Torsional Behavior of Reinforced Concrete T Beams Strengthened with CFRP Strips

Ban S. Abduljalil
Engineering College, University of Al-Mustansiryah /Baghdad
Email:ban_sahib@yahoo.com
Dr. Kaiss F. Sarsam
Building and Construction Engineering Department**,** University of Technology/Baghdad

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ABSTRACT

This work aims at studying the strengthening of T beams in torsion by using carbon fiber reinforced polymer (CFRP). The experimental work includes investigation of five reinforced concrete T beams tested under pure torsion. Variables considered in the test program include; effect of flange strengthening, effect of fiber orientation (90º or 45º CFRP strips with respect to the beam longitudinal axis), and the effect of using additional longitudinal CFRP strips with transverse CFRP strips. Test results were discussed based on torque - twist behavior, beam elongations, CFRP strain, and influence of CFRP on cracking torque, ultimate torque and failure modes. Results indicate significant increases in ultimate torque capacity with the use of CFRP.

Keywords: Torsional Reinforced Concrete, CFRP Strengthening, T Beams.

سلوك اللي للعتبات الخرسانية المسلحة ذات مقطع T المقواة بشرائح الياف الكاربون البوليمري

الخُلاصة

يهدف هذا العمل إلى دراسة تحسين مقاومة أللي للعتبات بشكل T باستعمال اللـــدائن الكاربونيـــة المسلحة (CFRP). يتضمن الجانب العملي للبحث (5) نماذج من العتبات الخرسانية المسلحة بشـــكل T تم فحصها تحت عزوم اللي الصرفة. تتضمن المتغيرات التي تم أخذها بنظر الاعتبار في برنـــامج الفحص: تأثير التقوية في الجناح، تأثير تغير اتجاه اللدائن الكاربونية (شـــرائح 90° أو 45° بالنســـبة للمحور الطولي)، تأثير استعمال شرائح من اللدائن الكاربونية طولية إضافية لشرائح اللدائن الكاربونية العرضية، تم مناقشة نتائج الفحص اعتمادا على تصرف اللي - الدوران واســـتطالة العتبـــة وانفعـــال اللدائن الكاربونية وتأثير اللدائن الكاربونية على عزم لي التشقق واللي الأقصى وأطوار الفشل. النتائج بينت ان استعمال اللدائن الكاربونية ساهم بزيادة التحميل الاقصى للعتبات.

INTRODUCTION

Modern civilization relies upon the continuing performance of its civil engineering infrastructure ranging from industrial buildings to power stations and bridges. For the satisfactory performance of the existing

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structural system, the need for maintenance and strengthening is inevitable. Commonly, engineering challenges such as the increase in service loads, changes in use of the structure, design or construction errors, degradation problems, changes in design code regulations, and seismic retrofits are some of the causes that led to the need for rehabilitation of existing structures. Complete replacement of an existing structure may not be a cost-effective solution and it is likely to become an increasing financial burden. In such occasion, repair and rehabilitation are the most commonly used solutions. Reinforcement corrosion and structural deterioration in reinforced concrete structures are common and prompted many researchers to seek alternative materials and rehabilitation techniques. While many solutions have been investigated over the past decades, such as using surface bonded steel plates, there is always a demand to search for use of new technologies and materials to upgrade the deficient structures. In this research [1], strengthening with carbon fiber reinforced polymers (CFRP) composite materials in the form of external reinforcement are of great interest to the civil engineering community. Externally bonded, FRP sheets are currently being studied and applied around the world for the repair and strengthening of structural concrete members [2], because of their superior properties such as high stiffness and strength as well as ease of installation when compared to other repair materials. Also the non-corrosive and nonmagnetic nature of the materials along with their resistance to chemicals makes FRP an excellent option for external reinforcement. The method of strengthening structures with externally bonded FRP composite materials gained significant attention in the last two decades. The addition of externally bonded FRP sheets to improve the flexural and shear performance of RC beams has been actively pursued during the recent years. Research reveals that strengthening with FRP provides a substantial increase in post-cracking stiffness and ultimate load carrying capacity of the members subjected to flexure and shear [3, 4, 5, 6]. Research related to the strengthening of torsional members with FRP composites is very limited. Few data or design guidelines are available in the literature [7, 8, 9, 10, 11]. The lack of experimental and analytical studies along with the increasing interest in the use of FRP materials in the strengthening and rehabilitation of concrete structures that failed in torsion led to this study on torsional behavior of reinforced concrete beams strengthened with CFRP laminates.

