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STRENGTHENING OF REINFORCED CONCRETE BEAMS UNDER COMBINED TORSION AND BENDING USING CARBON FIBER REINFORCED POLYMER STRIPS

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Abstract

Externally bonded, CFRP sheets are currently being studied and applied around the world for the repair and strengthening of structural concrete members. The experimental work includes investigation of four groups of beams. The first group includes two beams tested under combined torsion and bending (when torsion prevails T / M > 1). The second group includes two beams tested under pure torsion. The third group includes two beams tested under combined torsion and bending (when bending prevails T / M < 1). The fourth group includes two beams tested under pure bending.

Test results were discussed based on torque – twist behavior, bending moment-deflection, beam elongation, failure modes and influence of CFRP on ultimate torque, ultimate bending moment.

Keywords: Torsional Reinforced Concrete, CFRP Strengthening, Bending.

تقوية العتبات الخرسانية المسلحة تحت تأثير الحمل المركب من اللي والانحناء باستعمال شرائح من اللدائن الكاربونية المسلحة

الخلاصة

الدراسات والتطبيقات الشائعة لصفائح اللدائن الكاربونية المسلحة والتي تلصق خارجيا لتصليح وتقوية الأعضاء الإنشائية الخرسانية.

الجانب العملي يتضمن التحريات لأربعة مجاميع من العتبات. المجموعة الأولى تضمنت عتبتان تم فحصهما تحت تأثير أحمال اللي والعزم (عند وضوح تأثير عزم اللي T / M > 1). المجموعة الثانية تضمنت عتبتان تم فحصهما تحت تأثير أحمال اللي الصرفة. المجموعة الثالثة تضمنت عتبتان تم فحصهما تحت تأثير أحمال اللي والعزم (عند وضوح

تأثير عزم الانحناء (T / M < 1). المجموعة الرابعة تضمنت عتبتان تم فحصهما تحت تأثير أحمال الانحناء الصرفة.

تم مناقشة نتائج الفحص اعتمادا على تصرف عزم اللي – زاوية الدوران, عزم الانحناء– الهطول، استطالة العتبة, أطوار الفشل وتأثير اللدائن الكاربونية المسلحة على عزم اللي الأقصى وعزم الانحناء الأقصى.

1. Introduction

For the satisfactory performance of the existing structural system such as bridges, the need for maintenance and strengthening is inevitable. Engineering challenges such as increases 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.

Externally bonded, CFRP sheets are currently being applied around the world for the repair or strengthening of structural concrete members [1]. FRP materials are of great interest to the civil engineering community because of their superior properties such as high stiffness and strength as well as ease of installation, also the non – corrosive and non – magnetic nature with its resistance to chemicals.

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 [2, 3].

Researches related to the strengthening of R. C. members with CFRP under pure torsion are very limited [4, 5, 6, 7]. The lack of experimental and analytical studies along with the increasing interest in the use of FRP materials in the repair and rehabilitation of concrete structures led to this study to investigate the behavior of reinforced concrete beams strengthened with CFRP sheets under combined torsion and bending.

2. Research objective

The objective of this investigation is to evaluate the effectiveness of CFRP strengthening of reinforced concrete rectangular beams subjected to combined torsion and bending. Discussions are presented regarding the ultimate torque and ultimate bending moment, mode of failures, deflection and angle of twist of the beams and beams elongations.

3. Experimental Program

3.1. Test Beams

Eight medium scales reinforced concrete rectangular beams; 1500 mm long having 120 mm x 200 mm cross section were constructed for this study.

The tested beams were divided into four groups.

The first group contain two beams (B_1, S_1) were tested under combined torsion and bending, when torsion prevails $T / M > 1$, B_1 was tested without CFRP as a control beam while S_1 was tested with CFRP. The second group contain two beams (B_2, S_2) were tested under pure torsion; B_2 was tested without CFRP as a control beam while S_2 was tested with CFRP. The third group contain two beams (B_3, S_3) were tested under combined torsion and bending, when bending prevails $T / M < 1$, B_3 was tested without CFRP as a control beam while S_3 was tested with CFRP. The fourth group contain two beams (B_4, S_4) were tested under pure bending, B_4 was tested without CFRP as a control beam and S_4 was tested with CFRP.

