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Research Article

Flexural Behavior of RC T- Section Beams Strengthened with Different Configurations of CFRP Laminates

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Abstract

The objective of this investigation is to study the effect of using different configurations of CFRP laminates externally bonded to the tension side of RC T-beams on the behavior, flexural strength, stiffness, failure mode and ductility of the RC T-beams, and determine the most suitable configuration of the CFRP laminates to strengthen the beams. Two series of RC T-beams were strengthened for flexure with CFRP laminates. The axial stiffness of the CFRP laminates in each series was kept constant. The CFRP laminates in series II have twice the axial stiffness of that in series I. All beams were strengthened for shear with externally bonded CFRP sheet straps with the same configuration (U-wraps) along the shear span to prevent shear failure. Width, arrangements along the beam span and the number of plies of CFRP laminates were the main parameters that were investigated during experimental study. The test results showed that the externally bonded CFRP laminates used for flexural strengthening of the RC T-beams have enhanced the cracking load and showed a significant increase in the flexural load-carrying capacity but exhibited lower ductility compared with the corresponding unstrengthened control beam depending on the configuration and the axial stiffness of CFRP laminates that were used for strengthening.

Keywords: *RC T-beams; strengthening; flexural strength; deflection ductility; CFRP laminates.*

Introduction

When the flexural load-carrying capacity of existing reinforced concrete (RC) beams and girders are not sufficient for the service loads, structural strengthening becomes the acceptable way of improving their load-carrying capacity and extending their service lives. In recent years, fiber reinforced polymers (FRP) are an excellent option to be used as external reinforcing because of their high tensile strength, stiffness-to-weight ratio, resistance to corrosion, larger creep strain, good fatigue strength, high durability, and ease of installation. Externally bonded FRP reinforcement has been shown to be applicable for the strengthening of many types of RC structures such as columns, beams, slabs, walls, tunnels, chimneys, and silos, and can be used to improve flexural and shear capacities, and also provide confinement and ductility to compression members (Van Den Einde et al,2003). Externally bonded carbon fiber reinforced polymer (CFRP) laminates (plates) and sheets are currently the most commonly used technique for flexural and shear strengthening of concrete beams and girders. Due to the superior performance of the CFRP composite, the use of CFRP laminates and sheets for the flexural and shear strengthening of beams and girders has been studied by several researchers (Spadea et al onwards references).

In this research study, two series of RC T-beams were strengthened for flexure with CFRP laminates. In each series, CFRP laminates with different configurations were externally bonded to the tension side of the beams to provide additional flexural strength. The axial stiffness of the CFRP laminates in each series was kept constant. The CFRP laminates in series I have the axial stiffness, $(EA)_{CFRP}$, while the axial stiffness of the CFRP laminates in series II was twice of that in series I, $2(EA)_{CFRP}$, where E and A are the modulus of elasticity and the area of the CFRP laminates. In order to prevent shear failure in beams, all beams were strengthened for shear with CFRP sheet vertical straps with the same configuration (U-wraps). CFRP sheet straps were externally bonded to the beam sides and underside enclosing the CFRP laminates along the shear span. The presence of shear U-wraps to provide additional shear strength has the dual benefit of delaying debonding of CFRP laminates used for flexural strengthening. Width of the CFRP laminates, arrangements (positions) of the CFRP of laminates along the beam span, and the number of plies of CFRP laminates were the main parameters that were investigated during experimental study. The study investigates the load-carrying capacity and bending characteristics as the result of CFRP laminates application to RC T-beams by

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examining deflection and strains as a function of the external load.

Experimental Investigation

Test Specimens and Strengthening Systems

A total of six T-section RC beams were tested under static load in the experimental investigation. Dimensions and reinforcement details are shown in Fig. 1. The length of the beams was 1700 mm. The beam flange width and the slab thickness were 300 mm and 60 mm, respectively. The overall depth of the beam was 200 mm and the web was 100 mm wide. The cross-sectional geometries and longitudinal reinforcements were the same for all specimens. Longitudinal tension reinforcement consists of two 10 mm diameter deformed bars of high tensile steel. Two 8 mm diameter plain round mild steel bars were used as top steel. Vertical stirrups of 6 mm diameter plain round mild steel bars were spaced at 100 mm centers over the shear spans, while no shear reinforcement was provided in the constant moment region. Shear reinforcement was provided to assure bending failure prior to shear failure for all beams. One beam was tested without strengthening and served as control beam (CB) for comparison purposes to evaluate the improvement in flexural strength provided by the externally bonded CFRP laminates. Five beams were divided into two main series. Series I had 3 beams (B1, B2 and B3) strengthened for flexure with externally bonded CFRP laminates with different configurations and having the same axial stiffness, $(EA)_{CFRP}$. Series II had 2 beams (B4 and B5) strengthened for flexure with externally bonded CFRP laminates with different configurations and having the same axial stiffness, $2(EA)_{CFRP}$. All the beams were strengthened for shear with externally bonded CFRP sheet straps with the same configuration (U-wraps). The bonded straps were one-ply of high tensile strength CFRP sheets with the fiber direction oriented perpendicular to the longitudinal axis of the beam along the shear span.

