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Original Article

Behavior and Strength of Concrete Slab Reinforced by GFRP Bar and Strengthened by Pre-Stressed Laminated CFRP under Uniformly Distributed Loading

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Abstract *- A Total of six specimens, including a control without strengthening, were tested under the effect of pressure load that represented a solid concrete slab reinforced by Glass Fiber Reinforced Polymer (GFRP) bars with four edges fixed as boundary conditions and strengthened by different layouts of Carbon Fiber Reinforced Polymer (CFRP) strips laminated. The behavior and strength of the tested specimens were discussed and evaluated, including strength and deformation, stiffness, ductility, and energy dissipation, based on the recorded and observed results of each specimen. As a result, the presence of CFRP strips or laminated CFRP gave an increase in load strength capacity due to representing an additional reinforcement that was placed at the tension zone of tested specimens, which led to an increase in resistance against applied loadings and a decrease in deflection. The failure mode occurs as flexural due to the design requirements of a reinforced concrete slab by applying the methodology proposed by ACI-318-2019, as under reinforcement due to the yielding in reinforcement before concrete failure. The design principle of GFRP bars without traditional reinforcements is based on the equivalent tension force (differing in yielding strength).*

Keywords *- Reinforced concrete slab, Pre-stressed, Strengthening, CFRP strips, Laminated CFRP, Flexural failure, Concrete enhancement strength.*

1. Introduction

The presence of CFRP strips on the aperture slabs had an impact on the slab's collapse load pattern. The CFRP composites have become a possible replacement for traditional materials in the field of civil engineering. Using CFRP composites in various construction structural parts, as well as their features and qualities, including their rigidity, outstanding durability, and integration of temperature variables, as well as their fatigue and resistance to corrosion. Because of their remarkable strength, excellent resilience, and lightweight, CFRP composites are perfectly suited for civil engineering projects.

High-strength artificial or organic fibers suspended in an epoxy substrate typically make up FRPs. Carbon Fiber Reinforced Polymers (CFRP), Aramid Fiber Reinforced Polymers (AFRP), Glass Fiber Reinforced Polymers (GFRP), and Basalt Fiber Reinforced Polymers (BFRP) are the ones that are most often utilized for civil engineering projects. FRPs are frequently utilized in place of traditional steel reinforcing bars (rebar), when rust typically occurs, in the building of concrete structures, because of their outstanding electrolytic durability. In Germany, the first highway overpass ever precast with GFRP rebar was constructed in 1986.

The use of CFRP material placed at the bottom fiber of the concrete slab, restricting mechanisms, is among the most alluring uses for these materials. Shear strength, ductility, and energy dissipation capacity were all significantly improved by CFRP laminate shear reinforcement.

It is clear that the CFRP strips are under higher stress on their bottom side than on their top side, close to the area where the load is applied. The outcome of this procedure is determined by the load's intensity and the interactions of the adhesive surface with the CFRP strip and the host concrete surface. The right approach to this substrate concrete surface before attaching the CFRP strips could end up in a significant improvement in the corresponding force transfer capability, according to an earlier study conducted by the authors. Because the force transmission process and the accompanying capacity rely heavily on the anchoring device's efficient operation, it is to be assumed that the existence of attaching devices reduces the significance of this bonding process.

The slabs attained their utmost separating capacity prior to having attained their utmost piercing capacity because the pre-stressed force in the CFRP plates amplified the separating impact. The greater flexion rigidity of the CFRP plate, which significantly amplified the separating implications, is another aspect that contributed to the separating catastrophe. The adhesive on the surfaces of the CFRP sheets was seen to be extremely silky and to have very little concrete debris affixed.

As a result, it is thought that the concrete layer that lies just below the layer of adhesive is where the bond breakdown started. On the other hand, during its stress history, the pre-stressed slab did not experience any yielding. This is explained by the confined effect of the pre-stressing, which prevented the development of tangential flexural fractures in the vicinity of the column. According to the findings, pre-stressing the CFRP plate by up to 15% before attaching it to the tension surface of the slab slowed the cracking process. Nevertheless, the initial fracture load did not increase further when the pre-stressing ratio was raised over 15%.

According to the findings, early loading is when deboning fractures are most likely to form when pre-stressing forces are large (over 15%). This implies that if the substrate is unable to support the in-plane force in the FRP, lamination or FRP separating is more probable to happen.