In all the strengthened beams, one layer of CFRP was used with the same strengthening scheme using 40 mm wide CFRP strips spaced 150 mm c/c with a development length of (120 mm), the total length of each strip was (760 mm). The cylinder compressive strength of concrete was 30 N/mm^2.

3.2. Specimens Reinforcement

Torsion leads to an axial force which must be resisted by longitudinal reinforcement [8]. If torsion occurs in a region of a reinforced concrete beam when moment also acts, the longitudinal torsion reinforcement in the flexural torsion zone is added to the flexural reinforcement in the flexural compression zone. The compression due to flexural reduces the need for longitudinal torsion reinforcement.

In order to avoid failure of the beams at torsional and flexural cracking load, each beam was designed to have a steel reinforcement of 2% 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 [8], to maintain 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 (1).

The specimens were reinforced with (4Φ 10 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 0f (0.4 m) long on each end of the beam were reinforced with (Φ 6 mm) stirrups spaced at (40 mm) on centers. The test region of (0.7 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 6 mm) stirrups spaced at (70 mm) on centers.

The yield stress and ultimate strength of steel reinforcing bars used in this study are summarized in table (1).

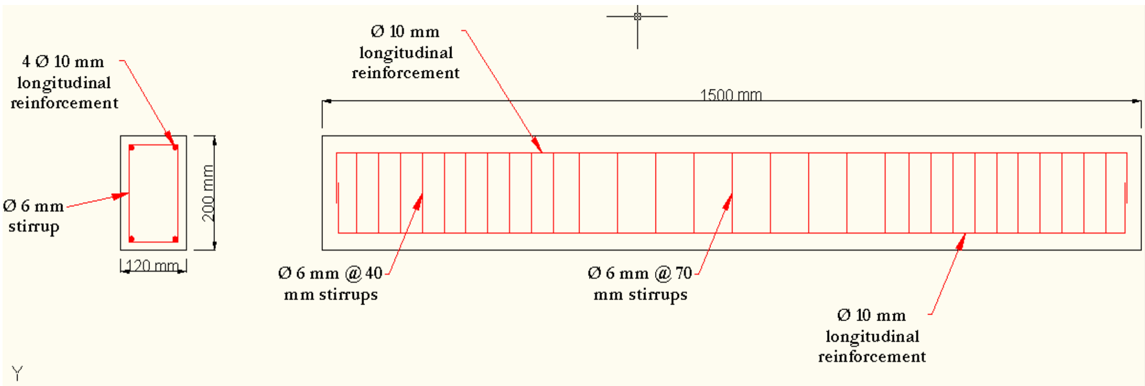

Fig (1) Details of Beam Reinforcement

Table (1) Specification and Test Results of Steel Reinforcing Bar Values

Nominal diameter (mm)	Measured diameter (mm)	Yield stress(*) (MPa)	Ultimate strength (MPa)	Modulus of elasticity(**) (GPa)
6	5.91	383	545	200
10	10.13	530	654	200

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

3.3. CFRP Material Properties

The Sika Wrap Hex – 230C is an externally applied strengthening or repairing system for structural members made of reinforced concrete. This system was supplied by (Sika Near East s. a, I. Beirut – Lebanon). Epoxy based impregnating resin Sikadur – 330 was used with fabric. The following information related to this system is listed in table (2) and table (3).

Table (2) Sika Wrap 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/m²**
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

Table (3) 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

3.4. Testing Procedure

The hydraulic universal testing machine (MFL system) shown in Fig (2A) 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 used in this research is shown in Fig (2A) and Fig (2B). This frame consists of two 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.

The steel girder of (100 mm) depth and (2 m) length is used to transmit the loads from the center of the universal machine to the two arms. This girder was clamped to the universal machine as shown in Fig (3).

Group one of beams (B_1, S_1) was tested under torque and bending T / M > 1 up to failure as shown in Fig (2B). Group two of beams (B_2, S_2) were tested under monotonically increasing torque up to failure as shown in Fig (2A). Group three of beams (B_3, S_3) were tested under torque and bending T / M < 1 up to failure as shown in Fig (3). Group four of beams (B_4, S_4) were tested under monotonically increasing bending up to failure as shown in Fig (4). At each load increment readings were acquired manually and cracks were recorded according to their occurrence.