Five CFRP sheet straps with 50 mm width and spaced at 100 mm center-to-center (half the beam depth) were bonded to the beam sides and underside enclosing the CFRP laminate ends. Variables in the test included width of the CFRP laminates, arrangements of the CFRP of laminates along the beam span, and the number of plies of CFRP laminates. In series I, beam B1 was strengthened with one-ply of 100 mm wide CFRP laminate bonded to the bottom face of the beam and beam B2 was strengthened with two-plies of 50 mm wide CFRP laminate bonded to the bottom face of the beam, while beam B3 was strengthened with one-ply of 50 mm wide CFRP laminate bonded to each side face of the beam. In series II, beam B4 was strengthened with two-plies of 100 mm wide CFRP laminate bonded to the bottom face of the beam, while beam B5 was strengthened with one-ply of 100 mm wide CFRP laminate bonded to the bottom face and one-ply of 50 mm wide CFRP laminate bonded to each side face of the beam. The details of strengthening that were applied to beams are shown in Fig. 2.

Material Properties

Average compressive strengths of concrete were determined from standard test of 150 mm^3 cubes that were cast from the same concrete as was used for the beams. The evaluation of the compressive strength of concrete was performed after 28 days. Three cube samples were taken from the concrete of each specimen for testing. The tests achieved an average concrete compressive strength of 30 MPa. The average laboratory obtained yield strength of the 10 mm high tensile steel, 8 mm and 6 mm mild steel reinforcing bars were 419 MPa, 274 MPa and 263 respectively.

Two CFRP systems were used in the present work: unidirectional dry lay-up CFRP Mbrace high tensile sheets CF 130 (300 mm wide × 0.176 mm thick) in the shear strengthening and pre-cured CFRP Mbrace laminates 150/2000 (50 × 1.2 mm^2 and 100 × 1.2 mm^2 cross sectional area) in the flexural strengthening. The epoxy bonding and structural adhesives were used to bond the CFRP sheets and CFRP laminates, respectively in according with the manufacturer's recommendations. The epoxy resin and the adhesive were cured for 7 days at room temperature before loading. Details of the mechanical properties of these strengthening materials, taken from the manufacturer's data sheets, are summarized in Table 1.

Test Setup and Instrumentation

All of the beams were tested in four-point bending over a simple span of 1550 mm. The ratio of the shear span length, 600 mm, to the effective height of the beam, 185 mm, was 3.25, and was the same for all specimens. The beams were loaded using universal testing hydraulic machine with 200 kN load capacity. Each test started by several cycles of small loading (i.e., about 5–10 kN) in order to get rid of any slack in the test setup and measuring devices. Afterwards, the load was applied gradually until failure with an increment of 2 kN/min. Beams have been instrumented with a 890 kN capacity load cell to control the load, a Linear Variable Displacement Transducer (LVDT) mounted at the midspan to measure deflection and electrical resistance strain gauges pasted on the tensile steel bars and on the CFRP laminates at the midspan to monitor the development of steel and CFRP strains throughout the loading history, as well as an electrical strain gauge bonded to the compression side of the beam at the midspan to measure the concrete compressive strain. A schematic view of experimental setup and the arrangement of the measurement devices are shown in Fig. 3. Beam deflection, strains, and the load values have been monitored by means of a data logger. Crack initiation and propagation were monitored by visual inspection during testing, and the crack patterns were recorded.