In the present study, the behavior and strength of concrete slab reinforced by GFRP and strengthened by pre-stressed strips or laminated CFRP under uniformly distributed loading are investigated. The adopted parameters included CFRP type as strips, laminated with different layouts, and pre-stressed before applied pressure loadings. Six tested specimens, including a control specimen without strengthening, were tested. The present study tries to fill the gap in this field by applying a pre-stressed CFRP strip and laminating it, which is placed at the bottom of the concrete slab to increase the flexural resistance that reflect on the strength capacity of concrete slab reinforced by GFRP bars, reduce the deformation and checkout if this type of reinforcement adequate or not under the effect of pressure loadings. Strength, carrying capacity, deformation as deflection, stiffness, ductility, and energy dissipation were explored and discussed for all tested specimens. The application of prestretched concrete is rising fast across several structural engineering disciplines owing to major developments in construction methods and the increasing demand for long-span elements [1]. Post- or pre-tensioned reinforced concrete offers a number of advantages [2]. Before pouring concrete over the wires, the pre-tension technique requires them to be tensioned between two permanent supports. Once the concrete has dried, they may detach the wires from their stems [3, 4]. The use of pre-existing formwork and corrugated ducts coupled to any appropriate profile allows for the distribution of post-tensioned concrete [5, 6]. Pouring concrete into ducts should not be done in a way that puts undue stress on the wires within. Just when the concrete is ready to crack, the wires are pushed taut. After putting the connecting plates into the mixture, the ends of the cables may be firmly prestressed and stress-dissolved in concrete [7, 8]. The reinstalled wires are usually covered with grout once they are placed into the corrugated ducts. The wires may be reinforced and their ability to control cracks improved by tying them to the concrete [9]. In other cases, the cost of grouting the wires and completely removing the bond makes it impractical. Complete prestressing is used for components that are subject to regular service loads [10], whereas partly prestressed concrete combines ordinary RC with partially prestressed concrete. [11]. The low ductility of fully prestressed concrete members has been one of the problems associated with Applications [10, 12, 13].

Yet it is highly encouraged that present structures be strengthened and updated due to changes in norms and laws, as well as adjustments regarding how buildings function [14, 15]. Research on Fiber-Reinforced Polymers (FRPs) for strengthening applications made significant advances in the remaining years of the previous century [16-18]. Because of their various characteristics, especially their high tensile capacity, non-corrosive nature, and lightweight nature, FRPs are considered to be a superior substitute for steel plates [19-21]. The process for making pre-cured laminate involves the manufacturer impregnating fibers with adhesive, after which the fibers are pultruded and allowed to cure. Pre-cured laminate manufacturing yields the most notable result if it relates to manufacturing laminates that are more robust and stiffer per unit volume than comparable wet lay-up laminates [22]. All of the fibers in laminates used to bolster concrete are usually orientated in a longitudinal direction and are unidirectional [23-25]. Because of the complex debonding failure methods of FRP-strengthened reinforced concrete slabs and also the material and geometrical nonlinearities of these frameworks, the bond behavior between FRP and concrete was extremely challenging and complex. The bond behavior between FRP (Fiber-Reinforced Polymer) and the concrete surface is influenced by various aspects, including the adhesive material's strength and stiffness [27-29], the length of the procedure for bonding, the FRP/concrete ratio, and the grade of the concrete [26]. The bond-slip models for FRP sheets/plates mounted to concrete were created by Lu et al. [30] using 253 pull tests on basic FRP-to-concrete bonded connections. A more accurate model is required, according to the results. The possibility of reinforcing P.T. concrete components with FRP was one of several factors examined by the researchers. The response of pre-stressed slabs with core holes was studied by Mohamedien et al. [31]. With length, breadth, and thickness measurements of 1.2 m each, the nine slabs make a total of 5.2 m. Reinforcing the slabs was a combination of CFRP strips and sheets. The study indicates that reinforced slabs may have their flexural capacity increased by up to 40% when CFRP is added to them. Chakrabarti et al. used these results as their foundation. [32] An experimental study of unbonded P.T. slabs comprised slab specimens that had undergone various CFRP pattern repairs. They came to an agreement that using CFRP for slab repairs lowered both the frequency and the width of the cracks at the high moment zone, and their findings of the repaired P.T. slabs revealed better serviceability conditions. Consistently joining the CFRP sheets greatly enhanced the flexural strength of the slabs. Results showed that two-way P.T. concrete slabs reinforced with CFRP strips and bonded tendons performed better in flexure tests than control specimens in terms of ductility (62.18% increase), initial stiffness (58.18% increase), and deflection (37.22% decrease).

More research on the behavior of concrete has been conducted as a result of advances in computing technology and the powerful processing capabilities of high-end computers [34, 35]. Several studies looked into the effects of various FRP strengthening techniques in the context of P.T. slab strengthening applications. Abdulamier and colleagues [36, 37] and Mahmood and colleagues [36, 37] modeled the CFRP (Carbon-Fiber-Reinforced-Polymers) laminates that were utilized for lab strength. ANSYS was employed for this purpose. Research and experimental findings are highly congruent with one another. El Mesk and Harajli [38] examined the possibility of employing FRP laminates to reinforce unbonded Post-Tension (P.T.) one-way slabs. The findings suggest that fiber-reinforced polymer sheet slabs may exhibit much more flexural stiffness and capacity and significantly less ductility. Using 3D Finite-Element Models (FEM), the behavior of P.T. slabs reinforced with CFRP laminates has been investigated.