OBJECTIVE

The main objective of this research was to investigate the torsional behavior of reinforced concrete T beams strengthened with externally bonded CFRP sheets and to identify the influence of the design variables considered in the effectiveness of strengthening. The variables considered were:

(1) Effect of flange strengthening.
(2) Effect of fiber orientation; (90º) and (45º) to the longitudinal axis of the beam.
(3) Effect of longitudinal strengthening in the web and flange with transverse CFRP strips.

Test Beams

To study the most influential strengthening variables on torsional behavior a total of five medium scale reinforced concrete T beams 1800 mm long were constructed for this work as shown in Fig (1). Out of the five beams, four were strengthened with CFRP strips and one beam was not strengthened to serve as a reference beam. Schematic representations of the strengthening schemes are shown in Fig (2) to Fig (6). Test beams were identified based on the following naming system. The first character in the name B is used to identify the beam. Second character is the number of the beam. Third character in the name (90, 45) is used to specify the fiber orientation with respect to the longitudinal axis of the beam. The fourth two characters are used to specify the strengthening in web or flange or both (W or F or WF). The fifth character is used to specify the longitudinal strengthening scheme (L). The beam designation and compressive strength of concrete $\left(f_c^{'}\right)$ are listed in Table (1).

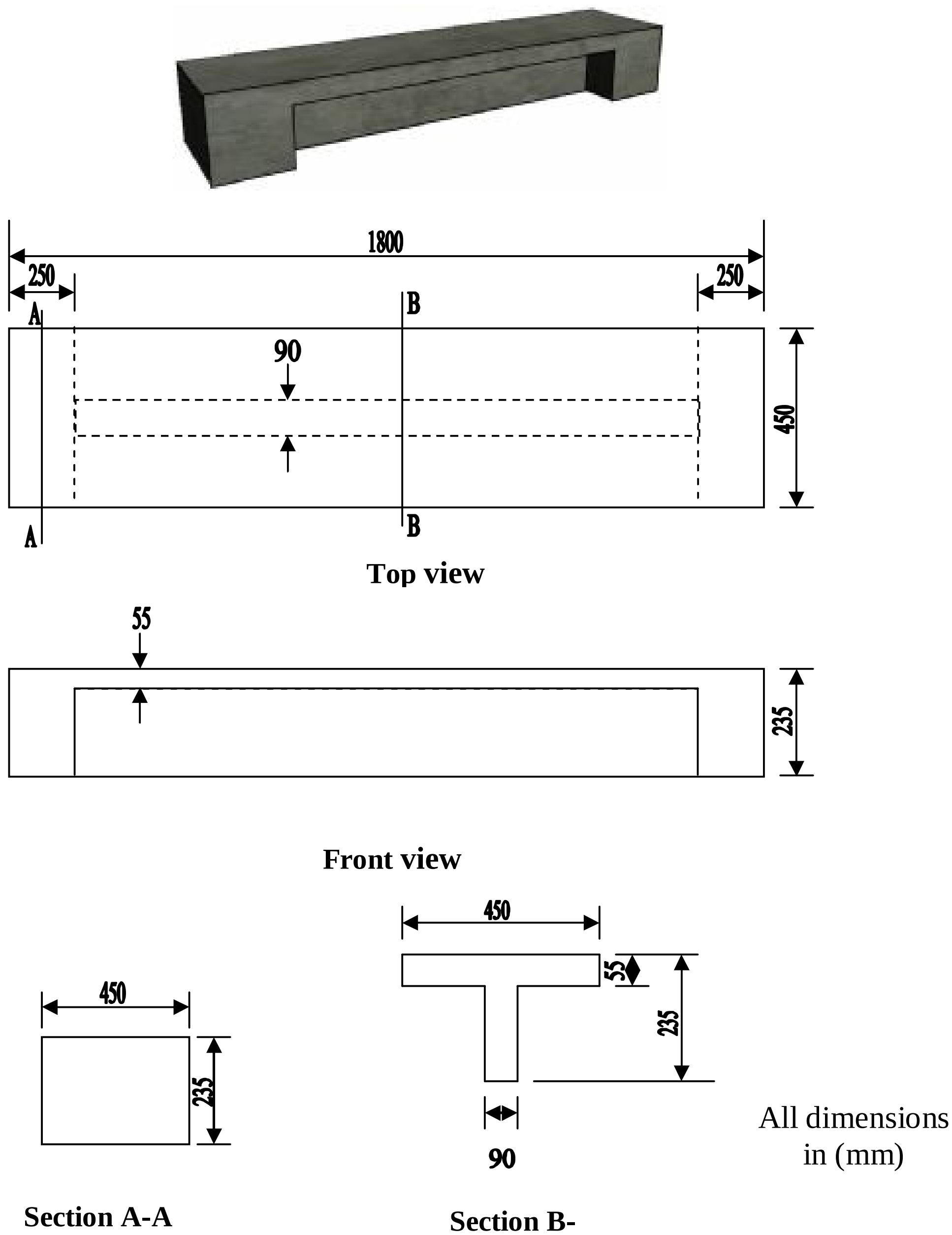

Figure (1) Beam Specimen with Dimensions

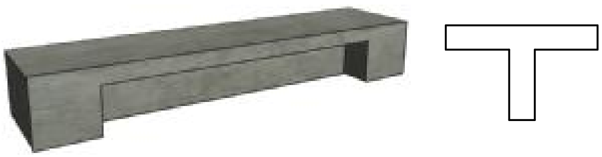

Fig (2) Reference Beam (B1)

