

BEHAVIOR OF LIGHTWEIGHT REINFORCED CONCRETE CONCAVELY-CURVED SOFFIT BEAMS STRENGTHENED WITH CFRP

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Abstract

The main goal of this research is to investigate how curvature influences the performance of concavely curved soffit lightweight reinforced concrete (LWRC) that has been strengthened with carbon fiber reinforced polymer (CFRP) sheets. This program conducted tests on a total of eighteen LWRC beams using a two-point load, namely a monotonically load. From these beams, thirteen had a concavely curved soffit beam with different degrees of curvature ranging from 30 mm/m, 40 mm/m, and 50 mm/m. Additionally, there were five prismatic beams, among which four were un-strengthened (reference). The beams were specifically designed to fail through flexural failure. The study includes a discussion of the beams' load-carrying capacity, failure mode, cracking patterns, and load mid span deflection. The experimental results showed that as the curvature degree increased from 30 to 50 mm/m, the load-carrying capacity reduced by 2.59-12.15%, as compared with the prismatic beams. Additionally, the test results indicate that the utilization of CFRP sheets for strengthening beams significantly increased the strength of the beam specimens. The ultimate load capacity exhibited an increase ranging from 15.53-38.19%, as compared to the reference beams. The theoretical value for the strengthened beam was estimated using ACI 440.2R-23 and then compared to the experimental value obtained from the test.

Keywords:

Curved soffit beams;
 Lightweight aggregate (LECA);
 Flexural behavior;
 Carbon fiber reinforced polymer (CFRP) sheet;
 Externally bonded reinforcement (EBR) ;
 Monotonic loading.

1 Introduction

The term "curved soffit" refers to a beam that has a decreasing depth from the supported end to the middle span [1]. Additionally, the utilization of more curved structures is becoming increasingly common for modern construction projects [2]. Structural flexural strengthening is necessary to increase the load-bearing capacity of the beam in response to extra loads or weaknesses in the members. This phenomenon occurs when there is a change in the usage of the structure, requiring it to bear a greater load capacity [3]. Externally bonded reinforcement (EBR) carbon fiber reinforced polymer (CFRP) sheets are the most used technique for strengthening structures [4]. CFRP can significantly improve the ability of weakened structural elements to resist flexural forces, prolonging their operational lifespan [5]. The main problem with this method is the so-called debonding issue. FRP debonding was observed in areas with a high concentration of stresses [6]. One of the primary benefits of using CFRP material in structural engineering applications is its ability to bond to structural parts in different configurations, besides its lightweight and flexibility. This material also possesses advantageous structural characteristics, including corrosion resistance, a high ratio of stiffness to weight, high tensile strength, and high fatigue resistance [5]. Using lightweight concrete, such as light clay expanded aggregate (LECA), has the benefit of decreasing the weight of a structure while also improving its fire resistance, sound insulation, and thermal characteristics compared to normal-weight concrete [7] [8].

Eshwar et al. 2003 [9] investigated the utilization of carbon fiber reinforced polymer (CFRP) to strengthen RC with concave curved soffits. All six beams were three-point static flexure tested. Three of these beams were 6000mm long, 200mm wide, and 400mm high with flat soffits. The remaining three beams have a cross-section of 530×200mm at the supports and 400×200mm at the middle. The length of external strengthening was 5m and the width of laminate was 100mm in all beams. The

beams were strengthened with 3 layers of CFRP wet layup sheet. The final layer was reinforced using pultruded precured laminate. One curved beam was designed with GFRP anchor spikes. External strength was 5m long and the laminate width was 100mm in all beams. The results indicated wet layup method of applying GFRP spike anchors delayed premature peeling better than the control specimen (flat soffit). Each strengthened beam has 27% to 82% higher flexural capacity than the control beam. Cracks were reduced with CFRP laminates. FRP laminates naturally straighten under tension due to their curvature. This provides direct transverse tensile stress on the glue, increasing early peeling. Tensile stresses may prematurely separate the cover.

Aljaafreh et al. 2016 [10] Investigated how CFRP affects lightweight concrete beams, eight beams underwent four-point bending tests. The beams in this experiment were 152.4mm wide x 203.2 mm deep x 1575 mm long. Two beams were used as controls, two beams were strengthened with an exterior sheet of CFRP bonded with epoxy. The next two beams are reinforced in the same way as the preceding two, but they are fastened to the concrete using an anchor bolt called a mechanical fixation, and CFRP sheets were utilized to reinforce two beams at the tension face on the bottom and as U-wraps at the ends to improve concrete anchoring. The results showed strengthened beam was greater in strength and deflected less than the control beam, most strengthened beams failed due to cover delamination, but the CFRP sheet was undamaged. Beams with U-wrap anchoring failed only due to debonding. When compared to un-strengthened beams, CFRP U-wrap is 12.11% stronger than control beams and may raise the flexural laminate's tensile strain by 81% and delay debonding longer than mechanical anchoring.

Salama et al. 2019 [11] Examined the behavior of reinforced concrete beams subjected to flexural experiments and had dimensions (150×300×2000) mm. Nine RC beams were constructed accordingly. Eight of them were reinforced in flexure by bonding carbon fiber-reinforced polymer (CFRP) sheets in various bottom and side configurations. and subjected to four-point bending until failure. The results indicated that the flexural strength of the bottom and side bonded strengthened RC beam specimens increased by 62 to 92% and 39.7–93.4%, respectively.

Salahaldin et al. 2020 [12] Studied the flexural performance of I-shaped reinforced concrete beams created from lightweight aggregate concrete in various ratios, strengthened with CFRP sheets (full, partial). Involved six specimens with a 1500mm effective span. Two of the samples were normal concrete beams. Two additional samples consisted of lightweight beams where 50% of the aggregate was replaced with pumice. The final two samples were lightweight concrete beams created by replacing 75% of the aggregate with pumice. Before and after strengthening, the samples were tested twice under load from two points. The findings indicated that strengthening by CFRP considerably increased the efficiency of LWRC beams from 57% to 113% for partially and fully strengthened beams compared to the beams before strengthening. Debonding of CFRP sheets happens late in the loading process after the specimens have reached their complete ductile behavior. Fully strengthening concrete beams with CFRP sheets improves their behavior more than partially strengthening them. CFRP sheet debonding was the failure mode for beams that had been fully strengthened, while beams that had been partially strengthened had a normal failure pattern.

Al-Mahaidi et al. 2022 [13] Assessed the flexural behavior of curved soffit-reinforced concrete strengthened CFRP sheets or laminates. They performed static testing on 32 RC beams. There were 23 curved soffit beams with 5 to 20 mm/m. In contrast, 9 flat beams served as control beams. All the flat and curved soffit beams had dimensions of 2700×140mm, with a depth of 260mm at the midpoint and varying depths (280, 300, 320, 340) mm at the end sections, depending on the degrees of curvature (5, 10, 15, 20) mm/m. The results showed that the use of concavely curved RC beams when the lowest degree of curvature was strengthened with EB-CFRP, performed better than comparable CFRP systems used to strengthen beams with greater curvature degrees. Concavely curved RC beams (5mm/m, 10mm/m, 15mm/m) strengthened with CFRP sheet or laminate decreased load-bearing capacity by 6% and 8%, respectively, compared to flat beams strengthened similarly. Curved soffit RC beams with 20mm/m curvature that were externally strengthened with CFRP sheet or laminate displayed a 14% and 15% decrease in ultimate capacity, respectively, compared to flat beams strengthened with the same CFRP system. Intermediate-span induced-crack CFRP delamination caused all strengthened beams to fail because of to high interface stresses between concrete and CFRP composites and each strengthened beam kept its strength after CFRP debonding.

Ahmed et al. 2022 [1] Studied the load-bearing capability of an RC beam with a concave curved soffit and compared it to a reference beam with a standard rectangular shape. The aim was to investigate the impact of the curved bottom face of the building on structural performance. There is one reinforced concrete (RC) flat beam with dimensions of 200×300×2500 mm. Additionally, three RC beams are also 2500 mm in length. These beams have a cross-section of 200×300 mm near the

supports, and the cross-section changes between 200×270 mm, 200×240 mm, and 200×210 mm at midspan. Every beam conducts a four-point static force test until it reaches its point of failure. As a result, a 14.72-45.66% decrease in load-bearing capability as the curvature degree rose from 7.5 to 22.5 mm/m. And the increase in the degree of the curve in the curved soffit concrete beams will lead to a gradual decrease in the compressive strain of the concrete compared to the flat soffit concrete beams. Increasing the degree of the curve in the specimen leads to decreasing the cracking load.