Fig (2A) Clamping Torsional Arm (pure torsion)

Fig (2B) Clamping Torsional Arm (T / M =1.38)

Fig (3) Clamping Torsional Arm
(T / M = 0.75)

Fig (4) Pure Bending Moment Setup

3.5. Measuring Instruments
3.5.1. Angle of Twist Measurements

A simple method was used to estimate the angle of twist by using dial gage attached to the bottom fiber of the end of the beam at a point (45 mm) from the center of the longitudinal axis of the beam as shown in Fig (5). The dial gage recorded the down value to find the twist angle in radians.

Fig (5) Angle of Twist Measurement

3.5.2. Deflection Measurements
Deflection of the samples is investigated at midspan by dial gage having an accuracy of (0.002 mm) Fig (4) and Fig (6).
3.5.3. Elongation Measurements
Two dial gages were fixed at the center of the beam ends to measure the elongation of the beam as shown in Fig (7).

Fig (6) Dial gage distribution

Fig (7) Elongation Measurements

4. Results and Discussion

4.1. Deflection analysis for combined loading case (T / M =1.38)

Fig (8) shows the relation between bending moment and midspan deflection under combined torsion and bending for unstrengthened R.C beam (B1) and strengthened beam with CFRP (S1). It can be noticed that midspan deflection decreases with strengthening the R.C beam.

Table (4) shows the results of ultimate bending moment and ultimate midspan deflection for specimens (B1, S1). It can be seen that the ultimate bending moment of the beam increases by (108.7 %) when strengthened with CFRP.

Table (4) Deflection results for beam specimens

Beam No.	Ultimate Bending Moment (KN m)	λ =T / M	Midspan Deflection (mm)
B1 without CFRP	4.6	1.38	8.2
S1 with CFRP	9.6	1.38	5.5

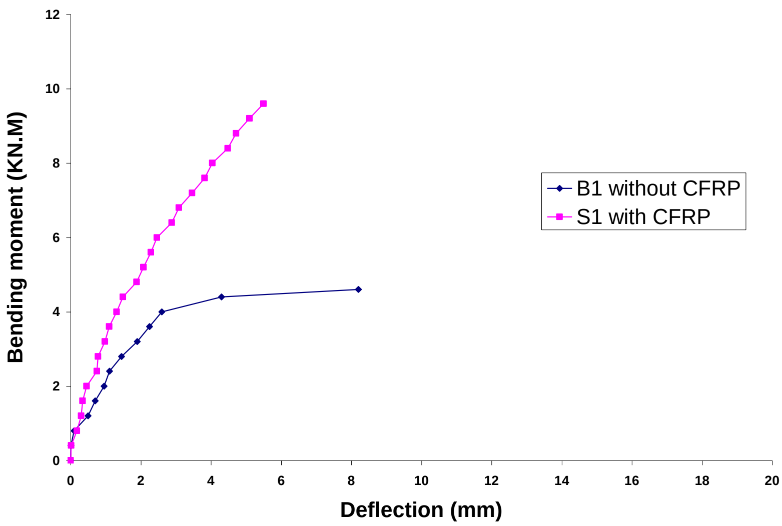

Fig (8) Bending moment-midspan deflection behavior (T / M = 1.38)

4.2. Angle of twist analysis for combined loading case (T / M = 1.38)

Fig (9) shows the relation between the applied torque and the angle of twist under combined torsion and bending for unstrengthened R.C beam (B_2) and strengthened beam with CFRP (S_2). The main result is the increasing of the angle of twist with respect to increasing of the torque and also it decreases with respect to strengthen the beam with CFRP.

Table (5) shows the results of ultimate torque and ultimate angle of twist for specimens (B_2, S_2). It can be seen that the ultimate torque of the beam increases by (108.5 %) when strengthened with CFRP.

