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Torsional Behaviour of Strengthened Reinforced Concrete Beam on Two Sides by CFRP using NSM and EBROG Techniques

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Abstract

Increased resistance of RC beams is one reason that CFRP materials are being used extensively. The high durability, electromagnetic neutrality, high strength and weight ratio, rapid execution with less work, ease of handling, dimensions and geometry are advantages of the use of CFRP. The utilization of the near-surface mounted (NSM) and externally bonding reinforcement on grooves (EBROG) techniques are becoming recognised as viable solutions to improving the strength of structures. These solutions are successful in effectively addressing and mitigating the problem of debonding. This paper presents four full-size RC box beams with hollow cross-sections measuring 400 mm x 400 mm and 3,000 mm in length (clear span from the face to face of supports was 2400 mm) that were selected in this study; one beam was used as control specimen whereas, the remaining three beams were partially strengthened on two sides by NSM-CFRP laminate strips and EBROG-CFRP sheet strips. The strengthening methods and the effect of spacing in NSM on the torsional behaviour have been discussed. The relationships between torsional moment and twisted angle, ductility of the beam specimens are investigated. The ultimate capacity torque of beam specimens strengthened by NSM and EBROG has resulted in improvements in the torque capacity of beams. Specifically, the enhancements have varied from 13% to 17% for NSM and 6% for EBROG compared to the reference beam.

Keywords: *CFRP, NSM, EBROG, reinforced concrete beams.*

1. Introduction

The NSM technique provides enhanced resistance to de-bonding in order to address and alleviate these concerns. [1]. It is possible to strengthen the beams by putting CFRP bars into grooves made in the concrete covering; as a bonding agent [2]. Al-Bayati et al. [3] studied ten RC rectangular beams 140 mm x 260 mm x 2000 mm, the CFRP laminates were placed on all four faces of eight beams to strengthen them, and two control beams were examined. Four beams had epoxy adhesive, and the remaining four had new cement-based adhesive. Two groove separation distances were tested for each adhesive type. Based on the outcomes of the experiment, the NSM method is effective for enhancing the capacity torsion of reinforced concrete beams. For spacings of 0.75D and 0.375D, the ultimate torsion capacity of CFRP NSM laminates increased by 28.2% and 35.9% since the epoxy was used and by 23.4% and 26.5% if the cement-based adhesive was used. Torsion strength is increased by decreased groove spacing. The strength of the NSM approach may be constrained by the number of grooves (and their spacing), which

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altered along with the failure mechanism of the epoxy-coated beams. Gowda et al. [4] evaluated eight box beams with a hollow interior section of 200 mm by 200 mm and an exterior cross-section of 400 mm by 400 mm. Each beam is 1900 mm long, including two control and six strengthened beams evaluated using various NSM CFRP configurations. Two series were created from the reinforced beams: Series 1 had four beams that were strengthened on all four faces, whereas Series 2 had just two beams that were strengthened on three faces. The adopted NSM-CFRP strengthening configurations have provided an increase of the torsional capacity varying between 38 and 46% with respect to reference beams and an increase of ultimate torsional angle between 27 and 57%, an indicator of the favourable effect in terms of ductility. Beams strengthened on three faces (series two) failed by concrete crushing on the unstrengthen surface, and the Laminate strengthened beams failed by CFRP-rupture in the transition zone followed by concrete crushing. These systems were very effective in arresting the crack propagation, limiting the maximum crack width, which also has a beneficial effect on the durability of the Strengthened RC structures. Obaidat et al. [5] constructed and tested seven rectangular reinforced concrete RC beams of 250 mm x 250 mm x 1600 mm; taking into account the effect of inclination, length, and configuration of NSM-CFRP strips, they concluded that the torsional moment of beams is increased when using NSM-CFRP, Furthermore, Using NSM-CFRP postponed the cracking in concrete, because of the NSM-CFRP offers greater torsional capacity, and toughness are increased. Strengthening the beams with 45º NSM-CFRP in the web showed a considerable improvement in the torsional strength than 90º NSM-CFRP. Additionally, using a more length of NSM-CFRP slightly improve the torsional capacity and cracking torsional moment.The findings indicated that, in comparison to the control beam and when the RC beam is strengthened with inclined (45 degree) and vertical (90 degree) NSM-CFRP strips, the torsional moment could increase by up to 115.9-123% and 103.6%, respectively. Also, the ultimate torsional capacity was higher with longitudinal NSM-CFRP at the beam soffit or web and vertical or inclined NSM-CFRP at the web than with vertical or inclined NSM-CFRP strips. At the current, No works are concerned the effect of CFRP laminate spacing on two sides only when using the same amount of laminate CFRP using NSM technuqe, there are no studies investigating the torsional strength of concrete beams using EBROG and many researchers have focused on the shear and flexural strength of concrete RC beams utilizing EBROG method [6-12].The current paper's ambition is to study the torsional performance of RC hollow beams strengthened on two sides only by NSM and EBROG and assess the influences of spacing in near-surface mounted (NSM).