Kareem et al., 2024 [2] Conducted a study on the influence of curvature on the effectiveness of curved reinforced concrete (RC) beams that were strengthened with fiber-reinforced polymers (FRP). Five models each measuring 6 meters in length, were utilized. These models had varying degrees of curvature, ranging from 1 to 5 mm/m. The modeling was conducted using Ansys software to simulate the girders. The purpose was to analyze the load deflection, failure load, and failure pattern at the mid-span. A single central load was placed at the midpoint of the girder's span until the failure. The result shows a girder with a curvature of 1mm/m may bear a higher load compared to others, The force applied is greater and the displacement is less as the curvature decreases. In the case of a girder with a curvature of 5mm/m, there are more cracks compared to a girder with a curvature of 1mm/m, and the deflection is higher under the same load as other girders:

The objectives of the research :

- To examine the effectiveness of thirteen concavely-curved soffits and five prismatic in the flexural behavior of lightweight reinforced concrete (LWRC) beams strengthened with carbon fiber-reinforced polymer (CFRP) sheets under monotonic loads.
- Studying the effect of different degrees of curvature (30mm/m, 40mm/m, and 50mm/m) on the behavior of LWRC concavely-curved soffits beams and compared with prismatic beams (without curvature).
- To examine the effect of various CFRP strengthening configurations on the structural behavior of the LWRC beam.
- Comparing the effectiveness of LWRC beams strengthened with CFRP with un-strengthened beams (reference beams).

2 Experimental work

This section will present the material properties, beam specimen details, apparatus used, and testing procedures.

2.1 Materials properties

- Ordinary Portland Cement complies with the specifications set by the Iraqi Standards (IQS No.5/1984 [14].
- Fine aggregate (Sand) obtained from the Al-Ukhaidher region meets the requirements specified in the Iraqi standards (I.Q.S No.45/ 1984) [15].
- Replacing fully coarse aggregate with Lightweight aggregate (LWA) using light expanded clay aggregate (LECA) with a particle size (0-8) mm, obtained from the (Najaf) complying with (ASTM C330/C330M – 23) requirements [16].
- Tap water for saturated surface dry of LECA, preparation of concrete mixtures, and curing of specimens.
- The longitudinal reinforcements comprise two 12mm bars arranged at the bottom and two 10mm bars installed at the top of the beam. For shear reinforcement, stirrups of 10 mm in diameter were used, as stated in the (ASTM A615-20) standard [17].
- The additives utilized in this study included PC600 superplasticizer complying with BS EN934-2:1998 [18] and ASTM C494 [19] standards, Type G.
- The tested beams were strengthened using unidirectional carbon fiber reinforced polymer (CFRP) sheets, as indicated in Fig. 1, Table 1. Showed the properties of (CFRP) sheets based on manufacturer specifications.
- Sikadur-330 is the adhesive used for (CFRP) sheets. consists of two parts, A (Resin) is white, and B (Hardener) is grey. As in Fig. 2 and Table 2. Shows typical Sikadur-330 properties.



Fig. 1: Unidirectional carbon fiber reinforced polymer sheet (CFRP).



Fig. 2: Epoxy (sikadur®-330).

Table 1: Mechanical properties of CFRP.

Material	Properties	SikaWrap-300 C
CFRP (Sheet)	Density [g/cm^3]	1.82
	Tensile strength [MPa]	4000
	Tensile modulus [GPa]	230
	Thickness [mm]	0.167
	Elongation at break [%]	1.7

Table 2: Properties of the epoxy.

Material	Properties	Sikadur®-330
Epoxy	Tensile strength [MPa] (7 days at +23 °C)	30
	Modulus of Elasticity [GPa] 7 days at +23°C (flexural)	3.8
	Modulus of Elasticity [GPa] 7 days at +23°C (tensile)	4.5
	Mix ratio (A: B)	4:1
	Elongation at break [%] (7 days at +23 °C)	0.9

2.2 Preparation of Test Specimens

2.2.1 Mix Design

Structural lightweight aggregate concrete has a cylinder compressive strength of greater than 17 MPa at 28 days. According to ACI 213R-14 [20]. The mixture's compressive strength was assessed after 7 days and 28 days. The findings were calculated as the average value of three cubes and three cylinders. The details of the mix design are outlined in Table 3.

Table 3: Proportion of mixed design.

Cement [Kg/m ³]	Sand [Kg/m ³]	LECA [Kg/m ³]	W/C ratio	PC600%	Compressive Strength of Cube, f_{cu} [MPa]		Compressive Strength of Cylinder, f'_c [MPa]	
					7 days	28 days	7 days	28 days
520	680	460	0.38	1.2 OPC	41.7	47.2	33.4	37.7

2.2.2 Mixing, casting, and curing

Step 1: All of the LWRC beams were cast using eighteen wooden molds. The inside surfaces of constructed molds were carefully cleaned and lubricated to prevent adhesion to the concrete after it hardened.

Step 2: Install the spacers in the bars to ensure the cover is securely fastened 20 mm, and then reinforcement is placed inside the wooden molds.

Step 3: The LECA is soaked in water for 24 hours to achieve saturated surface dry conditions according to the requirements of ACI 213R-14. Thus, LECA, PC600 is diluted with a portion of water, cement, sand, and the remaining water is added to the mixer.

Step 4: After completing the mixing process, the LWC mixture is placed in the molds, using a vibrator for 5 seconds each to give adequate compaction.

For compressive strength, 150 x 150 x 150 mm cubes, 150 x 300 mm cylinders, and 100 x 100 x 400 mm prisms were cast, oven-dry density for LWC, splitting tensile strengths, static elastic modulus, and modulus of rupture. After 24 hours, all specimens were removed from molds and cured in water for 28 days. Fig. 3 displays all steps.



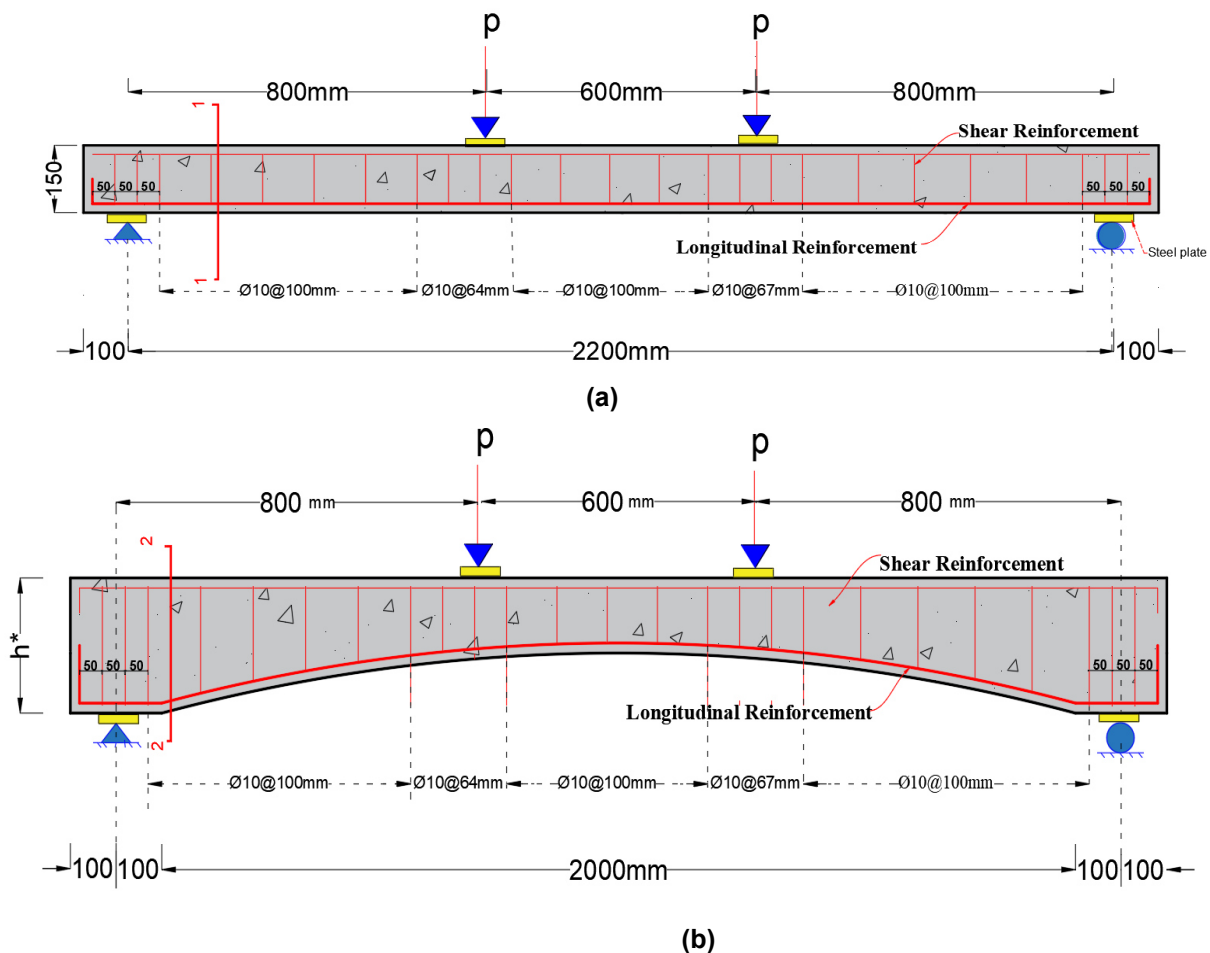
Fig. 3: Casting and curing process.