Experimental Results

The loads causing the initial cracks, loads causing the

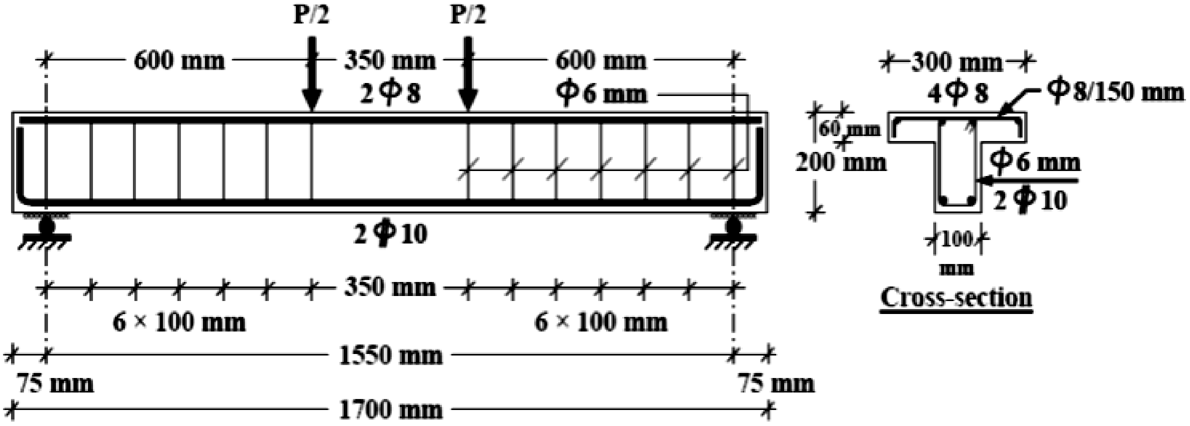

Fig.1 Dimensions and reinforcement details of the tested beams.

Fig. 2 CFRP laminates and U-wraps sheet arrangements of strengthened beams.

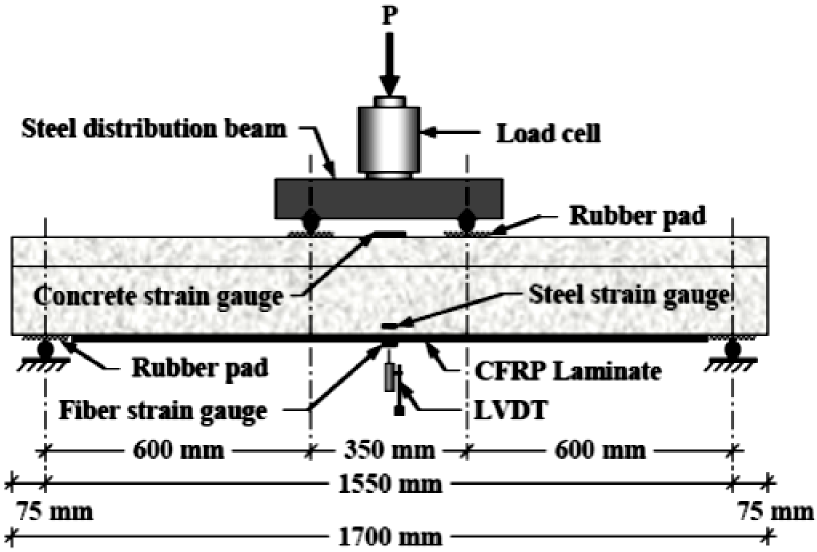

Fig. 3Test setup and instrumentation.

yield of tension steel reinforcement and the ultimate failure loads of the all beams with their corresponding failure modes are presented in Table 2. The midspan deflection of the beams at the load causing initial crack, at yield load and at failure load is also presented in Table 2. The value of midspan deflection and failure load of the CB is used as a baseline value for comparison with the strengthened beams. The ultimate load enhancement ratio

Table1 Properties of the CFRP materials

CFRP system		Main properties		
Type	Material	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain ($\mu\varepsilon$)
Shear strengthening Mbrace high tensile sheet CF 130 (Dry lay-up sheet)	Epoxy	-	-	-
	Sheet	3800	240	15.5×10^3
Flexural strengthening Mbrace laminate 150/2000 (Pre-cured laminate)	Adhesive	32	10	-
	laminate	2700 min.	165 min.	14×10^3