Fig (3) Strengthened Beam with 90° CFRP Strips in the Web Only (B290W)

Fig (4) Strengthened Beam with 90° CFRP Strips in the Web and Flange (B390WF)

Fig (5) Strengthened Beam with 90° CFRP Strips in the Web and Flange and Longitudinal CFRP in the Web and Flange (B690WFL)

Figure (6) Strengthened Beam with 45° CFRP Strips in the Web and Flange (B845WF)

Table (1) Summary of Specimen Details and Concrete Compressive Strength

Beam No.	**Details of strengthening**	**Compressive strength of concrete (f_c') (MPa)**
B1	Reference beam (control beam) without strengthening	33
B290W	B2 strengthened with 90° CFRP strips in the web only	34
B390WF	B3 strengthened with 90° CFRP strips in the web and flange	31
B690WFL	B6 strengthened with 90° CFRP strips in the web and flange and longitudinal CFRP in the web and flange	32
B845WF	B8 strengthened with 45° CFRP strips in the web and flange	34

Table (2) provides the summary of the parameters studied and the corresponding test beams used for comparison and discussions.

Table (2) Summary of Investigated Parameters and Corresponding Test Beams

Parameters investigated	Test beams	Illustrations
Flange strengthening	B1, B290W, B390WF	Fig (11), Fig (12), Fig (13), Fig (14)
Fiber orientation	B1, B390WF, B845WF	Fig (14), Fig (15), Fig (16), Fig (17)
Strengthening in longitudinal and transverse direction	B1, B390WF, B690WFL	Fig (14), Fig (18), Fig (19), Fig (20)

Note: (all test beams were strengthened with CFRP as strips of 50 mm width each 150 mm c/c).

The reinforcement provided in the beams are explained as follows. In order to avoid failure of the beams at torsional cracking load, each beam was designed to have a steel reinforcement of (1%) for each of transverse (stirrups) and longitudinal reinforcement, to the volume of the concrete. The percentage of reinforcement provided in the beam was slightly higher than the minimum required (minimum total reinforcement for torsion (1%) (Longitudinal reinforcement + stirrups) [12], for maintaining the integrity of the beam beyond cracking. Also, this will represent the case of a deficient beam in terms of reinforcement. All beams were reinforced as shown in Fig (7).

The specimens were reinforced with (4 φ 10 mm) and (2φ 6 mm) longitudinal bars located around the perimeter of the beam. In order to force failure in the mid zone of the tested beam, end zones 0.4 m long on each end of the beam were reinforced with (φ 5 mm) stirrups spaced at (40 mm) on center. The test region of (1 m) was selected in such a manner that at least two complete spiral cracks would form along the length of the tested region, so it was reinforced with (φ 5 mm) stirrups spaced at (70 mm) on center. Additional (φ 5 mm) hooks were placed in the beam flange representing the negative reinforcement from the connecting slab.

Yield strength and ultimate strength the reinforcement are summarized in Table (3).

