Journal of World Architecture

Research Article

Investigating Some Parameters Affecting Flexural Behavior of Reinforced Concrete Beams Strengthened with Carbon Fiber Reinforced Polymer Laminate

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Abstract: In this paper, the influence of some important parameters affecting the flexural behavior of reinforced concrete beams strengthened with one layer of carbon fiber reinforced polymer (CFRP) laminate has been studied. For this purpose, six reinforced concrete beams were cast and tested in the laboratory. Based on the obtained data, when CFRP laminate is applied to the tension face, too close to the steel rebar, the flexural strength of the strengthened beam is reduced. In general, the performance of the beam strengthened with one wide CFRP strip is better than that strengthened with two equivalent narrow strips. Ultimate load capacity of each strengthened beam was calculated based on the method given by the ACI 440.2R and compared with the test one. It is concluded that, to avoid the steel rebar-CFRP laminate interaction effect, the CFRP laminate depth-to-the effective depth ratio (d_f/d) should not be smaller than about 1.17.

Keywords: *carbon fiber reinforced polymer; concrete beam; flexure; strengthening*

Publication date: September 2018

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0 Introduction

Concrete structures are sometimes required to carry larger loads at a later date or fulfil new standards. Any structure subjected to severe conditions needs to be repaired. Another reason that can be considered is that errors have been made during the design or construction phase so that the structure needs to be strengthened before put in service. Upgrading refers to strengthening, increasing durability, and change of structure function or improving architectural aspects. Restoration, repairing, and reinforcing of old concrete structures are becoming increasingly common. If one considers the capital that has been invested in existing infrastructures, then it is not always economically viable to replace an existing structure with a new one. The challenge must be taken to develop relatively simple measures such as rebuilding, restoration, reparation, and reinforcement that can be used to prolong the life of structures. As a result, strengthening an existing structure will lead to a higher load capacity[1]. The introduction of fiber-reinforced polymers (FRPs) in civil engineering structures has progressed at a very rapid rate in recent years. They have many advantages when compared to traditional construction materials. FRPs offer excellent corrosion resistance to environmental agents as well as the advantages of high stiffness-to-weight and strength-to-weight ratios when compared to conventional construction materials. Other advantages of FRPs include low thermal expansion, good fatigue performance and damage tolerance, non-magnetic properties, the ease of transportation and handling, low energy consumption during fabrication of raw material and structure, and the potential for real-time monitoring[1]. Many experimental tests have been carried out to investigate the behavior of concrete beams strengthened with different FRPs. It is experimentally evident that the increase in flexural strength of beams is possible only when other failure modes do not interfere, such as shear and bond failures. The effect of externally bonded sheets on moment capacity was found to be greater on unreinforced or lightly reinforced concrete beams with steel reinforcement[2,3].

Duthinh and Starnes[3] found that, for the same (carbon FRP [CFRP]) addition, the flexural strength increased 2 times for lightly reinforced beams (11% of the balanced reinforcement ratio), but only 19% increase was obtained for moderately reinforced beams (46% of the balanced reinforcement ratio). Ramana *et al*.[4] found that the maximum increase in cracking and ultimate moments of reinforced concrete beams was 150% and 230%, respectively, compared to the unplated beams. Other tests[5] carried out on full-scale beams strengthened with CFRP sheets indicate that the ultimate moment was increased by 49%, while up to 58% increase was found for beams bonded with epoxy and anchored with steel bolts. The deflection at ultimate load reduced as the degree of strengthening increases and consequently the ductility of the composite beam reduced[2,4]. The lost ductility is higher when CFRP sheets are used for strengthening (due to its brittle behavior) as compared to the steel plate. However, other studies[6] demonstrated that a considerable increase in load capacity can be obtained by strengthening beams with glass FRP sheet without scarifying the ductility of the composite beam. Some researchers[7,8] believed that, if reinforced concrete beams are well designed by providing external anchorage system, the lost ductility can be regained.

The present study is considered as the continuity of the past ones on reinforced concrete beams strengthened with CFRP laminate subjected to flexure. This study is arranged to investigate the influence of applying two equivalent strips, instead of a single one for strengthening, on the flexural behavior of concrete beams. The steel rebar-CFRP laminate interaction effect on the flexural capacity is also presented. Ultimate load capacity of RC beams strengthened with CFRP laminate is calculated and compared with those obtained experimentally.

