

EXPERIMENTAL BEHAVIOR OF R.C. BEAMS PARTIALLY MAGED IN FLEXURE AND STRENGTHENED WITH CFRP LAMINATES⁺

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Abstract:

This study presents an experimental investigation on the monotonic flexural behavior and ultimate capacity of reinforced concrete beams partially damaged and cracked in flexure due to applying a 58% of the predicted ultimate flexural load capacity, and then repaired by external strengthening with high strength CFRP (Carbon Fiber Reinforced Polymer) laminates bonded with epoxy resin to the tension face of concrete after doing all the appropriate preparations for the concrete adhesion substrate. Five rectangular reinforced concrete beams were tested to obtain the effect of amount of CFRP laminate on beams cracking behavior, concrete strains, ductility ratios, ultimate loads and failure modes. The results obtained from the adopted repairing and strengthening technique showed a significant effect of external high strength CFRP laminates on improving behavior and capacity of reinforced concrete beams. An increase by 15%- 33% in ultimate load capacities, for the CFRP strengthened beams, was observed over the control beam with conventional reinforcement. This gain in strength was accompanied by a reduction in ductility ratio by 18%- 28% for the CFRP strengthened beams compared with the control R.C. beam. Also, the crack patterns show enhanced performance in crack distribution and propagation for the strengthened beams over the control beam.

المستخلص:

تشتمل هذه الدراسة على فحوصات مختبرية لتصرف الإنحناء الساكن والحمل الأقصى لعتبات خرسانية مسلحة متضررة جزئياً ومتشققة نتيجة لتسليط ٥٨% من حمل الإنحناء الأقصى المتوقع، ومن ثم تم معالجتها وتقويتها خارجياً بشرائح من ألياف الكربون والتي أُلصقت باستخدام مادة الإيبوكسي على جهة الشد للخرسانة بعد عمل كافة التحضيرات على سطح الخرسانة اللاصق. تم فحص خمسة عتبات خرسانية مسلحة مستطيلة المقطع لمعرفة تأثير كمية شرائح ألياف الكربون على التشقق، الإنفعالات في الخرسانة، نسبة المطيلية، الأحمال القصوى ونوع الفشل. إن النتائج المستحصلة من هذه الطريقة المستخدمة للتقوية أثبتت التأثير الفعال لإستخدام شرائح ألياف الكربون في تحسين التصرف والأحمال للعتبات الخرسانية المسلحة. كانت الزيادة بمقدار ١٥% - ٣٣% في سعة الحمل الأقصى للعتبات المقواة مقارنة بالعتبات غير المقواة. كما كان هنالك نقصان بنسبة ١٨% - ٢٨% في مقدار المطيلية للعتبات المقواة مقارنة بالعتبات غير المقواة. وقد أظهرت العتبات المقواة تحسناً في أداء نمط التشقق مقارنة بالعتبات غير المقواة.

Keywords: strengthening and repairing, carbon fiber reinforced polymer, reinforced concrete beam, crack, damage, ductility, concrete strain.

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1. Introduction:

In Iraq, most of the reinforced concrete bridges were designed and constructed prior to 1980 when existing bridge design specifications were limited and method of analysis was less precise. With today's considerably higher traffic loads, some of these bridges need to be retrofitted and repaired instead of replacement of parts or the whole ageing bridge infrastructure. An interest modern strengthening technique to increase strength and stiffness of an existing damaged member is to attach high strength FRP laminates externally to the face or faces of the structural members using an appropriate adhesive matrix like epoxy resin. The increase in strength and stiffness is sometimes realized at the expense of a loss in ductility, or capacity of the structure to deflect inelastically while sustaining a load close to its capacity. A number of issues still impede the routine use of FRP as a structural strengthening material. Chief among them is the absence of a long record of use, causing concern about durability with potential users.

The failure mechanisms of reinforced concrete beams strengthened with FRP laminates are detailed in [1]. The six failure modes explained are:

1. FRP rupture after the tensile steel has yielded.
2. Concrete compression failure.
3. Shear failure.
4. Debonding of the cover concrete along the layer of tensile rebar.
5. Delamination of the FRP laminates from the end due to peeling.
6. Delamination of the FRP laminates from the interior due to crack.

