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Analysis of prestressed concrete beams experimentally utilizing steel strands and CFRP bars

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HIGHLIGHTS

- The study uses an experimental method to investigate the flexural performance of CFRP prestressed beams.
- CFRP bar beams perform better than steel beams, with higher cracking and ultimate load ratios.
- All tested beams, especially those with CFRP bars, show reduced mid-span deflection, indicating better stability.
- CFRP-reinforced beams exhibit higher ductility than steel, showing robustness and deformation capability.

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ABSTRACT

This research seeks to improve the performance behavior of reinforced concrete (RC) beams by examining their load-deflection diagrams using ordinary and prestressed carbon fiber-reinforced polymer (CFRP) bars in place of standard steel reinforcement instead. Using CFRP bars as prestressed tendons to replace the bottom steel rebars, eight 1800-mm long RC beams with a 200 mm×300 mm cross-section were evaluated and split into three groups, evaluating critical loading phases (i.e., cracked, ultimate, and mid-span deflection). Relative to the reference beam, beams reinforced with CFRP had far higher load-carrying capacities and ductility. One beam, reinforced with regular CFRP bars, exhibited a mid-span deflection of 21.2 mm and an ultimate load of 157.2 kN, resulting in a cracked load of 57.7 kN. Another beam using regular CFRP bars also demonstrated improved performance with a mid-span deflection of 21.2 mm, an ultimate load of 160.6 kN, with a cracking load of 57.5 kN. Prestressed CFRP bars led to a significant decrease in mid-span deflection (7.3 mm), a rise in the ultimate load (254.2 kN), and a cracking load of 137.6 kN. Furthermore, the use of two different prestressed CFRP bars showed notable improvements. CFRP bars with these enhancements were employed instead of steel reinforcement in the tension zone, thereby greatly increasing the beam strength with respect to the bonding materials (cement grout and epoxy resin). Thus, using regular and prestressed CFRP bars in traditional steel reinforcement may significantly improve the load-carrying capacity and ductility, producing more robust reinforced concrete buildings.

1. Introduction

Steel corrosion is worse in countries that utilize road-deicing chemicals. Fiber-reinforced polymers (FRPs) may replace steel reinforcement in concrete reinforcement; hence, the building industry should research them [1]. Research and experiments increasingly use Fiber Reinforced Polymer (FRP) reinforcement instead of steel rebar or strands in concrete [2]. Due to its increased tensile strength, corrosion resistance, absence of magnetic characteristics, and lightweight composition, FRP reinforcement behaves differently from steel reinforcement. Fiber-reinforced polymer (FRP) reinforcement is extensively employed despite its limited flexibility, transverse strength, stress rupture sensitivity, and high cost [3,4]. Carbon fiber-reinforced polymer (CFRP) is the most used FRP because of its better tensile strength and stiffness. However, CFRP bars are generally non-ductile, with a linear stress-strain correlation and brittle fracture under uniaxial tension [4].

As reported in engineering construction media, standard flexural design methods for steel-prestressed concrete components assume the steel would be given before the beam fails. When steel gives, it deflects and absorbs inelastic energy, making it ductile [5]. Therefore, a substantial study has been done on CFRP-prestressed beams with bonded tendons' flexural behavior to eradicate this typical attitude. Test results show that CFRP- and steel-prestressed concrete beams have several differences despite their similarities. CFRP reinforcement's linear-elastic properties dominate the observed changes. Post-tensioned beams containing unbonded CFRP tendons have received less investigation on their flexural properties than bonded prestressed beams using CFRP tendons. Concrete crushing typically results from unbonded post-tensioned beam failure. Without cable bonding,

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tensions dissipate at critical locations and disperse down the tendon. Therefore, the tendon is under less strain than when attached. Thus, bonded specimens are stronger than unbonded ones regardless of tendon type [6].

To check the durability and fatigue, Belarbi et al. examined prestressed beams with various CFRP systems under monotonic and fatigue loadings and post- and pre-tensioned. The CFRP prestressed beams exhibited ample warning before failure in early experimental testing. Unbonded CFRP cable post-tensioned beams have greater deformability than other CFRP pre-tensioned beams. Its maximal strength was lower than all other bonded beams [6]. All facets of the structural behavior of prestressed concrete beams may be revealed via scientific inquiry. The first smart highway bridge in Calgary had four beams that matched rafters, which Abdelrahman et al. [7] looked into. Two prestressing CFRP types were subjected to fatigue and monotonic loads. Before the collapse, pretensioned beams underwent severe deformation. Similar to monotonic loading capacity, fatigue loading between 70–100% of the cracking load sustained over 2 million cycles with just a little change in stiffness. Seven rectangular and T-beam post-tensioned beams with internally unbonded CFRP tendons under simple support were investigated by Heo et al. [8]. Section geometry, loading type, beginning prestressing, and prestressing reinforcement ratio were all tested. Flexural collapse is brought on by concrete crushing, although unbonded prestressed tendons do not fracture. Rectangular beams held up well after the maximum load.

T-beam failure modes were impacted by loading type. Rectangular sections with bonded CFRP tendons were less flexible than beams with additional bonded steel bars. Enhancement of ductility was recommended by resilience assessment. Also, great realistic results, depending on previous scientific experimental research that studies the structural response of the prestressed CFRP beams, were studied by Kakizawa et al. [9]. The test defined their bonding as well as the prestress force. The research revealed that the mechanism of deflection reaching final failure and the absorbed energy through different loading stages were affected by a system of reinforcement. Partially prestressed beams absorb more energy than entire beams. Following the breakage of the FRP cable, the fully prestressed beams did not absorb energy. On the other hand, the same power was absorbed by beams that collapsed because the concrete was crushed after peak load. Fiber-reinforced polymer (FRP) technologies have become more popular for internal reinforcement of concrete infrastructure due to the growing need for sustainable construction practices. Prestressed CFRP is proven to be more durable than steel wire-reinforced concrete beams by Merton et al. [10]. Fifteen beams underwent testing to cover a range of mechanical and meteorological scenarios. A sustained load period of nine and eighteen months, continuous seawater spray at 15% by mass and 54 °C, air exposure, sustained stress (55% and 70% of the bar or wire's ultimate strength), and testing methods (cyclical loading followed by static testing till failure) were all listed. While steel-reinforced beams collapsed after 12 months, CFRP-reinforced beams withstood 18 months under harsh weather conditions. Steel beams were not as sturdy as CFRP prestressed beams. Environmental conditions caused steel-reinforced beams to endure 12 months, whereas CFRP-reinforced beams lasted 18 months.

Abdelrahman and Rizkalla [11] looked at cracks and deflections in eight CFRP-prestressed and two standard steel-stranded beams to study the bending properties of concrete beams. Experimental observation toward the tension zone's degree, percentage of prestressing force, and CFRP bar spread. Findings: This study looked at cracking and bending in CFRP-prestressed concrete beams before and after they cracked in different limit conditions. In the compression zone, CFRP beams bend similarly to steel beams as long as the failure is mainly caused by crushing the concrete. The failure of CFRP bars leads to less displacement than the failure of steel-strand prestressed beams. More than steel strand beams, CFRP bars partly prestressed beams have a stable fracture pattern at lower strain levels. Keeping the same issue but detecting a new behavioral feature, which is represented by ductility, three sets of beam experiments were conducted by Zou [12], Jeong [13], and Abdelrahman [14] provided significant information in developing the structural performance of the reinforced concrete beam, notably ductility, and deformability. Zou's research indicated that prestressing reinforcement rupture caused beams with low reinforcement ratios and no shear reinforcement to fail. Interpreting the deformed beams with growing cracks were warning indications before the collapse. Beams prestressed by steel strands have higher ductility than CFRP beams with consistent inelastic energy ratios. Jeong found that reinforcing configurations affect ductility. Abdelrahman found that CFRP- and steel-prestressed beams deform similarly under comparable circumstances, but larger prestressing pressures and failure modes decrease ductility.