1 Experimental program

1.1 Materials

Materials used in the present investigation were cement, fine aggregate, coarse aggregate, water, steel rebar, CFRP laminate, and epoxy. Ordinary Portland cement commercially available was used. Clean river sand of medium grading and rounded river gravel of 12.5 mm maximum size have been used. Grading of the aggregates used conformed to the ASTM C33 specification[9]. Clean potable water has been used for mixing concrete and curing specimens. 10-mm deformed steel rebar of yield stress equal to 420.2 MPa has been used for flexural reinforcement. 6-mm deformed rebar of 395 MPa yield stress has been used as shear reinforcement for beams. The CFRP sheet used in this investigation was unidirectional carbon fiber of SikaWrap-300 C/60. Properties of CFRP fabric are shown in Table 1. The CFRP sheet was applied to the concrete surface using Sikadur-330 epoxy (2-part epoxy impregnation resin).

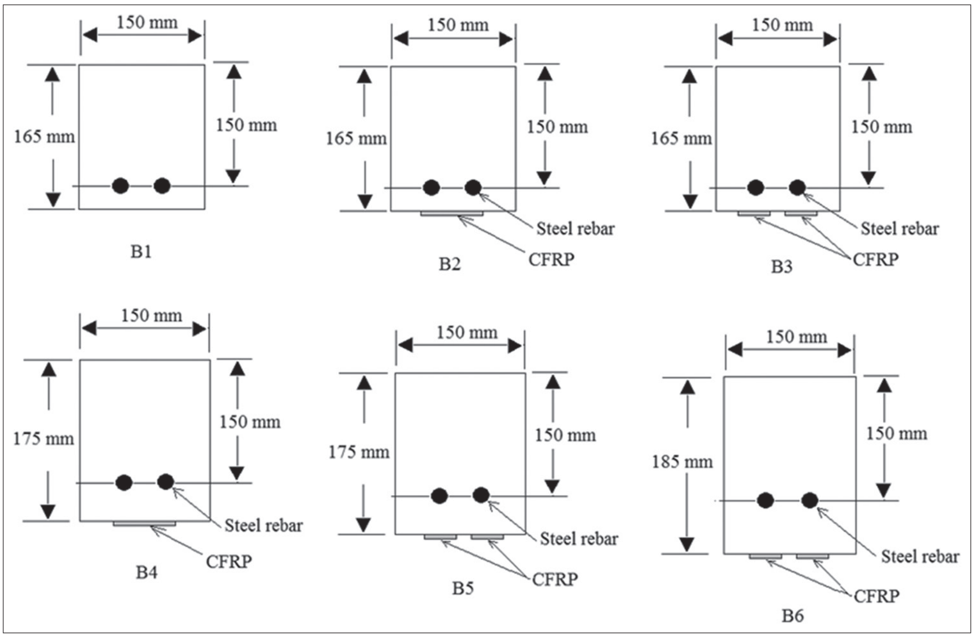

Figure 1. Beam dimensions and carbon fiber-reinforced polymer laminate configuration

1.2 Concrete mix, mixing, and curing

A single concrete mixture of 1:1.5:3 (cement:fine aggregate:coarse aggregate) by weight of water/cement ratio of 0.52 was used for casting specimens. For mixing concrete, the dry cement, fine aggregate, and coarse aggregate have been mixed manually for 2 min. Later, water was added and mixed for another 3 min. Mixing concrete has been done in the laboratory in 25 ± 1°C ambient temperature. Wooden mold of 1.1 m length, 0.15 m width, and variable depth has been used for beams. 100 mm×200 mm cylinder mold has been used for casting cylinders for measuring concrete compressive strength. Before casting fresh concrete, all inner surfaces of molds were oiled to facilitate demolding. The later process was done after 24 h from casting. Curing of concrete was done for 28 days. Later, specimens were taken from water tank and left in the laboratory to dry for a few days before applying CFRP laminate for strengthening.

