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R.C. Beams Strengthening by Carbon Fiber Reinforced Polymer Against Two Points Load Divergence.

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Abstract

The results of an experimental study of the behavior of the beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets with the load divergence are presented. 100x100x100 mm CFRP sheets are epoxy bonded in U shape around the tension face and web of concrete beams to enhance their ductility and strengths. The effect of CFRP sheets on strength and stiffness of the beams is considered for various lengths of the CFRP with respect to the distance from the center of beams, which are increased according to the distance between the two points load.

Six beams were fabricated, strengthened with CFRP systems (6 different lengths). The beams were loaded to failure. Different mode of failure and gain in ultimate strength ***were observed, depending on the length of the Carbon Fiber.***

Keywords: Carbon fiber, CFRP, beams strengthened, flexural-shear crack, failure zone

أعتاب خرسانية مسلحة ومقواة بألياف الكاربون البولمرية مع تغيير المسافة بين نقطتي التحميل الثنائي

الخلاصة :

يقدم هذا البحث نتائج الدراسة العملية لسلوك العتبات المقواة بشرائح الياف الكاربون البوليمرية مع تغير المسافة بين نقاط الحمل . تم تثبيت شرائح كاربونية بأبعاد (100x100x100 ملم) بأستخدام الايبوكسي بشكل يحيط المقطع السفلي للعتبات (على وجه الشد ووترة العتبة الخرسانية) لزيادة المطيلية والمقاومة.

الشرائح الكاربونية ذات أطوال مختلفة حيث تزداد أطوالها عن خط المركز للعتبات تبعاً لزيادة المسافة بين نقطتي التحميل. تم دراسة تأثير تلك الشرائح على المقاومة والصلادة لستة عتبات تم تنفيذها وتقويتها بنظام ألياف الكاربون (بستة أطوال مختلفة)، وتسليط الحمل على العتبات حتى حدوث الفشل.

ظهرت أنماط مختلفة للفشل واختلاف في المقاومة القصوى اعتماداً على طول شرائح الكاربون المستخدمة.

1. Introduction

The development of new material systems like carbon fiber reinforced polymers (CFRP) used for strengthening and rehabilitation of existing structures are getting higher demands and wide range of applications in recent years. CFRP laminates gained importance over steel plate bonding because they offer superior performance such as resistance to corrosion, and high stiffness-to-weight ratio. Even though CFRP laminates are produced and utilized in different applications, the most common form is built-up woven fabric that is externally bonded to a structural element by the wet lay-up method. Because the CFRP strengthening provides additional flexural or shear reinforcement, the reliability for this material application depends on how well they are bonded and can transfer stress from the concrete component to CFRP laminated (1).

Strengthening of existing reinforced concrete (RC) beams is required for various reasons such as design for havier loads, and restoration of the capacity due to deterioration or due to errorsin design and construction. The strengthening typically requires increasing not only the flexural but also the shear capacity of the beams. Beams suffering from inadequate concrete strength due to difficulties during concrete production and/or construction require more shear than flexural upgrade. This is due to the more significant dependence of the shear capacity on the concrete quality and strength.Several methods are available to designers to select from for shear strengthening. Examples include (1) adding external stirrups, (2) jacketing, (3) bonding external plates using epoxy or bolts and (4) bonding external FRP laminates (2).

(a) (b)

Figure (1)Typical FRP applications as strengthening materials of RC structures (a) wrapped or U-shaped FRP for strengthening of beam and column; (b) application of angles (3).

1.1 Mechanical Properties of FRP Composites

All three types of FRP composites, namely GFRP, CFRP and AFRP have been used for strengthening RC structures in both engineering practice and laboratory research activities. Table (1) for FRP composites with unidirectional fibers illustrates the wide variety of strength and stiffness that FRP composites may possess. It should be noted that the ranges given in this table are indicative, and a particular product may have properties outside the ranges given here, particularly when the fiber content is different from the ranges considered here. It should further be noted that, in discussing the elastic modulus and tensile strength for an FRP composite formed in a wet lay-up process, the thickness of the FRP composite is generally difficult to control or define precisely (3).