2. Materials proprieties

All of the materials utilized in the experiment, such as steel, aggregate and cement, were tested according to the ASTM standards. The longitudinal reinforcement of each beam consists of eight rebars with a 12 mm diameter with a yield strength of 484 Mpa . In contrast, stirrups with an 8 mm diameter with a yield strength of 330 Mpa were spaced along the beam at 155 mm and 100 mm to 80 mm for ends region centre to centre to prevent sudden failure. The CFRP sheet used in this study was Sika Wrap®-300 C, and the adhesive paste was Sikadur ®-330, the CFRP laminates used in this study were Sika carbodur. Sika carbodur is black material bonded upon the structural element as external strengthening by (sikadur-30LP) epoxy resin as binding material.

1. Test specimens preparation

The moulds have been made from steel plates for the outside body with a thickness of (3 mm) supported with steel angles L50x50x5. The internal dimensions of the moulds are 3000 mm in length, 400 mm in width, and 400 mm in depth; plywood of 3mm thickness was used for the inner parts to form a box with outside dimensions 200mm by 200 mm. Figure 1.a shows the mould used in the current study. The identical concrete mix with an average compressive strength (fcu) of 43 MPa was utilised in all of the reinforced concrete beams. The moulds were thoroughly cleaned, and a thin layer of oil was applied to the inside surfaces. Prior to the deposition of concrete into the mould, the process involved the placement of reinforcement within that mould. The concrete was poured into the mould in three distinct thicknesses. The compaction of each layer was achieved by the utilization of an electrical vibrating mechanism, which effectively eliminated any trapped air, as illustrated in Figure 1.b. The uppermost layer of the surface was skillfully completed with a steel trowel, shown in Figure 1.c. Also, three cubes (150x150x150) mm and two standard cylinders (300x150) mm were also cast for the batch. After casting, all specimens (beams, cubes and cylinders) were covered by polyethene sheets to prevent evaporation of water; after 2 days, moulds were dismantled, and the specimens were subjected to a curing process by being covered with a moistened canvas until reaching the necessary testing age of 28 days, as seen in Figure 1.d.

(a)

(b)

(c)

(d)

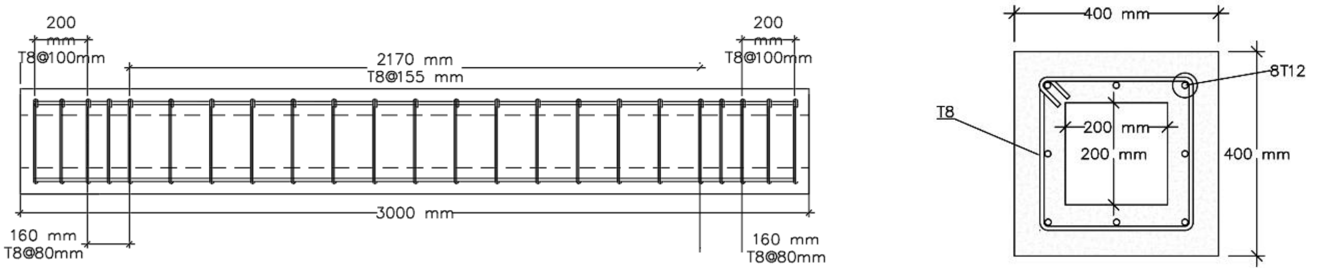
Figure 1. Test specimens preparation (a) Steel Mold preparation (b) Casting (ES-2) (c) Finishing (d) Curing