In one method currently used, the composite laminate is adhesively bonded to the concrete surface with a room-temperature curing using two-part epoxy adhesive (Sikadur-330). Concrete surface must be clean and smooth, which may require sandblasting, to make it suitable for bonding. In some cases, a hand grinder must be used before sandblasting, and in some cases a vacuum pressure must be maintained over the surface of the FRP for six hours in order to properly cure the adhesive [2]. In addition, the two-part epoxy system must be mixed in a precisely controlled fashion and must be applied in a labor intensive manner to produce a good bond line. Following the application of the adhesive, the laminate must be clamped in place while the adhesive cures. Other available systems apply the epoxy resin system simultaneously to preformed fiber fabrics and the concrete surface. These systems encounter the same difficulties with concrete surface preparation and post curing [3].

The bond between the composite laminate and the concrete surface depends mainly on the quality of the surface preparation and the quality of the concrete substrate itself [4, 5]. The standard procedure in almost all laminate-bonding techniques is to prepare the concrete surface for bonding by mechanically abrading or sandblasting followed by the application of a primer. New research has shown that a concrete surface that is roughened by chiseling may be better than a surface that is prepared using the standard procedure of sandblasting [6]. The results of three half-scale R.C. beams partially damaged in shear and repaired with CFRP laminates is presented [7]. These beams were tested under a point load to failure. Increases of 68%-87% in shear capacity of these beams were observed. All beams failed by debonding of the main bars on one end.

2. Aim of the Research:

Little work has been done in investigating the behavior of partially flexure-damaged beams repaired with CFRP laminates. In the present research, the results of five rectangular beams tested first at a specific percentage of expected ultimate flexure load capacity, and then strengthened with CFRP laminates attached at the bottom face with epoxy, to study the effect of CFRP amount on the behavior and ultimate load capacity of these damaged and repaired beams.

3. Experimental Work:

3.1. Preparing Test Beams:

To strengthen reinforced concrete beams, most experimental investigations and researches have suggested using CFRP laminates externally bonded to the surface of these beams, with an appropriate resin material, because of its good engineering properties [8, 9, 10]. The experimental program consisted of two-point monotonic flexural load tests on five reinforced concrete beams, the first one was a control R.C. beam without strengthening (B-1), as shown in Table (3.1). This R.C. beam tested for 30 kN total flexure load, then the load was released and the beam was reloaded again monotonically up to failure load which was 52 kN. This means that the unloading load level was about 58% of the ultimate reloading flexural capacity. The other four beams are tested to the same load level of control beam (B-1) and unloaded, then strengthened with different amounts of CFRP laminates and tested monotonically up to failure to examine the effect of amount of CFRP strengthening on the behavior of these beams. All the R.C. beams had a length of 1520 mm, and cross-sectional dimensions of 100 mm x 180 mm each, and they were reinforced, as shown in Fig. (3.1). All the beams were tested for two-point loading with a clear simple span of 1400 mm.

Table (3.1) Beams strengthening and loading scheme

Beam	Width (mm)	Depth (mm)	CFRP Width (mm)	Unloading Level (kN)	Ultimate Capacity (kN)
B-1	100	180	-	30	52
B30-1	100	180	30	30	60
B40-1	100	180	40	30	65
B50-1	100	180	50	30	68
B60-1	100	180	60	30	69

3.2. Properties of Construction Materials:

Iraqi Ordinary Portland cement (Type I) manufactured at Kubesa cement factory was used in this study. Karbala natural river sand of maximum size of 4.75 mm, dried before use, was used. The gradation of fine aggregate lies within the upper and lower limits of Iraqi specification No. 45/1984 for Zone(2) [11], with specific gravity of 2.6.