For this reason, the natural features of reinforced concrete parts are improved by CFRP strengthening. If there is enough stiffness and not much distortion, the reaction to failure is linearly elastic, with little to no plastic deformation. Under heavy loads, this steel contract made of high-tensile steel loses a lot of its stiffness. Tension in a joined beam causes cracks in the concrete, which puts a lot of stress on it. When used in strengthened concrete, CFRP threads are stretched to their fullest extent, resulting in fracture of CFRP before the pressures in the concrete become too much to handle is not likely. On the other hand, prestressed concrete uses a lot of fiber strain capacity, so the tendon is more likely to be damaged by high loads near cracks.

Forth and Beeby's work [15] demonstrated that prestressing or CFRP reinforcement might raise the chance of a bonded tendon breaking before concrete crushing, which allows us to offer further suggestions after this presentation. In unbonded tendons, the absence of these systems prevents significant local strains, leading to a little change in stress [16]. Typical efforts to improve the ductility of CFRP in prestressed concrete beams include unbonded steel strands with two beneficial longitudinal shapes (harped and straight). This study examined the flexural performance of post-tensioned prestressed concrete beams utilizing CFRP bars as ordinary rather than steel rebar in the bottom layer and the unbonded steel strands. Therefore, this research provides a novel experimental approach to analyze the flexural behavior of nine rectangular beams by applying static loading on two-point stresses. It employed the same number and diameter of CFRP bars to replace the steel rebar in the stress zone and investigated the effect of using CFRP bars to enhance the strength capacity and ductility by using two types of bonding: epoxy resin and cement grout.

2. Experimental work and methodology

The primary objectives of this study are to investigate and examine the effect of replacing the bottom longitudinal steel reinforcement with prestressed CFRP bars in concrete beam specimens. This replacement appeared through an experimental gradual trial by casting and testing eight reinforced concrete beams divided into three groups depending on whether CFRP bars were used as an alternative to bottom steel rebars. CFRP bars are used as prestressed tendons to make a great substitution with a steel strand. Many other parameters are experimented with and tested in this chapter, such as the bonding type, shape of prestressed steel strands and evaluating the flexural behavior, including deflection, cracking loads, and ultimate loads capacity of the beam specimens considering the influence of concrete compressive strength and longitudinal reinforcement ratio and the losses of prestressed tendons. All beams are designed according to ACI-318-19 and ACI-440-1R [17,18] as rectangular 200 mm×300 mm to carry the prestressing force of two CFRP bars with steel grips at both ends. The length of the beam was specified to 1.8m because the CFRP bars imported in length 2m minus the length of steel grips at both ends.

2.1 Test specimens

The experimental work was based on testing eight simply supported beams with rectangular cross-sections 200 mm×300 mm to be adequate for the tensile reinforcement of 2 prestress CFRP bars. Each bar has a steel grip of 33 mm diameter and a 1.8 m length (the CFRP bars imported in length 2 m minus the length of steel grips at both ends). Loaded statically by two concentrated loads pointed at the middle third of every beam. The following details of abbreviations that are considered in this study, as illustrated in Table 1 and also Figures (1-3), show the longitudinal profile and cross-sectional details for the shape and type of reinforcement and the mechanical bond for the CFRP reinforcement and the prestressing shape for the steel strand (straight or harped strands) and clarified in every group.

Table 1: Details of specimens and material properties

Group (No.)	Beam (No.)	Top Reinf.	Bottom Reinf.		Prestressed Reinf.	
			Type	Bond.	Type	Shape
Group (1)	G1B1	St.(2Ø16)	St.(2Ø12)	Concrete	---	---
	G1B2	St.(2Ø16)	CFRP. (2Ø12)	Concrete	---	---
	G1B3	St.(2Ø16)	CFRP. (2Ø12)	Epoxy	---	---
Group (2)	G2B1	St.(2Ø16)	St.(2Ø12)	Concrete	St. Strand (1Ø12.7)	Harped
	G2B2	St.(2Ø16)	St.(2Ø12)	Concrete	St. Strand (1Ø12.7)	Straight
	G2B3	St.(2Ø16)	St.(2Ø12)	Concrete	CFRP	
Group (3)	G5B1	St.(2Ø16)	---	Concrete	CFRP. (2Ø12)	Straight
	G5B2	St.(2Ø16)	---	Epoxy	CFRP. (2Ø12)	Straight

