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Torsional behavior of strengthened reinforced concrete beams on two sides by CFRP using EBR Techniques

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Abstract
Retrofitting existing buildings or increasing the strength of new buildings has become a major issue in the world today to meet the new requirements. Many studies have sought new techniques to renovate old concrete structures. This paper presents four large scale RC box beams with hollow cross-sections measuring 400 mm x 400 mm and 3,000 mm in length that were tested under torsion; two beams were used as a control specimen whereas, the remaining two beams were partially strengthened for torsion on two sides by EBR-CFRP strips. The effeteness of the number of the layer have been discussed. The relationships between torsional moment and twisted angle, and the failure modes of the beam specimens are investigated. The ultimate torque capacity of beam specimens strengthened by EBR has resulted in improvements in the torque capacity of beams. Specifically, the enhancements were 15% when using one layer of CFRP while when using two layers of CFRP was 29%.

Keywords: CFRP, EBR, debonding, reinforced concrete beams.

1. Introduction

CFRP, as an external strengthening system, is the most common strengthening method. From 1980 to the present, the externally bonded reinforcement (EBR) system has been used to strengthen concrete structures. It consists of connecting the CFRP to the external surface of structural elements. The advantages of EBR are speed and easy application. The performance and effectiveness of this method depend on the adhesive matrix. The adhesive matrix is an influencing factor in the RC members' strengthening as an externally bonded reinforcement system. The epoxy adhesive is commercially available and widely used in the exhibition of structures. Nevertheless, the epoxy mortar loses bond properties in elevated temperatures and makes the externally bonded reinforcement system face the de-bonding problem of CFRP from concrete members' surfaces [1,2]. This problem is considered a disadvantage of the EBR technique. CFRP materials are possible to utilize as EBR when CFRP laminates or sheets are utilized as bonds using moist lay up to the outer surface of the members [3-5]. The enhancement of shear and torsional capacity may be necessary in both beams and bridge box girders. [6]. CFRP has demonstrated successful utilization for this specific objective [7,8].
Ameli et al. [9] showed several FRP configurations on twelve RC beams, each of which was 150mm wide and 350mm deep. Ten beams were wrapped with FRP in various configurations; two were used as reference specimens. Results were compared between different configurations, such as U-jacket along the beam length and U-jacket strip and complete wrap with single and double layers of FRP and vertical strips, employing GRFP and CFRP materials. For the purpose of illustrating the influence of FRP strengthening on flexibility, the ductility factor was calculated by dividing the twisted angle of maximum torque by the twisted angle at the yield point. The ANSYS program was used to perform the numerical modelling of FRP-reinforced RC beams. For the full-wrap strengthening method, the percentage improvement in ultimate torque ranged from 34% to 110% for GFRP and 45% to 143% for CFRP, based on the configurations. The outcomes also demonstrated an improvement in ductility and twisted angle for different FRP configurations. GFRP post-peak behavior takes some time to develop, but CFRP-strengthening beams almost immediately collapse after reaching their peak. Therefore, GFRP might be a preferable option for methods of earthquake strengthening. Experimental results showed that EBR FRP restricted crack width development and extended along the span, improving the contribution of concrete for torsion. In comparison to other configurations, the cracks were spread more regularly in completely wrapping beams. Mohammadizadeh et al. [8] studied the influence of various ratios of steel reinforcing on the behavior of strengthened beams having similar CFRP voluminous