This has led to the use of the fiber sheet thickness or a nominal thickness as recommended by the manufacturer. Consequently, the elastic modulus and the tensile strength reported are dependent on the definition of thickness and can be outside the values indicated in Table (1) by a large amount (3) and graphed in Figure (2) .

Table (1) Typical mechanical properties of GFRP, CFRP and AFRP composites(3)

Tensile strength (MPa)	Longitudinal tensile modulus (GPa)	Density (kg/m^3)	Fiber content (%by weight)	Unidirectional advanced composite materials
400-1800	20-55	1600-2000	50-80	Glass fiber/polyester GFRP laminates
1200-2250	120-250	1600-1900	65-75	Carbon/epoxy CFRP laminate
1000-1800	40-125	1050-1250	60-70	Aramid/epoxy AFRP laminate

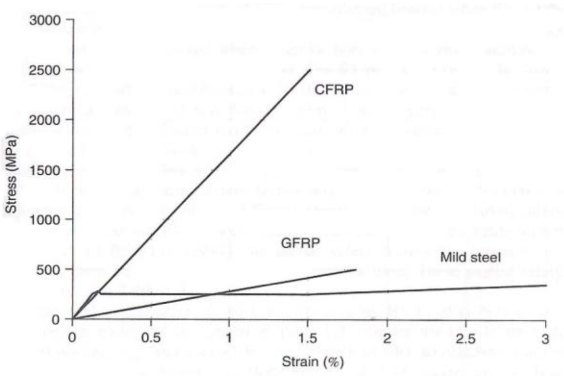


Figure (2) Typical FRP and mild-steel stress-strain curves (3)

1.2 Ductility

Ductility is a desirable structural property because it allows stress redistribution and provides warning of impending failure. Steel-reinforced concrete beams are under-reinforced by design so that failure is initiated by yielding of the steel reinforcement, followed, after considerable deformation at no substantial loss of load carrying capacity, by concrete crushing and ultimate failure. This mode of failure is ductile and is guaranteed by designing the tensile reinforcement ratio to be substantially below (ACI 318 requires at least 25 % below) the balanced ratio, which is the ratio at which steel yielding and concrete crushing occur simultaneously. The reinforcement ratio thus provides a metric for ductility, and the ductility corresponding to the maximum allowable steel reinforcement ratio provides a measure of the minimum acceptable ductility.

The design of FRP external reinforcement for flexure is fairly rational and straight forward. It is based on Bernoulli's hypothesis of strain compatibility that plane sections remain plane, which requires perfect bonding between FRP and concrete, and the ability of the concrete to transfer stresses to the FRP laminate by shear. In a beam reinforced internally with steel and externally with FRP, there is usually substantial reserve capacity at steel yielding. After the steel reinforcement yields, the beam can still carry increasing loads, even though at a lower rate (with respect to deflections) than prior to steel yielding, and the FRP maintains elastic behavior until failure occurs suddenly. Failure is precipitated by FRP debonding, rupturing, or concrete crushing. All of these modes of failure are brittle, i.e., load capacity is reached with little in elastic deformation (4).

2. Literature Review

In strengthening, FRP reinforcement can be externally bonded to the tension face of a member with fibers oriented along the length of the member to provide an increase in flexural capacity, use the U shape warping, or use the CFRP as strips with or without external anchorages to provide increase in shear and flexural capacity. Despite the many advantages of FRP strengthened RC flexural members, their ultimate failure may occur in a brittle manner due to sudden debonding of the FRP system from the concrete. Such a failure mode not only diminishes the strengthening potential of externally bonded FRP system but it is also unacceptable from the structural safety point of view. The premature FRP debonding failure has been experimentally identified by a number of investigators. The failure can be classified into two distinct categories: (a) failure that occurs in the zone of high bending moment and low shear force; and (b) failure that originates at or near FRP system cutoff end in a region of high shear force and low bending moment. While FRP system debonding in the first category is often very local, the latter type, which occurs almost exclusively near the FRP system cutoff end, is due to high stress concentrations in the interface layer. The shear crack at the cutoff end causes an eccentricity between the tension force in the external FRP and the forces in the beam, which leads to peeling of the concrete cover.