Table 2 Summary of significant experimental results for all beams

Beam	Initial crack load P_{cr} (kN)	Yield load P_y (kN)	Ultimate failure load P_u (kN)	Midspan deflection at			Ultimate load enhancement ratio λ	Ductility index μ_Δ	Failure mode
				Initial crack δ_{cr} (mm)	Yield δ_y (mm)	Failure δ_u (mm)			
CB	**18.8**	**39.2**	**50.1**	**8.2**	**18.1**	**72.8**	**-**	**4**	**(A)**
B1	**72.2**	**-**	**94.3**	**22.1**	**-**	**29.6**	**1.88**	**-**	**(B)**
B2	**42.3**	**64.1**	**92.2**	**15.5**	**21**	**32.1**	**1.84**	**1.53**	**(C)**
B3	**38.5**	**55.4**	**90.5**	**13.4**	**20.1**	**30.2**	**1.81**	**1.5**	**(C)**
B4	**78.2**	**-**	**113.3**	**15.9**	**-**	**20.1**	**2.26**	**-**	**(C)**
B5	**73.4**	**-**	**105.4**	**17.9**	**-**	**21.8**	**2.1**	**-**	**(D)**

Failure Mode Description

(A) Yielding of tension steel and crushing of concrete (Typical ductile flexural behavior).

(B) Critical diagonal crack (CDC) debonding.

(C) Intermediate crack (IC) debonding.

(D) CDC debonding in combination with concrete cover separation.

and the ductility index are calculated and presented in Table 2.

Enhancement of Load and Moment Capacities

Table 2 presents the ultimate failure load, P_u, and ultimate load enhancement ratio (λ), which is the ratio between the ultimate load of an externally strengthened beam and that of the corresponding unstrengthened CB. The results shown in Table 2 indicate that using of externally bonded CFRP laminates with different configurations increased the ultimate load-carrying capacity at the midspan by 88%, 84% and 81% for beams B1, B2 and B3 of series I, respectively, and by 126% and 110% for beams B4 and B5 of series II, respectively, as compared to the CB. For the case of simply supported beams strengthened with external reinforcement, the moment and load enhancement ratios are always the same. Consequently, all the strengthened beams resisted a higher moment than the corresponding unstrengthened CB. It can be seen from Table 2 that beams B1, B2 and B3 of series I have nearly similar load capacity (B1 = 94.3 kN, B2 = 92.2 kN and B3 = 90.5 kN). The slight increase of flexural strength of beam B1 (2.28% and 4.20%) than those of beams B2 and B3, respectively, may be attributed to the contribution of the CFRP laminate, having the same width of the beam web (100 mm) attached to the bottom tension side of the beam, to the beam's section moment capacity because of its ability to carry more tensile stresses. Also, the results of Table 2 clearly show that the failure loads of beams B4 and B5 of series II were 113.3 kN and 105.4 kN, respectively, which is more than twice of the failure load of the CB. There is about 126% gain in the flexural strength of beam B4 as a result of bonding two-plies of 100 mm wide CFRP laminate to the bottom face of the beam. The flexural capacity of beam B4 increased by 7.5% over the capacity of beam B5, which was strengthened with one-ply of 100 mm wide CFRP laminate bonded to the bottom face and one-ply of 50 mm wide CFRP laminate bonded to each side face of the beam. From these results, it can be concluded that strengthening the bottom tension side of the beam with two-plies of CFRP laminate having the same width of the beam web is the most effective arrangement of the CFRP laminates to enhance the beam flexural capacity. By comparing beam B4 of series II with the beams B1 and B2 of series I, a significant increase in the flexural capacity was achieved as a result of doubling the axial stiffness of CFRP laminates. Beam B4 exhibited a gain in the flexural load-carrying capacity over the beams B1 and B2 by about 20% and 23%, respectively. Also, the results of Table 2 clearly indicate that the cracking loads for beam B1 of series I, and beams B4 and B5 of series II were 72.2, 78.2 and 73.4 kN, respectively, these values are 3.84, 4.16 and 3.90 times the cracking load of the corresponding CB and the yielding load of tension steel of these beams was not attained. This effect is attributed to the compressive force induced in the RC beams as a result of the composite action with the CFRP laminates. The compressive stresses neutralize the tensile stresses in the concrete, reduce the tensile force in the steel reinforcement, and postpone their yielding.

Failure Modes

The failure modes for the CB and strengthened beams are shown in Fig. 4. The observed failure modes are illustrated in Table 2 and are described.

The unstrengthened CB failed by typical steel yielding followed by concrete crushing. The beam showed wide flexural cracks at mid-span. These cracks extended to the compression flange. Concrete crushing happened between the loading points. Figure 4-I (a&b) illustrates the failure mode of the CB.