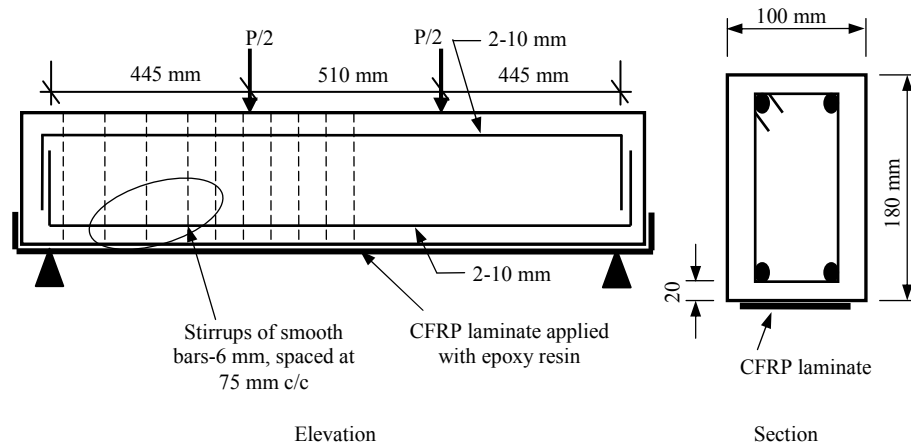


Figure (3.1) Dimensions and reinforcement details for a typical tested beam

The coarse aggregate was natural river gravel brought from Al-Nebaei region. They were mostly rounded in shape and its gradation lies within the upper and lower limits of Iraqi specification No. 45/1984 [11]. A maximum gravel size of 10 mm was used in the current experimental work which satisfies ACI-318 Building Code [12] requirements for maximum aggregate size. Care was taken to ensure that the gravel was saturated surface dry before use. The gravel had the following properties;

Absorption: 7.979%

Specific gravity: 2.65

Reinforcing steel bars used for longitudinal and stirrup reinforcement met the ASTM A615 requirements. All the longitudinal bars used were of the same type and had the same mechanical properties and rib geometry. Longitudinal reinforcing steel bars, which were of Ukrainian origin and distributed by the Local General Company of Construction Materials, have crescent deformation pattern (C pattern) (deformation pattern C consists of diagonal ribs inclined at an angle of 60 degree with respect to the axis of the bar). The bars have been tested in the Material Laboratory of Civil Engineering Department at Al-Mustansiriya University. The mean data obtained from testing two specimens are shown in Table (3.2).

To ensure a bending type failure for the tested conventional and CFRP strengthened reinforced concrete beams, closed stirrups, bent in direction of core center according to ACI-318 Building Code [12], of smooth bars having a diameter of 6 mm were used as shear reinforcement along axis of the beam with spacing of 75 mm c/c. Two specimens of smooth stirrup reinforcements were also tested in the Material Laboratory of Civil Engineering Department at Al-Mustansiriya University. Test mean data are, also, shown in Table (3.2). The longitudinal and shear reinforcement details and spacing are designed according to the ACI-318 Building Code [12] recommendations for flexure and shear design of reinforced concrete beams. Carbon fiber fabric laminate of type SikaWrap Hex-230C and epoxy based impregnating resin of type Sikadur-330 , as shown in Fig. (3.2), have been used to externally strengthen and repair the partially damaged reinforced concrete beams. The important technical data are shown in Table (3.3), and Table (3.4). The CFRP and the resin were submitted from Sika Near East s.a.l., Beirut, Lebanon.

Table (3.2) Longitudinal and transverse reinforcement properties

Bar size (mm)	Area A_b (mm ²)	Perimeter (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Grade of Steel	Elongation
10-Deformed	78.54	29.97	518	665	60	15.4%
6-Smooth	28.27	18.85	327	442	40	12.3%

Table (3.3) Properties of carbon fiber laminate (according to Manufacturer)

Type	f_f (MPa)	ε_f (%)	E_f (GPa)	Thickness (mm)	Width (mm)	Weight (g/m ²)
SikaWrap Hex-230C	3500	1.5	230	0.13	305	225

Table (3.4) Properties of the epoxy resin (according to Manufacturer)

Type	Appearance	Mixing ratio (by weight)	Pot life 15-35 °C (minute)	Viscosity	f_t (MPa)	Density (Kg/l) (mixed)
Sikadur -330	Comp.A:white Comp.B:gray	A:B 1:4	30-90	Pasty, not flowable	30	1.31

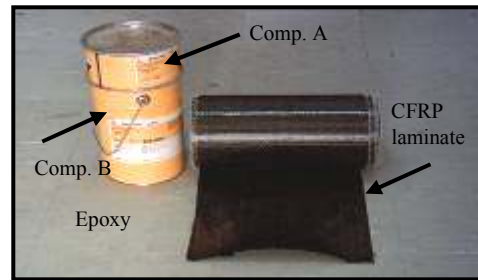


Figure (3.2) CFRP laminate and epoxy used.