Many studies were focused on the effect of CFRP on strength or in failure type, but very few of investigations study the strengthening by CFRP against two points load divergence as in this experimental study.

At 2007, Mohammed presented a thesis containing an experimental and theoretical investigation of flexural behavior of reinforced concrete beams externally bonded by CFRP strips with or without external anchorages.

The experimental work included testing nine reinforced concrete beams. Eight of these beams were strengthened with CFRP strips. The experimental variables considered in the test program include, number of CFRP strips (1 strip or 2 strips), shape and configuration of external anchorage, and the effect of using CFRP strips throughout the total length of the beam with and without using external anchorages.

The experimental results showed that the ultimate loads were increased up to 111.76% for the beams strengthened with bonded CFRP laminates and external anchorage with respect to the unstrengthened reinforced concrete beam (reference beam). Also, these strengthened beams showed a lower deflection at corresponding loads with respect to the unstrengthened reinforced concrete beam. The results obtained from the finite element analysis showed a very good agreement with the results obtained from the experimental results (5).

Duthinh and Starnes (6) reported seven concrete beams reinforced internally with steel and externally with CFRP laminate applied after the concrete had cracked. They were tested under four – point bending. Results showed that FRP is very effective for flexural strengthening. As the amount of steel increases, the additional strength provided by the carbon decreases. Compared with a beam reinforced heavily with steel only, the beams reinforced with both steel and carbon have adequate deformation capacity. Clamping or wrapping of the ends of FRP laminate combined with adhesive bonding is effective in anchoring the laminate (6).

3.Experimental Work

3.1 Material Properties

3.1.1 Concrete and Steel

The design strength of the concrete and the yield strength of the steel were determined as (f'_c = 52.88 MPa, f_{cu} = 64.35 MPa and f_r= 4.75 MPa) and (Ø10 mm, f_y = 484 MPa ,f_u = 719 MPa) , (Ø6 mm, f_y = 383 MPa, f_u = 620 MPa), respectively. Cement, fine and coarse aggregate analyses were shown in Tables (2,3,4,5 and 6). The mix proportion was 400 kg/m^3, 600kg/m^3, 1200kg/m^3 (cement: sand: gravel) and 152 kg/m^{3}water, the superplastisizer was

703 (complies with requirements of the following standards: ASTM C494 type A, B, D, F and G – BS 5075 Part 1) add by 1.75% as aratio from cement weight.

Table (2) Physical Properties of Taasloja Cement

Property		Result	Iraqi Specification Limits I.O.S 5/1984
Fineness by air permeability method (Blaine)		3015	Not less than 2300cm^2/gm
Initial Setting time		170 min	Not less than 45min.
Final Setting time		4.167 hr	Not more than 10hrs.
Soundness (Autoclave method)			Not more than 0.8 %
Compressive Strength	3-day age	30	Not less than 15MPa
	7-day age	42	Not less than 23MPa

Table (3) Chemical Analysis and Compound Composition of Taasloja Cement

Oxides	Content %	Iraqi Specification Limits I.Q.S 5/1984
CaO	63.46	60 -67 %
SiO_2	19.94	17- 25 %
AL_2O_3	4.67	3.0-8.0 %
MgO	2.86	5 % max.
Fe_2O_3	3.29	0.5- 6.0
SO_3	2.30	2.8 % max.
L.O.I	3.32	4 % max.
Insoluble Residue	0.72	1.5 % max.
L.S.F.	0.97	0.66-1.02
Compound Composition		
C_3S	39.28	
C_2S	32.63	
C_3A	11.98	
C_4AF	8.00	

Table (4) Grading of Fine Aggregate.

Sieve Size (mm)	% Passing by Weigh	
	%Fine Aggregate Passing	IOS 45/1984 Limits
10	100	100
4.75	93.40	90-100
2.36	85.40	75-100
1.18	75.60	55-90
0.6	41.70	35-59
0.3	9.10	8-30
0.15	0.04	0-10

Table (5) Grading of Coarse Aggregate.