All the strengthened beams of the two series I and II failed due to tensile rupture and/or debonding of the CFRP sheet straps accompanied by debonding of the CFRP laminates. The failure of beams were sudden and accompanied by a loud noise, indicating a rapid release of energy and a total loss of load capacity. The tensile rupture of the CFRP sheet straps occurred due to the high tensile stresses that develop in the straps, while debonding of the straps occurred due to the bond shear stresses that develop in the concrete near the adhesive layer in the constant shear region. Debonding of the CFRP laminates from the beams occurred in different modes :

In beam B1, laminate end debonding was occurred due to the Critical diagonal crack, which were caused by the increase in flexural capacity of the beam (Critical diagonal crack (CDC) debonding). The debonding of the CFRP laminate was initiated at the edge of the laminate in the form of a horizontal crack between the priming layer and the adhesive layer that propagated in a stable manner toward the midspan. The failure mode for beam B1 is shown Fig. 4-II (a&b).

In beam B2, intermediate crack debonding (IC debonding) was occurred due to the flexural cracks. The debonding of the CFRP laminate was initiated at midspan and extended towards one of the supports. Based on experimental observation, the debonding failure of the CFRP laminate can be explained as follows: due to the flexural cracks formed in the midspan as the load increased, the bond between the CFRP laminate and concrete started to fracture at a certain load level and the failure propagated towards one of the supports until most of the CFRP laminate detached from the concrete beam. Figure 4-III (a&b) illustrates the failure mode of beam B2.

In beam B3, intermediate crack debonding (IC debonding) was occurred due to the flexural cracks. The debonding of the CFRP laminate in each beam side was initiated at midspan due to the flexural cracks and extended towards one of the supports in two opposite directions. The failure mode for beam B3 is shown Fig. 4-IV (a&b).

In beam B4, intermediate crack debonding (IC debonding) was occurred due to the flexure-shear cracks. The debonding of the CFRP laminate was initiated at the flexure-shear crack in the form of a horizontal crack between the priming layer and the adhesive layer that propagated in a stable manner toward one of the supports. Figure 4-V (a&b) illustrates the failure mode of beam B4.

In beam B5, Critical diagonal crack (CDC) debonding in combination with concrete cover separation was occurred. The debonding of the CFRP laminates in each beam side and at the bottom of beam web were initiated at the edge of each laminate and concrete cover was separated up to the longitudinal tension reinforcement. The failure mode for beam B5 is shown Fig. 4-VI (a&b).

Beam Deflection

Figure 5 shows the comparison of the load-deflection curves for strengthened beams with the unstrengthened CB. These deflections are recorded at the mid-span. The figure indicates that the curves of beams B2 and B3 of series I exhibited almost three straight lines with slightly different responses up to failure, representing the concrete pre-cracking, concrete post-cracking tension steel pre-yield, and tension steel post-yield stages. While, beam B1 of series I, and beams B4 and B5 of series II showed only two straight lines of pre-cracking and post-cracking behaviour. The beams failed without reaching the yield strength of tension steel reinforcement. Also, the figure shows that the deflection of the strengthened beams of the two series was significantly lower than the deflection registered on its corresponding CB, revealing that the strengthening with different configurations of CFRP laminates has increased the beams' flexural stiffness. The CB has exhibited a high ductile flexural behaviour like expected and produced large deflection up to failure (72.8 mm), which is remarkably gradual.

(I)

(II)

(III)

(IV)

(V)

(VI)

(a) (b)

Fig. 4 Failure modes of the tested beams. (a) Overall view; (b) Close-up view.

The behaviour of beams B1, B2 and B3 of series I was very similar in the uncracked elastic stage. In other words, the beams' flexural stiffness was almost the same until the occurrence of cracks in the concrete. In the cracked pre-yield stage, the stiffness of the strengthened beams B2 and B3 was significantly higher than that of beam B1 and the CB; however, significant decrease in beams' stiffness were observed after yielding of tensile steel. The maximum deflection compared to the CB. Hence doubling axial stiffness of CFRP laminates has a significant effect

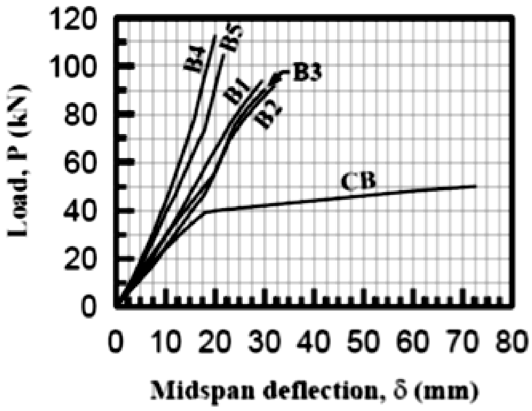

Fig. (5): Load - deflection behaviour for all beams.