3.3. Mixing and Curing:

A typical concrete mix proportion by weight was assumed and used throughout the present study. The mix used was 1: 1.8: 2.3 with a water/cement ratio of 0.45. This mix yielded an average cylinder compressive strength of approximately 28 MPa, and an average cube compressive strength of approximately 35 MPa. A wooden framework of two bays was constructed for casting the reinforced concrete beams. Casting and curing processes for all the beams were made in the Material Laboratory of the Civil Engineering Department at Nahrain University.

3.4. Strengthening Beams with CFRP Laminates:

After testing the R.C. beams for the specified load level, which then released and the external strengthening of reinforced concrete beams with the carbon fiber fabric (CFRP) laminates began and followed the procedure recommended by Manufacturer. Adhesion concrete surface was roughened with a steel brush to expose the aggregate, then dried and cleaned by air jet and acetone to rid it from loose particles and dust. The adhering face of the carbon laminate was also cleaned with acetone.

After wearing protective clothing, the two-part adhesive (white and black) (comp. A and comp. B, respectively), shown in Fig. (3.2), was mixed first separately each one alone with an electric mixer (here electric drill is used) and mixed in 1:4 proportion, until the color was a uniform gray, then some acetone was added to the mix. The final mix then stirred with the electric mixer for approximately 3 minutes until all the colored streaks have disappeared. This mix has been used as a prime coat for the concrete surface and cracks and CFRP laminate surface. The prime coat was poured on the concrete roughened surface and on the CFRP laminates using a paint brush and leaved to dry for about one hour. Then, the two-part adhesive was mixed with the same mix proportion and the same procedure mentioned previously (without acetone) to make the final resin matrix. This resin (epoxy) was applied to concrete surface and to the CFRP laminate with a thickness of 1.5 mm on each. The laminate was then placed on the concrete, epoxy to epoxy, and a roller was used to properly seat the laminate on concrete surface, and to let the resin squeeze out between the roving of the fabric by exerting enough pressure so the epoxy was forced out on both sides of the laminate. Then final layer of resin was added on the exposed layer. The strengthened reinforced concrete beams then left undisturbed inside the lab to cure for about seven days.

3.5. Beam Testing:

All the beams were tested at the Material Laboratory of Civil Engineering Department at Al-Mustansiriya University. An electric two-point load Germany-made machine named (MFL SYSTME) has been used. The capacity, stiffness and dimensions of the testing machine make it adequate to test large-scale beams made with normal or high strength concrete. Deflection readings were taken at mid-span for each beam using a dial gauge graduated to 0.01 mm divisions with a maximum travel of 25 mm. In addition, an ELE mechanical strain gauge (Extensometer gauge) having an accuracy of 1.07×10^{-5} mm/mm was used to measure concrete strains.

Before testing the beams, they were white painted to facilitate the detection of cracks, and the position of Demec discs were drawn on the front face along two vertical lines at the constant bending moment zone as shown in Fig. (3.3). Ten Demec discs were used for each tested beam (five in each vertical line), and the horizontal initial distance between each two Demec discs were calibrated using an accompanying special ruler. Arrangement and distribution of these Demec discs are shown in Fig. (3.3), and Fig. (3.4). The discs were then glued to the surface at the marked positions and the required separation distances were controlled to a high degree of accuracy with an extensometer special ruler. After the preparations were finished and the initial readings of the Demec discs were taken, the load was applied with a loading increment rate of about 50 N/sec. and deflection readings of dial gauge were taken.

When the applied load reaches a pre-determinate level, unloading was carried out gradually by loosing the valve of the hydraulic cart until a zero load reading was obtained. Concrete strains were recorded at selected levels of loading. In addition to that, cracks were detected and drawn on the side face of the tested beam. In general, loading stage was accomplished in about 30–40 minutes. For the re-loading, the same procedure was followed, and after each beam test, the cracks were also outlined by a thick black marking pen and photographed.