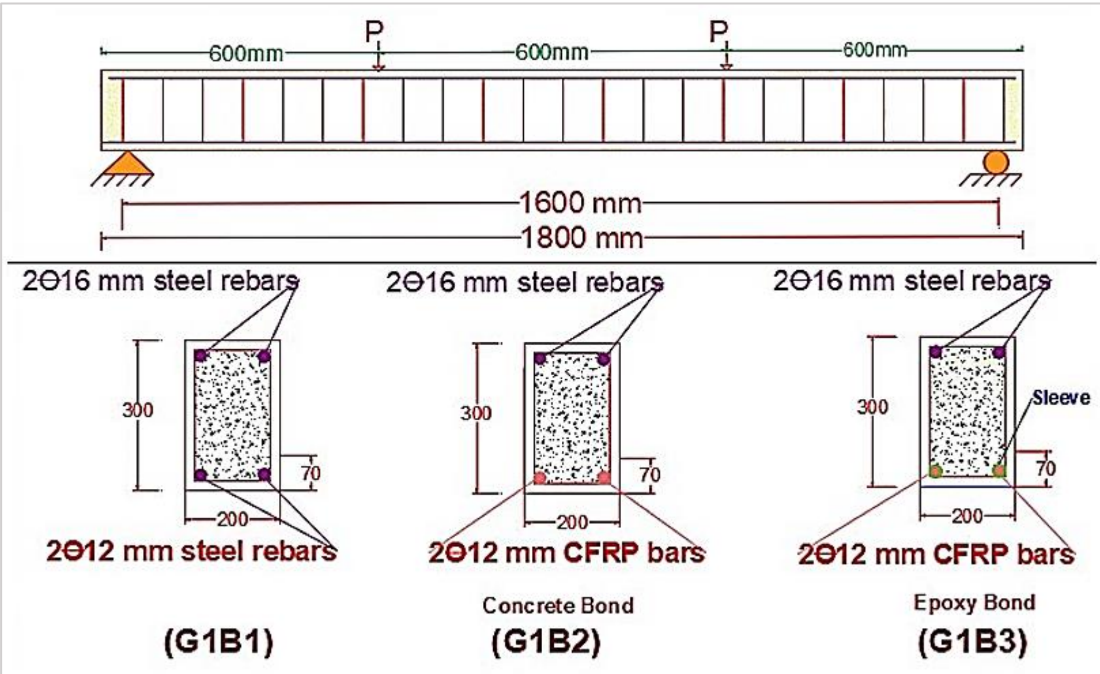

Figure 1: Specimens' details of the first group

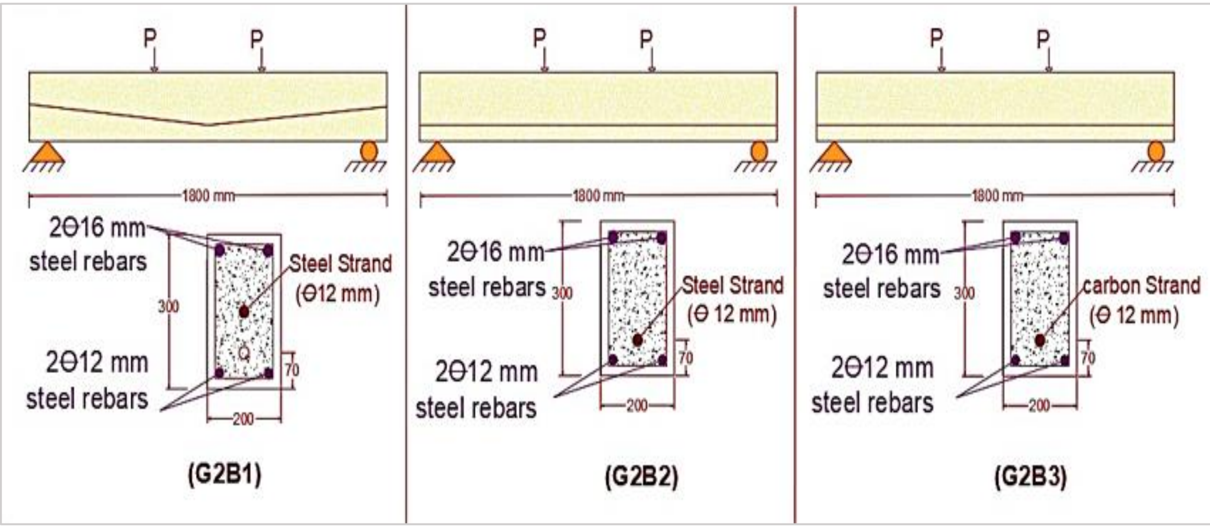

Figure 2: Specimens' details of the second group

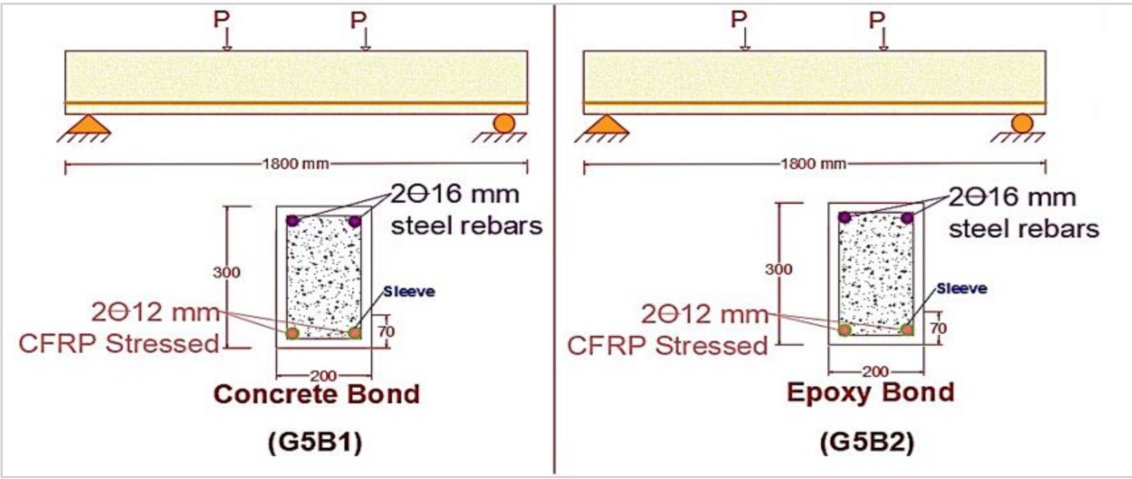

Figure 3: Specimens' details of the third group

2.2 Sequences of the Post-Tensioning process

To make each beam according to the previously classified group, the intended beam, and its own group features, the plastic pipes were put into the molds in either a straight or a harped shape. Once the concrete was poured (less than 30 minutes), the plastic sleeves were removed from the molds to make the perfect longitudinal hollows (straight or harped). Then, the length was given as 3 m, which was found by adding up the length of the beam plus 0.6 m on both ends. After that, strain gauges were carefully put on top of them. Two strain gauges were attached at the center and quarter length, as seen in Figure 4a. Steel plates that support the ends were put on the ends of each example. The endplates were skillfully cut with transverse lines from the duct holes to the far edge of the cross-section.

The strain gauge wires were carefully placed at a certain depth in the grooves. This kept the wires from moving under the pressure of the end plates during the post-tensioning process. The wires were then securely taped within the grooves that had already been formed on one of the bearing and prestressing faces of the concrete, as shown in Figure 4b. Anchor grips were attached to both ends of the strands to make a tight link, as shown in Figure 4c. A reference mark was also made on the strand to show how far it needs to be pulled out.

To monitor and assess Strand elongation during and after prestressing, the surfaces of the strands were marked to facilitate the determination of the individual pre-strain value (ΔL), representing a predefined change in length of 10.8 mm (0.64 σu) to reach the stress of 1200 Mpa as stipulated by the member design requirements as shown in Figure 4d. Following the initial phase, the process was repeated for the remaining strand to achieve the targeted prestressing value upon the jack's release.

A similar procedure was employed for prestressing CFRP tendons through post-tensioning, utilizing PVC pipes of Ø50 mm diameter, exceeding the steel grip shafts (Ø33 mm), followed by the plastic sleeve pulled out after pouring concrete by approximately less than 30 minutes to prepare the desired straight hollow. Upon completion of casting and curing of all girders, Two grips were made for both CFRP tendon ends for prestressing; the grip was made of a threaded-hollow steel shaft with an inner diameter (25 mm) and outer diameter (33 mm) and with adapted bolts to lock the prestressing forces on each end bearing plate after completion the desired elongation by the prestress machine. The adhesive material was sikadur-30 LP, a thixotropic, structural 2-component adhesive with great properties such as compressive strength reaching 110 Mpa, tensile strength axial tension, and flexure reaching 28 Mpa and 40 Mpa, respectively. It is suitable for use in high-temperature environments.

Figure 4: (a)-Fixing a strain gauge sensor in the middle length of strands.(b)- Inserting the steel strand;(c)-Signing a reference point for pulling.(d)-Detecting the magnitude of prestressing the steel strand.

The method of installing the CFRP bars inside the hollow steel shaft by filling the adhesive material is summarized by mixing the two adhesive parts; the procedure was similar to that of researchers Saed and Rad [16] and samples of four different grip lengths (10 cm, 15 cm, 20 cm, and 25 cm) and tested in the materials laboratory of consultant engineering bearau of the university of Baghdad and the tensile strength resulted were (931.2 Mpa, 1220.8 Mpa, 1859.6 Mpa, and 2086 Mpa) all those samples failed by slipping the CFRP barth through fracture the adhesive materials from one or both ends except the last one which has a failure in the CFRP bars at the end of grip's length sue to sufficient inside length to reach the tensile strength of CFRP bar. The adhesive epoxy is then injected into the hollow steel shaft from both sides according to the design shown in Figure 5a. Two strain gauges were attached to the bar to collect detailed information on the prestressed condition of each CFRP bar, as shown in Figure 5b. One was placed midway of the tendon, and the other at the quarter length. To determine the individual pre-strain value (ΔL), representing a predefined change in length of 10.5 mm (0.6 σu) to reach 1200 MPa as stipulated by the member design requirements illustrated in Figure 5c and detecting the distance pulled as shown in Figure 5d, a pressure gauge connected to an electrical hydraulic jack was used for post-tensioning. Additionally, a dial gauge was used for camber measurement. The CFRP bars' surfaces were marked.