Sieve Size mm	% Passing	
	% Coarse Aggregate	IOS 45/1984 Limits
12.5	100	100
9.5	98	85-100
4.75	25	10-30
2.36	3	0-10
1.18	0.5	0-5

Table (6) Typical Properties of Topflow SP 703.

Appearance	Dark Brown / Black Liquid
Specific gravity	1.235 @ 25±2C
Chloride Content	Nil
Flash Point	N/A

3.1.2 Carbon Fiber

The SikaWrap 230C/45 is an externally applied strengthening or repairing system for structural members made of reinforced concrete, masonry or timber. This system was supplied by (Sika Near East s. a. I. Beirut - Lebanon).

The carbon fiber was applied against the load divergence, according to that the lengths were different form beam to another. The U shape was (100×100×100) mm around the beams section as shown in Figure (3) , the properties of CFRP and epoxy are shown in Tables (7 and 8).

Table (7) SikaWrap 230C/45 (Carbon Fiber Fabric) (*)

Fiber type	High strength carbon fibers
Fiber orientation	0° (unidirectional). The fabric is equipped with special weft fibers which prevent loosening of the roving (heat set process).
Areal weight	230 ± 10 g/m^2
Fabric design thickness	0.1 mm (based on total area of carbon fibers)
Tensile strength of fibers	4300 MPa
Tensile E – modulus of fibers	234 GPa
Elongation at break	1.8 %
Fabric length/roll	≥ 50 m
Fabric width	300/600 mm

(*) Provided by the manufacturer

Table (8) Sikadur-330 (Impregnating Resin) (*)

Appearance	Comp. a: white, Comp. b: grey
Density	1.31 kg/l (mixed)
Mixing ratio	A : B = 4 : 1 by weight
Open time	30 min (at + 35°C)
Viscosity	Pasty, not flow able
Application temperature	+ 15°C to + 35°C (ambient and substrate)
Tensile strength	25 MPa (cured 7 days at +23°C)
Flexural E-modulus	3800 MPa (cured 7 days at +23°C)

(*) Provided by the manufacturer

Figure (3) shows the U shape of carbon fiber around the beams section

3.2 Sample Preparation

The experimental work consisted of casting six concrete beams, applying CFRP in U from, and then tested the specimens.

The concrete beams were (150×100) mm in size, with a length of (1500) mm. The dimensions and cross-sectioned details of the test beams were shown in Figure (3).

All six beams were strengthened with CFRP sheets. CFRP lengths are shown in Table (9).

The CFRP sheets applied as single ply throughout the lengths are shown in Table (9). The surface was clean, CFRP applied on it and a final layer of epoxy was applied when the epoxy was still in fresh state.

Table (9) The Details of The CFRP

Beam	CFRP dimention of U shape (mm)	CFRP length (mm) from center line	Distance between 2 pt. load (mm)
B1	100×100×100	20	0
B1	100×100×100	30	20
B3	100×100×100	40	40
B4	100×100×100	50	60
B5	100×100×100	60	80
B6	100×100×100	75	100