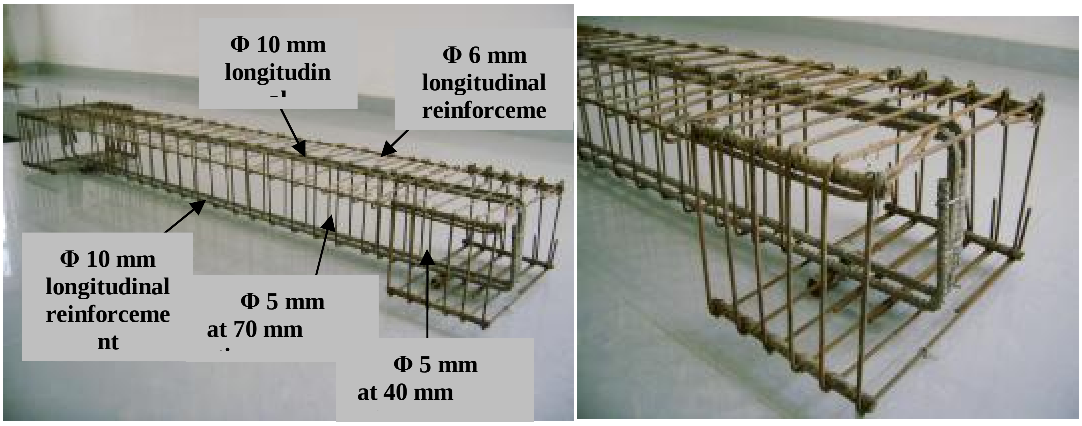

Figure (7) Details of Beam Reinforcement

Table (3) Specification and Test Results of Steel Reinforcing Bar Values

Nominal diameter (mm)	**Yield strength(*) (MPa)**	**Ultimate strength (MPa)**	**Modulus of elasticity(**) (GPa)**	**ASTM C370-05a [13] Ultimate Strength (MPa) Class 400**
5	442	589	200	--
6	294	515	200	--
10	530	654	200	600

(*)Each value is an average of three specimens (each 40 cm long).
(**)Assumed value.

CFRP Material Properties

Carbon fiber fabric SikaWrap Hex-230C and epoxy based impregnating resin Sikadur-330 are used in the testing program. The properties of these materials, as provided by the manufacturer, are shown below.

(1) SikaWrap Hex-230C (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 (heatset process).**
Areal weight	**225 g/m^2**
Fabric design thickness	**0.13 mm (based on total area of carbon fibers)**
Tensile strength of fibers	**3500 MPa**

Tensile E – modulus of fibers	**230 GPa**
Elongation at break	**1.5 %**
Fabric length/roll	**≥ 45.7 m**
Fabric width	**305/610 mm**

(*) Provided by the manufacturer

(2) 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 flowable**
Application temperature	**+ 15°C to + 35°C (ambient and substrate)**
Tensile strength	**30 MPa (cured 7 days at +23°C)**
Flexural E-modulus	**3800 MPa (cured 7 days at +23°C)**

(*) Provided by the manufacturer

CFRP Installation

The effectiveness of strengthening or rehabilitation with externally bonded CFRP laminates depends on the bond between the CFRP and concrete. To insure such proper bonding the following steps were followed:

(1) The specimens were cleaned by washing with pressurized water and allowed to dry prior to composite application. This procedure removed loose particles and contaminations from the specimen's surface.

(2) Just before composite application, the beams were wire brushed and vacuumed as well.

(3) The corners of the specimens were rounded (radius of approximately 15 mm) to avoid any stress concentration in the CFRP sheets at corners of the beams. This stress concentration will lead to a rupture failure of CFRP sheets at corners before reaching their ultimate strength.

(4) The mixed resin Sikadur-330 was applied to the prepared substrate using a trowel or brush in a quantity of approximately (0.7 to 1.2 kg/m^2), depending on roughness of substrate.

(5) The SikaWrap Hex-230C fabric was cut by scissors to strips at (50 mm) width and for the required length for all the specimens.

(6) The SikaWrap Hex-230C fabric was applied onto the resin with the plastic roller until the resin was squeezed out between the roving.

(7) Beam (B690WFL) is required to be strengthened in the longitudinal direction, the longitudinal strips were fixed and then applying more resin was applied, consumption approximately (0.5 kg/m^2). This must be done within (60) minutes after the application of the previous layer. If this is not possible, a waiting time of at least (12) hours must be observed before the next layer is

applied, then the SikaWrap Hex-230C fabric was applied onto the resin coating in the required direction.

(8) As a covering layer an additional resin layer of approximately (0.5 kg/m^2) broadcast with the brush can be added, which will serve as a bonding coat for following cementitious coatings.

(9) After allowing the laminate to cure for a couple of days, the specimens will be ready to test. All apparent concrete surface beams were painted white so that crack propagation can be easily detected.

Test Setup

The hydraulic universal testing machine (MFL system) was used to test the beam specimens. The normal load can just be applied by this machine on the specimen at several points and the supports should be remaining fixed without rotating around the longitudinal axis. In this research the applied loads outside the bed of the universal machine are needed in order to get torsional movement.

The experimental requirements need to move the supports circularly (ball bearing) and transmitting the load from the center of the universal machine to the two external points that represent the moment arm.

The special clamping loading frame on each end of the beam used in this research is shown in Fig (8). This frame consists of two large steel clamps which work as arms for applied torque with separated faces to connect them over the sample by large bolts; four bolts are used for each arm. This frame is made of thick steel plate (10 mm) with two steel shafts attached by welding. This final shape is similar to a bracket. These arms were capable of providing a maximum eccentricity of (600 mm) with respect to the longitudinal axis of the beam. In order to get pure torsion the center of support should coincide with the center of the moment arm.

The steel girder of (300 mm) depth and (3 m) length is used to transmit the loads from the center of the universal machine to the two arms (pure torsion). This girder was clamped to the universal machine as shown in Fig (9a).