2. Details of beam samples

Four beams, 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. One control beam was considered, while the rest of the beams were strengthened using the NSM and EBROG techniques with epoxy resin. All beams designed to fail under torsion. Figure 2 shows the details of reinforcement and the beam cross-section dimensions adopted for specimens. According to ACI 318-19 [13], 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 [13]. Un-strengthen beam was tested under pure torsion and denoted C-0. The second beam was enhanced with NSM-CFRP laminate strips 10 mm wide at 210 mm spacing with groove dimensions 10 mm wide and 8 mm deep, and for the third beam, 20 mm width laminate strips at 460 mm spacing 20 mm wide and 8 mm, the amount of CFRP laminate and volume of grooves were the same for the second and third beams to identify the effect of the spacing. Finally, the fourth beam was strengthened by EBROG-CFRP, 20 mm sheet width with vertical grooves 20 mm width at 460 mm spacing perpendicular to the longitudinal axis of the beam on two sides only in the same way as the third beam. Figure 3 shows the details of the strengthening techniques. The saw cut machine is used to create the grooves in the cover of concrete with dimensions of 400 mm length, 10 mm / 20 mm width and 8 mm depth, the grooves were subsequently subjected to cleaning using direct brushing and compressed air. The grooves formation is depicted in Figure 4.

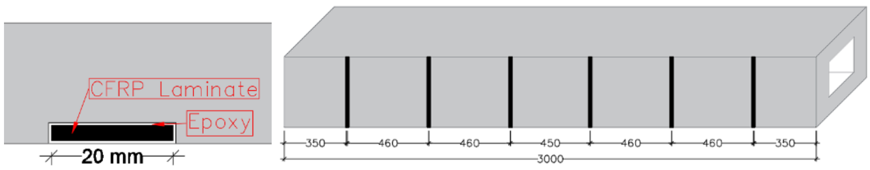
Table 1. Summary of the test program.

Beam	CFRP type	CFRP orientation	Grooves orientation	Dimensions of CFRP pieces (mm)		No. CFRP strip on both sides
				Width	Length	
C-0						
NL-10	Laminate	90	90	10	400	24
NL-20				20	400	12
EBS-S	Sheet			20	400	12

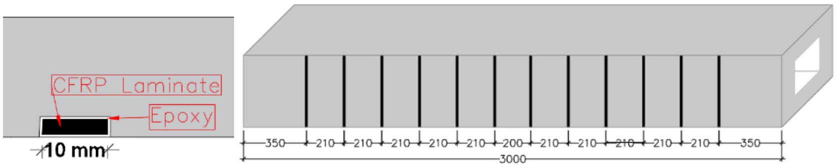


(a) (b)

Figure 2. beams details: (a) longitudinal -section of beams; (b) the cross-section of beams



(a)



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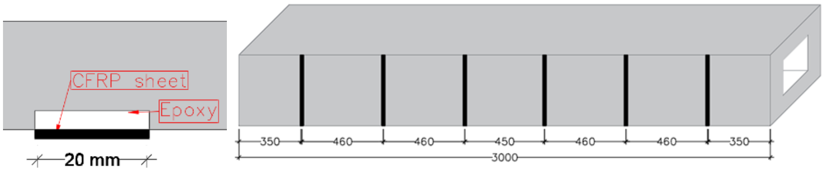

(c)

Figures 3. (a) NSM-CFRP on two sides, groove width=20 mm (NL-20), (b) NSM-CFRP on two sides, groove width=10 mm (NL-10). (c) EBROG on two sides with one layer width=20 mm (EBS-S).

Figure 4. The grooves formation.

3. Testing Methods

Figure 5 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 800 mm from the free end and 40 mm from the bottom surface in order to gauge the mean torsional angle of rotation accurately.