Figure 5: (a) - Inserting CFRP bars in a hollow steel shaft; (b) - Fixing a strain gauge sensor in the middle and quarter length of strands. (c) - Signing a reference point for pulling. (d)- Detecting the magnitude of prestressing the CFRP bars

2.3 Carbon fiber grout and epoxy

2.3.1 Bonding the CFRP tendons by cement grout

Per the study design, the CFRP bars may be placed within PVC pipes (Ø25 mm) that were temporarily fastened with steel stirrups before casting and removed for about half an hour to finish the conventional reinforcing. With confidence that the drill bits would reach the longitudinal hollow's center, three hollows were drilled from the sidewalls of both girders. Once the hollo is clean and open, place the CFRP bars with their strain gauges inside. Mineral filler and polymer-reinforced cement grout FOX GROUT FC 155. Following 28 days of curing, this particular cement reaches 60 Mpa in compression and 2 Mpa in bond strength with the concrete.

2.3.2 Bonding the CFRP tendons by epoxy resin

Utilizing a mixture of epoxy resin type CERMGROUT EP 3 C epoxy (three parts)—Part A: liquid 1 kg (hardener material), Part B: liquid 2 kg (adhesive material), and Part C: powder 12 kg (expansive material) the epoxy resin injection was executed in the same manner to coat the CFRP bars within the longitudinal hollow. A 14-day curing resulted in compressive and tensile strengths of 30-50 Mpa and 80-100 Mpa, respectively, as specified by the material.

3. Results and discussion

3.1 Response of Load - Displacement

After ensuring that all beams were adequately prepared for the testing phase in the structural laboratory of Civil Engineering Department at University of Technology, they underwent evaluation using a hydraulic testing machine (specifically, an Avery Denison testing machine) with a load-controllable maximum capacity of 2500 kN. A 50-ton load cell was installed at the loading tip of the Avery machine and was linked to a computerized data logger as part of a comprehensive system comprising all sensors associated with the load that was being measured, as shown in Figure 6.

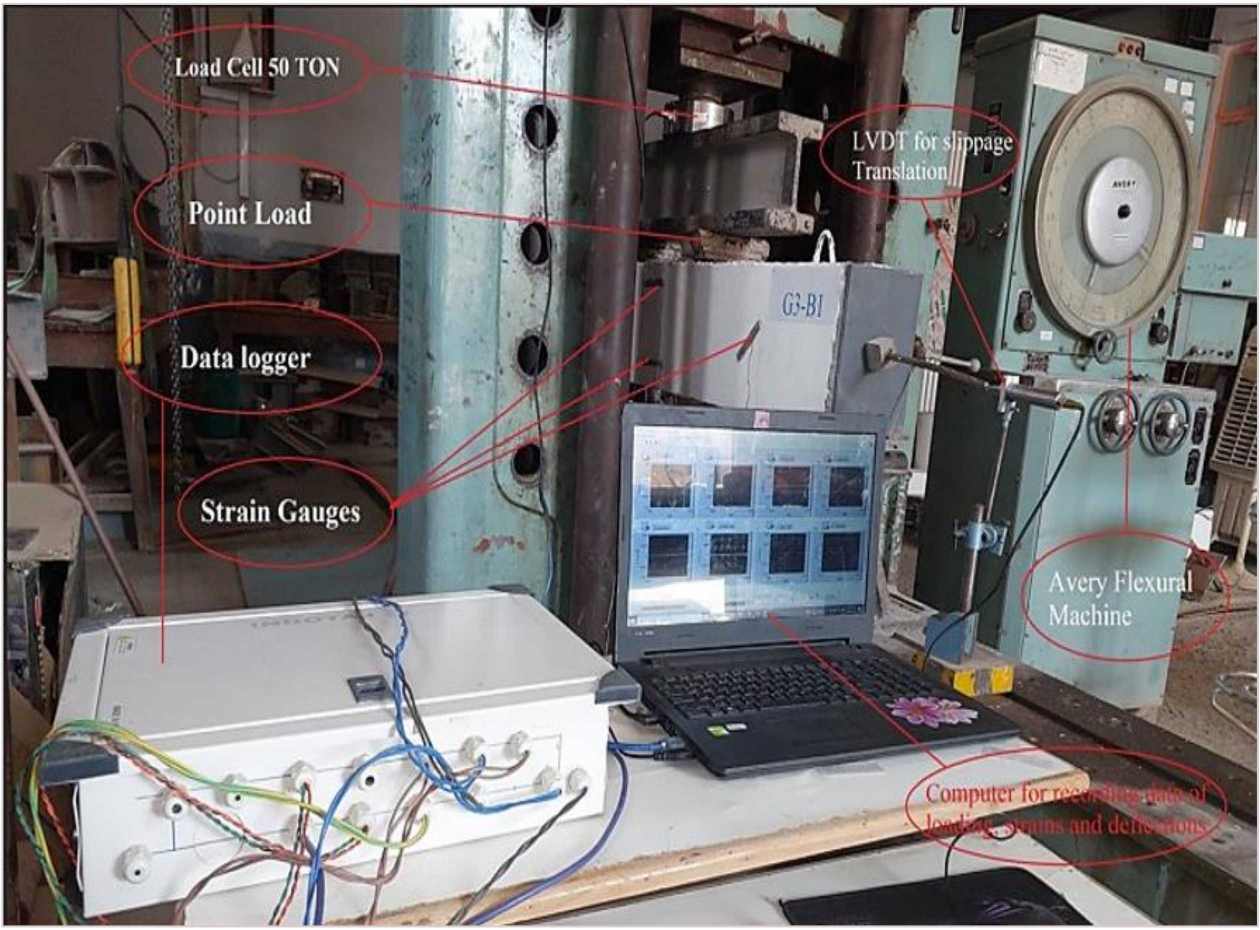

Figure 6: Computerized mechanical system for testing beams

The load application occurs in three distinct phases: the uncracked elastic behavior is represented by the first phase, which concludes at the onset of the first crack; the second phase, which concludes at the ordinary tensile rebars yielding and is bounded by the first crack; and the third phase, which represents the ultimate, cracked elastic behavior. Because of the bonded steel's increased rigidity variation after fracture and yielding, the elongation rate was greater in the second and final zones compared to the first zone. Table 2 demonstrates the cracked, ultimate load, and deflection with their different ratios related to the values of the reference beam.

Table 2: Cracked, ultimate loads and deflection for experimental beams

Beam Specimen	Cracked load (Pcr.) Exp. kN	Difference Ratio $(\frac{Value}{Reff.})$	Ultimate load (Pult.) Exp. (kN)	Difference Ratio $(\frac{Value}{Reff.})$	Deflection at mid-span (mm)	Difference Ratio $(\frac{Value}{Reff.})$
G1B1 (Reff.)	21.7	----	114.2	----	44.7	----
G1B2	57.7	2.65	157.2	1.37	21.2	0.47
G1B3	58.5	2.69	160.6	1.40	16.2	0.36
G2B1	111.8	5.15	240.3	2.10	19.6	0.43
G2B2	93.9	4.32	212.9	1.86	17.8	0.39
G2B3	137.6	6.34	254.2	2.22	7.3	0.16
G5B1	218.7	10.07	300.2	2.62	32.2	0.72
G5B2	221.1	10.18	309.3	2.70	27.3	0.61

When a load is applied before the first flexural cracking occurs, the beam's deflection within the first group increases linearly. The initial flexural stiffness of these beams was seen to vary somewhat at this point. More strength reinforcement resulted in higher initial cracking loads for the beams G1B1 than G1B2 and G1B3. Using two CFRP bars rather than using steel reinforcing bars at the bottom layer, the G1B2 and G1B3 beams were improved. Further flexural fractures appeared in the region of the first damaged area as the load increased after the first flexural fracture appeared. Then, the material's rigidity decreased. Before the non-prestressed auxiliary bonded bottom steel bars reached their yield point, they continuously increased and remained at a lower slope in the load-deflection curves. The stiffness of every beam in the second group was further reduced by adding the steel strand. Few cracks were shown in the shear span, but the bulk of the fractures were seen at the loading points, referring toward the compression failure. The strength of the post-tensioned beams with higher prestressing forces dropped more quickly when the loads were at their highest. The concrete close to the topmost layer showed horizontal cracks in certain places when the stress was at its highest.