1.3 Testing and instrumentation

Tension surface of the beam to be strengthened with CFRP laminate was mechanically abraded using a grinding wheel, creating somewhat rough surface to remove laitance, grease, loosely adhering particle, and other dirt. Later, a vacuum cleaner was used to remove the dust. No moisture was observed on the rough surface of the concrete beam. The fabric was cut with special scissors to the desired dimensions. A mixture of epoxy resin (Sikadur-330) (Part A and Part B) mixed at proportion of 1:4 by weight was applied and then cured at room temperature. The bonding procedure was carried out according to the manufacturer instruction. 1.25 kg/m^2 Sikadur-330 epoxy adhesive was applied on the cleaned and prepared surface, and then, CFRP laminate was placed on the epoxy layer. The composite laminates were attached starting at one end and applying enough pressure by rubber roller to press out any excess epoxy from the sides of the laminates. All the excess epoxy was removed from the sides of the laminates. In this study, six beams have been tested to highlight the interaction effect of steel-CFRP laminate on the flexural strength. One layer of CFRP laminate was provided for all beams. The detail of strengthening configuration in addition to the beams dimensions is illustrated in Figure 1. One can observe that beams B2 and B4 were strengthened with 70-mm width CFRP laminate, while beams B3, B5, and B6 were strengthened with two 35-mm width CFRP laminate.

All cylinders were tested for compression following the procedure given by ASTM C39[10] and the average of three measurements was taken as compressive strength of concrete. Few days before testing, all beam specimens' sides were white painted to show cracking pattern during loading until failure. All beams were tested under two central point loadings under loading rate of 5 kN/min on 1 m span till failure. The arrangement of loading in addition to the beam reinforcements is shown in Figure 2. To measure a central deflection, a digital dial gauge was installed near the beam center. For testing beams and cylinder specimens, a universal testing machine of Testcenter-Turkey model was used. One beam ready for testing is shown in Figure 3. It should be noted that, to catch a large amount of test data, a digital video recorder was utilized for measuring the load acting on the beam and the corresponding deflection. After testing, photographs were taken to show crack pattern of the tested specimen.

Table 1. Properties of CFRP material used in the present study

Property	Results
Tensile strength (MPa)	3900
Tensile elastic modulus (MPa)	230000
Elongation at failure (%)	1.5
Fabric thickness (mm)	0.166

CFRP: Carbon fiber reinforced polymer

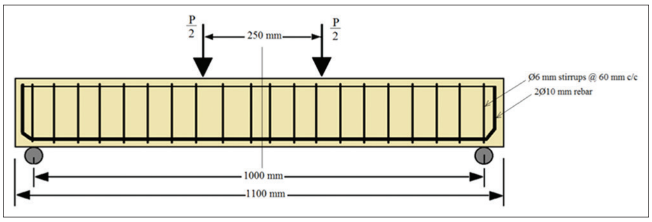

Figure 2. Loading arrangement, dimensions, and reinforcement details of beams

Figure 3. One beam inside the loading cell ready for testing

Table 2. Results of ultimate load capacity of beams

Beam	Beam depth (mm)	CFRP laminate (mm)	$P_{u,t}$ (kN)	$P_{u,t}$ (% control)	c (mm)	$P_{u,ACI}$ (kN)	$P_{u,t}/P_{u,ACI}$
B1	165	-	61.05	100	17.15	50.21	1.216
B2	165	1–70	68.85	112.8	27.32	68.0	1.013
B3	165	2–35	65.90	107.9	27.32	68.0	0.969
B4	175	1–70	72.20	118.3	28.0	69.12	1.045
B5	175	2–35	71.78	117.6	28.0	69.12	1.038
B6	185	2–35	74.61	1222.2	28.63	70.25	1.062

CFRP: Carbon fiber-reinforced polymer

2 Results and discussion

Test results of concrete cylinders indicate that the average cylinder compressive strength is equal to 35.5 MPa. Results of the ultimate load capacity of tested beams are given in Table 2. Load-central deflection relationships of tested beams are shown in Figure 4. Results indicate that there is an enhancement in the ultimate load capacity ranging from 12.8% to 22.2% as a result of strengthening beam with CFRP laminate. According to the obtained results, the stiffness of the beam, denoted by the slop of the initial portion of the load-deflection curve, is not well enhanced when two narrow CFRP strips are used instead of one wide strip. Changing the depth of the beam has some effect on the stiffness, knowing that the effective depth of the beam (d) is constant for all beams. The important observation can be made here is that, when two CFRP strips are used (for beam B3) instead of one strip (for beam B2), this will lead to a lower load capacity of the beam. This observation can be attributed to the interaction effect between CFRP laminate and steel rebar because the clear distance is only 10 mm for beam B3. This effect is able to weaken the performance of the bonded CFRP strip but has a low importance for the two beams B4 and B5, in which the clear distance is 20 mm. Therefore, the ratio of CFRP laminate depth-to-the effective depth (d_f/d) of 1.1 for a bonded CFRP strip directly on the rebar (for beam B3) is critical and not useful for practical applications. The author recommends a useful ratio of d_f/d not smaller than 1.17 (used for beams B4 and B5) for concrete beams of bonded CFRP strip applied directly on the rebar, to avoid low ultimate load enhancement, due to the interaction effect. Results given in Figure 4 indicate that the shape of the load-deflection relationship is well changed as a result of strengthening with CFRP laminate. One can observe that both the deflection at peak load and the maximum deflection are reduced as a result of strengthening. In general, the two mentioned deflections are not vulnerable to change when two CFRP strips are used instead of one equivalent strip. Figure 5 shows the cracking pattern of tested beams. Flexural mode of failure was observed for all beams. For strengthened beams, debonding of CFRP laminate can be well observed. Using two equivalent CFRP strips instead of one strip seems to have no appreciable effect of changing mode of failure or cracking pattern.