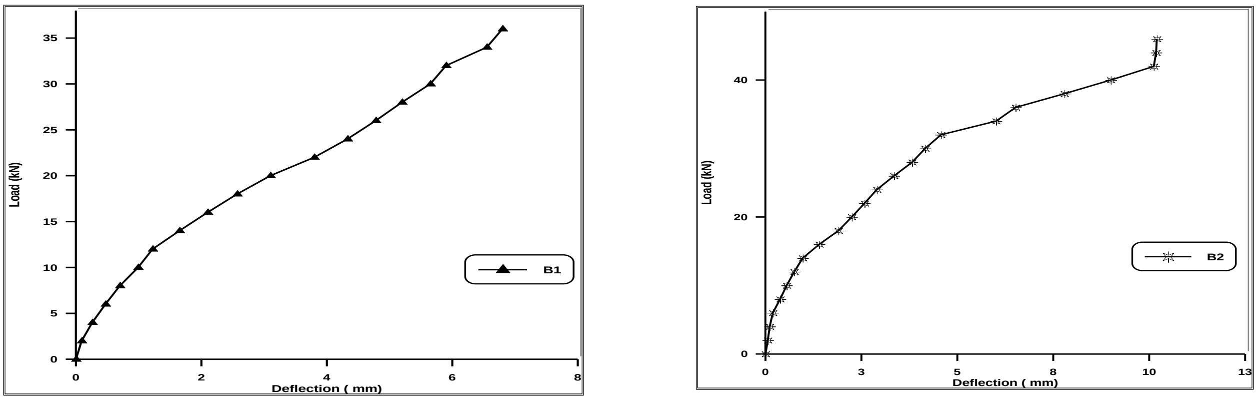
3.3 Testing

The testing was made by using the machine of MFL constant stress system.The specimens were simply supported and then tested by the one point load for B1, and two points of load at distance according to specimen (200, 400, 600, 800, 1000) mm for beam (B2, B3, B4, B5, B6) respectively. The deflection was measured by using the dial gauge (0.01 occurancy) at the center of beam.

4. Results and Discussion

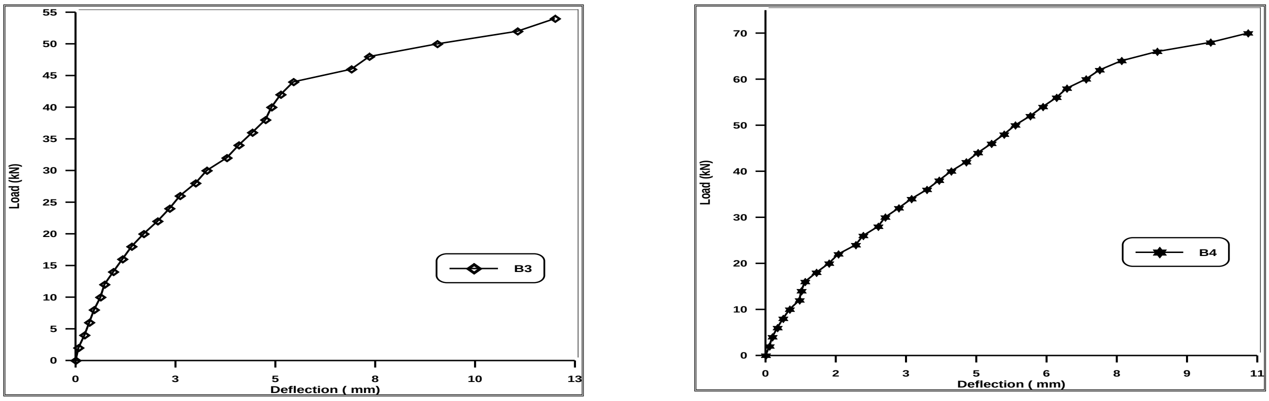
From the load - deflection relationships in Figure (4) it could be recognized the effect of using CFRP on the strength and ductility of beams. Figure (5) shows the comparative between the beams in load - deflection relationships. The effect of CFRP lengths was very clear, the ductility increased as the strengthening length increased and the stiffness also increased, the effect of the strengthening by CFRP against the load divergence appeared obviously in all beams.The first crack load increased as the CFRP length increased, also the crack width was affected by CFRP, the cracks width decreased as the strengthening length increased the crack zone also decreased as the CFRP length increased.

From the structural response, that the failure would have occurred as it was assumed, i.e. flexural moment failure in all beams due to the crushing of the concrete in the compression zone, the load -deflection curves also reflected that the maximum moment capacity was reached.