2.2.3 Test beams

This study involved the construction of eighteen beams with simple supports, consisting of five beams with a prismatic shape and thirteen beams with concavely-curved soffits with different degrees of curvature. The beams were designed to ensure flexural failure. As per the ACI 318.19 [21]. The beams experienced a two-point load (monotonic load). The prismatic beam had dimensions of 2400 mm in length, 150 mm in depth, and 200 mm in width. About the concavely-curved soffit beams, their dimensions in terms of length and width are similar to prismatic beams. However, the depth of the end section (h^*) varies depending on the degree of curvature, 270mm, 310mm, and 350mm for degrees of

curvature of 30mm/m, 40mm/m, and 50mm/m, respectively. All beams have a uniform depth of 150 mm at their mid-span. Figure 4 displays the dimensions and specific details of the steel reinforcement in the specimen. Two 12 mm diameter bars were utilized as flexural reinforcement in the tension zone. A 20 mm is employed to cover all sides. Furthermore, compression reinforcement consisting of two 10 mm bars was utilized. To prevent shear failure and maintain the rigidity of the longitudinal bars, the beams were reinforced with 25 closed stirrups of 10 mm in diameter. The variables in the test consisted of the curvature degree of the beams, the number of layers of CFRP sheets, and the strengthening configuration using CFRP sheets. Table 4 describes the beam specimens. The beams are classified into five categories, which are described as follows:

Each group consists of four beams, the first beam in each group is prismatic, and the remaining three beams with degrees of curvature of 30, 40, and 50 mm/m. The first group is without strengthening (reference beams), while group 2 is strengthened with one layer of CFRP sheet on the bottom (soffit). Also, in group 3, the form of strengthening is two layers at the bottom (soffit). Group 4, consists of two beams, one prismatic and the second curved with a degree of curvature of 50mm/m, strengthened with three layers from the bottom (soffit), and Group 5 consists of 4 beams strengthened with one layer at the bottom (soffit) and on both sides. Table 4 and Fig. 5 show the details of the strengthening.



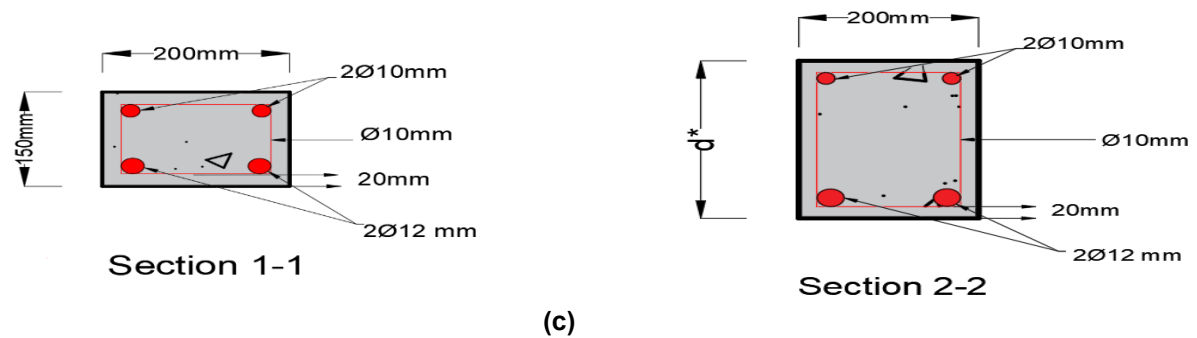
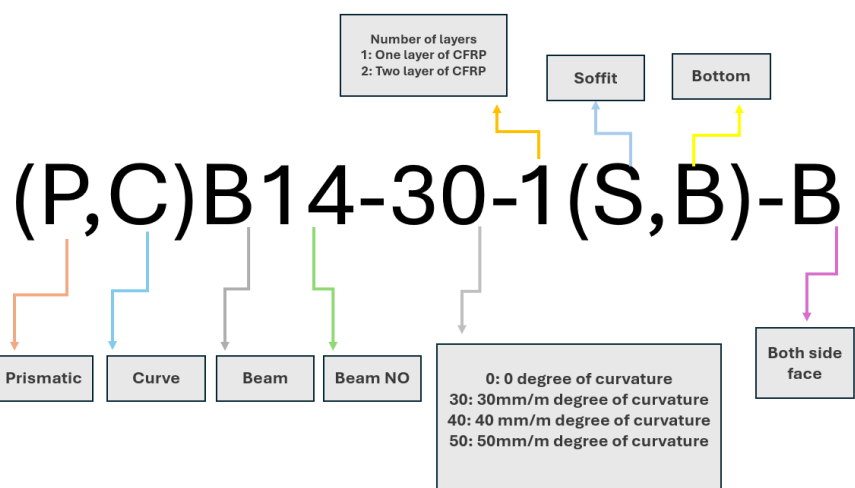


Fig. 4: Details of the test beam (all dimensions in mm): (a) the longitudinal section of the prismatic beams; (b) the longitudinal section of the concavely-curved soffit beams; (c) the cross-section of the (a&b).

Table 4: Details of beam specimens.

Group No	Configuration Type	Specimen symbols	Strengthening details
G1	A	PB1-0	None
		CB2-30	None
		CB3-40	None
		CB4-50	None
G2		PB5-0-1B	One layer of CFRP at the bottom of the prismatic beam
		CB6-30-1S	One layer of CFRP at the soffit of the curved beam
		CB7-40-1S	One layer of CFRP at the soffit of the curved beam
		CB8-50-1S	One layer of CFRP at the soffit of the curved beam
G3		PB9-0-2B	Two layers of CFRP at the bottom of the prismatic beam
		CB10-30-2S	Two layers of CFRP at the soffit of the curved beam
		CB11-40-2S	Two layers of CFRP at the soffit of the curved beam
		CB12-50-2S	Two layers of CFRP at the soffit of the curved beam
G4		PB13-0-3B	Three layers of CFRP at the bottom of the prismatic beam
		CB14-50-3S	Three layers of CFRP at the soffit of the curved beam
G5	B	PB15-0-1B-B	One layer of CFRP at the bottom of the prismatic beam&both sides face
		CB16-30-1S-B	One layer of CFRP at the soffit of the curved beam&both sides face
		CB17-40-1S-B	One layer of CFRP at the soffit of the curved beam&both sides face
		CB18-50-1S-B	One layer of CFRP at the soffit of the curved beam&both sides face



2.2.4 Strengthening procedure

This study focused on the utilization of the externally bonded (EB) method for LWRC prismatic and curved soffit beams. This research examined a total of eighteen beams. The beams in Group 1 were un-strengthened, while the beams in Groups 2, 3, and 4 were strengthened with one, two, and three layers of CFRP on the bottom (soffit) beams (configuration type A). Group 5 beams were strengthened with one layer at the bottom (soffit) and both sides of the face (configuration type B), as illustrated in Fig. 5. The strengthening procedure involved the removal of a tiny layer of the concrete cover using a specialized disc grinding machine. The exposed surface was then cleaned using compressed air. The CFRP sheets were carefully cut to the specified requirements of 2100 mm in length and 180 mm in width for the bottom (soffit) beams. Additionally, sheets with dimensions of 2100 mm in length and 100 mm in width were used for both sides of the face. An application of epoxy resin was applied to the carefully prepared concrete surface and the CFRP parts. Subsequently, a roller was employed to eliminate any air retained under the CFRP sheets and uniformly spread the epoxy. The beams conducted testing seven days after the installation of CFRP, according to the specifications provided in the product data sheet. Fig. 6 displays the method used for strengthening.