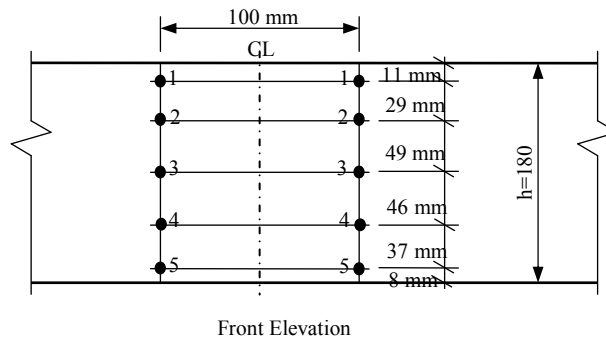


Figure (3.3) Arrangement of Demec points for measuring concrete strains

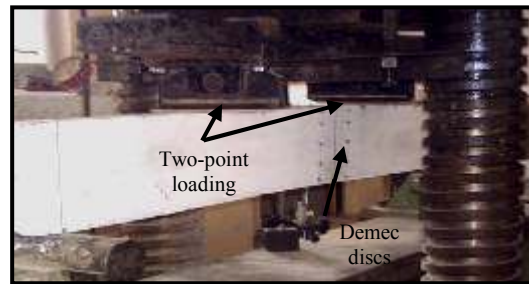


Figure (3.4) Two-point loading with the arrangement of Demec discs

4. Results and Discussion:

The general behavior of the tested beams can be described as follows; at early stages of first loading several cracks initiated in the tension zone within constant moment region. With further loading, these cracks extended upward and become wider. When loading reached the prescribed level and unloading began, small cracks are closed and some of these cracks are disappeared, and the wide cracks became narrower.

Reloading the control beam (B-1) accompanied with rapid re-opening and widening of cracks, as shown in Fig. (4.1). While reloading the CFRP repaired beams (Fig. (4.2) to Fig. (4.5)) showed stiffer response for cracks initiation and propagation, and small percent of cracks are re-opened while most of these cracks are completely repaired and do not re-opened. This means that the epoxy resin used is enhanced the behavior of the damaged beams in crack repairing and crack formation. This enhanced behavior was proportional to CFRP amount and epoxy used in repairing the damaged R.C. beams.

Load versus mid-span deflection results for the control beam and the four CFRP repaired beams are shown in Table (4.1), Table (4.2), and Fig. (4.6). As increasing CFRP amount used in repairing beams, yield and ultimate load capacities are increased. This increase in strength is accompanied with a significant reduction in ductility ratio (ductility ratio is defined as deflection at ultimate load divided by deflection at yield load), when compared with reference beam B-1.



Figure (4.1) Crack pattern for control conventional beam B-1



Figure (4.2) Crack pattern for strengthened beam B30-1

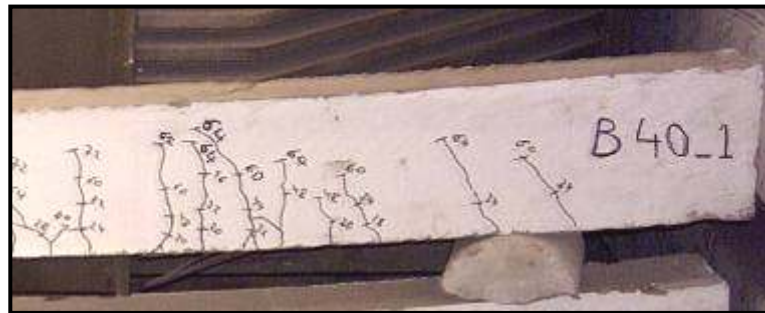


Figure (4.3) Crack pattern for strengthened beam B40-1



Figure (4.4) Crack pattern for strengthened beam B50-1



Figure (4.5) Crack pattern for strengthened beam B60-1

Table (4.1) Experimental results for the tested beams

Beam	Load (kN)			Deflection (mm)		Ductility Ratio (Δ_u / Δ_y)	Failure Mode	
	P_{cr}	P_y	P_u	Δ_y	Δ_u		CFRP Rupture	Concrete Crushing
B-1	7	46	52	10.0	30.0	3.00		X
B30-1	7	52	60	9.7	23.8	2.45	X	
B40-1	7	56	65	8.2	20.2	2.46	X	
B50-1	7	58	68	7.6	16.4	2.16	X	
B60-1	7	60	69	7.1	16.7	2.35		X