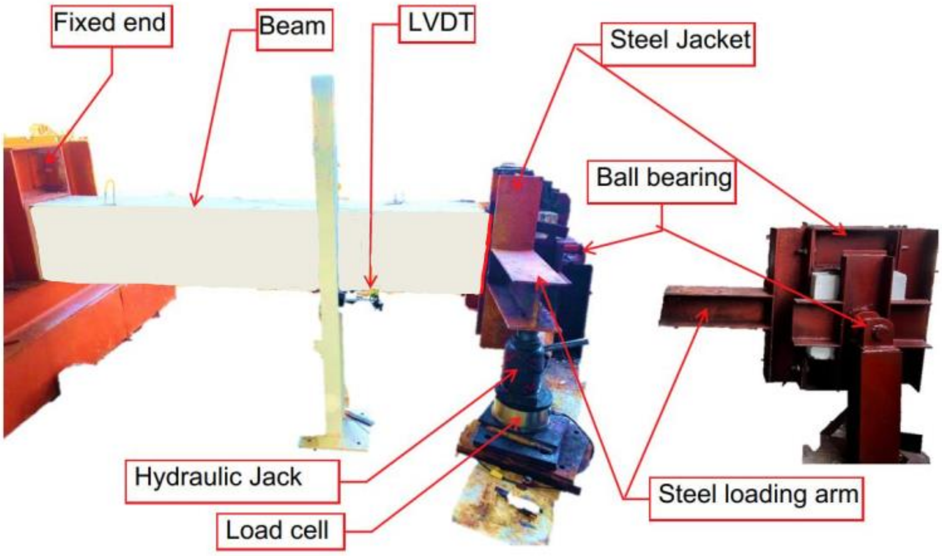

Figure 5: Torsional test systems

3. Results and Discussion

3.1 Torsional moments-angle of twist relationships and failure modes

Figure 6 displays the torque-twist curves for all four beams. All beams initially exhibited linear elastic behaviour, which was then followed by a significant rise in the twisted angle and a progressive increase in 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 behaviour of each beam during the experimental test is presented and discussed in the sections below:

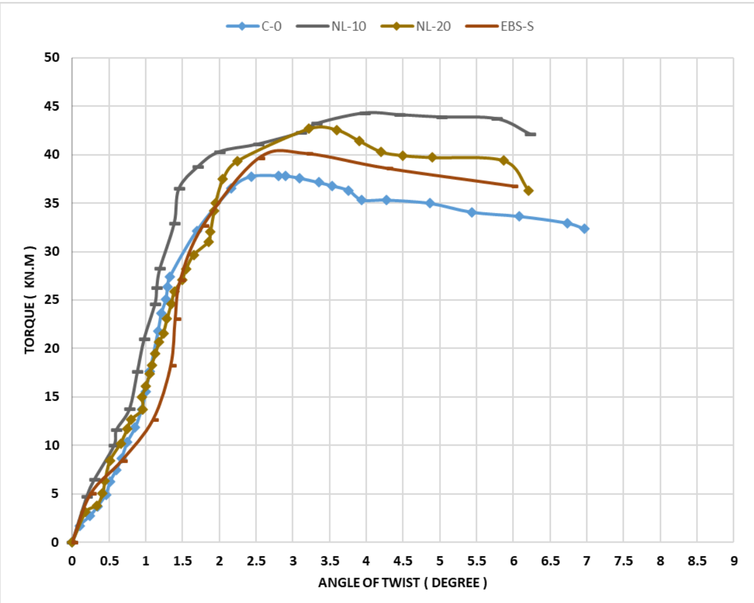

Figure 6. Torque-twist curve of the beams that were tested.

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

Beam	Tcr	θ_{cr}	Tu	θ_u	I.C	Mode of failure
C-0	32.141	1.693	37.835	2.81	-	Concrete crushing
NL-10	32.916	1.387	44.318	3.974	17%	Concrete crushing
NL-20	31.015	1.852	42.678	3.221	13%	Concrete crushing
EBS-S	32.70	1.780	40.120	3.393	6%	Concrete crushing

Tcr :Cracking torque (kN.m),θ_{cr}:The angle of twist at cracking torque (Degree), Tu:Ultimate torque (kN.m) , θ_u:The angle of twist at the ultimate torque (Degree) , I.C :Increasing in capacity

Control beam (C-0): The first crack appeared at the loading side face and later progressed to the other three faces, the crack torques were 32.141 kN.m and the control beam have failed at ultimate torques of 37.835 kN.m with a corresponding twisted angle of 2.81^o, the crushing of concrete failure occurred, as shown in Figure 7.