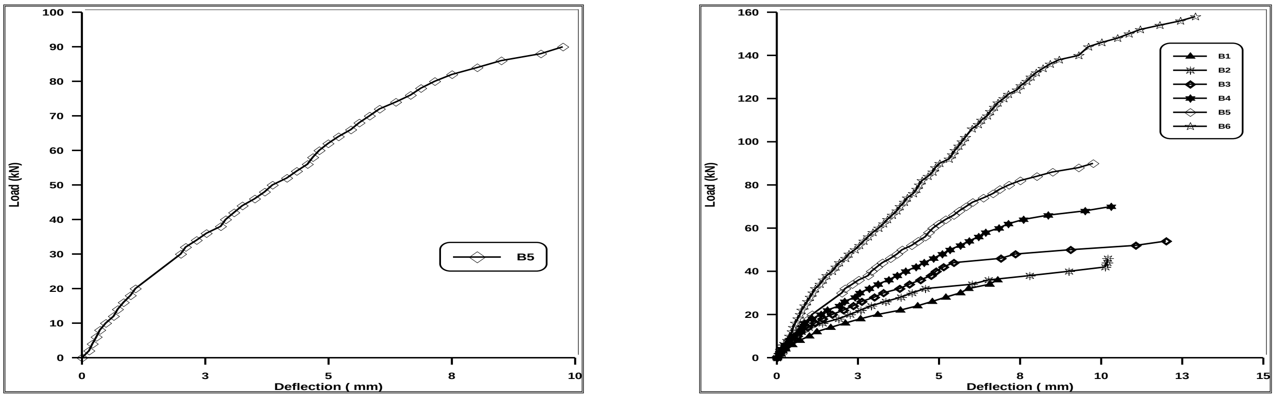
Beam 1

Beam 2



Beam 3

Beam 4



Beam 5

Beam 6

Figure (4) Load_ Deflectio relationships for beams

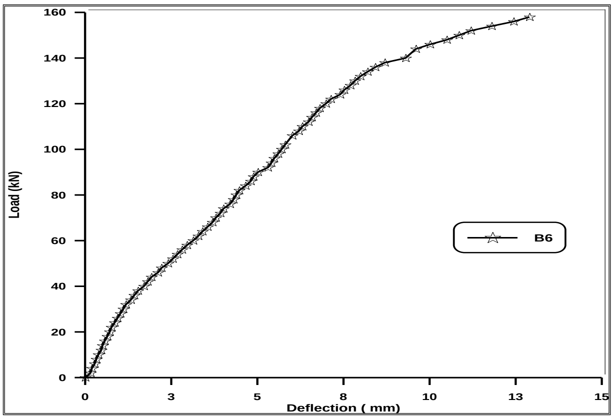


Figure (5) Comparation between Load_Deflection relationships for all beams.

For beams (B5 and B6) the structural response, however, showed that also the maximum moment capacity was almost reached, but at the last load increameant the beam was already severely damaged by wide flexural-shear cracks, the failure occurred in such a way that the CFRP plate split apart from the concrete as in all beams along a horizontal surface starting from a wide flexural -shear crack. This type of failure may be a concern for this technology. It may be explained with the combination of high shear stresses between the concrete and the CFRP plate, high normal stresses concentration in the plate at the crack opening and coexisting transverse shear stresses due to vertical movement at the crack opening. Figures (6,7) shows failure mode of concrete beams.

Figure (6) shows the beams crack and failure type

Figures (7) The beams crack and failure type.

5.Conclusions

1- CFRP sheets can provide increase in strength and stiffness of beams when bonded to the web and tension face.
2- The magnitude of the increase and the mode of failure are related to the length of the CFRP and the load divergence.
3- The mode of failure associated with the application of CFRP was more ductile and proceeded by warning signs such as snapping sounds or peeling of the CFRP.
4- The results of this study show that CFRP may be used to increase the strength against the load divergence and stiffness of beams without causing catastrophic brittle failures associated with this strengthening technique.

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Notation:

RC: reinforced concrete.
CFRP: carbon fiber reinforced polymer.
f'_c: compressive strength of concrete cylinder sample.
f_{cu}: compressive strength of concrete cube sample.
f_r: flexural strength of concrete.
f_y: tensile yield strength of internal steel bars and external CFRP sheets.
f_u: ultimate strength of internal steel bars and external CFRP sheets.