Table (4.2) Comparison of experimental results for the tested beams

Beam	CFRP Width(mm)	P_y (kN)	$\frac{P_y}{(P_y)_R^*}$	P_u (kN)	$\frac{P_u}{(P_u)_R^*}$	Reduction in ductility (%)
B-1*	-	46	1	52	1	-
B30-1	30	52	1.13	60	1.15	18
B40-1	40	56	1.22	65	1.25	18
B50-1	50	58	1.26	68	1.31	28
B60-1	60	60	1.30	69	1.33	22

* Reference beam

For the tested R.C. beam B30-1, which was partially damaged in flexure and repaired and strengthened with 30 mm width bottom CFRP laminate, the gain in strength was by 15% accompanied in a reduction by 18% in ductility. When increasing the width of CFRP to 40 mm in beam B40-1, which was damaged and strengthened then tested monotonically up to failure, the gain in strength was by 25% compared to control beam B-1, but with a reduction by 18% in ductility. Increasing the amount of CFRP to 50 mm in beam B50-1 led to more gain in strength, by 31%, but with a reduction by 28%. These three strengthened beams failed in CFRP rupture followed by top concrete crushing. More increasing width of CFRP to 60 mm increased the gain in strength by 33% and the reduction in ductility was by 22%, but its failure mode was by crushing top concrete before rupture of CFRP laminate. As expected, all the damaged and externally strengthened beams tested in the present work exhibited reduced ductility ratios and increased stiffness and ultimate load capacities due to the presence of externally attached CFRP laminates. The catastrophic failure of all the CFRP repaired and strengthened beams makes use of high strength, brittle, CFRP laminates in strengthening technique needs more development and adjustment to be more acceptable and safe.