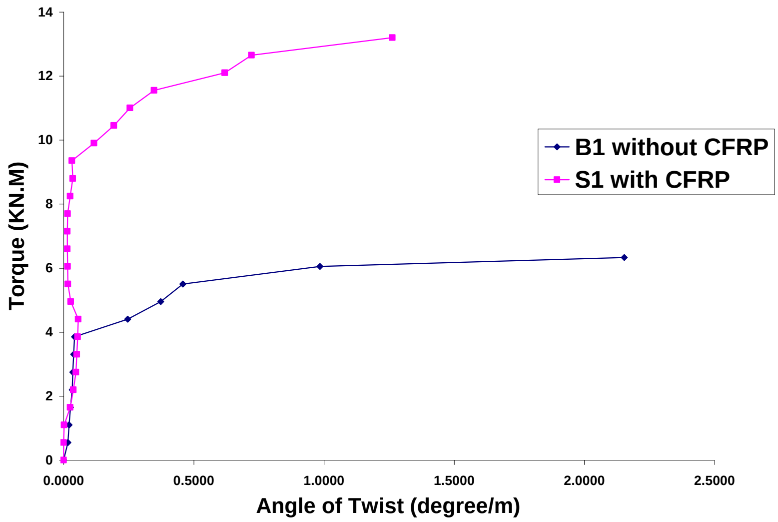

Fig (9) Torque-angle of twist behavior (T / M = 1.38)

4.3. Angle of twist analysis for pure torsion case

Fig (10) show the relation between the applied torque and the angle of twist for the specimens tested under pure torsion (B2, S2). The strengthening with CFRP decreases the angle of twist of the R.C beam. Fig (9) and Fig (10), shows the comparison between the angle of twist of specimens (B1, S1) for combined bending and torsion (T / M = 1.38) and specimens (B2, S2) for pure torsion.

Table (5) shows the results of ultimate torque and ultimate angle of twist for specimens (B2, S2). It can be seen that the ultimate torque of the beam increases by (150 %) when strengthened with CFRP.

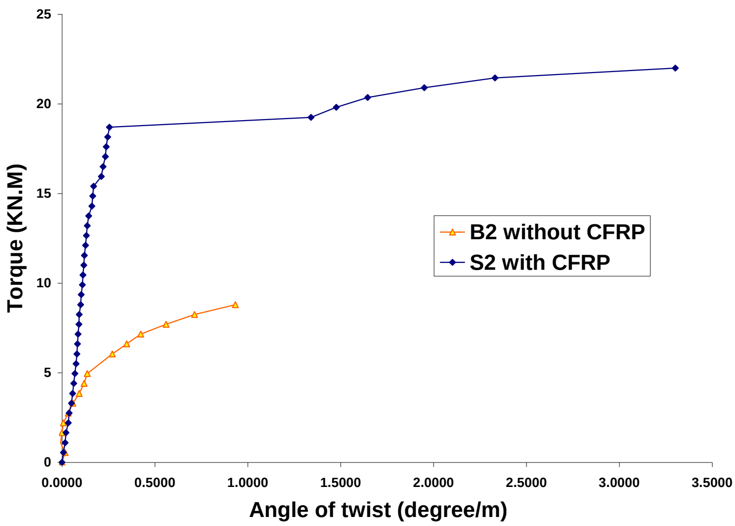

Fig (10) Torque-angle of twist behavior (pure torsion)

Table (5) Angle of twist results for beam specimens

Beam No.	Ultimate Torque (KN m)	λ =T/M	Ultimate Angle of twist θ (degree/m)
B1 without CFRP	6.33	1.38	2.154
S1 with CFRP	13.2	1.38	1.894
B2 without CFRP	8.8	**Pure torsion**	0.934
S2 with CFRP	22	**Pure torsion**	3.302

4.4. Elongation analysis

Fig (11) and Fig (12) show the relation between the elongations of the beams under applying load.