Three beams were strong even after they were loaded to their fullest weight. As the beams bent more, the number of tendons that were not attached rose, even after the maximum load was reached. The third group worked on delaying the tensile breakup of bonded prestressed CFRP bars by finding the highest splitting load values. This was done to keep the beams from breaking for the first time and to keep these small deflections. Because the concrete's compressive side slowly broke down, all beams lost all of their remaining strength when they bent past their peak load. When looking closely at the results of the bending behavior study, it was also possible to compare them to the first beams in group one (G1B1). With a broken load difference ratio of 2.65 and a final load difference ratio of 1.37, beams G1B2 and G1B3 did much better in the first comparison. These beams used alternate CFRP bars instead of traditional steel rebar. The difference ratios for G1B3 were 1.4 for the ultimate load and 2.69 for the broken load. The CFRP strengthening made both of these values much better.

In conclusion, these results show that regular CFRP bars bonded with epoxy make a small difference in the final load and breaking. The above example shows how prestressing techniques can successfully raise a structure's load-bearing capacity. That information can be seen in Figure 7. Low mid-span deflections are seen in beams strengthened with CFRP bars and prestressed steel strands compared to beams reinforced with regular steel.

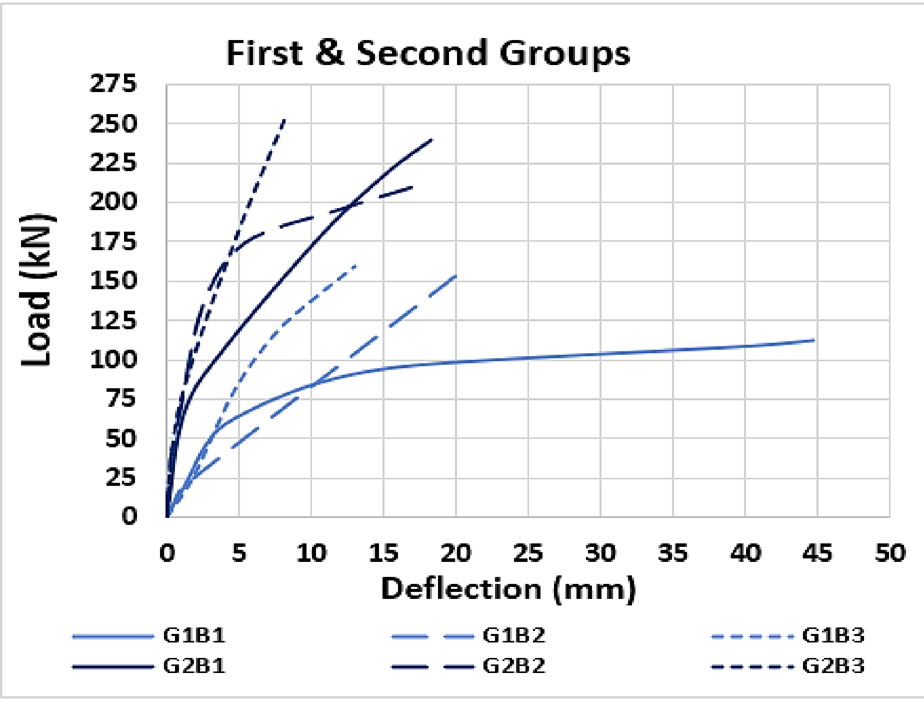

Figure 7: Load – mid-span deflection curves of the first and second groups

Compared to the standard beam G1B1, the first group of beams (G1B1, G1B2, and G1B3) had mid-span deflections ranging from 17.8 mm to 21.2 mm. The difference ratios were also between 0.39 and 0.47. Group 2's G2B1 and G2B2 had low mid-span deflections. In G2B1, the displacement was 19.6 mm at a difference ratio of 0.43; in G2B2, it was 17.8 mm at a difference ratio of 0.39. The CFRP hardening and prestressing worked to lower the movement, as you can see from these numbers. In Group 2, G2B1 changed shape a little less than G2B2. This might mean that steel strands harped are better at keeping them from bending than straight steel strands. Results like these show how important it is to use CFRP strengthening and prestressing methods on reinforced concrete beams if you want them to work better and bend less. Civil engineering projects are stable, and last a long time, these steps are very important.

In addition, G5B1 had a broken load of 218.7 kN, which was a big increase over the standard beam (a difference ratio of 10.07). The maximum load reached 300.2 kN, and the difference ratio went down to 2.62. With a difference ratio of 0.72, the mid-span displacement was found to be 32.3 mm. These improvements were made by switching out the steel rebar in the bottom support for different prestressed CFRP bars. This shows how important the concrete grout bond is for strengthening the beam. In the same way, the broken load in G5B2 was even higher at 221.1 kN, which shows a big gain over the reference beam (a difference ratio of 10.18). The final load went up to 309.3 kN as the loading went on, and the difference ratio went down to 2.7. With a difference ratio of 0.61, the mid-span displacement was 27.3 mm. It was possible to change this by switching out the steel rebar in the bottom support for different prestressed CFRP bars. The epoxy resin bond made the beams much stronger. Also, the results of Heo et al. [8] are mostly agreed upon when it comes to raising the cracked and final loads and lowering the mid-span displacement. he shift of the load mid-span. Figure 8 clarfies curves that show how prestressed CFRP bars can lower mid-span deviation.

It is important to note that beam G2B3 behaves in a straight line and only bends slightly, up to 7.3 mm. This sign of tension failure causes the prestressed CFRP bar to break. On the other hand, the beams G5B1 and G5B2 have higher bending values, though they are still within accepted limits. The upper part of the concrete structure also shows signs of compression failure. One important thing to note is that the prestressed CFRP bars in these beams did not get cut. The results showed big improvements when experiments added carbon fiber-reinforced polymer (CFRP) strengthening and prestressing methods to reinforced concrete beams. It greatly impacted the cracked, ultimate, and mid-span bending for all beam groups when standard steel reinforcing was switched out for CFRP rebars and prestressed steel strands were added. These improvements are a big step forward in structure engineering because they solve the problems with old steel strengthening methods.