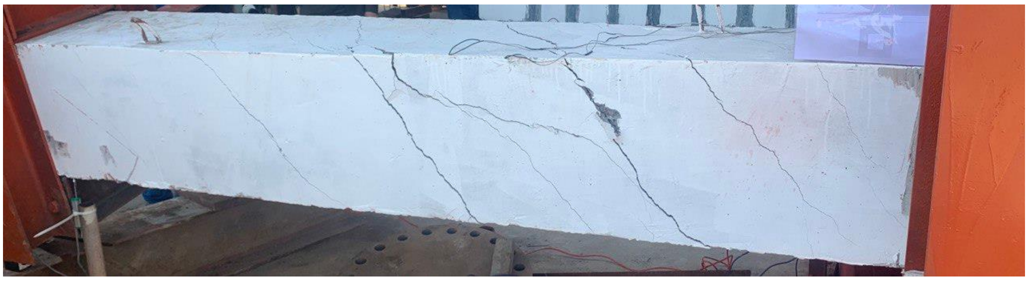

Figure 7: Control beam (C-0) failure and crack configuration

Beam (NL-10):The torsional strength of this beam has been enhanced through the application of a singular layer of carbon fibre-reinforced polymer (CFRP) laminate, utilizing the NSM technique. The crack torque was observed at 32.916 kN.m at a twisted angle of 1.387^o;The failure of this beam can be attributed to the concrete being crushed under the applied maximum torque of 44.318 kN.m, resulting in a corresponding twisted angle of 3.974. Figure 8 depicts the failure mode and crack pattern seen in beam NL-10.

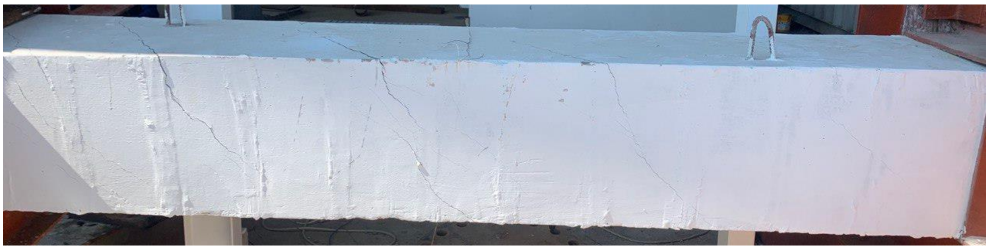

Figure 8. Strengthened beam NS-10 failure and crack configuration

Test results indicated that the ultimate capacity of beam NL-10 increased up 17% compared to the beam without strengthening. Furthermore, it is evident that the utilization of the NSM method has greatly improved the capacity. However, there a little improvement in crack torque, only by 3% and effectively mitigating crack formation.

Beam (NL-20):By adding a singular layer of CFRP laminate and utilizing the NSM with the same area of laminate as the beam (NL-10), this beam has been strengthened. However, the width of the laminate was 2 cm; therefore, the spacing was 45 cm from centre to centre. The visible cracks were noted firstly at the loading face, and then the cracks propagated to the other faces like control beams. The crack torque was observed at 31.015 kN.m at a twisted angle of 1.852^o; thus, this beam has not improved the cracking torque. This beam experienced failure due to concrete crushing under a torque of 42.678 kN.m and a torsional deformation of 3.221 degrees. The collapse mode and crack configuration of beam NL-20 are depicted in Figure 9. A 13% rise in the ultimate torque of beam NL-20 has been observed in comparison to the reference specimens. The test findings have also demonstrated that reducing the spacing between CFRP laminate has resulted in an enhanced in the torsional capacity when employing the NSM strengthening method.

Figure 9: Strengthened beam NL-20 failure and crack configuration.

Beam (EBS-S):This beam is enhanced by a single CFRP layer utilizing EBROG with a 2 cm transverse strip and grooves at a spacing of 46 cm. The crack torque was observed at 33 kN.m at a twisted angle of 1.78^{o}; this beam has improved the cracking torque only by 2%. The failure of this beam was due to the concrete crushing at the load of 40.120 kN.m. The recorded twisted angle at the ultimate torque of the beam was 3.393. The improvement in the maximal torque compared to the reference specimen was only about 6%. Figure 10 illustrates the failure mode of a beam (EBS-S). The use of EBROG with a 2cm strip only and grooves at a spacing of 46 cm did not have a significant effect on the carrying capacity; however, an increase in the twisted angle was observed.

Figure 10. Strengthened beam EBS-S failure and crack configuration.