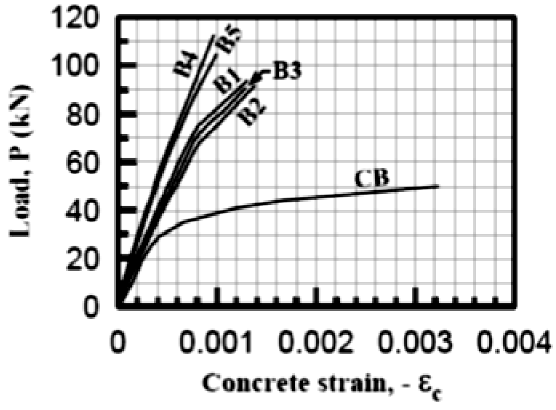

Fig. (6): Variation of concrete compressive strain for all beams.

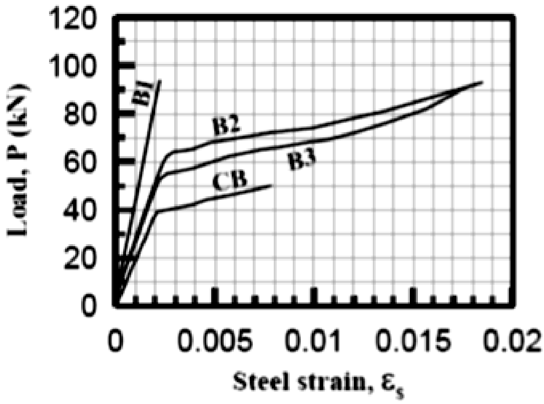

Fig. (7): Variation of tensile steel strain for beams CB, B1, B2 and B3.

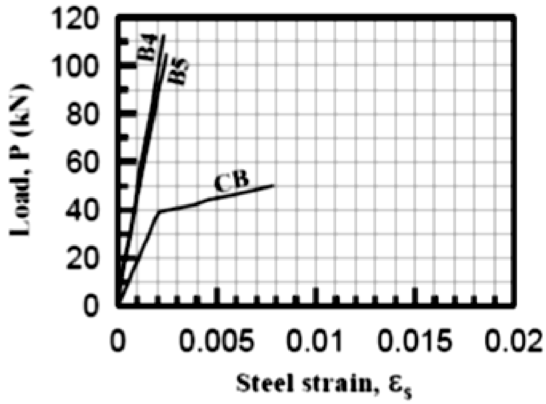

Fig. (8): Variation of tensile steel strain for beams CB, B4 and B5.

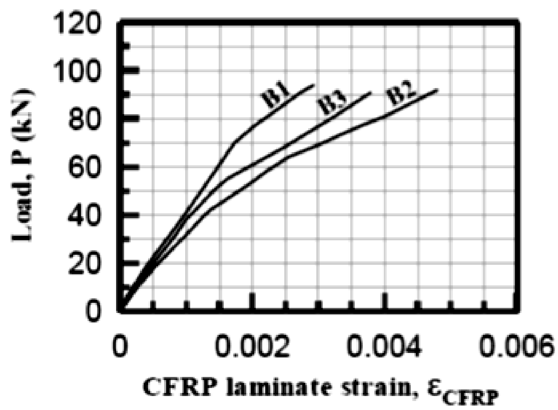

Fig. (9): Variation of ten. strain in CFRP lam. for beams B1, B2 and B3.