Strengthened beams were tested under monotonically increasing torque up to failure, the load was applied gradually. At each load increment (2 kN), readings were acquired manually. In addition, at each load stage, cracks were recorded according to their occurrence. The torque increased gradually up to failure of the beam, Figs. (9a) and (9b) shows the test setup.

Figure (8) Clamping Torsional Arm

Figure (9a) Testing Setup

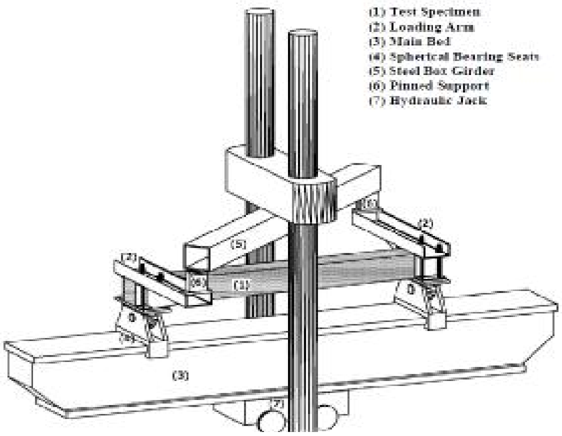

Figure (9b) Schematic Diagram Testing

MEASURING INSTRUMENTS

Angle of Twist Measurements

A simple method was used to estimate the angle of twist by using two dial gages attached the bottom fiber of the end of beam at a point (100 mm) from the center of the longitudinal axis of the beam as shown in Fig (10). The two dial gages on the right and on the left recorded the uplift and down values to find the twist angle in radians.

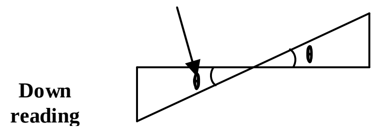

Figure (10) Angle of Twist Measurement

Strain Gages to Measure the CFRP Strain

Demec gages were used to measure the strain developed in the CFRP at concrete failure. They are mounted in the direction of the CFRP fiber at the edge strip and middle strip of CFRP at the side faces of the tested beam (left side and right side).

Elongation Measurements

Two dial gages were fixed at the center of the beam ends to measure the elongation of the beam.

TEST RESULTS AND DISCUSSIONS

Table (4) Percentage of Increase in Cracking Torque

Beam No.	Strengthening scheme	Cracking torque (kN.m)	Angle of twist (degree/m)	Percent of increase (%)
B1	Reference beam unstrengthened beam	2.4	0.092	----
B290W	90˚ CFRP strips in the web only	2.4	0.086	0
B390WF	90˚ CFRP strips in the web and flange	2.4	0.143	0
B690WFL	90˚ CFRP strips in the web and flange with longitudinal CFRP strips in the web and flange	2.4	0.024	0
B845WF	45˚ CFRP strips in the web and flange	3	0.39	25

Table (5) Percentage of Increase in Ultimate Torque

Beam No.	Strengthening scheme	Ultimate torque (kN.m)	Angle of twist (degree/ m)	Percent of increase %
B1	Reference beam unstrengthened beam	4.2	2.434	0
B290W	90˚ CFRP strips in the web only	5.4	2.12	29
B390WF	90˚ CFRP strips in the web and flange	5.4	1.74	29
B690WFL	90˚ CFRP strips in the web and flange with longitudinal CFRP strips in the web and flange	6.6	3.165	57
B845WF	45˚ CFRP strips in the web and flange	4.8	2.13	14

EFFECT OF FLANGE STRENGTHENING

Fig (11) shows the influence of strengthening in the web only and strengthening in the web and flange on torsional behavior of the reinforced concrete T beams strengthened with CFRP strips. This group of beams was used to illustrate this effect, (B1, B290W, B390WF).

When comparing (B390WF) and (B290W), (tables (4, 5)), the additional strengthening in the flange for beam (B390WF) will not contribute to increasing the ultimate torsional resistance that contrasts with the fact that the reinforcement in the flange increased the ultimate torque of the RC beam [14]. The reason for that is the discontinuity of the CFRP between the web and flange, which resulted in discontinuity of the shear flow. One way to improve the performance of this scheme (strengthening in the web and flange) is to anchor the ends of the wrap to the beam. The anchoring of CFRP in the web and flange will cancel the discontinuity of the shear flow of CFRP strips between the web and flange and prevent the delamination of the CFRP.

It can be seen from Fig (12), that beam elongations at the center of the supported end had been started at early stages after cracking. Beam (B390WF) has the same behavior for beam elongation as for beam (B290W). There is, however, a little difference due to restraint of cracks from propagation and widening with the presence of CFRP strips in the flange.