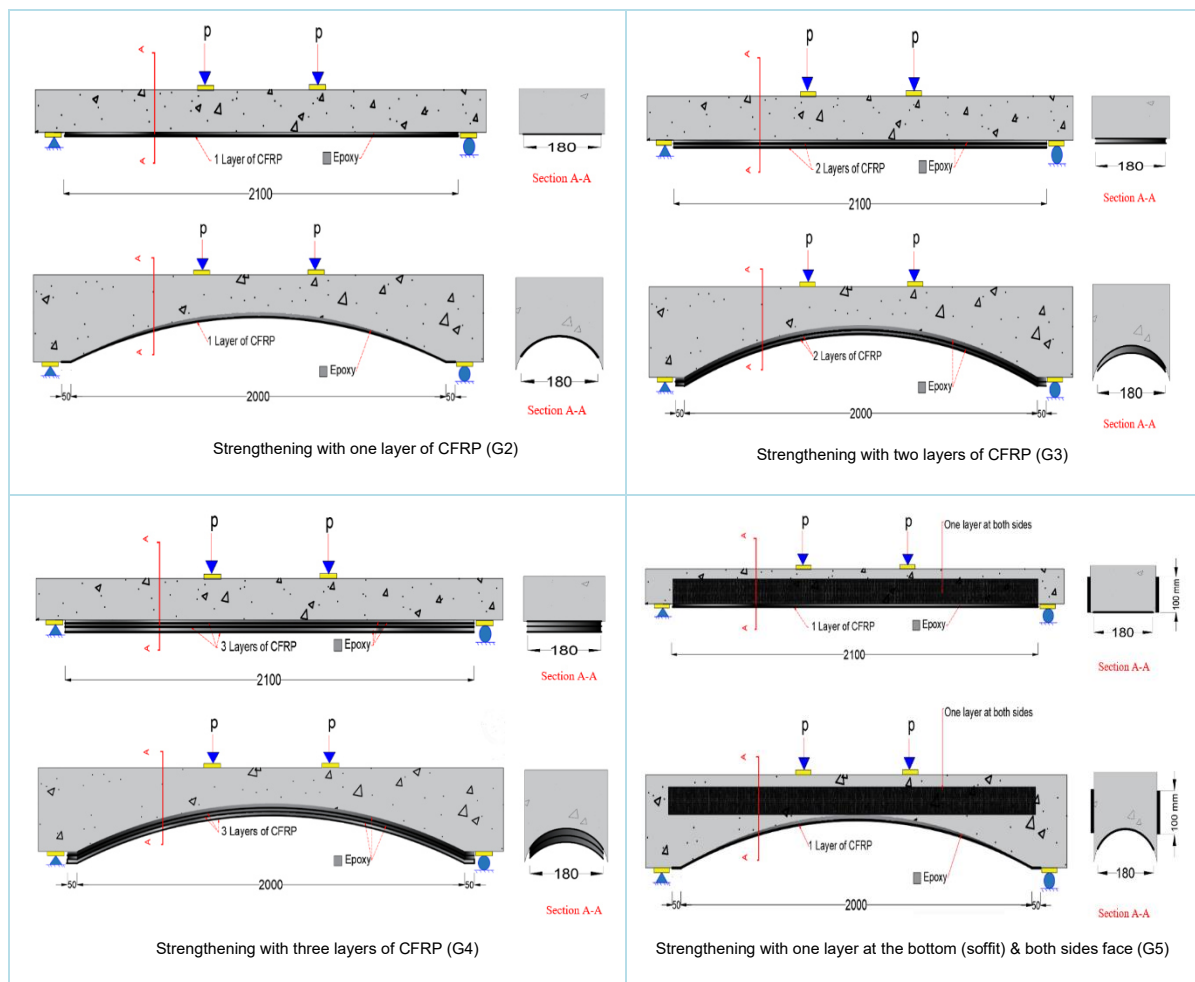


Fig. 5: Strengthening details for G2, G3, G4, and G5.



Fig. 6: Application of CFRP sheet.

2.2.5 Testing Procedure

All LWRC prismatic and concavely-curved soffit beams are simply supported on two stiff steel rollers at each support to avoid any axial restraints at the ends over an effective span of 2200 mm and tested under two concentrated loads. Tests are made in the Structural Laboratory of Civil Engineering Department at the University of Al-Nahrain by hydraulic testing machine with a maximum capacity of (2000) kN. Each beam was tested with monotonic loading until failure. The distance between the loads is 600 mm (shear span). To measure the deflection of the specimens, one dial gauge was placed at mid-span, as shown in Fig. 7.

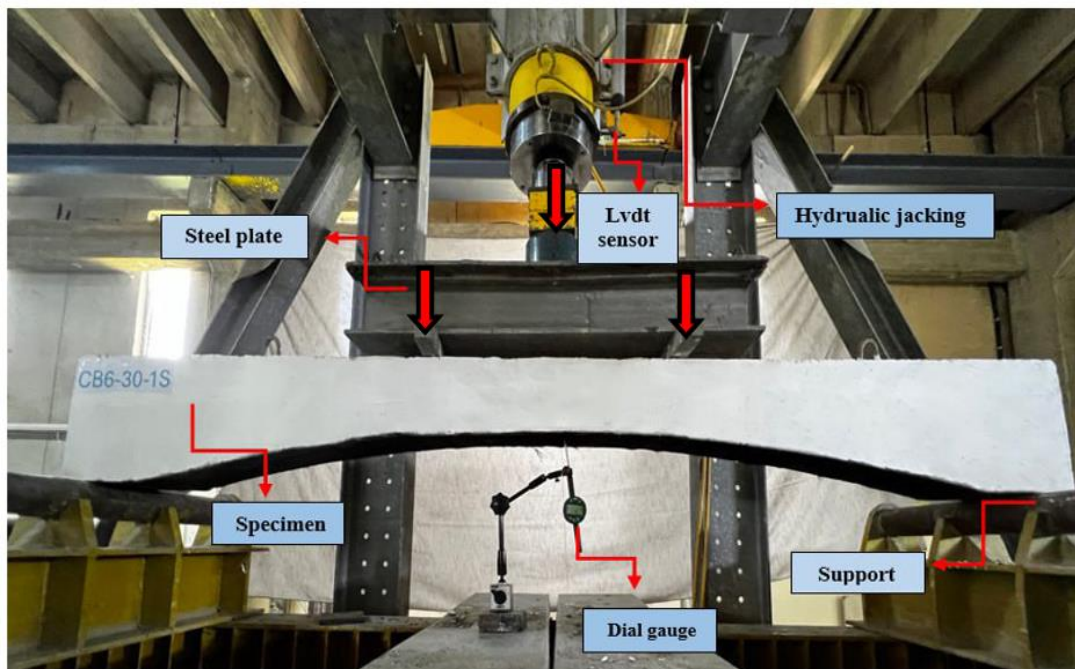


Fig. 7: Test setup for beam specimen.

3 Experimental results

This section contains the experimental results for LWRC strengthened and un-strengthened prismatic and concavely-curved soffit beams. The results included details describing modes of failure and crack patterns, load-carrying capacity, and load-deflection relationships.

3.1 Mechanical properties

Table 5 shows the compressive strength of cubes and cylinders, oven-dry density, splitting tensile strengths, modulus of elasticity, and modulus of rupture of two LWC mixes at 28 days.

Table 5: Experimental and theoretical results of hardened LWC.