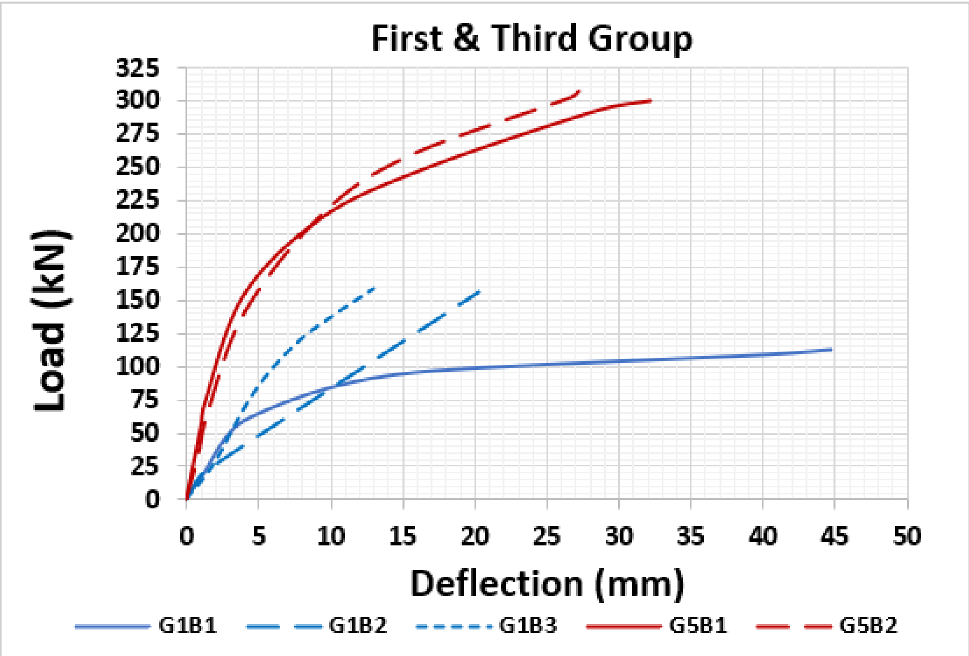

Figure 8: Load – mid-span deflection curves of the first and third groups

3.2 Load capacity and ductility in beam reinforcement analysis

Two important factors are the main results of the flexural testing, which are listed in Table 3. The study began by examining the load-increment measure, which describes the link between the final load that causes failure and the load at which cracking first appears. This study evaluated the effectiveness of replacing traditional steel rebars in the bottom layer using high-performance substitutes such as carbon fiber-reinforced polymer (CFRP) bars in regular and prestressed configurations. Mid-span deflection at yield and ultimate loading—two crucial loading stages—was calculated to assess ductility in the second part of the investigation. Significant variations in the performance of the studied beams were found in the results.

The conventionally reinforced beam G1B1 showed a ductility value 2 and a load increment (load capacity) of 5.26. If CFRP rebars were substituted for steel rebars, G1B2 showed a lower load increase of 2.72. The epoxy resin bond around the CFRP bar in this replacement significantly improved the ultimate load stages and cracking, leading to increased ductility at 2.08.

Comparably, G1B3 showed a reduced load increment of 2.74 due to substituting CFRP rebars for steel rebars. This ultimately resulted in increased ductility of 2.49 as well as a considerable improvement in cracking and the final stage of the concrete bond around the CFRP bar. It can be noticed that the change in reinforcement type from ordinary reinforcement to prestressed resulted in a great improvement, such as enhanced cracking and ultimate loads. The prestressed beam G2B1, including a single harped steel strand and conventional steel reinforcement at the bottom layer, demonstrated the lowest ductility of 2.15 and the lowest load increment of 2.15. Similarly, G2B2, a prestressed beam with a single straight steel strand and normal steel reinforcement at the bottom layer, showed a 2.26 load increment, leading to significant increments in ultimate and cracked loads but a 2.0 decrease in ductility.

With the prestressed CFRP rebar, G2B3 showed the lowest ductility (1.75) and load increment (1.847). On the other hand, G5B1, which also used prestressed CFRP rebar, demonstrated greater ductility at 1.88 but a lower load increment of 1.372. Lastly, G5B2 showed greater ductility at 2.02 and a reduced load increment at 1.398. When these data are interpreted, it becomes clear that conventionally reinforced beams needed more time to attain their maximal load. On the other hand, using prestressed CFRP rebar bonded with the epoxy resin and cement grout enhanced the beam performance and decreased load increments. This suggests that prestressed CFRP rebar may improve structural resilience and efficiency in beam building. This study showed reasonable deflections through the use of bonding material and through the method of injecting these materials inside the longitudinal hollow from three hollows on both sides, which also reached a partial bond due to the high viscosity of that epoxy resin. This agrees with the study by Lees and Chris [5], which suggests that partial bonds rather than fully bonded tendons are used to get a suitable deflection.

Focusing in the final analysis criteria named "ductility," which represents the ratio of values of ultimate deformations to the values of the yielded deformations, were all in excellent agreement with some previous experimental studies related to computing the ductility of the beams researched by Zou, Jeong, and Abdelrahman's earlier research [12, 13 and 14]. These validations provided further evidence in favor of the results, emphasizing the critical role that prestressing force, type, and configuration play in dictating the ductility and deformability of reinforced concrete beams. These validations highlighted The need to consider these aspects when designing a structure to achieve maximum performance and safety.

Table 3: Compares the capacity ratio of cracked and ultimate loads and ductility for other beams to reference one

Beam Specimen	Cracked load (Pcr.) Exp. (kN)	Ultimate load (Pult) Exp. (kN)	Load-Increment Ratio $(\frac{Pult}{Pcr.})$	Yield Deflection (Δy) (mm)	Ultimate Deflection (Δult) (mm)	Δ_{ult}/L	Ductility μ $(\frac{\Delta_{ult}}{\Delta_{y.}})$	$(\Delta_{ult}M_{ult})/(\Delta_{cr}M_{cr})$ $(\frac{\Delta_{ult}}{\Delta_{y.}})*(\frac{Pult}{Pcr.})$
G1B1 (Reff.)	21.7	114.2	5.26	22.35	44.7	1/36	2	10.46
G1B2	57.7	157.2	2.72	10.15	21.2	1/75	2.08	5.65
G1B3	58.5	160.6	2.74	6.5	16.2	1/99	2.49	6.83
G2B1	111.8	240.3	2.15	9.1	19.6	1/82	2.15	4.62
G2B2	93.9	212.9	2.26	8.88	17.8	1/90	2	4.53
G2B3	137.6	254.2	1.847	4.16	7.3	1/219	1.75	3.23
G5B1	218.7	300.24	1.372	17.1	32.2	1/50	1.88	2.58
G5B2	221.1	309.3	1.398	13.5	27.3	1/59	2.02	2.82

3.3 Analyzing fracture patterns and failure modes in concrete beams

Structural engineers need to comprehend the rupture process of reinforced concrete beams. In particular, the form, extension, and beginning position of primary tensile or shear fractures are the main topics of this study's interpretation of experimental data concerning fracture characteristics. The experimental program aims to investigate eight reinforced concrete beams under various mechanical and physicochemical reinforcing parameter settings to validate and debate model parameters. Beam failure is mostly determined by the original crack's properties, even when the cracks propagate throughout the beam with additional reinforcement. Concrete beams reinforced with ordinary CFRP bars, prestressed steel strands, and prestressed bonded CFRP exhibit a range of failure modes, from ductile to severely brittle, as the research identifies. For an extensive examination, thorough explanations of the failure mechanisms seen in various beam specimens are included.

Various reinforcing parameters were applied on eight reinforced concrete beams as part of the experimental program. The uniform preparation of every beam for reliable testing conditions is done with great care. The form, extent, and origin of initial tensile or shear cracks were among the fracture features that were closely monitored and quantified. It is possible to evaluate the shape, number, location, and width of crack patterns to stipulate the failure mechanisms by applying loading conditions that cause failure. Detailed observations are tracked during the trials to allow for a thorough study. In the case of revealing the cracks, they range from analyzing the experimental results to characteristics and failure modes in reinforced concrete beams.