The failure mode was almost the same for beam (B290W) and (B390WF) as shown in Figs. (13) and (14), which was excessive diagonal cracks in the concrete in the web.

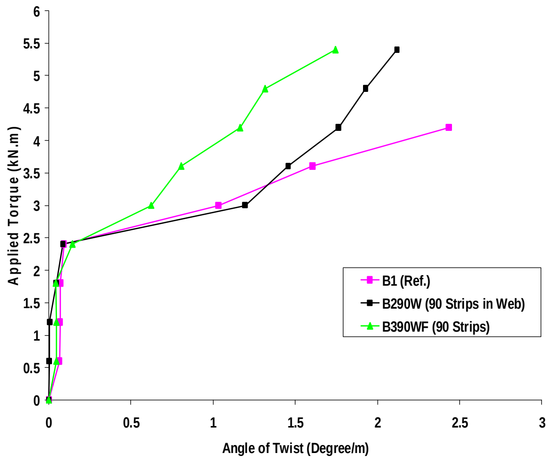

Figure (11) Torque - Twist Behavior: Effect of Flange Strengthening

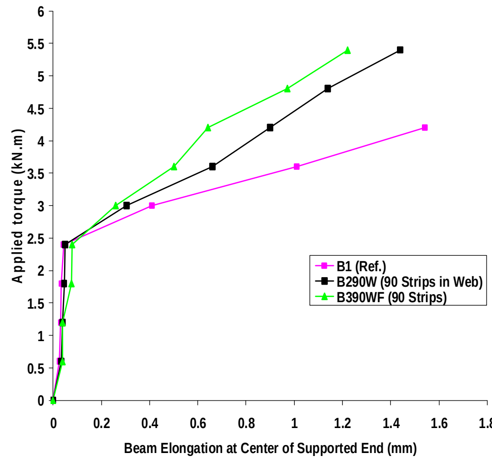

Figure (12) Beam Longitudinal Elongation Behavior: Effect of Flange Strengthening

Figure (13) Mode of Failure of Strengthened Beam B290W (90° Strips in the Web Only)

Figure (14) Mode of Failure of Strengthened Beam B390WF (90˚ Strips in the Web and Flange)

EFFECT OF FIBER ORIENTATION

Fig (15) shows the influence of fiber orientation on the torsional behavior of the reinforced concrete T beams strengthened with CFRP strips. This group of beams was used to illustrate this effect (B1, B390WF, and B845WF).

As can be seen in Fig (15) and Tables (4, 5), the composite strengthened beams reached higher torsional resistance as compared with the reference beam (B1). At the early stages of loading, the CFRP carried little load unlike the steel reinforcement. The CFRP started carrying load once torsional cracks had formed and propagated. The presence of the CFRP strips inhibited these cracks from propagating and widening compared to the reference beam (B1).

Cracking torque increases for beam (B845WF) by (25 %), while the cracking torque will not increase for beam (B390WF) as compared with the reference beam (B1).

Post - cracking stiffness of beam (B390WF) is higher than the reference beam (B1) with a decrease in post cracking twist and absorption capacity.

It is important to note from previous researches [6, 8], that the strengthening scheme of (45˚) CFRP strips with continuous form around the section enhanced the ultimate torsional resistance of the beam. The (45˚) CFRP was quickly engaged as the test progressed. This quick involvement was due to the (45˚) orientation of the laminate, which matched the direction of the principal stresses with respect to the beam longitudinal axis.

But applying the (45˚) CFRP strips in a discontinuous form around the beam (B845WF) resulted in little increase in the torsional moment capacity as compared with the reference beam (B1), the increase was (14 %) only, the (45˚) fiber strip should be wrapped in a continuous spiral around the beam or anchoring the (45˚) CFRP strips in the web and flange. Presence of fiber in beams (B390WF) and (B845WF) decreases the ductility and absorption capacity as compared with the reference beam (B1).

Beam (B390WF) attained higher ultimate torque than beam (B845WF) (the increase of about 15%).

It can be seen from Fig (16), that the presence of fiber decreases the elongation of the T beam, but the (45º) CFRP strengthening restricted the beam elongation more than (90º) CFRP strengthening.

The failure mode of beam (B390WF) was excessive concrete cracking, which caused diagonal cracks in concrete in the web and led to premature debonding of the fiber sheets and thus allowing concrete failure as shown in Fig (14). In contrast, the failure mode of beam (B845WF) was delamination of CFRP strips at the edge of flange and cover spalling of concrete at the edge of flange as shown in Fig (17).