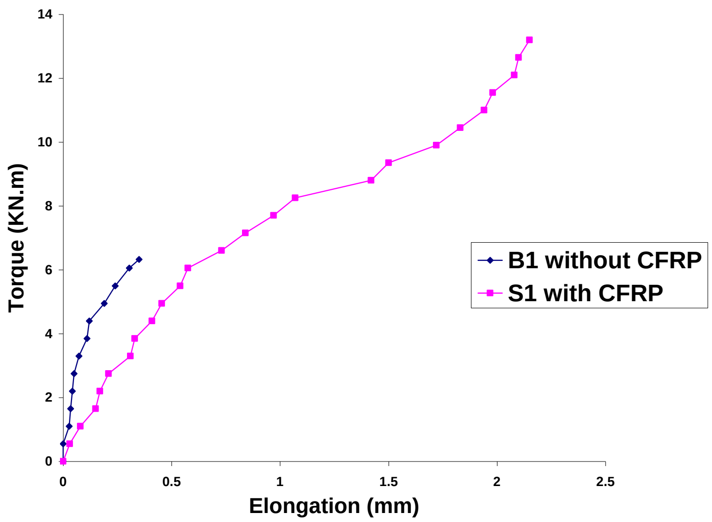

Fig (11) Torque-Beam elongation behavior (T / M = 1.38)

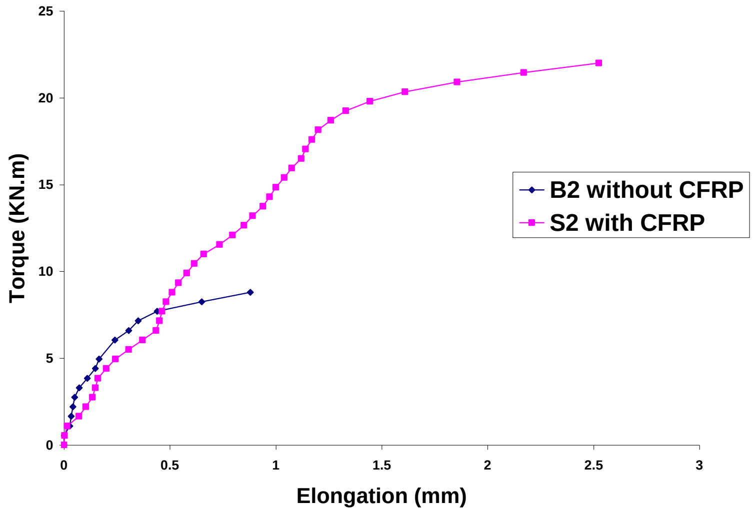

Fig (12) Torque-Beam elongation behavior (pure torsion)

4.5. Modes of failure

Figures (13), (14), (15) and (16) show the failure modes for the tested beams.

The mode of failure of (B1) was concrete cracking (the torsional cracks appears first followed by bending cracks).

The mode of failure of (S1) was a partial CFRP delamination followed by extensive concrete cracking between CFRP strips which ultimately resulted in beam failure. The mode of failure of (B2) was extensive diagonal concrete crack (torsional spiral cracks). The mode of failure of (S2) was rupture (tearing) the CFRP followed by extensive diagonal concrete cracks.

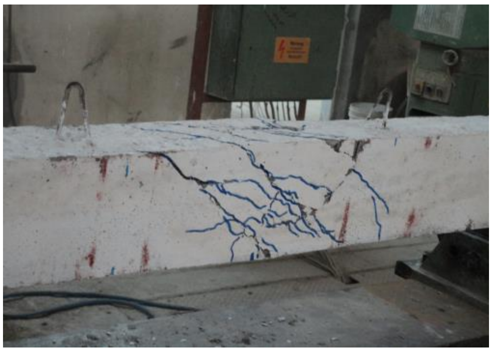

Fig (13) Mode of failure of unstrengthened Beam B1 (T / M = 1.38)

Fig (14) Mode of failure of strengthened Beam S1 (T / M = 1.38)

Fig (15) Mode of failure of unstrengthened Beam B2 (pure torsion)

Fig (16) Mode of failure of strengthened Beam S2 (pure torsion)

4.6. Deflection analysis for combined loading case (T / M = 0.75)

Fig (17) shows the relation between bending moment and midspan deflection under combined torsion and bending for unstrengthened R.C beam (B3) and strengthened beam with CFRP (S3). It can be noticed that midspan deflection increases with strengthening the R.C beam (M >T).

Table (6) shows the results of ultimate bending moment and ultimate midspan deflection for specimens (B3, S3). It can be seen that the ultimate bending moment increases by (68.8 %) for the CFRP strengthened beam.