Group No.	Oven-dry density, Kg/m ³	Compressive strength, MPa			Splitting strength (fct), MPa		Modulus of Rupture(f_r), Mpa		Modulus of Elasticity (Ec), MPa	
		$f_{c'}$	f_{cu}	$\frac{f'_c}{f_{cu}}$						
					Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
1	1818	38.25	46.38	0.824	2.972	2.943	4.009	3.259	23123	20614
2	1834	36.78	44.46	0.827	3.191	2.887	3.757	3.196	22675	20482

The predicted value obtained from ACI 318-19 [21]: $f_{ct} = \lambda * 0.56 \sqrt{f'_c}$, $f_r = \lambda * 0.62 \sqrt{f'_c}$, and $E_c = 0.043 * \sqrt{f'_c} * w_c^{1.5}$

3.2 Testing and results beams

All LWRC Prismatic and concavely curved soffit beams were tested under the monotonic two-line loads. The deformations of beams were within the elastic ranges at an early loading stage. When the applied load increases, the behavior of the beams changes from elastic to plastic range, and then first cracks begin to appear between the loading positions at the tension zone in the beams. Generally observed this crack at approximately between (11-23) KN. All of the LWRC beam findings are displayed in Table 6.

Table 6: Summary of the test results.

Group No.	Configuration type	Specimen symbols	Load at first crack P _{cr} (KN)	Deflection at first crack Δ _{cr} (mm)	Ultimate load P _u (KN)	Ultimate deflection Δ _u (mm)	Effect of strengthening on load %	Decrease in Mid-span deflection on %	Effect of curvature on load %	Failure Mode	
G1	A	PB1-0	13.54	5.81	69.42	48.02	-	-	-	FL & CC	
		CB2-30	12.30	4.43	67.38	38.05	-	-	-2.94	FL & CC	
		CB3-40	14.72	7.34	64.9	39.2	-	-	-6.51	FL & CC	
		CB4-50	15.62	7.22	60.98	42.52	-	-	-12.15	FL & CC	
G2		PB5-0-1B	14.04	9.69	81.12	45	+16.85	6.28	-	SROC	
		CB6-30-1S	20.26	9.02	79.02	33.9	+17.28	10.91	-2.59	SROC	
		CB7-40-1S	16.92	7.00	74.98	36.12	+15.53	7.86	-7.57	SDOC & SROD& CC	
		CB8-50-1S	23.55	12.6	73.09	39.06	+19.86	8.14	-9.9	ROC & CC	
G3		PB9-0-2B	16.11	8.9	88.53	43.05	+27.53	10.34	-	CCS	
		CB10-30-2S	19.32	7.86	85.23	31.83	+26.42	16.34	-3.73	DOC	
		CB11-40-2S	18.52	5.84	83.15	33.94	+28.12	12.83	-6.07	DOC	
		CB12-50-2S	14.73	11.86	81.2	37.96	+33.16	10.72	-8.28	DOC	
G4		PB13-0-3B	12.22	7.24	86.54	41.86	+24.66	12.83	-	CCS	
		CB14-50-3S	11.34	5.36	84.27	35.42	+38.19	16.70	-2.62	DOC	
G5		B	PB13-0-1B-B	-	-	83.03	44.02	+19.61	8.33	-	ROC
			CB14-30-1S-B	15.47	4.68	80.13	32.86	+18.85	13.63	-3.49	SROC& CC
	CB15-40-1S-B		17.36	8.01	77.1	39.25	+18.79	12.67	-7.14	SROC& CC	
	CB16-50-1S-B		12.82	15.8	73.99	40.82	+21.33	12.39	-10.88	ROC	

FL: Flexural failure; CC: Concrete crushing; DOC: Debonding of CFRP; ROC: Rupture of CFRP; CCS: Concrete cover separation; SROC; Slight Rupture of CFRP.

3.3 Failure mode and crack pattern

The test results show that five failure modes can be identified in the tested specimens: flexural failure, debonding of CFRP, rupture of CFRP, concrete cover separation, and concrete crushing, as presented in Table 6. In general, no cracks were observed in the region of the pure bending moment or shear in the early loading stages. As the load increased, the first Hairline flexural cracks in all beams were between two-point loads that became visible at midspan in both faces of the beam where the bending moment was the greatest and cracks formed along the curve at the bottom face. Then, these cracks formed along the curve, increasing in number, and moving towards the compression zone to failure. The crack pattern of each of these specimens is described in Table 6 and Fig. 8.

It can be concluded that when using one layer of CFRP, the mode of failure is a rupture, but when using two layers of CFRP or three layers, the mode of failure is de-bonding and concrete cover separation, as shown in Fig.8 to Fig. 12.

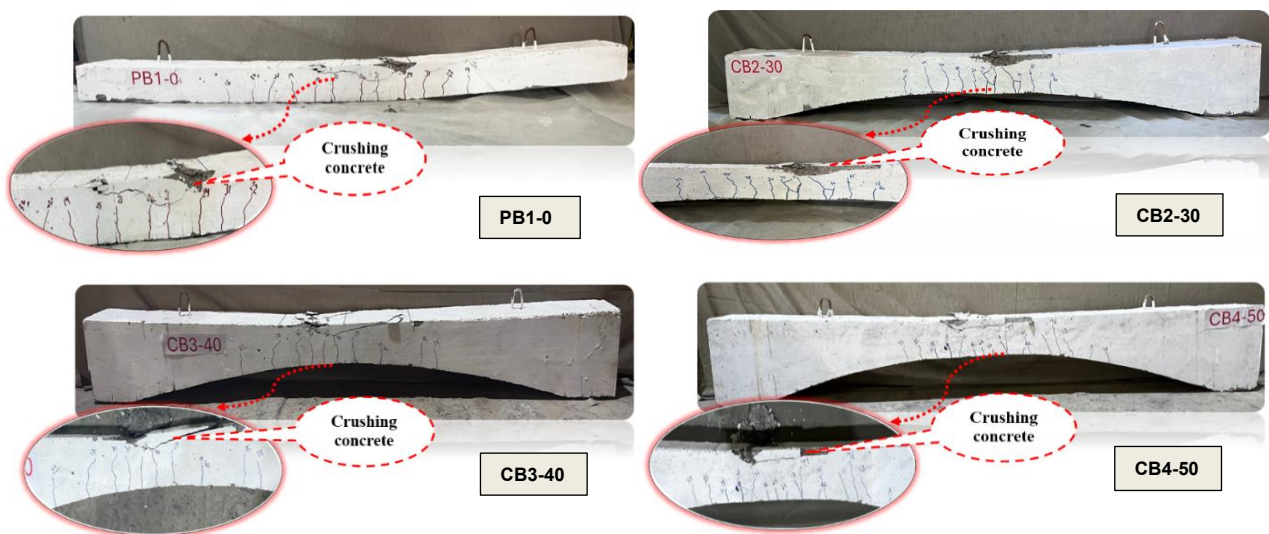


Fig. 8: Cracks pattern and failure mode of reference beams (G1).