2. Experimental Work

A total of six specimens included a control specimen without strengthening that represents concrete slabs reinforced by GFRP bars and strengthened by CFRP strips of laminated CFRP with different layouts. The specimen dimensions were 1550x1550x100 mm with all edges fixed as boundary conditions. Wooden molds with precise dimensions of 1550 mm x 1550 mm x 100 mm were meticulously prepared for casting concrete specimens. Ten identical molds were crafted to facilitate simultaneous concrete casting, ensuring uniformity and minimizing variations during the experimental process. These molds were carefully constructed to prevent leakage or deformation during the concrete pouring process. Their assembly was carried out with precision to guarantee their straightness and stability, ensuring the highest scientific accuracy in the concrete casting and testing procedures.

The type of cement is commercially available and is known as "Al-Jisier" in the market. It is selected due to its resistance to sulfates.

Fine aggregates were chosen to enhance the workability of the concrete mix, improving its ability to be placed and compacted during construction.

Course aggregate was chosen based on its quality, including particle size, absence of impurities, and geometric shape of the stones.

The average concrete compressive strength adopted in the present study was 31 MPa by applying concrete specimens with dimensions of a cube with 150 mm sides.

Each of the six slabs was uniquely reinforced with GFRP bars. The properties of the GFRP reinforcement were consistent with the data provided by the manufacturing company. Table 1 lists the properties of the GFRP reinforcement.

Table 1. Properties of GFRP Reinforcement

Type No.	Size	Nominal Diameter (mm)	Nominal Area (mm^2)	Guaranteed Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Bl00-1	3	10	71.26	827	46

Table 2. Properties of CFRP Sika Wrap 300-C

Parameter	Value
Thickness	0.167 mm
Tensile Strength	4000 MPa
Elastic Modulus	230000 MPa
Ultimate Tensile Strain	1.7%
Density	1.82 g/cm³

The mechanical properties of the CFRP material, Sika wrap 300-C, are detailed in Table 2.

The CFRP Laminate is a HM-1.4T, which stands as a high-strength, high-modulus unidirectional carbon fiber laminate. The CFRP laminate presented in Table 3 is bonded externally onto structures using Sikadur-32LP epoxy resin as an adhesive.

Table 3. Properties of CFRP Laminate (Model HM-1.4T)

Parameter	Value
Tensile Strength	3044 MPa
Tensile Modulus	158 GPa
Elongation at Break	0.0177
Flexural Strength	2122 MPa
Temperature Resistance	>150°C
Fiber Content	≥65%
Density	1.6 g/cm³
Width	50 mm
Thickness	1.4 mm
Shelf Life	10 ears

3. Tested Specimens' Details

The concrete slabs subjected to testing were composed of six specimens, each reinforced with GFRP bars with a diameter of 10 mm placed at intervals of 200 mm center to center for the two bottom layers. These slabs were subjected to pressure loading. The CFRP strips or laminated layouts are shown in Figure 1, and the tested specimen's details are listed in Table 4. Specimen S1 is the control specimen without strengthening by CFRP, specimen S2 one laminated CFRP along the specimen with width 50 mm, specimen S3 cross laminated CFRP with width 50 mm, specimen S4 two parallel CFRP with width 50 mm and away 475 mm from each face, specimen S5 cross CFRP with width 50 mm placed at middle without reached the edges, specimen S6 same as specimen S5 but the CFRP width is 100 mm.

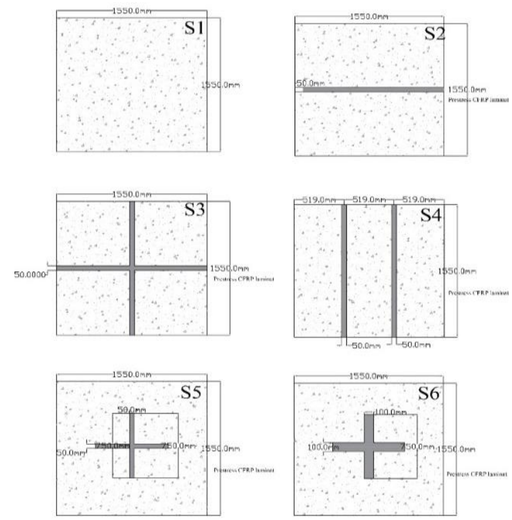

Fig. 1 Tested specimens layouts

Table 4. Specimen details

Specimen Mark	Strengthening Layout
S1	N\A
S2	One laminated CFRP reached two edges with a 50 mm width.
S3	Two cross-laminated CFRP panels reached two edges with a 50 mm width.
S4	Two parallel laminated CFRP sheets reached two edges with a 50 mm width.
S5	Two cross CFRP strips do not reach the edges with a 50 mm width.
S6	Two cross CFRP strips do not reach the edges with a 100 mm width.