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ratios. Beams reinforced with different quantities of torsional steel were divided into three groups and tested under purely torsional loads. All beam cross-sections were 150 mm wide and 350 mm deep. In the first group, the steel-to-concrete ratio was 1.56%; in the second group, it was 2.13%; and in the third group, it was 3.03%; these ratios account for both longitudinal and transverse reinforcements. Different steel stirrup ratios were found not to affect the strength of beams that had been completely wrapped with either one or two plies of reinforcement. However, the different steel reinforcing ratios were more noticeable for the strengthened beams with strips. Jing et al. [10] studied the influence of the U-wrapping strengthening procedure on box RC beams that responded to the combination effects of shear, cyclic torque and bending moment. Three EBR FRP box RC beams and one reference specimen were examined. One specimen was enhanced with transverse vertical strips, and the other two beams were refitted by anchorage on the top and bottom surfaces of two FRP longitudinal strips and vertical (single or double layers) strips. In this research, skeleton curves were displayed as an envelope derived depending on the torque- twisted angle cycle curve by collecting the ultimate value of every cycle in a similar direction loading. It was found that the FRP sheet's number of the vertical direction increased the deformation and torsional capacities. However, the FRP in the longitudinal direction had a lower strength effect than the vertical FRP. In a study conducted by Ameli et al. [4] examined four beams; the cross sections were rectangular, and the beams were enhanced with U-wrapping along the length of the beam and a strip U-wrapping, utilizing CFRP and GRFP materials. Results showed an improvement in torque capacity utilized by the U-jacket strengthening method, ranging from 14% to 32% for GFRP and 16% to 33% for CFRP, respectively. Furthermore, the GFRP material was less effective than CFRP. The entire wrapping technique's ultimate strengths were significantly more than the U-wrapping method.
At the current, there is no available data in the literature on the torsional behavior of RC beams strengthening on two sides only with the EBR technique. The current paper's ambition is to study the torsional performance of RC hollow beams strengthened by CFRP on two sides by EBR methods and assess the influences of the number of the layers.

2. Materials proprieties

Sulfate–resisting Portland cement type V supplied by a local supplier was used in this study. For the experimental work, natural coarse aggregate with a particle size of 19 mm was used. The concrete mixture utilized natural sand with a maximum particle size of 4.75 mm. In the present study, the Sika -Visco Crete 5930 (SP) was employed at a proportion of 0.4% relative to the weight of cement. SP is alternatively referred to as "High Range Water-Reducing Admixtures" (HRWRA). This form of superplasticizer effectively mitigates water content, enhances workability, and serves to mitigate the problem of segregation. The longitudinal reinforcement of each beam consists of eight rebars with a 12 mm diameter. In contrast, stirrups with an 8 mm diameter were spaced along the beam at 155 mm and 100 mm for ends region center to center to prevent sudden failure. One type of fiber has been utilized as CFRP materials. The epoxy was utilized in this study as an adhesive for the CFRP sheet in order to attach the CFRPs onto the surface of the concrete. The CFRP sheet used in this study was Sika Wrap®-300 C, and the adhesive paste was Sikadur ®-330. Furthermore, steel formwork was used to pour the concrete beams. The identical concrete mix with an average compressive strength (fcu) of 43 MPa was utilized in all of the reinforced concrete beams.

3. Details of beam samples

Four beams arranged into two groups, as illustrated in **Table 1**, were examined in the main experimental work with hollow section RC beams: 400 mm deep x 400 mm wide x 3000 mm long. Two control beams were considered, while the rest of the beams were strengthened using the EBR technique with epoxy resin. All beams designed to fail under torsion. **Figure 1** shows the details of reinforcement and the beam cross-section dimensions adopted for specimens. According to ACI 318-19 [11], all samples were under-reinforced; in order to model beams that might not be able to withstand twisting loads in the future, it was chosen to use a minimum distance between the reinforcement hoops based on ACI 318-19 [11]. For the first group, un-strengthen two beams as control beams were tested under pure torsion and denoted C-0 and C-1, respectively. For the second group, two beams were strengthened with EBR-CFRP sheet strips 100 mm width and 400 mm length on two sides only at 275 mm spacing perpendicular to the longitudinal axis of the beam with one layer and two layers for the first and second beams and denoted ES-1 and ES-2, respectively. **Figure 2** shows the details of the

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strengthening techniques.

Table 1. Summary of the test program.