G1B1 (Reff.): Tensile rupture of the concrete via large fissures was followed by the yielding of the tensile steel reinforcement, resulting in flexural collapse. G1B2: Because of the bars' strong bond confinement and tensile strength, shear failure in the beam reinforced by two CFRP bars implanted in concrete reached its shear limit before any flexural failure. G1B3: The transmission of shear stresses from the FRP plate to the concrete also contributes to this failure mode. Midspan debonding begins at a flexural crack in the area of the highest bending moment close to the concentrated load. G2B1: Before the concrete was crushed, the tensile prestressed steel strands gave, causing flexural fractures to form throughout the reinforcing. G2B2: Tensile steel reinforcement was given first, and then tensile prestressed steel strands were yielded before the concrete was crushed, causing flexural cracking. Flexural cracking occurred in G2B3, where the concrete was crushed due to the tensile steel reinforcement giving way before the prestressed CFRP ruptured. Similar to G5B1 and G5B2, this failure mechanism was partly caused by the transfer of shear loads from the CFRP bars to the concrete, resulting in a mix of flexural and shear fractures at the highest bending moment between supports. Figures (9, 10, and 11) show the fracture patterns seen in all beams ordered as (a, b, and c), respectively. They mostly correspond with a failure mode found in numerical models examined using finite element software (Abaqus 2019), as denoted in Table 4.

At the end of this study, the experimental investigation supported the aim of this research by providing useful indications about how reinforced concrete beams react to different types of loads and a variety of reinforcement systems. Breakage patterns show the importance of material qualities, bond confinement, and stress transfer processes in deciding how these structures will fail.

Table 4: First cracking, ultimate load, and deflection for the tested beams

Beam Code	First Cracking			Ultimate State				Pu Exp/FEA	Δ_u Exp/FEA
	Exp.	FEA		Exp.		FEA			
	P_{cr} (kN)	P_{cr} (kN)	Δ_{cr} (mm)	P_u (kN)	Δ_u (mm)	P_u (kN)	Δ_u (mm)		
G1B1	17.53	23.36	0.46	114.2	44.7	127.3	31.2	0.90	1.43
G1B2	49.04	52.14	0.69	157.2	21.2	168.6	19.3	0.93	1.10
G1B3	49.63	53.70	0.92	160.6	16.2	167.8	14.85	0.96	1.09
G2B1	89.84	83.24	1.16	240.3	19.6	241.4	19.00	1.00	1.03
G2B2	88.52	86.93	0.76	212.9	17.75	225.3	14.85	0.94	1.19
G2B3	97.61	87.52	0.60	254.2	7.3	261.9	10.53	0.97	0.69
G5B1	191.78	129.58	3.78	300.2	32.2	308.1	28.42	0.97	1.13
G5B2	193.15	133.62	3.78	309.3	27.3	319.8	29.21	0.97	0.93