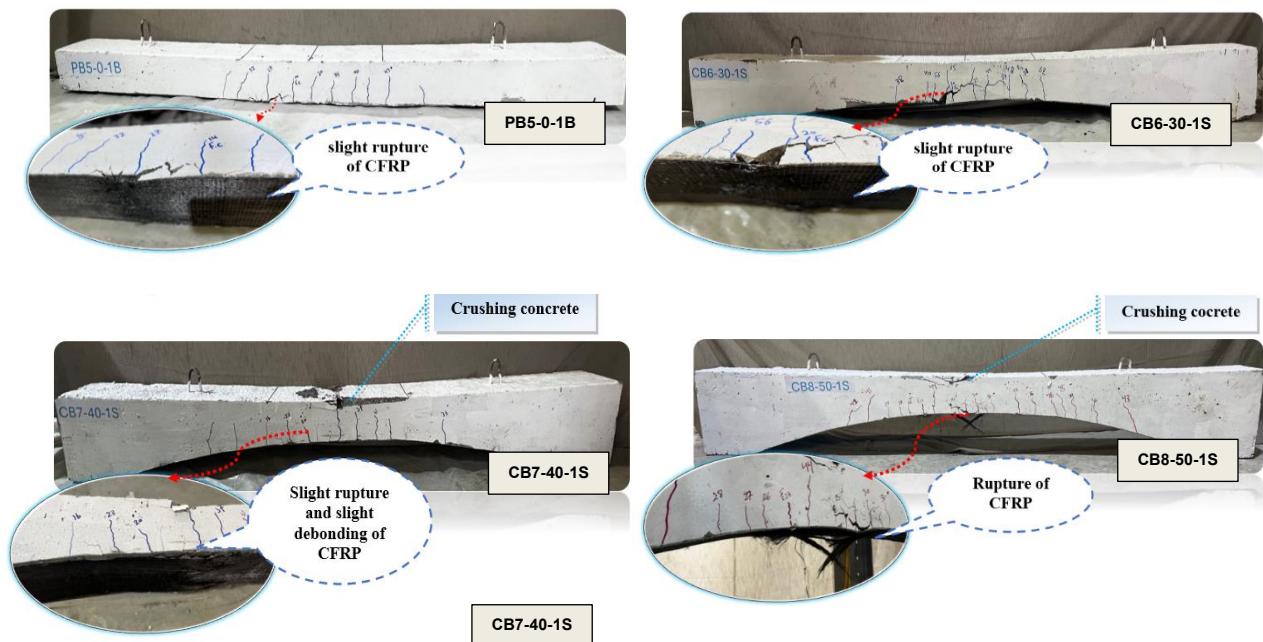


Fig. 9: Cracks pattern and failure mode of G2

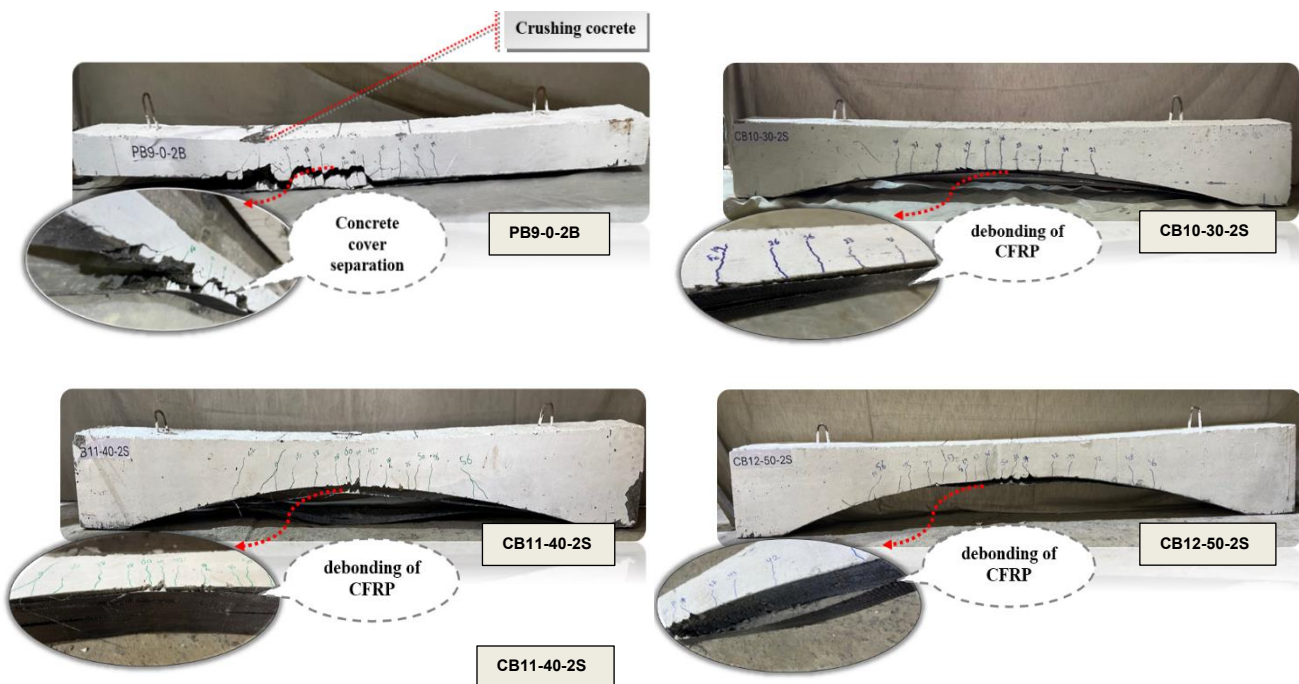


Fig. 10: Cracks pattern and failure mode of G3

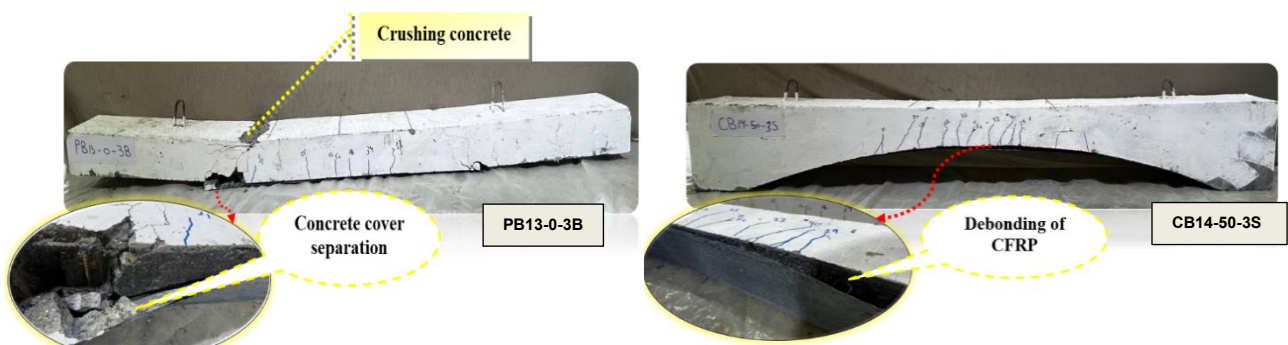


Fig. 11: Cracks pattern and failure mode of G4

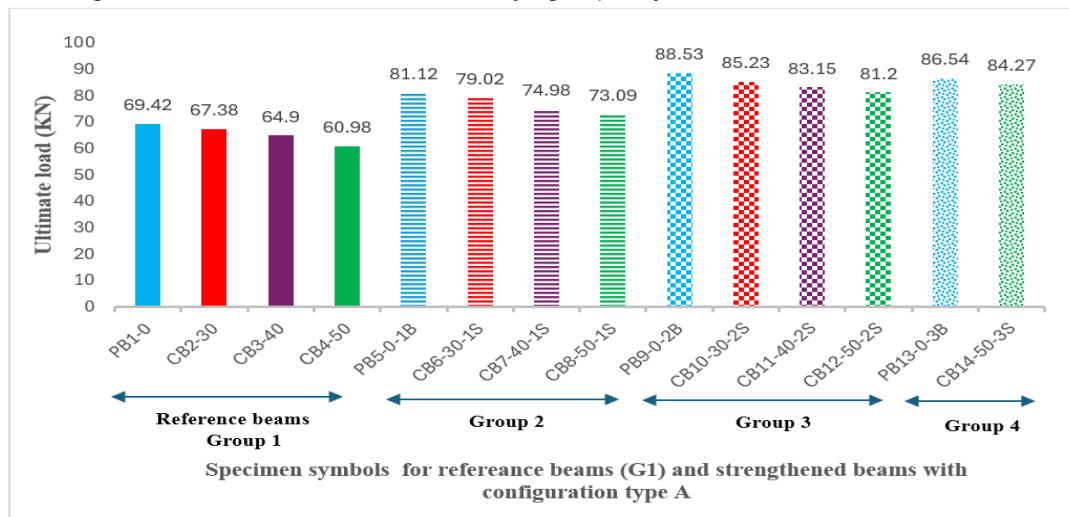


Fig. 12: Cracks pattern and failure mode of G5

3.4 Load-deflection relationships

Fig. 13 illustrates the ultimate load of all the beams. In group 1, the un-strengthened prismatic and concavely curved soffit beams with degrees of curvature of 30 mm/m, 40mm/m, and 50mm/m (reference beams). (PB1-0, CB2-30, CB3-40, and CB4-50) failed under a load of (69.42, 67.38, 64.9, and 60.98) KN respectively, it was noted that a slightly decreased load carrying capacity of curved soffit beams by (2.94 -12.15)% compared with the PB1-0. All strengthened beams in group 2,3,4 depending on the number of layers (configuration type A), observed an increase in load-carrying capacity of about (15.53-38.19)% compared with reference beams, utilizing two layers of strengthening can be considered acceptable to improve the flexural capacity and be more cost-effective. As for strengthened beams in (configuration type B) where strengthening by both sides face and at one layer at the bottom (soffit), note that the load carrying capacity has increased by about (18.79 - 21.33)%, compared with reference beams.