Group	Code	CFRP type	No. of CFRP layers	CFRP orientation	Dimensions of CFRP pieces (mm)	
					Width	Length
1	C-0	-	-	-		-
	C-1	-	-	-		-
2	ES-1	Sheet	1	90^o	100	400
	ES-2		2	90^o	100	400

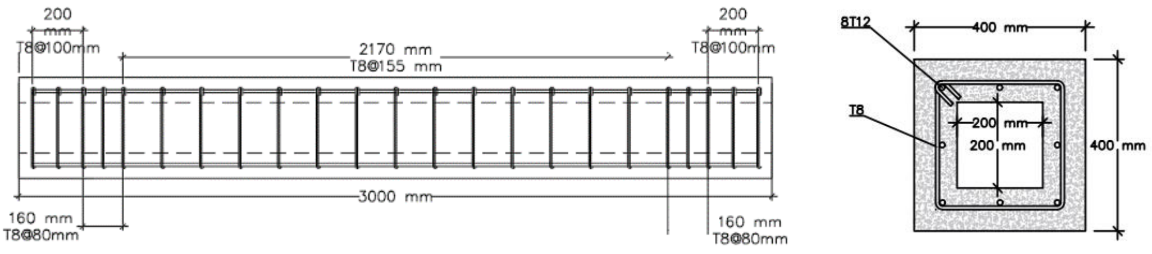
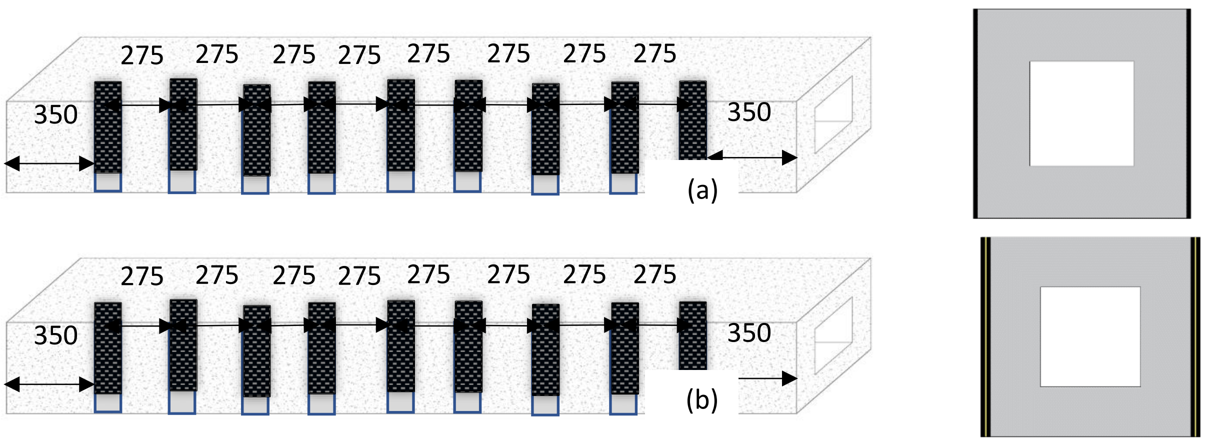


Figure 1: beams details: (a) longitudinal -section of beams; (b) the cross-section of beams



Figures 2: Strengthening configuration (a) EBR CFRP-sheet on two sides with one-layer (**ES-1**) (b) EBR CFRP-sheet on two sides with two-layers (**ES-2**)

4. EBR strengthening

In this method, the concrete surface was prepared prior to the CFRP application using a grinder machine with a special disk to remove a thin covering of the concrete. Then, the exposed surface was cleaned using compressed air after preparing the concrete surfaces; the CFRP was cut to the specified lengths and widths. The epoxy resin was prepared by mixing components A and B according to the manufacturer's instructions. It utilized an electric drill-mounted mixing spindle in a container for about three minutes, or until the material's consistency changed to smooth and its colour became uniformly grey. A layer of epoxy resin was then spread on the concrete surface and the CFRP pieces. Eventually, the CFRP was carefully applied to the concrete surface. A roller plastic tube that moved in a direction parallel to the fibre was used to remove any existing air underneath the CFRP and distribute resin evenly beneath the CFRP once the CFRP materials had been applied successfully. Finally, all strengthened specimens were cured for seven days at laboratory temperature according to the manufacturer's instructions. **Figure 3** shows the EBR strengthening.

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Figure 3: EBR strengthening.