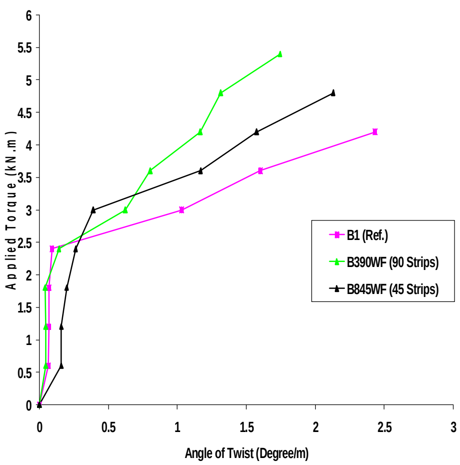

Figure (15) Torque - Twist Behavior: Effect of Fiber OPrientation

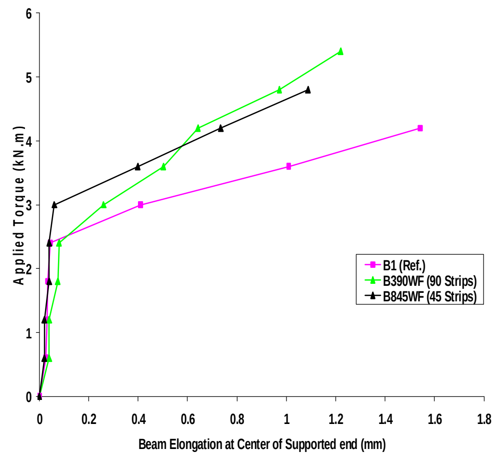

Figure (16) Beam Longitudinal Elongation Behavior: Effect of Fiber

Figure (17) Mode of Failure of Strengthened Beam B845WF (45˚ Strips in Web and Flange)

EFFECT OF STRENGTHENING IN LONGITUDINAL AND TRANSVERSE DIRECTION

To understand the influence of strengthening in the transverse direction in both web and flange (CFRP strips as stirrups of 50 mm width each 150 mm c/c) and additional CFRP strips of (50 mm) width parallel to the longitudinal axis of the beam in web and flange, this group of beams was used to show this influence (B1, B390WF, B690WFL).

Beam (B690WFL) is compared with beam (B390WF) from Tables (4, 5) and Fig (18). The cracking strength was not increased when the beam was strengthened with additional longitudinal CFRP strips (beam B690WFL). This kind of strengthening in beam (B690WFL) provides considerably higher ductility and energy absorption capacity when compared with beam (B390WF) and reference beam (B1). Also, the post - cracking torsional twist will increase when the T beam was strengthened with additional longitudinal CFRP strips.

The longitudinal CFRP was slightly effective in upgrading the ultimate strength of the T beam; beam (B690WFL) carried an ultimate torque (28 %) over beam (B390WF).

As can be seen from Fig (19), the presence of longitudinal CFRP strips in beam (B690WFL) reduced the beam elongation as compared with the reference beam (B1) and beam (B390WF). That means the longitudinal CFRP restrains cracks from propagation and widening.

The failure mode of beam (B390WF) was that excessive concrete cracking occurred, which caused diagonal cracks in concrete in the web leading to premature debonding of the fiber sheets and thus allowing concrete failure as shown in Fig (14). In contrast, the failure mode of beam (B690WFL) was vertical splitting of concrete in the corner between the web and flange as shown in Fig (20).

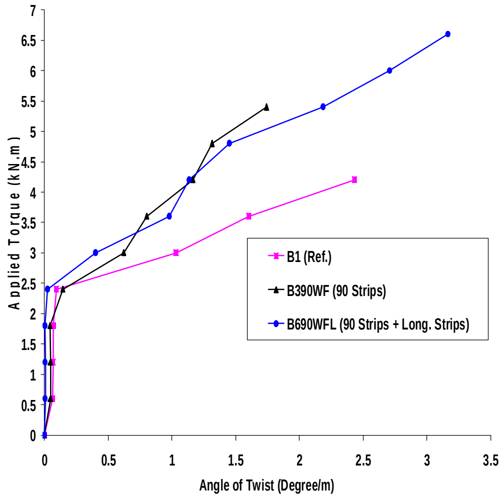

Figure (18) Torque - Twist Behavior: Effect of Strengthening in Longitudinal and 90˚ Transverse Direction

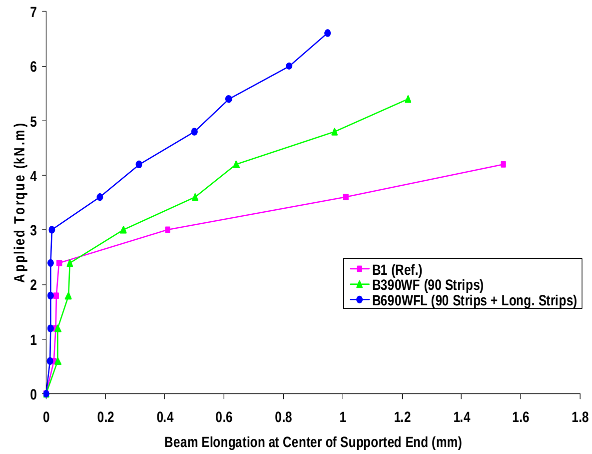

Figure (19) Beam Longitudinal Elongation Behavior: Effect of Strengthening in Longitudinal and 90˚ Transverse Direction