N/A Not Applicable:

The experimental works that were conducted on different parameters were considered, in which the specimens were tested to investigate the behavior and strength of concrete slabs reinforced by GFRP bars. The uniformly distributed applied load was imposed at the top surface area for each specimen up to failure.

The primary objective of pre-stressed CFRP strengthening is to enhance the structural performance and strength-carrying capacity of tested specimens. By introducing pre-compression, this technique counteracts tensile forces that may arise due to external loads. The processes of pre-stressing that are applied to the CFRP before applied loading are as follow, install the traction device consisting of the fixed part to which the end of the CFRP tape is attached and the second end of the device has a movable joint to which the second end of the tape is attached to which the traction device connected to the hydraulic pump is attached. The end contains a movement joint connected to the pulling device, which in turn is connected to the hydraulic pump. The areas for placing the tape on the surface are identified and marked, after which the surface is prepared for the pasting processes. The hydraulic pump then operates the pulling device, and in turn, the device pulls the tape. After that, put the adhesive on the surface of the concrete specimen and also put it on the surface of the tape, and then glue the tape on the concrete after the drawing processes. After the installation processes, cut the tape to return to its original position and complete the pre-stressing processes. (Figure 2) shows the pre-stressed processes of the tape. The deflection for each tested specimen was recorded with a load step of 40kN by using a dial gauge with an accuracy of 0.01 mm that was placed at the middle-bottom of the tested specimen.

Fig. 2 Pre-stressed processes of CFRP tape

4. Test Results-General Behavior of Tested Specimens

In general, with the progress of the increase in the loads imposed on any tested specimen, the specimen becomes deflected more, with a reduction in strength-carrying capacity and a reduction in stiffness. During the applied load, the cracks will appear, starting from the first crack that occurs within the elastic deformation. The load caused the first crack relies on the type of the CFRP strips or CFRP laminated and the layout of strengthening.

The magnitude of the applied force is uniformly distributed over the top surface area and gradually increased up to failure, which depends on the strengthening type and layout, and in addition to the methodology. An increase in applied load led to a bend in the specimen that increased at the midpoint of the tested specimen, with zero deflection at the edges. All tested specimens behaved elastically during the early stages of the test.

Based on the experimental investigations, Table 5 presents details of tested specimens, such as ultimate strength capacity, failure load, and the corresponding deflection. The failure load for each specimen was less than the ultimate strength due to the drop in the specimen stiffness, while the deflection was higher than the maximum deflection that occurred at ultimate load, because each specimen failed at that load.

Table 5. Ultimate strength capacity, failure load, and deflection at failure and maximum deflection for each tested specimen

Specimen mark	Failure load (kN)	Ultimate load (kN)	Deflection at failure load	Deflection at ultimate load
S1	816	872	8.36	7.07
S2	1032	1473	3.83	2.95
S3	1500	1880	4.97	3.55
S4	1298	1450	3.93	3.35
S5	1130	1476	3.99	3.01
S6	1320	1548	3.95	3.20

The maximum strength capacity of the tested specimens occurs in specimen S3, with deflection at loads 1473, 1450, 1467, and 1548 kN of 1.29, 1.19, 1.27, and 1.61 mm, respectively, when compared with the specimens S2, S4, S5, and S6. All tested specimens started linear in behavior as shown in Figure 3**,** up to the inflection point, which differs for each specimen due to the strengthening layout.

The linear behavior of each specimen represents the zone of elastic deformation, so that the delay of load that caused the first cracks means that there is an enhancement in ductility in that zone. The behavior of tested specimens after the point of inflection becomes nonlinear as mathematical behavior and the explanations as physics, the cracks developed inside each specimen, and the stiffness of each tested specimen decreases due to the increased crack propagations that reflect at the surface of each specimen (engineering behavior). The best strengthening layout was specimen S3, which gave higher strength capacity and lower deformation when compared with other specimens at specific loads.

Specimens S2, S3, S4, S5, and S6 showed the first traces of cracks appeared under loads 443, 685, 608, 529, and 854 kN, respectively, which represent 30, 37, 42, 36, and 55% of the ultimate strength capacity of each tested specimen.