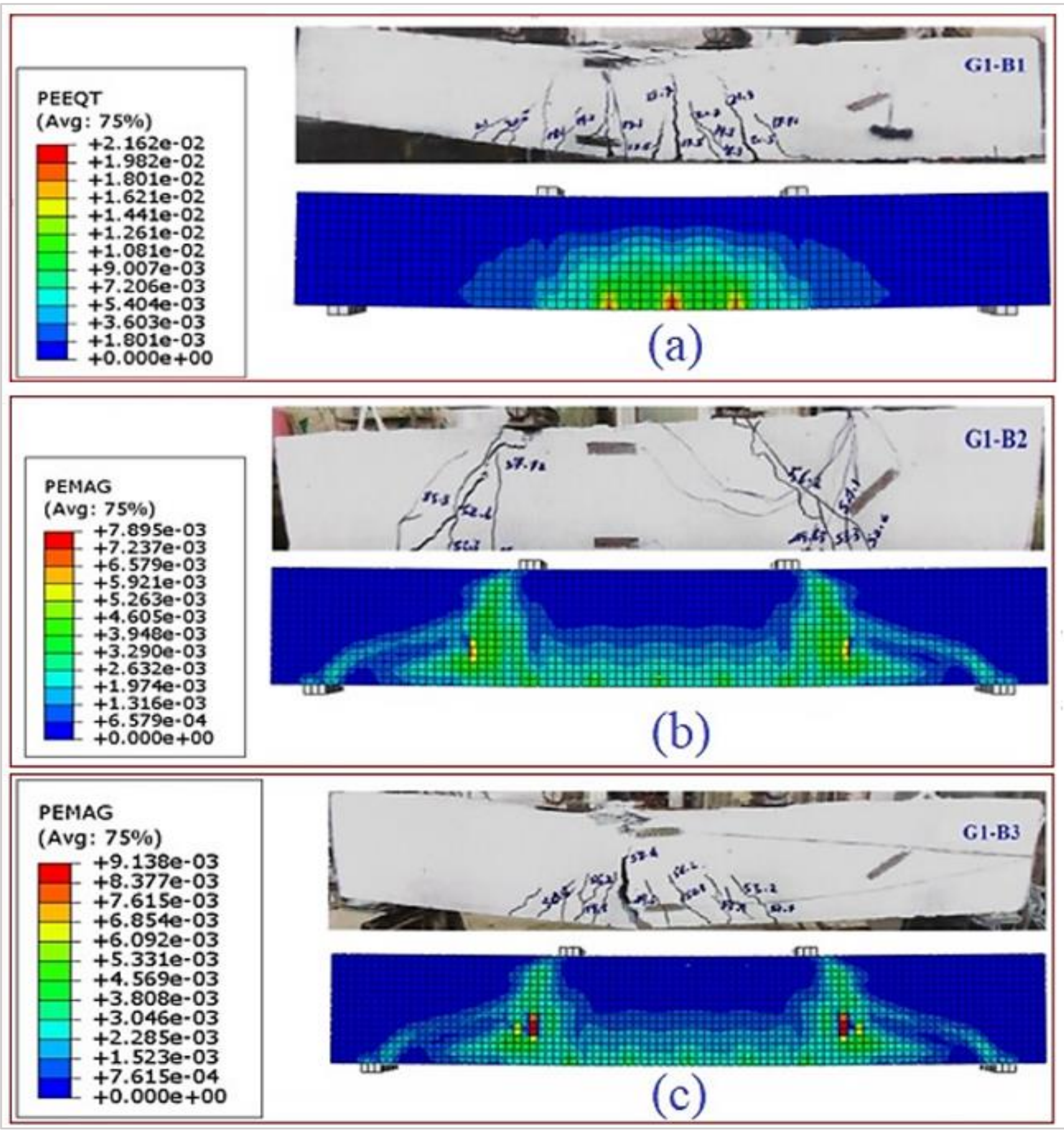

Figure 9: Failure beams' modes of (a) G1B1 (b) G1B2 (c) G1B3

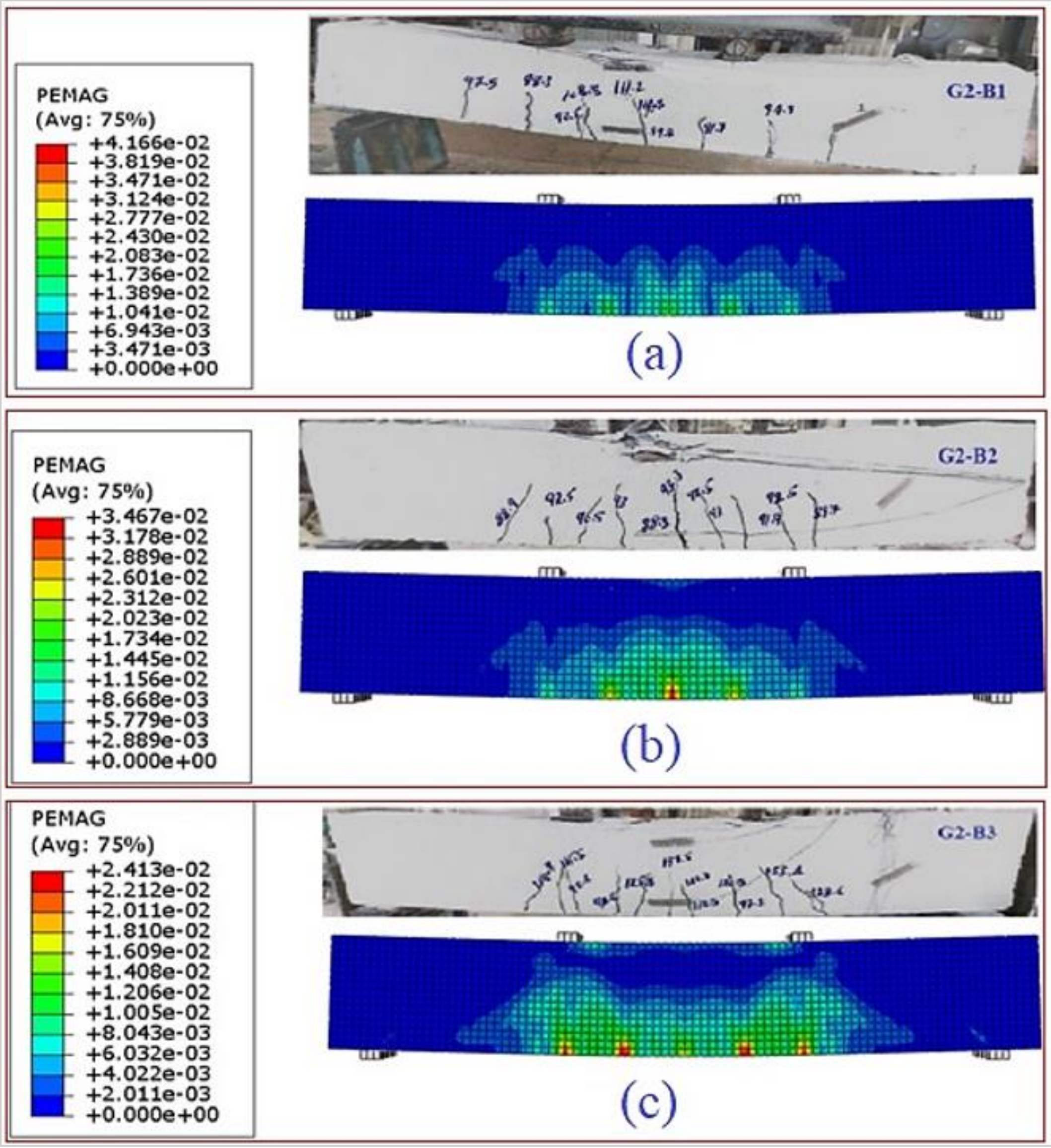

Figure 10: Failure beams' modes of (a) G2B1 (b) G2B2 (c) G2B3

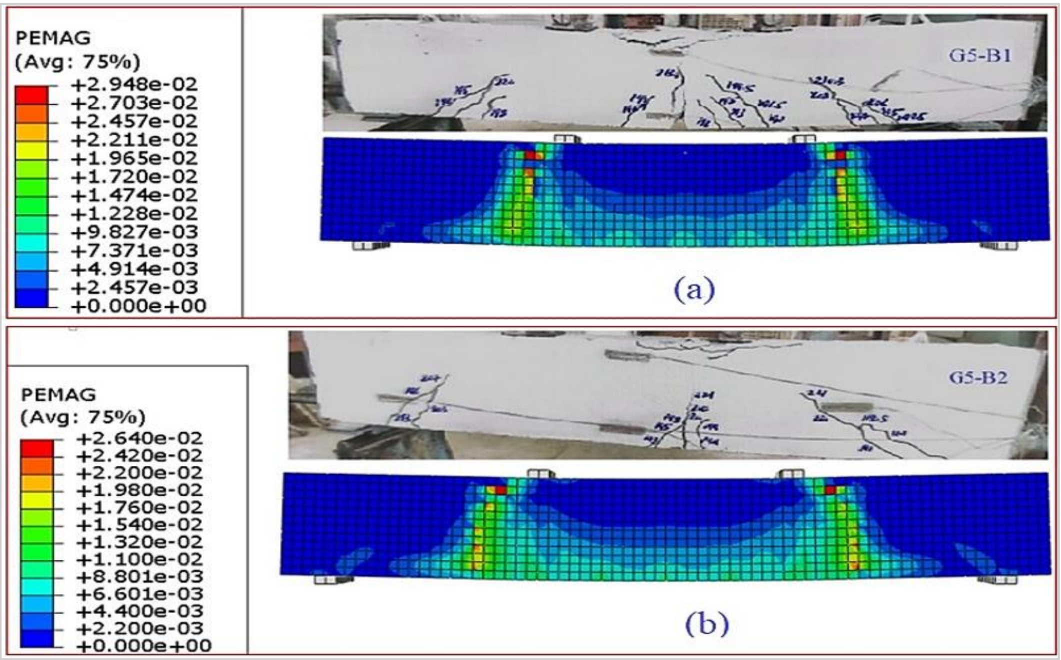

Figure 11: Failure beams' modes of (a) G5B1 (b) G5B2

4. Conclusion

After showing all results and graphs that related to the eight supported concrete beams, all were investigated experimentally. It is possible to conclude the following:

1) It was discovered that the beams strengthened with increased strength reinforcement (bonded CFRP bars were used in place of regular steel rebar) had higher ultimate loads of 1.37 and 1.4 for G1B2 and G1B3, respectively, and larger first cracking, reaching 2.65 and 2.69.
2) When comparing the epoxy resin bond to the cement grout bond, a little increase in bonding type was also seen, contingent upon the bonding material of the regular CFRP bars.
3) In producing both harped and straight steel strands into beams reinforced with unbonded steel strands. The results: G2B1 made the difference ratios for a cracked load of 5.15 and an ultimate load of 2.1, whereas G2B2 displayed ratios of 4.32 and 1.86, respectively. This demonstrated that harped steel strands, as opposed to straight ones, are primarily used to increase strength.
4) The two steel rebars were swapped out for additional prestressed CFRP bars, which produced a different ratio than the reference beam of 10.7 and 10.18 cracked load and 2.62 and 2.7 ultimate load for beams G5B1 and G5B2, respectively. This was the biggest improvement among the experimental eight beams.
5) Based on the study's findings, we discovered that the bonding effect by using an epoxy resin is essential in postponing the onset of cracks by increasing the ultimate load strength and fractured area.
6) In addition, the examined fracture patterns and failure mechanisms showed a variety of participating shear and flexural behaviors affected by the configured kind of reinforcement. Diverse degrees of ductility and deformation were seen in shear failure, mid-span deboning, and flexural cracking. In conclusion, substituting the CFRP bars and replacing the bottom steel rebar result in a maximum ductility of 2.49 in G1B2 and a reduction in G5B2. So, this value is similar to many previous related studies to encourage the researchers to ensure this method enhances the flexural properties as a general and the ductility as a special.

Author contributions

Conceptualization, A. Edan and W. Abdulsahib; data curation, A. Edan and W. Abdulsahib.; formal analysis, A. Edan.; investigation, A. Edan; methodology, A. Edan; project administration, A. Edan and W. Abdulsahib, resources, A. Edan and W. Abdulsahib.; software, A. Edan.; supervision, W. Abdulsahib.; validation, A. Edan and W. Abdulsahib.; visualization, A. Edan.; writing—original draft preparation, A. Edan.; writing—review and editing, A. Edan. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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