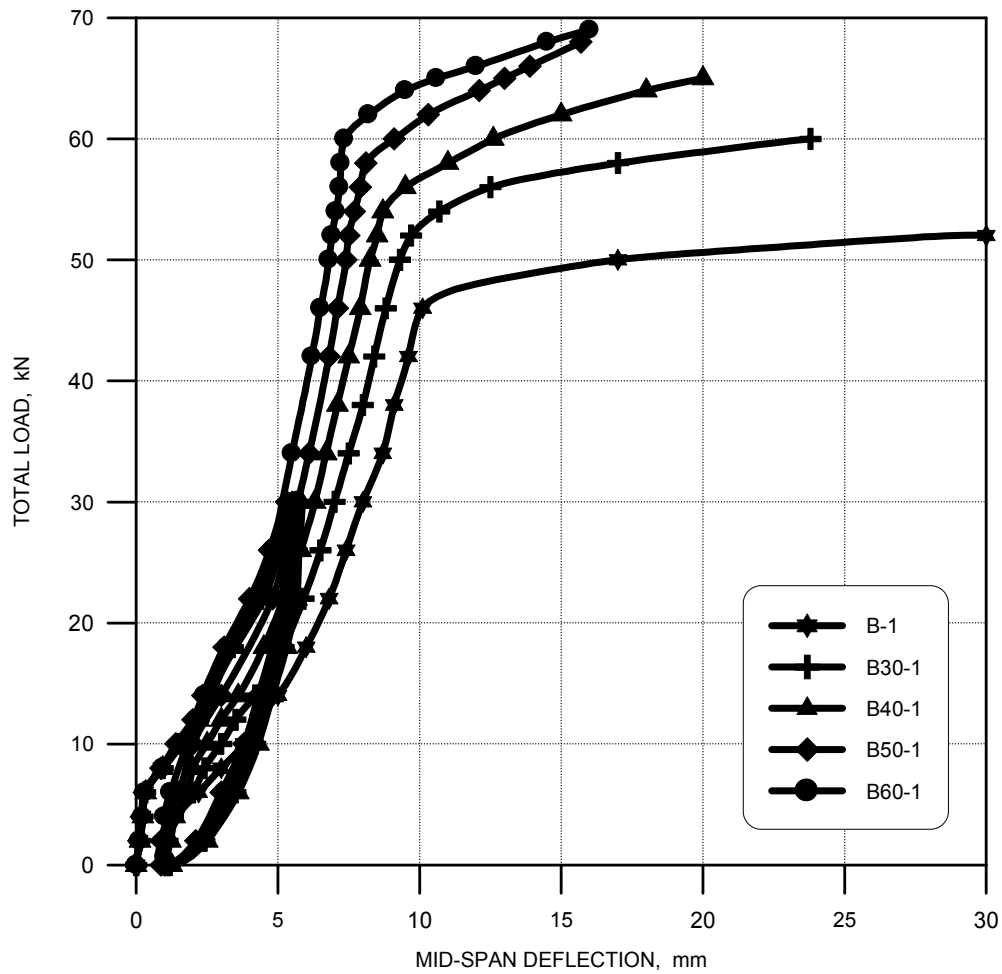


Figure (4.6) Mid-span deflection curves for the five tested beams

The distribution of concrete strains in the concrete at mid-span section of the tested beams was measured using ten Demec discs over the depth of each beam, as shown previously in Fig. (3.3). The concrete strain distribution over the depth of all the tested beams at different load levels is shown in Fig. (4.7) to Fig. (4.12).

From these figures, it can be seen that the strain distribution remained approximately linear in the compression zone through out loading range. While in the tension zone, the strain distribution is approximately linear at low loads and become nonlinear at higher loads due to cracking. At stages of loading close to ultimate load, as shown in Fig. (4.7) for strain distribution of tested control reinforced concrete beam B-1, location of neutral axis lies within upper half of the cross section, this confirms that the tested beams behaved as under-reinforced sections.

For the concrete strains of the damaged and strengthened tested beams, shown in Fig. (4.8) to Fig. (4.12), the presence of CFRP laminates at the bottom tension zone face reduced the concrete strains, and this reduction was reflected to strains at the bottom tension steel bars (i.e., reducing the tension steel bar strains), which means that some of tensile stresses have been carried by CFRP laminates.

Another important fact which can be seen from concrete strains distribution of the tested strengthened beams (B30-1, B40-1, B50-1, and B60-1), is the gradual and uniformly

distributed strain through the beam depth. This means that the presence of CFRP laminates at the tension zone surface arrests crack propagation and increases beam ultimate load capacity, as shown in Fig. (4.12) where a comparison is made for concrete strain distribution for the strengthened beams at the same loading level.