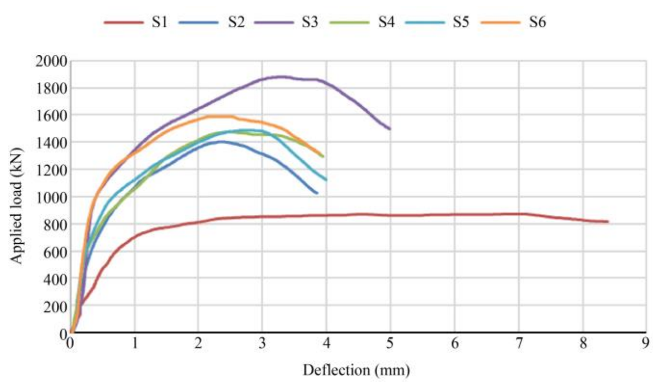

Fig. 3 Load-deflection of all tested specimens

Table 6 lists the stiffness, ductility, and energy dissipation for all tested specimens. The maximum stiffness (internal resistance against applied load) occurs in specimen S3, while the lower stiffness occurs in specimen S4, which is a strengthened specimen. Higher ductility in specimen S3 means that this type of strengthening layout gave higher deflection as compared with other specimens within the group. Energy dissipation for specimen S3 is higher than that of the other tested specimens due to higher load resistance with large deformation. (Figures 4 to 6) presents the variations of stiffness, ductility, and energy dissipation for all tested specimens, respectively.

Table 6. Stiffness, ductility, and energy dissipation for all tested specimens

Slab mark	Stiffness (kN/mm)	Ductility	Energy dissipation (kN · m)
S1	123.34	1.18	6.67
S2	499.32	1.29	4.30
S3	529.57	1.40	7.67
S4	432.84	1.17	4.77
S5	490.37	1.33	4.81
S6	483.75	1.23	5.25

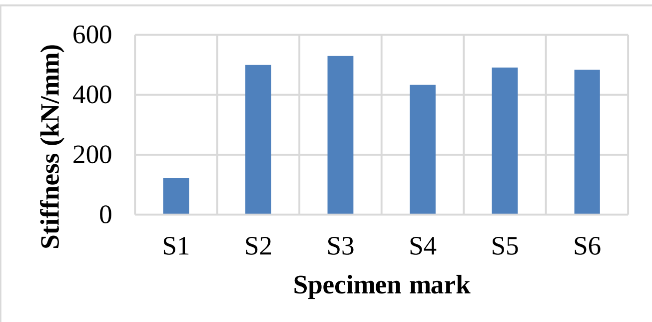

Fig. 4 Variations of stiffness for all tested specimens

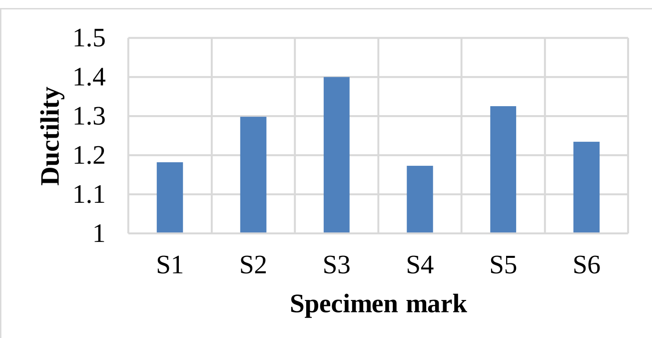

Fig. 5 Variations of ductility for all tested specimens

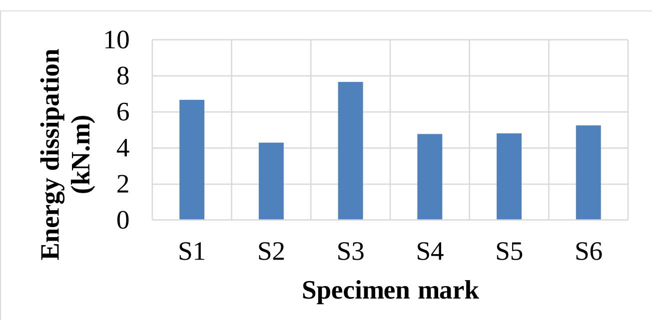

Fig. 6 Variations of energy dissipations for all tested specimens

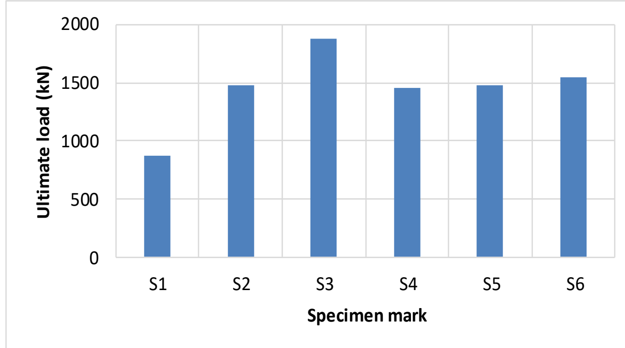

Fig. 7 Ultimate load variations for all tested specimens

Figures 7 and 8 show the ultimate strength capacities and the corresponding deflections for each tested specimen.