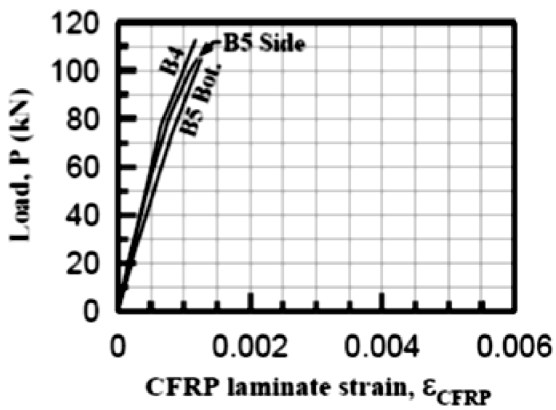

Fig. (10): Variation of ten. strain in CFRP lam. for beams B4 and B5.

deflections observed in beams B1, B2 and B3 are 59.3%, 55.9% and 58.5% lower compared to the CB, respectively. On the other hand, beams B4 and B5 of series II exhibited higher flexural stiffness and the load-deflection curve showed much stiffer behaviour compared to beams of series I and the CB. Behaviour of the beams B4 and B5 was very similar in the uncracked and cracked stages. Their stiffness have increased more significantly after the occurrence of cracks in the concrete, where the deflection has decreased due to doubling the axial stiffness of CFRP laminates. Moreover, non-ductile variation in the load-deflection curve could be observed in these beams, which change the ductile behaviour observed in the CB. Beams B4 and B5 show 72.4% and 70.1% decrease in the max the on the stiffness of these beams. By comparing the strengthened beam B4 of series II with the beams B1 and B2 of series I, a significant decrease in the deflection capacity was observed as a result of doubling the axial stiffness of CFRP laminates. Beam B4 exhibited a reduction in the deflection capacity by about 32% and 37% compared to beams B1 and B2, respectively.

Beam Ductility

Ductility has generally been measured by a ratio called the ductility index. The deflection ductility index, μ_Δ, used for simply supported beams by Spadea et al. [4] is adopted to measure the ductility of the beams tested by the author as given in Table 2. The deflection ductility index, μ_Δ, is defined as: $\mu_\Delta = \Delta_u / \Delta_y$ where Δ_u is the midspan deflection at ultimate load and Δ_y is the midspan deflection at yielding of tension steel reinforcement.

As can be seen from Table 2, all strengthened beams exhibited less ductility than the corresponding unstrengthened CB. The CB has revealed a ductility index of 4.0. The ductility indices for beams B2 and B3 of series I have nearly similar value, they were 1.53 and 1.50, respectively, which are about 61.8% and 62.5% lower than that of the CB, respectively. On the other hand, beam B1 of series I, and beams B4 and B5 of series II have exhibited non-ductile behaviour in comparison to the CB.

Concrete, Steel and CFRP Laminates Strains

The maximum recorded strain values for the compressive concrete, tensile steel reinforcement and CFRP laminates at the midspan at beam failure load are given in Table 3. Figure 6 shows the variation of the concrete compressive strain at the midspan of the unstrengthened CB and strengthened beams versus the applied load. All the strengthened beams exhibit lower strain values compared to the CB (the compressive strain in concrete reaches 3.238×10^3 $\mu\varepsilon$). The decrease in the concrete strain in beams B1, B2 and B3 of series I has been found 59.67%, 57.26% and 60.25%, respectively, while for beams B4 and B5 of series II, the reduction in compressive strain of concrete has been found 70.11% and 69.21%, respectively (see Table 3). The decreased strains in beams B4 and B5 at the ultimate failure load indicate the significant increase in stiffness of the beams due to doubling the axial stiffness of CFRP laminates. The variations of strains in the strengthened beams B1, B2 and B3 of series I are uniform and similar to each other. The same behaviour is observed in beams B4 and B5 of series II. From the above results, it is concluded that the reduced ultimate concrete compressive strain values for the strengthened beams indicate the significant stiffening effect of the CFRP laminates.

The applied load versus midspan strains at the level of tension steel reinforcement are shown in Fig. 7 for the CB and beams B1, B2 and B3 of series I, while that for beams B4 and B5 of series II are shown in Fig. 8. Figure 7 showed that the variation of steel strains for beams B2 and B3 exhibits almost identical behavior up to failure. The increased strain values for the strengthened beams B2 and B3 at ultimate load indicate the significant loss in stiffness of the beams. Figures 7 and 8 indicated that the strains vary almost linearly up to the ultimate failure load for beams B1, B4 and B5, whereas the linear behavior for beams B2 and B3 can be seen only up to a load of 60.3 kN and 45.1 kN, respectively. The lower values of the maximum steel strains for beams B1, B4 and B5 indicate that the CFRP laminates act as external reinforcement replacing the steel reinforcement.