5. Testing Methods

Figure 4 depicts the specialized torsion rig system employed for the purpose of testing the beams. In this experimental setup, a steel frame, which was outfitted with an exterior clamping collar, was employed to establish a stationary support for the beams at one extremity. Meanwhile, torsion was induced by means of a hydraulic piston and a steel arm loading located at the opposite end of the beam. The experimental testing was conducted using displacement control as the governing parameter. Linear Variable Differential Transformers (LVDTs) were strategically positioned at a distance of 800mm from the free end and 40mm from the bottom surface in order to gauge the mean torsional angle of rotation accurately.

Figure 4: Torsional test systems

6. Results and Discussion

This section includes the results achieved from the experimental testing of reinforcing concrete beam enhancement with CFRP sheet. The relationships between the torsional moment and angle of twist, crack figuration, the failure modes of the beam specimens, EBR strengthening method are investigated.

6.1 <u>Torsional moments-angle of twist relationships and failure modes</u>

Figure 5 displays the torque-twist curves for all seven beams. All beams initially exhibited linear elastic behavior, which was then followed by a significant rise in the twisted angle and a progressive increase in

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torque until failure. An overview of the test findings is presented in **Table 2**, measured torsion moments and angle of twist and failure patterns for all tested beams. The behavior` of each beam during the experimental test is presented and discussed in the sections below:

Control beam (C-0 and C-1): The first crack appeared at the loading side face and later progressed to the other three faces for the control beams. The crack torques were 32.141 kN.m and 31.74 kN.m for beams C-0 and C-1, respectively. The control beams have failed at ultimate torques of 37.835 kN.m and 38.014 kN.m with a corresponding twisted angle of 2.81^o and 2.88^o for beams C-0 and C-1, respectively. The ultimate strengths were close, with less than 0.5% difference; the average cracking torque and ultimate torque of two control beams were used for comparison; the crushing of concrete failure occurred, as shown in **Figure 6**.

Beam (ES-1): By using the EBR, this beam has been enhanced with a layer of CFRP sheet. The crack torque was 35.45 kN.m at a twisted angle of 1.746^{o,} and CFRP sheet de-bonding was encountered at an ultimate torque of 43.500 kN.m and twisted angle of 3.990^o. The failure pattern of beam ES-1 is depicted in Figure 9. In comparison to the reference specimen, the cracking and ultimate torque strength of the beam (ES-1) has risen by 11% and 15%, respectively. Furthermore, **Figure 7** shows that the twisted angle of the beam (ES-1) at failure was greater than the twisted angles of control beams (C-0 and C-1).

Beam (ES-2): The configuration of this beam has been enhanced through the application of two CFRP sheet layers utilizing the externally bonded reinforcement (EBR) technique. During the experiment, it was seen that when the applied load neared its maximum value, there was an occurrence of de-bonding of the carbon fibre-reinforced polymer (CFRP) sheet, which was then followed by the crushing of the concrete, as depicted in **Figure 8**. The crack torque was observed at 39.41 kN.m at a twisted angle of 1.26^o, and the maximum torque was observed at a value of 48.903 kN.m, accompanied by a rotational displacement of 4.326 degrees. The experimental beam exhibited a significant enhancement in its crack and ultimate capacity, with a notable increase of 23% and 29%, respectively, relative to the control specimens. The behaviour exhibited by this specimen was mostly comparable to that of (ES-1). The test results have shown that the implementation of a dual-layer strengthening technique has resulted in notable improvements in both torque capacity and twisted angle.