It was observed that all concavely-curved soffit beams with a degree of curvature of 30mm/m, 40mm/m, and 50mm/m in groups 1,2,3,4,5 showed a slight decrease in load carrying capacity by about (2.59 – 12.15)%, compared with prismatic beams for all groups. Also, it was concluded that the greater the degree of curvature, the less load-carrying capacity.



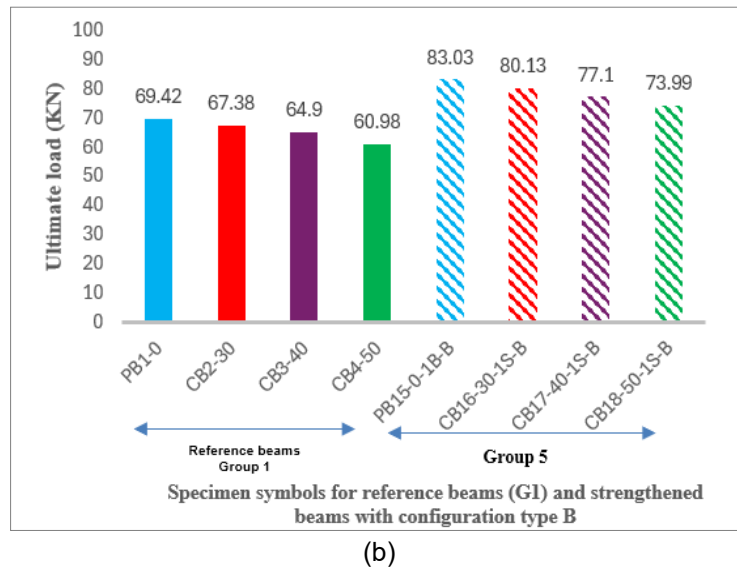
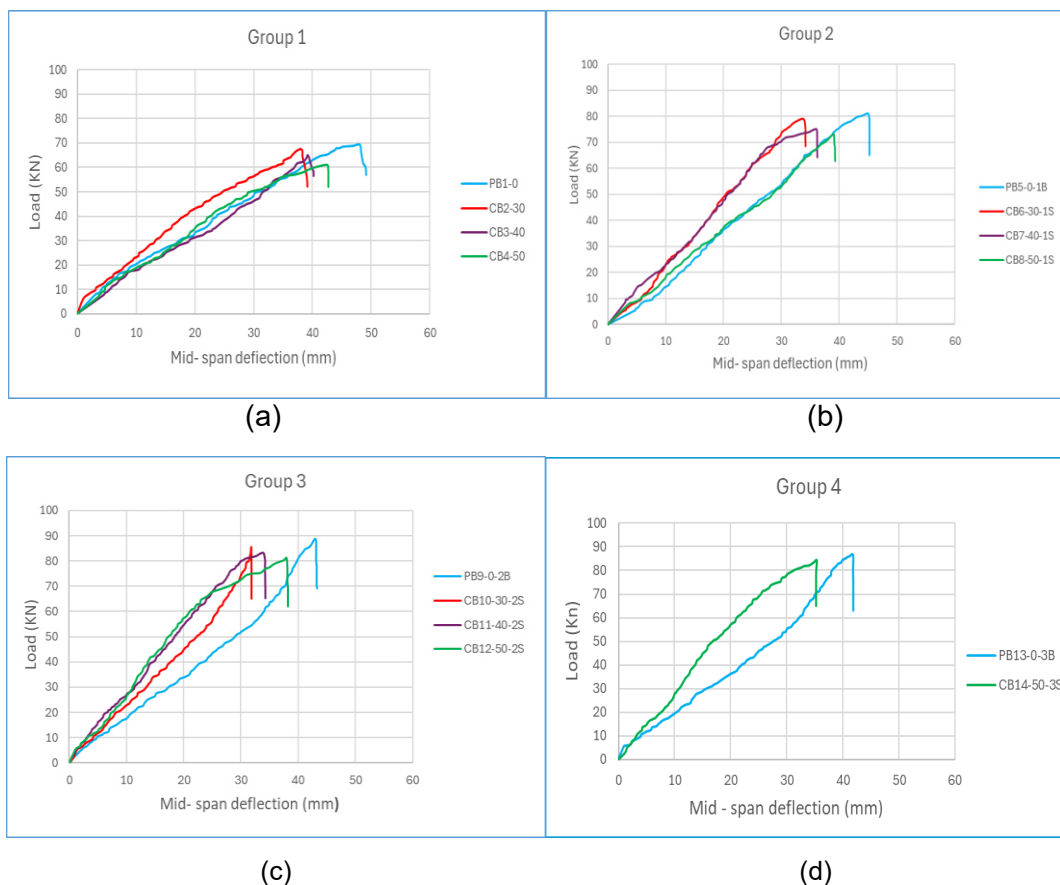


Fig. 13: Ultimate load for (a) G1 and strengthened beams with configuration A, and (b) G1 and strengthened beams with configuration B

The load-deflection relationship is an important variable that characterizes the behavior of structural specimens. Only one dial gauge was set up in the midpoint of the beams to determine the deflection. Fig. 14 displays the load-mid span deflection curves of all the specimens in this study. It was concluded from the curves below, that the deflection in prismatic beams is higher than the deflection in curved beams. When comparing between curved soffit beams, we find that the increased the degree of curvature, the increased the deflection concerning strengthened or un-strengthened beams. As for strengthened beams, the more layers of CFRP, the less deflection at mid-span.



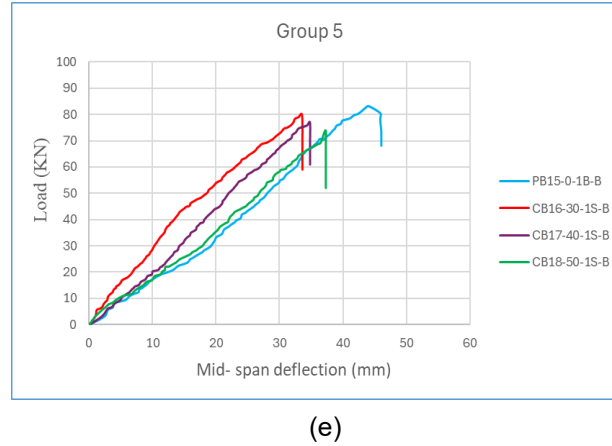


Fig. 14: Load-deflection curves for (a) group 1, (b) group 2, (c) group 3, (d) group 4, and (e) group 5.

4 Analytical models for predicting the flexural strength

LWRC beam specimens strengthened with CFPP sheets had an empirical equation for flexural strength in the ACI 440.2R-23 code [22]. According to the strain diagram shown in Fig. 15, the effective strain in FRP (ε_{fe}) and the effective strain of reinforcing steel bars in tension (ε_s) and compression (ε_s') are calculated using equations below :

$$\varepsilon_{fe} = \varepsilon_{cu} \left(\frac{d_f - c}{c} \right) - \varepsilon_{bi} \leq \varepsilon_{fd} \quad (1)$$

$$\varepsilon_s = \varepsilon_{fe} + \varepsilon_{bi} \left(\frac{d - c}{d_f - c} \right) \quad (2)$$

$$\varepsilon_s' = \varepsilon_{fe} \left(\frac{d' - c}{d_f - c} \right) \quad (3)$$

Where (ε_{cu}) is the ultimate usable compressive strain in concrete (i.e. 0.003), (d_f) is the effective depth of the FRP in mm, (d) is the distance from extreme compression fiber to centroid of tension reinforcement in mm, (c) is the depth of the neutral axis from extreme compression fiber in mm, (d') is the distance from the extreme compression fiber to the centroid of compression reinforcement in mm, (ε_{bi}) is the strain in a concrete substrate at the time of FRP installation, calculated by the equation below :

$$\varepsilon_{bi} = \frac{M_D(d_f - kd)}{I_{Cr} E_c} \quad (4)$$

Where (M_D) is the dead load moment N.mm, (k) ratio of the depth of the neutral axis to reinforcement depth measured from extreme compression fiber, (I_{Cr}) is a moment of inertia of a cracked section transformed to concrete in mm⁴, (E_c) is a modulus of elasticity of concrete in MPa. (ε_{fd}) is the upper limit of the FRP strain at which the debonding failure may occur and can be calculated from the equation below :

$$\varepsilon_{fd} = 0.41 \sqrt{\frac{f'_c}{N E_f t_f}} \leq 0.9 \varepsilon_{fu} \quad (5)$$