Figure (20) Mode of Failure of Strengthened Beam B690WFL (90˚ Strips + Long. Strips)

EXPERIMENTAL CFRP STRAIN RESULTS

Table (6) includes the experimental CFRP gauge strain readings for all beams at concrete failure. All values of strain were below the CFRP ultimate strain of (1.5 %) (from the manufacturer).

It is clear that the large values of strain means that very high localized stresses in the strips occur where the cracks pass through, while much lower values will be recorded away from the cracks.

It is important to note that the stress values in the CFRP were negligible up to the load level corresponding to the formation of the first cracks for the reference beam [15]. This result proves that the retrofitted material begins working only after sufficient cracking occurred in the concrete member.

Table (6) Experimental CFRP Strain Gauge Readings for Beams at Concrete Failure

Beam No.	Strain in right face		Strain in left face		Range of strain
	Edge strip	Middle strip	Edge strip	Middle strip	
B1	---	---	---	---	---
B290W	0.0015	0.00081	0.000082	0.0061	0.00061-0.0015
B390WF	0.0036	0.00057	0.0009	0.0006	0.00052-0.0036
B690WFL	0.005	0.0015	0.000077	0.00035	0.000077-0.005
B845WF	0.009	0.00042	0.0003	0.0002	0.0002-0.009

CONCLUSIONS AND RECOMMENDATIONS

Based on the results obtained from the experimental work, the following conclusions are presented.

(1) Reinforced concrete T beams strengthened with (90º) CFRP strips in the web only exhibited slight increases in the ultimate strength up to (29 %) without increase in cracking torque. The results showed the same percentage of increase with additional strengthening in the flange with the strengthening in the web.

(2) Effect of fiber orientation on reinforced concrete T beams strengthened with discontinuous form of CFRP in the web and flange showed increases in ultimate strength up to (29 %) for (90º) CFRP scheme with no increase in cracking torque. While, the increase in ultimate strength for (45º) CFRP scheme was (14 %) with an increase in cracking torque by (25 %). For effective strengthening, the (90º) or (45º) CFRP strips should be applied continuously in a spiral form all around the beam or anchoring the CFRP in the web and flange. Fiber bonded on the web and flange separately without continuity failed to provide significant torsional resistance.

(3) When combining CFRP strips in the longitudinal direction of the T beam in the web and flange followed by transverse (90º) CFRP strips in the web and flange, the results showed that there was an additional increase in ultimate strength (28 %) without any increase in cracking strength. The longitudinal CFRP was slightly effective in upgrading the ultimate strength of the T beam similar to the longitudinal torsional reinforcement; this kind of strengthening influenced the crack propagation and enhanced the failure mode and ductility.

(4) The strengthening scheme of (90º) CFRP strips in the web and flange with additional longitudinal CFRP strips in the web and flange is more efficient in upgrading the torsional resistance of reinforced concrete T beams than (45º) CFRP scheme.

(5) The scheme of CFRP for both (90º) and (45º) CFRP showed the least twist capacity as compared with the reference beam (unstrengthened beam), due to peeling of CFRP strips along the sides or upper flange of the T beam.

(6) The presence of (90º) or (45º) CFRP in the web and flange decreases the ductility and energy absorption capacity of the T beam as compared with the reference beam.

(7) Using the longitudinal CFRP strips with (90º) or (45º) CFRP enhanced the twist capacity of the T beam and the failure was splitting of concrete between web and flange.

(8) Ductility and energy absorption capacity of the T beam increase considerably when the T beam is strengthened with additional longitudinal CFRP strips.

(9) The strengthening of T beams in torsion with external CFRP strips is more effective in restraining the beams from elongation.

The following recommendations are made for future research in CFRP field.

(1) Investigation of the torsional behavior of reinforced concrete T beams strengthened with CFRP using anchoring.

(2) Studying the torsional behavior of prestressed reinforced concrete T beams strengthened with CFRP laminates.

(3) Investigation of the behavior of reinforced concrete beams with different cross sections (i.e. rectangular section, T section and L section) strengthened with CFRP under combined effect of bending, shear and torsion.

(4) Studying the behavior of reinforced concrete columns strengthened with CFRP under the effect of pure torsion.

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