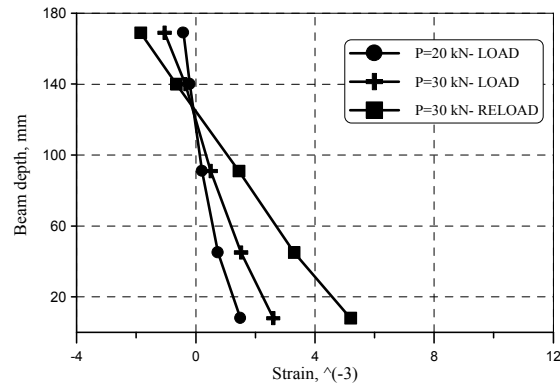


Figure (4.7) Concrete strain distribution for tested control beam B-1

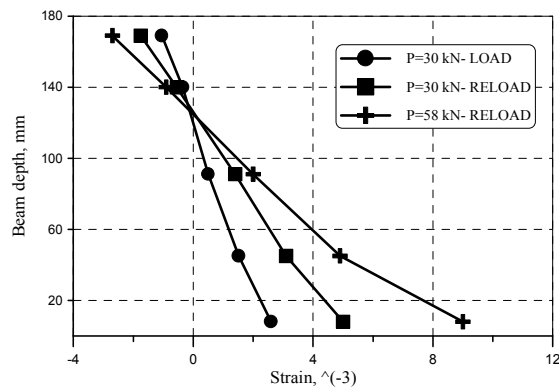


Figure (4.8) Concrete strain distribution for tested strengthened beam B30-1

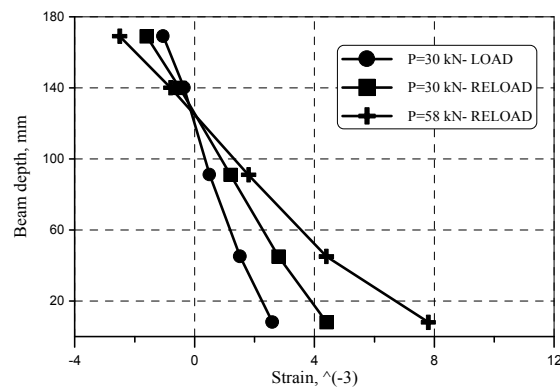


Figure (4.9) Concrete strain distribution for tested strengthened beam B40-1

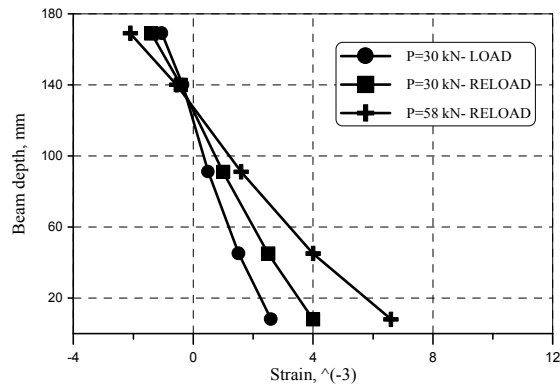


Figure (4.10) Concrete strain distribution for tested strengthened beam B50-1

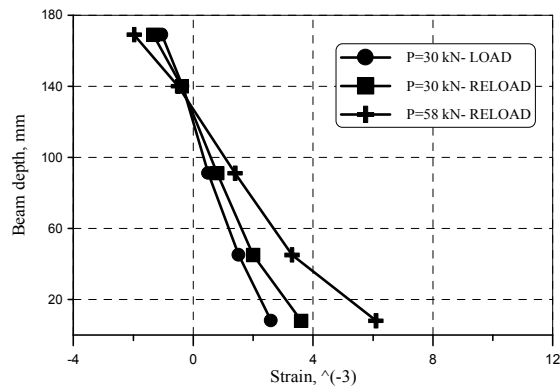


Figure (4.11) Concrete strain distribution for tested strengthened beam B60-1

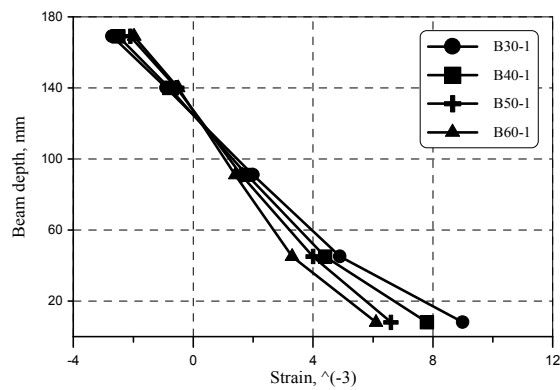


Figure (4.12) Comparison for concrete strain distribution of the tested strengthened beams at 58 kN loading level

5. Conclusions:

An experimental program has been performed and an attempt has been made to study the effect of flexural repairing and strengthening of reinforced concrete beams, damaged in flexure, with carbon fiber reinforced polymer (CFRP) laminates attached with epoxy to bottom concrete face of the beams after doing all surface preparations for the concrete adhesion surface.

The present experimental work indicated that the adopted repairing and strengthening technique significantly increased the monotonic capacity as well as other properties, but with reduction in ductility ratios. Therefore it has been concluded that an increase by 15%- 33% in ultimate load capacities for the damaged and CFRP strengthened beams (B30-1, B40-1, B50-1, and B60-1) was observed over the control beam with conventional reinforcement only. A reduction in ductility ratio was by 18%- 28% for the CFRP strengthened beams compared with the control conventional reinforced concrete beam B-1. Also, the crack patterns show enhanced performance in crack distribution and propagation for the strengthened beams over the control beam B-1.

The concrete strain distribution at the mid-span for all the tested beams remained approximately linear in the compression zone throughout loading range. While in the tension zone, the strain distribution is approximately linear at low loads and becomes nonlinear at higher loads due to cracking.

Finally, strengthening R.C. beams with CFRP laminates enhanced concrete strains especially at ultimate load stages, but the catastrophic brittle failure of these beams makes use of CFRP laminates generally in strengthening technique needs more attention and more researches.

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