Where (f'_c) is the given compressive strength of concrete in MPa, (t_f) is the thickness of FRP in mm, (N) is the number of FRP layers and (ε_{fu}) is the rupture strain of FRP. The nominal flexural strength (M_n) for each beam can be predicted using the equation below:

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fd} \left(d_f - \frac{\beta_1 c}{2} \right) + A_s' f_s' \left(d' - \frac{\beta_1 c}{2} \right) \quad (6)$$

Where (A_s), (A_s'), and (A_f) are the areas (cross-sectional) of tension reinforcement steel, compression reinforcement steel, and CFRP, in mm^2 , respectively. (ψ_f) is the factor of reduction of the flexural strength contribution of CFRP, which is equal to 0.85 as recommended by ACI 440.2R. (β_1) is the ratio of rectangular stress block depth to that of the neutral axis. (f_s), (f_s'), and (f_{fe}) are the stresses in tension reinforcement steel, compression reinforcement steel bars, and CFRP in MPa, which can be calculated from the equation below:

$$f_s = E_s \varepsilon_s = f_y \quad (7)$$

Where (E_s) is the modulus of elasticity of steel in MPa, (f_y) is the specified yield strength of non-prestressed steel reinforcement in MPa

$$f_s' = E_s \varepsilon_s' \quad (8)$$

$$f_{fe} = E_f \varepsilon_{fe} \quad (9)$$

Where (E_f) is the modulus of elasticity of FRP in MPa.

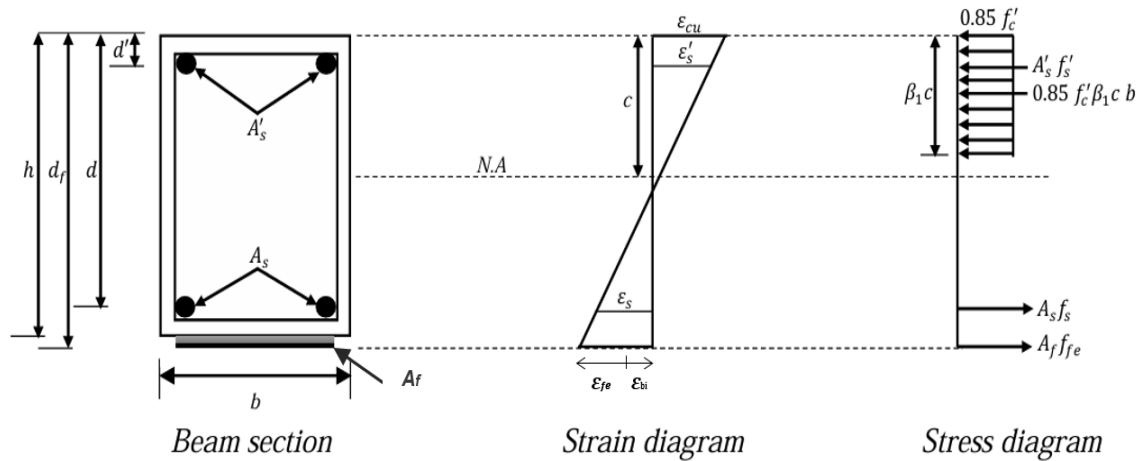


Figure 15: The strain and stress diagram for the strengthened specimens.

4.1 Comparison of the Test and Prediction Results

The flexural capacity of each strengthened beam tested in this experimental work is estimated in this section. The ACI 440.2R-23 equations are used to check their accuracy and validity.

Table 7. illustrates the ratio between the predicted load using the ACI 440.2R-23 code and the experimental load (P_{ACI} / P_{Exp}) of all the strengthened beam specimens by externally bonded (EB). The study has utilized the code equations to compute the moment capacity of prismatic and concavely-curved soffit LWRC beams. The ACI 440.2R-23 over-estimated the load-carrying capacity of curved beams with 30 mm/m, 40 mm/m, and 50 mm/m strengthened with two layers of CFRP sheet by 2.2%, 4.5%, and 6.8%, respectively and PB13-0-3B and CB14-50-3S are strengthened with 3 layers by 14.7%, and 16.98%. Moreover, it has under-estimated the capacity of prismatic beams, 30 mm/m beams, 40mm/m beams, and 50 mm/m beams strengthened with one layer of CFRP by 27.98%, 24.68%, 18.16%, and 15.32%, respectively. Also, all LWRC beams strengthened with one layer at the bottom and both sides face of the CFRP sheet by 31%, 26.43%, 21.65%, and 16.74%, and the prismatic beams strengthened with two layers of CFRP sheet by 1.5%.

Table 7: Predicted and experimental loads of LWRC beams.

Specimen symbols	f'_c [N/mm ²]	Number and location of CFRP	P_{Exp} [kN]	P_{ACI} [kN]	$\frac{P_{ACI}}{P_{Exp}}$
PB5-0-1B	38.25	1 layer at the bottom	81.12	63.38	0.78
CB6-30-1S	38.25	1 layer at the soffit	79.02	63.38	0.80
CB7-40-1S	38.25	1 layer at the soffit	74.89	63.38	0.85
CB8-50-1S	38.25	1 layer at the soffit	73.09	63.38	0.87
PB9-0-2B	36.78	2 layers at the bottom	88.53	87.15	0.98
CB10-30-2S	36.78	2 layers at the soffit	85.23	87.15	1.02
CB11-40-2S	36.78	2 layers at the soffit	83.15	87.15	1.05
CB12-50-2S	36.78	2 layers at the soffit	81.2	87.15	1.07
PB13-0-3B	36.78	3 layers at the bottom	86.54	101.5	1.17
CB14-50-3S	36.78	3 layers at the soffit	84.27	101.5	1.20
PB15-0-1B-B	36.78	1 layer at the bottom @both side face	83.03	63.38	0.76
CB16-30-1S-B	36.78	1 layer at the soffit @ side faces	80.13	63.38	0.79
CB17-40-1S-B	36.78	1 layer at the soffit@ side faces	77.1	63.38	0.82
CB18-50-1S-B	36.78	1 layer at the soffit @ side faces	73.99	63.38	0.86

5 Conclusion

1) All tested prismatic LWRC beams showed a slight increase in ultimate load capacity and deflection at mid-span when compared with all concavely-curved soffit LWRC beams.

2) The concavely curved soffit beams with a degree of curvature of 30mm/m give the best ultimate load compared to the beams with a degree of curvature of 40mm/m and 50mm/m. It was concluded that the increase in the degree of curvature reduces the ultimate load capacity and increases deflection at mid-span.

3) The tested LWRC specimens exhibited five failure modes, which were flexural failure, debonding of the CFRP, rupture of the CFRP, crushing concrete, and concrete cover separation. In this study, the common failure mode was debonding and rupture of the CFRP.

4) Results from this study indicate that the use of only one layer of CFRP causes rupture as the mode of failure. However, when using two or three layers of CFRP, the mode of failure changes to de-bonding and separation of the concrete cover.

5) It was concluded from the results that the increased the number of layers, the decreased the deflection at mid-span.

6) All strengthened beams with different numbers of layers (one, two, three) of CFRP sheet (configuration type A), observed an increase in load-carrying capacity of about (15.53-38.19)% compared with reference beams, As for strengthened beams in (configuration type B) where strengthening by both sides face and at one layer at the bottom (soffit), note that the load carrying capacity has increased about (18.79 - 21.33)%, compared with reference beams.

7) The load-carrying capacity of the one layer at the bottom (soffit) and both sides faces slightly increased by about (1.23-2.83)% compared to strengthened beams with only one layer at the bottom (soffit).

8) The results obtained from the ACI 440.2R-23 were under-estimated with the experimental results for all LWRC beams that were strengthened by one layer at the bottom(soffit), one layer at the bottom with both sides, and the prismatic beam strengthened with two layers at the bottom of the CFRP sheet, but the results for beam specimens that were strengthened by three layers, and all curved soffit beams strengthened with two layers of the CFRP sheet were over-estimated.

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