Table 3 Maximum stain in concrete, steel and CFRP laminate at failure for all beams

Beam	Concrete compressive strain, $\varepsilon_c \times 10^3$ ($\mu\varepsilon$)	Tensile steel strain, $\varepsilon_s \times 10^3$ ($\mu\varepsilon$)	Tensile strain in CFRP laminate, $\varepsilon_{CFRP} \times 10^3$($\mu\varepsilon$)
CB	**-3.238**	**7.861**	**-**
B1	**-1.306**	**2.223**	**2.934**
B2	**-1.384**	**18.5**	**4.8**
B3	**-1.287**	**17.653**	**3.789**
B4	**-0.968**	**2.331**	**1.177**
B5	**-0.997**	**2.463**	**1.265 Bot. & 1.202 Side**

The relationships between the applied load and the recorded strains in the CFRP laminates are shown in Fig. 9 for beams B1, B2 and B3 of series I and Fig. 10 for beams B4 and B5 of series II. Figure 9 shows that the load-strain relationship for beams B2 and B3 is composed of three linear branches, the first one up to cracking load, the second one up to the yielding of the conventional reinforcement and the last one up to the point of beam failure load. While, beams B1 of series I, B4 and B5 of series II showed only two linear branches, the first one up to cracking load and the second one up to the point of beam failure load as shown in Figures 9 and 10. The maximum strains registered in the CFRP laminates for beams B1, B2 and B3 of series I were 20.96%, 34.29%, 27.06% of its ultimate strain, respectively, while that for beams B4 and B5 of series II were 8.41% and 9.04% bottom & 8.59% side of its ultimate strain, respectively (see Table 3). From the above results, it can be seen that doubling the axial stiffness of CFRP laminates in strengthened beams reduced the tensile ultimate strain in the CFRP laminates.

Based on the recorded strain values for the strengthened beams that given in Table 3, it appears that the concrete did not exceed its crushing strain (3.0×10^3 $\mu\varepsilon$) and the CFRP laminates did not reach its rupture strain (14×10^3 $\mu\varepsilon$). It means that the strengthened beams did not exceed its potential flexural capacity due to the premature failure of the beams caused by the tensile rupture and/or debonding of the CFRP sheet straps accompanied by debonding of the CFRP laminates.

Conclusions

The following conclusions can be drawn based on the experimental study carried out under this investigation:

1. The control beam has been exhibited a high ductile flexural behavior and produced large deflection prior to failure which is remarkably gradual.
2. The externally bonded CFRP laminates used for flexural strengthening of the RC beams have enhanced the cracking load and showed a significant increase in the flexural load-carrying capacity but exhibited lower ductility compared with the corresponding unstrengthened control beam depending on the configuration and the axial stiffness of CFRP laminates that were used for strengthening.
3. For the same axial stiffness, $(EA)_{CFRP}$, the strengthened beams B1, B2 and B3 of series I exhibited nearly similar flexural load-carrying capacity and deflection capacity (approximately about 1.85 and 0.42 times the load and deflection of the corresponding CB, respectively). There is no significant difference in performance between the three CFRP laminate configurations that were used for strengthening. So, each one of the three CFRP laminate configurations could be considered as a valid alternative solution for strengthening the beams and the effective choice of each one depends on the situation of the beam.
4. Strengthening RC beams B4 and B5 of series II with externally bonded CFRP laminates having double the axial stiffness, $2(EA)_{CFRP}$, indicated significant increase in the flexural stiffness and the ultimate load-carrying capacity of the strengthened beams in comparison with the strengthened beams of series I as well the unstrengthened CB. The failure loads of beams B4 and B5 are more than twice of the failure load of the CB, while the maximum deflection is approximately about 0.30 times of that of the corresponding CB. The flexural capacity of beam B4 increases by 7.5% over the capacity of beam B5. Therefore, the CFRP laminate strengthening arrangements applied in beam B4 may be considered the most effective one.
5. The potential flexural capacity of the strengthened beams of the two series I and II have not been utilized, as the CFRP laminates did not reach their ultimate strains due to the premature failure of the beams caused by debonding of the CFRP laminates.
6. Using the single-ply CFRP sheet straps distributed over the shear span did not prevent debonding failure of the CFRP laminates because of either its tensile rupture or occurring debonding failure due to the high tensile and bond shear stresses. In all cases, the single-ply CFRP sheet straps appeared to be effective in delaying debonding failure of the CFRP laminates. The premature failure of the beams could be prevent by using double-ply CFRP sheet straps and increasing the CFRP sheet-concrete bond strength.

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