3.2 Ductility performance of strengthened beams

The enhanced ability of the reinforced beams to carry torsional moments is clearly demonstrated in the preceding section. For the purpose of enhancing the assessment of the effectiveness of strengthening, a ductility index ratio is presented to quantitatively indicate the ductility performance of beams enhancing with (EBR), (NSM) and (EBROG). The ratios are computed based on Equations 1 as provided below:

$$\mu_{t,cr} = \frac{\theta_{t,u}}{\theta_{t,cr}} \quad [14] \qquad (1)$$

where $\theta_{t,u}$, $\theta_{t,cr}$ referring to the ultimate and cracking torsional angles, respectively, Table 3 shows the values of $\theta_{t,u}$, $\theta_{t,cr}$ and $\mu_{t,cr}$ for each beam. Based on the obtained results, it is apparent that NL-10 had the most contribution to improving the ductility and it improved by 73%, while NL-20 did not have a clear effect on the ductility and the reason may be that the icrease in spacing between the CFRP-laminate, which created enughe space for the formation of the cracks and thus led to reduced the confinement of the concrete, in addition to that, EBS-S improved the ductility slightly, by only 15%, it is clear that EBS-S is better than NL-20 in improving the ductility, and perhaps because NL-20 was strengthen by laminate and EBS-S was strengthen by sheet, and due to the sheet is more ductile than laminate.

Table 3. An overview of the ductility index ratio for the beams that were tested.

Beam	$\theta_{t,cr}$	$\theta_{t,u}$	$\mu_{t,cr}$	Increase in ductility
C-0	1.693	2.81	1.659	
NL-10	1.387	3.974	2.865	73%
NL-20	1.852	3.221	1.739	5%
EBS-S	1.780	3.393	1.906	15%

3.3 Strengthening technique effect:

The present study examines the efficacy of two strengthening techniques, namely, Near Surface Mounted (NSM), and Externally Bounded Reinforcement On Grooves (EBROG), in enhancing the torsional strength of structures. Upon analysis of Table 2, it can be shown that the methods, NSM, and EBROG have resulted in improvements in the torque capacity of beams. The NSM approach demonstrates a greater efficacy than the EBROG method in enhancing the torsional capacity of reinforced beam specimens when employing an equivalent area of CFRP. This discrepancy can likely be attributed to the disparity in laminate thickness utilized, with the former employing a thickness of 1.2 mm. In comparison, the latter only utilizes a CFRP sheet thickness of 0.167 mm and it is clear that EBROG is better than NSM in improving the ductility, and perhaps because NSM was strengthen by laminate and EBROG was strengthen by sheet, and due to the sheet is more ductile than laminate..

3.4 Effect of spacing in NSM:

Investigating the impact of CFRP laminate spacing on the torsional behaviour of RC beams enhanced by CFRP utilizing the NSM was one of the main goals of this study. As evident from Table 2, it is noted that reducing the distances between laminates leads to an increase in resistance when the amount of laminate remains constant. For example, decreasing laminate spacing from 46 cm in beam NL-20 to 21 cm in beam NL-10 when the amount of laminate remains constant at both beams has resulted in an extra torsional capacity. 4% (i.e., 17% versus 13%). Also, the twisted angle of the beam (NL-10) is greater than the twisted angle of the beam (NL-20) the reason may be that the spacing between the CFRP-laminate allow to created enughe space for the formation of the cracks and thus led to reduced the confinement of the concrete.

4. Conclusions

The present study aims to assess the efficacy of the EBROG, and NSM procedures in enhancing the torsional strength of reinforced concrete (RC) beams through the application of carbon fibre reinforced polymer (CFRP) sheets/laminates. A total of four beams were fabricated and subsequently subjected to testing as part of the experimental investigation, The conclusions summarized based on the test results are presented.

1. In general, the results obtained from the test showed that NSM and EBROG utilization of carbon fibre-reinforced polymer (CFRP) sheets/laminate has 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 NSM, and EBROG has resulted in improvements in the torque bearing capacity of beams. Specifically, the enhancements have varied from 13% to 17% for NSM, and 6% for EBROG compared to the reference specimen.

3. The NSM approach demonstrates a greater efficacy than the EBROG method in enhancing the torsional capacity of reinforced beam specimens while employing an equivalent area of CFRP.

4. Reducing the distances between laminates in NSM leads to an increase in resistance when the amount of laminate remains constant.

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