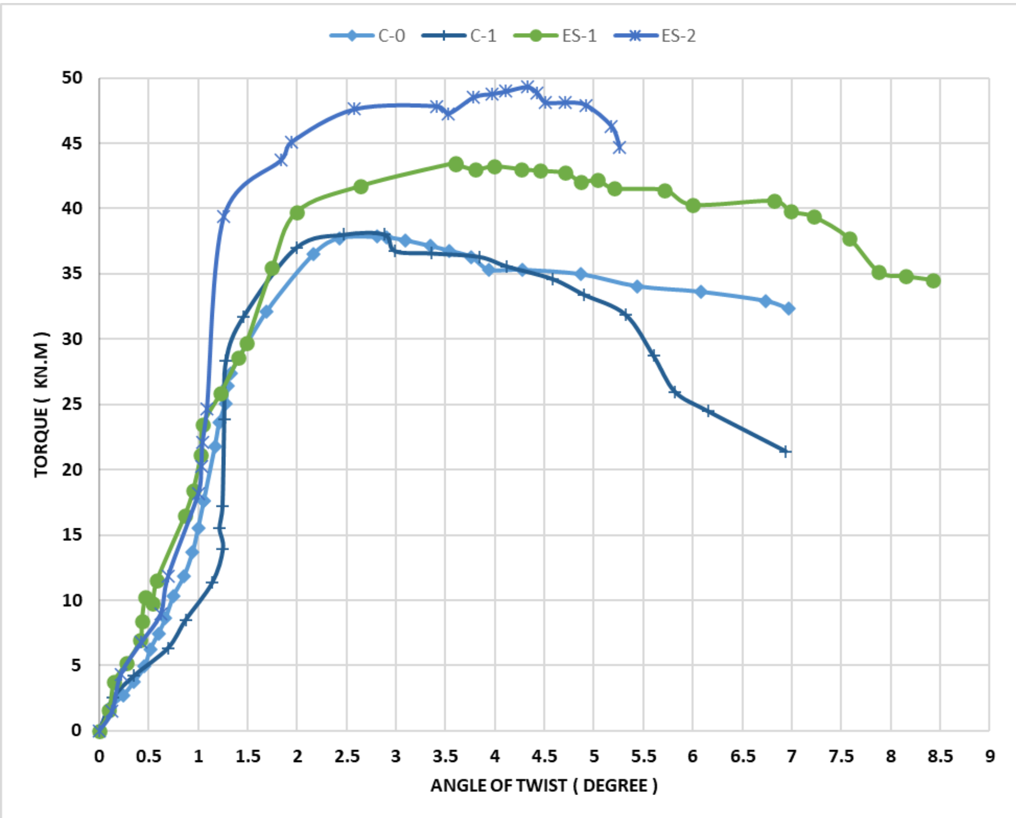

Figure 5: Torque-twist curve of the beams that were tested.

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Table 2. An overview of the test findings for the beams that were tested.

Identification code	Cracking torque kN.m (Tcr)	The angle of twist at cracking torque (Degree)	Ultimate torque kN.m (Tu)	The angle of twist at the ultimate torque (Degree)	Increasing in capacity	Mode of failure
C-0	32.141	1.693	37.835	2.810	-	Concrete crushing
C-1	31.74	1.459	38.014	2.880	-	Concrete crushing
ES-1	35.452	1.746	43.500	3.990	15%	Debonding of CFRP
ES-2	39.41	1.261	48.903	4.326	29%	Debonding of CFRP

Figure 6: Control beam C-0 and C-1 failure and crack configuration

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Figure 7: Strengthened beam ES-1 failure and crack configuration

Figure 8: Strengthened beam ES-2 failure and crack configuration**.**

6.2 Layers of CFRP Number effect

The behavior of EBS-1 and EBS-2 has been tested in order to determine the effectiveness of the layers number of CFRP. **Table 2** shows that employing double layers in place of a singular layer has an increased capacity of 14% (i.e., 15% versus 29). Beams strengthened with singular layers or double layers fail similarly. Also,

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the twisted angle of the beam (ES-2) with two layers is greater than the twisted angle of the beam (ES-1) with one layer.

7. Conclusions

The present study aims to assess the efficacy of EBR procedures in enhancing the torsional strength of reinforced concrete (RC) beams through the application of carbon fiber reinforced polymer (CFRP) sheets. The following conclusions can be noted.

1. In general, the results obtained from the test showed that EBR utilization of carbon fiber-reinforced polymer (CFRP) sheets have led to a substantial enhancement in the ultimate torque and angle of twist of the tested beam specimens.
2. The torque capacity of beam specimens strengthened by EBR has resulted in improvements in the torque bearing capacity of beams. Specifically, the enhancements have varied from 15% to 29% for EBR for one and two layers of CFRP respectively.
3. The twisted angle of beam specimens strengthened by EBR increased by 40.2% to 52%.
4. Employing double layers in place of a singular layer has an increased capacity of 14% (i.e., 15% versus 29).
5. The failure mode of strengthened beams using EBR occurred due to CFRP de-bonding.

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