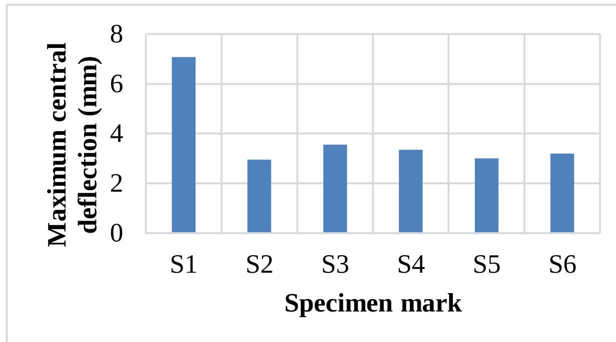

Fig. 8 Ultimate deflection variations for all tested specimens

Table 7 lists the increase in strength carrying capacities and the reduction in deflections with control specimen S1. The higher increase in strength occurs in specimen S3, and when the load of 816 kN is applied to the load-deflection curve of specimen S3, the corresponding deflection is rounded to 0.27 mm, so that the reduction becomes 96.18% which represents the higher reduction in deflection compared with other tested specimens.

Table 7. Comparisons between the ultimate load strength capacity and the central deflection of the tested specimens and the control specimen

Slab mark	Ultimate load (kN)	%Increase in ultimate strength capacity	Deflection (mm)	% Decrease in deflection
S1	816	---	7.07	---
S2	1473	80.51	2.95	58.27
S3	1880	130.39	3.55	49.79
S4	1450	77.70	3.35	52.62
S5	1476	80.88	3.01	57.43
S6	1548	89.70	3.2	54.74

5. First Crack of Tested Specimens

Figure 9 shows the first cracks that appeared during the testing of specimens. The appearance of the first crack is related to the strengthening type and the strengthening layout. The first crack represents the beginning of the elastic deformation zone, so that when the first crack is delayed and requires more applied loads, it means this concrete structural member has higher ductility and has resistance to the internal tensile strength that is less than the modulus of rupture, so that the crack is delayed and does not develop with minimum applied load.

The composite action (assumed as unity, i.e., no slips develop at the interface surface between concrete and CFRP material) enables the tested specimens to resist higher loading due to an increase in modulus of elasticity and moment of inertia (EI increased, which represents the stiffness). Specimen S3 gave the best and highest load that caused the first crack when compared with other tested specimens. The presences of CFRP that is pre-stressed before the applied load reduce the crack initiation. The contribution of CFRP strips or laminated materials delayed the cracks.

In case specimen S1, the first crack appeared as shown in Figure 9(a) at the middle of the tested specimen.

Specimen S2, the first crack appeared as shown in Figure 9(b), normal to the laminated CFRP, which means the strengthening prevented the cracks from developing in the direction of the laminated CFRP. The first crack load appeared at 443 kN, which represents 30% of the ultimate carrying capacity with deflection 0.23 mm.

Figure 9(c) shows the first crack of specimen S3 that started from the center of the specimen toward the edges in two directions and crossed the CFRP, but the crack propagation was limited inside the CFRP strengthening and did not reach the edges. The first crack load appeared at 685 kN, which represents 37% of the ultimate carrying capacity with deflection 0.28 mm.

Figure 9(d) presents the first crack that appeared in specimen S4, which started at the middle zone of parallel CFRP, in which the intensity was higher than in specimen S7. The first crack load appeared at 608 kN, which represents 42% of the ultimate carrying capacity with deflection 0.24 mm.

Figure 9(e) shows the specimen S5 crack that appeared at the top middle of the tested specimen toward the corner edge, while on the opposite side, the cracks appeared parallel to the horizontal and vertical CFRP. The first crack load appeared at 529 kN, which represents 36% of the ultimate carrying capacity with deflection 0.20 mm. Figure 9(f) shows the specimen S10, in which a crack developed from the edge of the CFRP strengthening toward the edge of the tested specimen. The first crack load appeared at 854 kN, which represents 55% of the ultimate carrying capacity with deflection 0.30 mm.

The appearance of the first crack for the tested specimens depends on the locations of the CFRP layout and type. The composite action of pre-stressed CFRP with concrete slab improved the ductility in the elastic deformation zone due to the pre-stressed the make the specimens carry higher loadings without deformation up to specific load and the wires embedded inside CFRP strip or laminated lead to enhanced the flexural resistance of concrete so that it can be able to prevent crack and need more loading to appeared the crack, same explanations that mentioned above the flexural resistance is higher and the internal tensile strength that developed inside concrete due to flexural was less than the modulus of rupture of tested specimens due to the presences of CFRP.