Table (6) Deflection results for beam specimens

Beam No.	Ultimate Bending Moment(KN m)	λ =T/M	Midspan Deflection (mm)
B3 without CFRP	6.4	0.75	2.6
S3 with CFRP	10.8	0.75	5.04
B4 without CFRP	17.6	Pure bending	6.2
S4 with CFRP	29.2	Pure bending	11.9

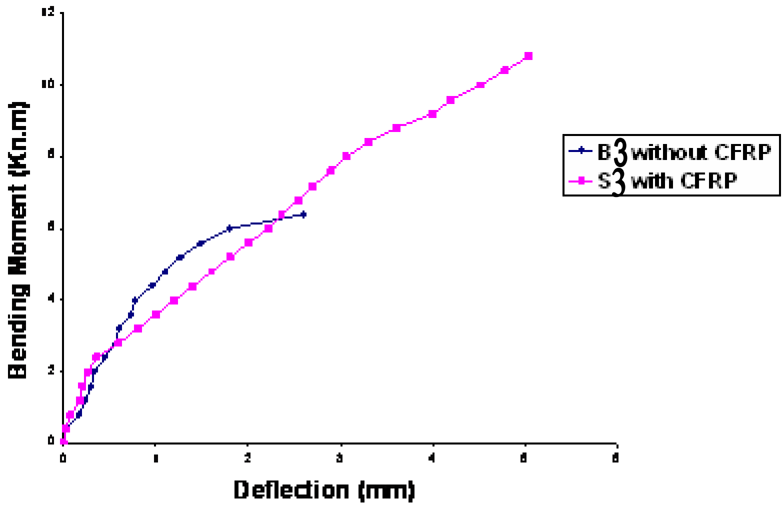

Fig (17) Bending moment-midspan deflection behavior

$$\left(\frac{T}{M} = 0.75\right)$$

4.7. <u>Angle of twist analysis for combined loading case (T / M = 0.75)</u>

Fig (18) shows the relation between the applied torque and the angle of twist under combined torsion and bending for unstrengthened R.C beam (B3) and strengthened beam with CFRP (S3). The main result is the increasing of the angle of twist with respect to increasing of the torque and also it increases with respect to strengthen the beam with CFRP.

Table (7) shows the results of ultimate torque and ultimate angle of twist for specimens (B3, S3). It can be seen that the ultimate torque increases by (69.6 %) when the beam was strengthened by CFRP.

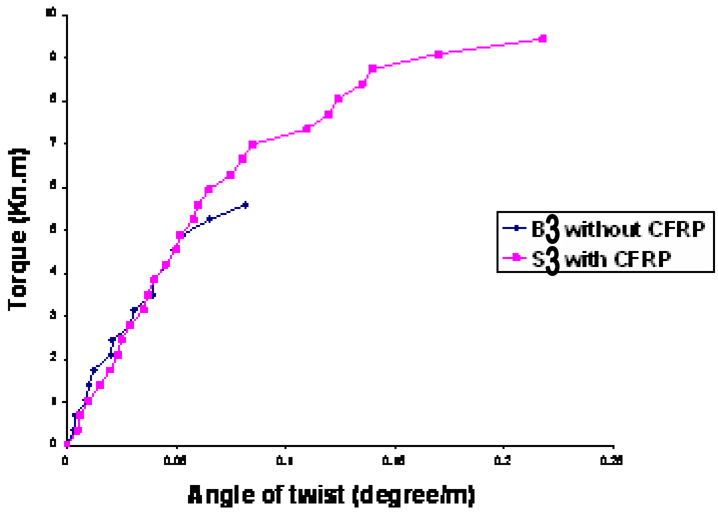

Fig (18) Torque-angle of twist behavior

$$\left(\frac{T}{M} = 0.75\right)$$

Table (7) Angle of twist results for beam specimens

Beam No.	Ultimate Torque (KN m)	λ=T/M	Ultimate Angle of twist θ (degree/m)
B3 without CFRP	5.6	0.75	0.0815
S3 with CFRP	9.5	0.75	0.218

4.8. Deflection analysis for pure bending moment case

Fig (19) shows the relation between bending moment and midspan deflection under pure bending moment for unstrengthened R.C beam (B4) and strengthened beam with CFRP (S4). It can be noticed that midspan deflection increases with strengthening the R.C beam.

