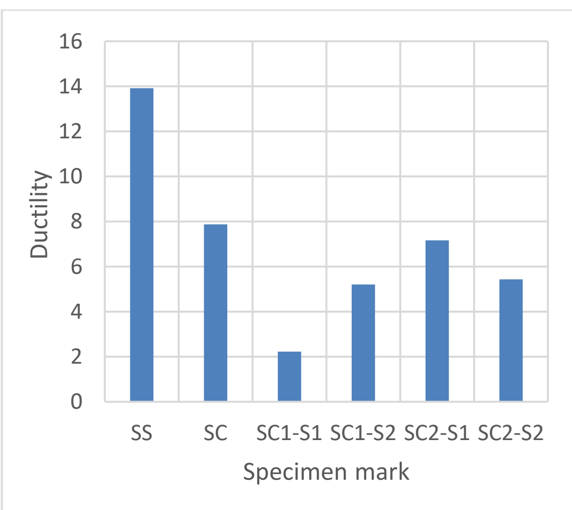
Figure 17. Load-deflection, and load-strain in concrete variations for all simulated models

Table 5. 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



(a) Stiffness



(b) Ductility

Figure 18. Stiffness, and ductility for all models

6. Discussions

Numerical models - finite element approach with ANSYS that adopted to simulate reinforced concrete slab under uniformly distributed static load. The finite element models result in deflections, concrete strain, and various crack propagations depending on reinforcement type, amount, and CFRP laminated layout. The lower deflection in numerical analysis is due to the effect of some parameters such as open and closed cracks that led to a decrease or increase in model deformation.

Due to the application of the same diameter of conventional reinforcement with smaller spacing and better yield strength but different mechanical properties, the inclusion of CFRP bars in model SC, which are similar reinforcements of model SS, achieved a strength capacity higher than model SS.

The intensity of cracks and the direction of crack spread differ from model to model. Cracks spread around the CFRP, with little cracks inside specimens strengthened with CFRP laminates. Because the CFRP bars have no yielding strength, the crack intensity for model SC is more than the rest of the models, increasing the applied load until concrete failure.

When the slab model's strength capacity increases at the maximum stage, deflection also increases. The maximum deflection and strength capacity are nearly the same in the laminated CFRP scheme. To reduce deflection and enhance slab strength capacity, less spacing is required (an increase in CFRP bar quantity).

The ductility of the SS model exhibits higher ductility compared with the SC model reinforced by CFRP bars. CFRP bars' elastic modulus is lower than conventional reinforcements so the deflection and crack width of RC slab models reinforced with CFRP bars are higher than that of traditional RC slab models at a serviceability state.

7. Conclusions

Six RC slab models reinforced by CFRP bars and conventional and CFRP laminate are analyzed using a finite elements analysis.

The use of CFRP bars as equivalent reinforcements in the concrete slab model exhibits a greater strength percentage of 5.07% of the load capacity but with eventual change in the mode of failure. Strengthening of the concrete slab by CFRP laminates leads to cracks propagated in the zone surrounding the laminated CFRP and little cracks inside the CFRP laminates. The intensity of cracks and crack spread differ from one model to the other. To reduce deflection and enhance slab strength capacity, less spacing is required (an increase in CFRP bar quantity). The maximum deflection and strength capacity are nearly the same in the laminated CFRP scheme. An increase in ultimate loads occurred with percentages of 42% and 10% for the slab layout type 2 respectively. The strengthening layout Type 2 exhibits performance and strength capacity better than Type 1. Concrete slabs have higher stiffness reflected by less deflection and higher strength capacity. Comparing a specimen reinforced with CFRP bars with a control specimen reinforced by conventional reinforcement, the former shows a 3.33% increase in ductility.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

βo	Open coefficient of shear transfer for
βc	Close coefficient of shear transfer for
Ec	Modulus of elasticity of concrete
Es,	Modulus of elasticity of Steel, CFRP
f_u,	Ultimate tensile strength
fc’	Cylinder Compressive strength
Pm	Maximum applied load
Δm	Maximum deflection at ultimate
v	Poisson’s ratio

Author Contribution Statement

Contribution Statement of Author Authors Mu'taz Kadhim Medhlom: proposed the research problem and supervised it.

Author Entidhar Najm Abed: developed the theory and performed the computations.

Authors Mu'taz Kadhim Medhlom, and Entidhar N. Abed: checked the theoretical analysis methods and supervised the results of this research, and they contributed to the final manuscript.

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