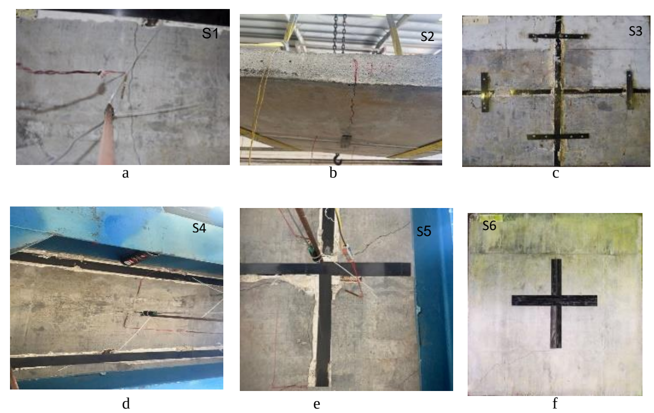

Fig. 9(a)-(f) First crack of all tested specimens

6. Mode of Failure

As a result, the tested specimens within Group II in which all specimens were tested up to failure. Flexural failure mode was predominant for all tested specimens but differed in the amount of deflection and radius of curvature, which relies on the CFRP types and layouts. The tested specimens were deflected when the applied load increased further, and the cracks began to develop from the top surface of each specimen toward the direction of specimen thickness and then propagated in two directions of the tested specimen. The pre-stress of tested specimens within this group was cambered and became such a small arch that it made the specimens stiffer and resulted in zero deflection. When the applied load reaches the magnitude that releases the specimens to return to the horizontal status (the amount of load depends on the CFRP type and layout), the specimens deflect in the direction of the applied load (down). All edges of each specimen have zero deflections and slopes due to the fixity boundary condition, so that the deflection at the center represents the cumulative sum of deflections that lie along the line of action. Strengthening the use of CFRP strip or laminated not spilling, rupturing, or debonding, but the concrete failed due to an increase in cracks, and no more resistance against applied loadings. The small radius of curvature means less deflection occurs in specimen S3, which has less deflection when compared with the same loads of each of the tested specimens. The crack intensity for the tested specimens presented in Figure 10 (a)-(f) shows that the specimens S2, S4, S5, and S6 are greater than that of specimen S3. As mentioned above, the strengthening by CFRP strips or laminated materials enhances the equivalent modulus of elasticity and increases the whole moment of inertia of the specimen, which increases the flexural resistance of the specimen. Increase in deflection, which means an increase in strength capacity when compared with the other strength capacities of the tested specimens. Specimen S3 gave the best test results. Figure 10 (a)-(f) shows the failure mode of the tested specimens.

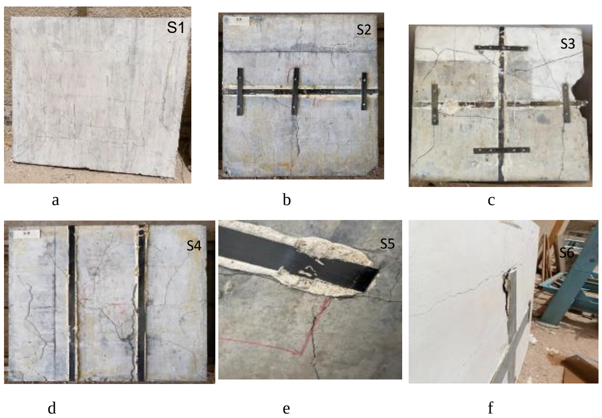

Fig. 10(a)-(f) Failure mode of all tested specimens

7. Discussion

According to test results, the following are the discussions based on the observation and the recorded data:

1. Presences of CFRP strips or laminated in all tested specimens except control specimen S1 lead to enhancing the strength capacity (increase) and reduce deformation (deflection) when compared with specimen S1 because the composite action that worked as unity (full interaction or with little slips) that increase the equivalent modulus of elasticity, increase the reinforcements in bottom soft and increase the equivalent moment of inertia and equivalent modulus of elasticity of whole structural system.
2. Improved the load-carrying capacity of the tested specimens when compared to the specimen S1 due to an increase in tension reinforcement due to the presence of CFRP, which led to resisting higher loading because of an increase in moment resistance and carrying higher flexural loadings.
3. The presence of CFRP strips or laminated material increased the specimen’s ductility.
4. The application of CFRP materials, including sheets and laminates, proved highly effective in preventing crack propagation. The confinement effect of CFRP laminates played a crucial role in enhancing performance.
5. The findings hold implications for structural engineering, suggesting that the combination of GFRP reinforcement and CFRP strengthening is a viable strategy to enhance the performance of concrete slabs under uniformly distributed loads. This approach aligns with designing resilient and durable structures.
6. Pre-stressing of the strip or laminated CFRP provided more strength capacity to the tested specimens. Specimen S3 gave high strength capacity when compared with other control specimen S1 due to the layout of the CFRP, which was cross and continuous with edges that provided high restraint.
7. Specimen S3 has less deformation (deflection) when compared to the same ultimate strength of other specimens, as projected to the load-deflection curve of specimen S3. This is due to the strengthening configuration that makes the specimen hold all edges together, which enhances the deformation resistance against applied loadings.
8. Increase in strength carrying capacity with respect to the control specimen S1, as mentioned above. The increase in specimen S3 was 130.39% due to the strengthening configuration as a two-way cross of CFRP, which increases the reinforcements in the tension zone, so that the resistance of this specimen increased.
9. Specimen S3 had higher specimen ductility because this specimen gave higher deflection before failure with less deflection at ultimate load, so that the ductility became higher and the disutility index became less, which means there was enhancement in ductility with the elastic deformation zone. Specimens S2 and S8 gives lower ductility, which means this type of single or parallel CFRP is not the best solution.
10. Little post-crack intensity in specimens strengthened by laminated CFRP, such as specimen S4, when compared with other tested specimens strengthened by CFRP strips, due to the laminated CFRP having higher thickness and stiffness than the CFRP strip, which leads to an increase in reinforcement in the tension zone. This layout configuration carries a higher deflection at failure load, which gives an indication before failure (large deformation) without collapse.
11. The application of CFRP materials, including sheets and laminates, proved highly effective in preventing crack propagation. The confinement effect of CFRP laminates played a crucial role in enhancing performance.
12. The energy dissipation of specimen S2 gave lower dissipation, so it gave more advantage to resist a greater applied load. The energy dissipation of S3 for the same deflection of the tested specimens was lower than that of the other tested specimens.
13. Increase the equivalent modulus of elasticity, increase the reinforcements in the bottom soft, and increase the equivalent moment of inertia and equivalent modulus of elasticity of the whole structural system.
14. The presence of CFRP strips or laminated impact on the

failure mode of tested samples by reducing the flexural and radius of curvature of the tested samples as compared with the control sample.

Application of pre-stressing makes the specimen so that it needs higher loadings to rest the specimen at the initial stage, so that each specimen, compared with the control S1, has less maximum deflection at the ultimate applied load. First crack loading, deflection at first crack load, ultimate strength capacity, maximum deflection at ultimate strength capacity, percentages of first crack load based on ultimate strength capacity, and percentages of deflection at crack load to the maximum deflection are listed in Table 8.

Table 8. Test results for all tested specimens

Specimen mark	First crack load Pcr (kN)	Deflection at first crack δcr (mm)	Ultimate load Pu	Maximum deflection δu (mm)	%Pcr/ Pu	%δcr / δu
S1	186	0.22	(kN)	7.07	21	3.11
S2	443	0.23	872	2.95	30	7.80
S3	685	0.28	1473	3.55	37	7.88
S4	608	0.24	1880	3.35	42	7.16
S5	529	0.20	1450	3.01	36	6.65
S6	854	0.30	1476	3.2	55	9.38

8. Conclusion

According to the test results mentioned above, as Tables, Figures, and discussions, the concrete slab specimens reinforced by GFRP bars instead of conventional reinforcements and strengthened by CFRP strips or laminated. The presence of CFRP strips or laminated CFRP gave an increase in load strength capacity. It represents an additional reinforcement that is placed in the tension zone of the tested specimens, which leads to an increase in resistance against applied loadings. The failure mode occurs as flexural due to the design requirements of a reinforced concrete slab, by applying the methodology proposed by ACI-318-2019, which involves under-reinforcement due to the yielding of reinforcement before concrete failure. The design principle of GFRP bars without traditional reinforcements is based on the equivalent tension force (differing in yielding strength). Crack intensity and crack propagation differ from one tested specimen to another due to the CFRP type and layout. The cross layout with and without CFRP pre-stressed gives a lower crack intensity and needs higher loading to produce the first cracks. Flexural CFRP strengthening significantly enhances the reinforced concrete tested specimen's stiffness, resulting in increased load capacities and reduced deformations. Deflection reduced in magnitude due to the presence of CFRP strips or laminated because they enhanced the strength resistance of the tested specimens (additional reinforcements in the tension zone). Ductility of specimen S1 without CFRP showed lower ductility when compared with other tested specimens S2 to S6 because the concrete is a brittle material, so that there is no elastic-plastic zone but a direct plastic zone, which means the concrete fails suddenly. The stress–strain relationship of GFRP bars is linear up to rupture. The flexural behavior of the tested specimens without CFRP strips or laminated showed lower ductility, so they failed suddenly. Use of CFRP strips or laminated (the laminated CFRP gave the best results in terms of strength capacity and lower deflection than CFRP strips) in strengthening of concrete slab reinforced by GFRP bars can significantly enhance the actual load capacity beyond ACI code predictions and can reach the optimized structural performance. The use of CFRP strips or laminated first must be checked for the tension face, so that highlighting the shift in section classification from tension-controlled to transition with increasing GFRP bars and CFRP reinforcement, which indicates a reduction in ductility and necessitates careful selection of the FRP reinforcement ratio to maintain beams within the desired tension-controlled classification.

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