Table (6) shows the results of ultimate bending moment and ultimate midspan deflection for specimens (B4, S4). It can be seen that the ultimate bending moment increases by (65.9 %) when strengthened the beam with CFRP.

Fig (20) and Fig (21) show the deflection at midspan and under applied load for pure bending moment case.

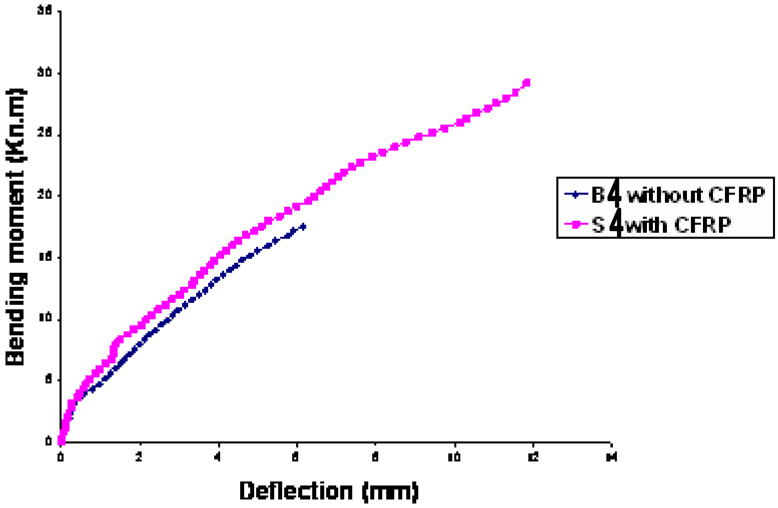

Fig (19) Bending moment –midspan deflection behavior (pure bending)

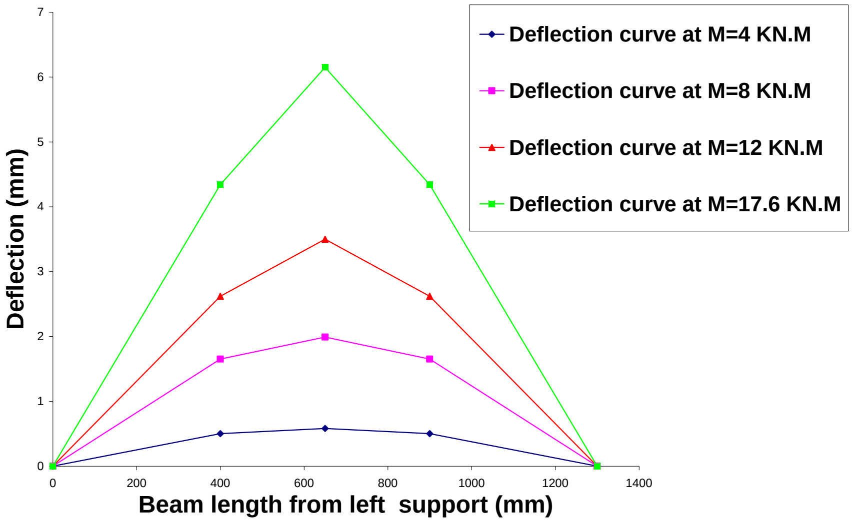

Fig (20) Deflected curves at various bending moment levels for beam (B4) without CFRP

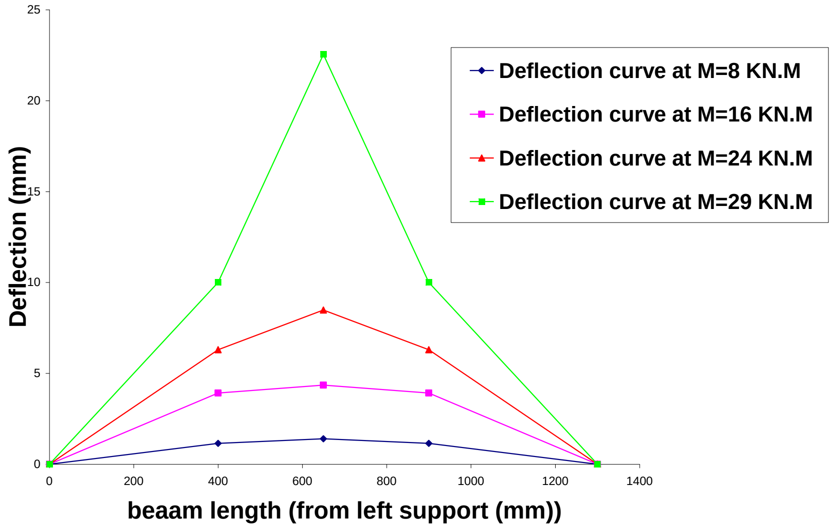

Fig (21) Deflected curves at various bending moment levels for beam (S4) with CFRP