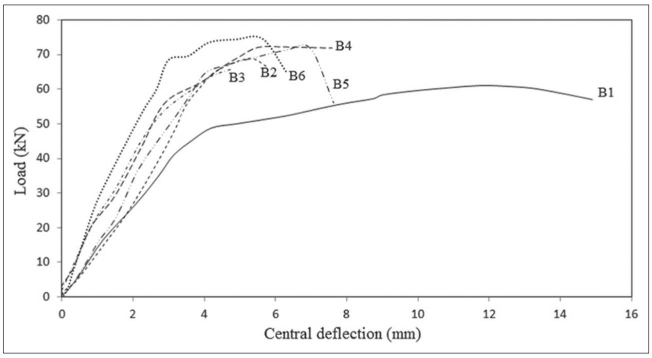

Figure 4. Load-central deflection of concrete beams

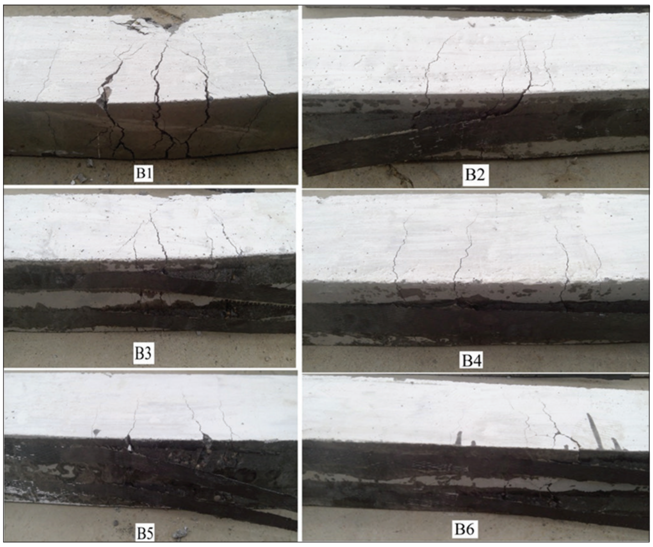

Figure 5. View of beams after testing

3 Calculation of the ultimate load capacity

It is useful to perform prediction of the ultimate load capacity of any strengthened beam. For this purpose, the procedure given by ACI 440.2 R[11] is followed for the strengthened beams and that given by ACI 318 code[12] is followed for the normal beam. For the latter case, the following steps are necessary to complete the analysis. First, tensile mode of failure is assumed, and later depth of equivalent compression block (i.e., $a = \beta_1 c$) is calculated from equilibrium of forces. Having the calculated value of a, moment capacity is calculated by multiplying the tensile force ($A_s f_y$) by the moment lever arm (d-a/2), in which A_s is the total area of steel rebar and f_y is the yield stress of steel. From the loading arrangement on the beam as shown in Figure 2, the load capacity of the beam is equal to the moment divided by 187.5 (measured in N). Calculation of the moment capacity of the strengthened section can be made following the steps given below:

a. Calculate the ultimate tensile stress (f_{fu}) and the corresponding strain (ε_{fu}) of CFRP laminate.
b. Calculate β_1, elastic modulus of concrete (E_c), total area of steel rebar (A_s), and total area of CFRP strip (A_f).
c. Calculate the existing state of strain (ε_{bi}). Since there is no preloading, ε_{bi} is taken as zero.
d. Assume bond-dependent coefficient (κ_m) equal to 0.7.
e. Assume depth of compression block c. For first trial, c is taken as 0.2 d.
f. Calculate the effective strain in CFRP laminate (ε_{fe}) and then calculate κ_m ε_{fe}. Check if the mode of failure is debonding.
g. Calculate concrete strain at failure (ε_c) and strain in steel (ε_s).
h. Calculate stress is steel ($E_s\varepsilon_s$) and stress in CFRP laminate ($E_f\varepsilon_{fe}$), in which E_s and E_f are the elastic moduli of steel and CFRP laminate, respectively.
i. Calculate strain corresponding to compressive strength (f_c) (i.e., ε_c) and the factors β_1 and α_1, and then depth of concrete block (c). Now, c is compared with the assumed value. If they close to each other, there is a chance to calculate moment capacity of the section, otherwise repeat steps e to i.
j. Calculate moment capacity of the section based on the contributions of steel and CFRP laminate to bending and later calculate the design flexural strength. Since there is a need to compare the predictions with the test one of specimens fully loaded to failure as done in this study, only a reduction factor of $\psi_f = 0.85$ is applied to the contribution of CFRP laminate. Having the calculated moment capacity, ultimate load capacity ($P_{u,ACI}$) is calculated.

Table 2 shows the results of calculated $P_{u,ACI}$ and the ratio of test/calculated ultimate load ($P_{u,t}/P_{u,ACI}$). It is observed that the predicted load capacity is safe for all beams except beam B3.

4 Conclusions

From this research study, the following conclusions can be drawn:

a. There is an enhancement in the ultimate load capacity ranging between 12.8 and 22.2% as a result of strengthening beam with CFRP laminate. Beam stiffness is not well enhanced, but the deflection corresponding to the peak load as well as the maximum deflection are reduced, as a result of strengthening beams with CFRP laminate.
b. Using two equivalent strips of CFRP laminate instead of one equivalent, one has a low effect on both the load capacity of the beam and the load-deflection response. In general, the performance of one wide CFRP laminate is better.
c. If CFRP laminate is applied on concrete directly of the steel rebar, of CFRP laminate depth/effective depth of 1.1 used in the study or smaller, the performance of strengthened laminate is low. As a result, poor moment capacity of the section is obtained. For this purpose, a depth of CFRP laminate to the effective depth is recommended to be 1.17 or larger.

Conflicts of interest

No conflicts of interest were reported by all authors.

References

[1] Täljsten B. CFRP-Strengthening-Concrete Structures Strengthened with Near Surface Mounted CFRP Laminates. San Francisco, California: Proceeding of 3rd International Conference on Composites in Infrastructure; 2002.

[2] Rao HV, Vijay PV. Bending behavior of concrete beams wrapped with carbon fabric. J Struct Eng 1993;124:3-10.

[3] Duthinh D, Starnes M. Strengthening of reinforced concrete beams with carbon FRP. In: Figueiras *et al*. Composites in Constructions. Rotterdam: A Balkema; 2001. p. 493-8.

[4] Ramana VP, Kant T, Morton SE, Dutta PK, Mukherjee A, Desai YM. Behavior of CFRPC strengthened reinforced concrete beams with varying degrees of strengthening.

Compos B 2000;31:461-70.

[5] Alagusundaramoorthy P, Harik IE, Choo CC. Flexural Behavior of R/C Beams Strengthened with CFRP Sheets or Fabric. Research Report KTC -02- 13/SPR 200-99-1F; 2002.

[6] Al-Musallam T. Flexural Strength of Concrete Beams Externally Reinforced with GFRP Sheets. Proceedings of the Fifth Saudi Engineering Conference; 1999. p. 117-27.

[7] Mukhopadhyaya P, Swamy N, Lynsdale C. Optimizing structural response of beams strengthened with GFRP plates. J Compos Constr 1998;2:87-95.

[8] Spandea G, Bencardino F, Swamy RN. Structural behavior composite RC beams with externally bonded CFRP. J Compos Constr 1998;2:132-7.

[9] ASTM Designation C33, Standard Specification for Concrete Aggregates, Annual Book of ASTM Standards; 2013.

[10] ASTM Designation C39, Standard Specification for Compressive Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standard; 2013.

[11] ACI 440.2R, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI Committee Report 440.2R-08; 2008.

[12] ACI Committee 318, Building Code Requirements for Structural Concrete, American Concrete Institute, Farmington Hills, First Printing; 2015.