4.9. <u>Elongation analysis</u>

Fig (22) shows the relation between the elongation of the beams under applying load.

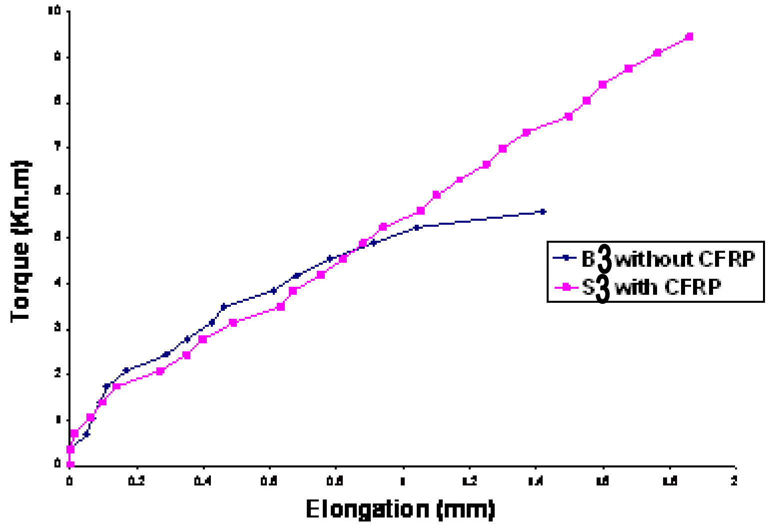

Fig (22) Torque-Beam elongation behavior

$$\left(\frac{T}{M}=0.75\right)$$

4.10. <u>Modes of Failure</u>

Figures (23), (24), (25) and (26) show the modes of failure for the tested beams.

The mode of failure of (B3) was concrete cracking (the bending cracks appears first followed by torsional cracks).

The mode of failure of (S3) was rupture (tearing) the CFRP followed by extensive diagonal concrete cracks.

The mode of failure of (B4) was extensive concrete cracks.

The mode of failure of (S4) was extensive concrete cracks between CFRP strips.

Fig (23) Mode of failure of unstrengthened Beam B3 (T / M = 0.75)

Fig (24) Mode of failure of strengthened Beam S3 (T / M = 0.75)

Fig (25) Mode of failure of unstrengthened Beam B4 (pure bending)

Fig. (26) Mode of failure of strengthened Beam S4 (pure bending)

5. Conclusions

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

(1) The strengthening of R.C rectangular beam with CFRP strips under combined torsion and bending (T / M > 1) increases the ultimate torque up to (108.5 %) and ultimate bending moment up to (108.7 %).

(2) The strengthening of R.C rectangular beam with CFRP strips under pure torsion increases the ultimate torque up to (150 %).

(3) The strengthening with CFRP will increase the cracking strength, post cracking twist and cracking stiffness for the case of pure torsion more than the case of combined torsion and bending.

(4) The strengthening of R.C rectangular beam with CFRP strips under combined torsion and bending (T / M < 1) increases the ultimate bending moment up to (68.8 %) and ultimate torque up to (69.6 %).

(5) The strengthening of R.C rectangular beam with CFRP strips under pure bending increases the ultimate bending moment up to (65.9 %).

(6) The strengthening with CFRP will increase the deflection corresponding to maximum bending for the case of pure bending more than the case of combined torsion and bending (T / M < 1).

(7) Elongation of the beam strengthened with CFRP under combined torsion and bending and under pure torsion cases were nearly the same because when the delamination or rapture of CFRP occurred, the cracks were developed and widened and the elongation of the beam increases with increasing of torque.

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