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# Strengthening Reinforced Beams Subjected to Pure Torsion by Near Surface Mounted Rebars

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**ABSTRACT**

This paper investigates the possibility of strengthening Reinforced Concrete (RC) beams under pure torsion loadings. The torsional behaviour of strengthened RC beams with near-surface mounted steel and CFRP bars was investigated. The verification with the experimental work was performed to ensure the validity and accuracy which revealed a good agreement through the torque-rotation relationship, ultimate torque, and rotation, and crack pattern. This numerical study included testing of thirteen specimens (one of them was control beams while the remaining 12 were strengthened beams) with several parameters such as mounting spacing and configuration. The analytical results revealed that the addition of NSM rebar redistributed the internal stresses and enhanced the ultimate torsional strength, torque-rotation capacity, ductility, and energy absorption of the concrete beams. Most of the strengthened beams revealed the appearance of the cracks at a phase less than the reference beam by an average of (9%). Concerning the NSM strengthening, the CFRP bars provided a higher enhancement ratio when compared with the beams that strengthened with NSM steel rebar especially for the strengthening space equal to 130 mm and more. The ultimate torsional strength increased by (3.5%) and rotation decreased by (4%) approximately when the steel rebar was replaced by the carbon bar. The ductility and energy absorption of the analysed beams showed that the strengthening enhanced the ductility of the twisted beams. The ductility values varied according to the method of strengthening used, as it showed the highest values of the beam that was strengthened small spacing.

## 1. Introduction

Apart from the flexure and shear resistance of (RC) structural elements, torsion resistance is also a crucial factor that must be considered for beams in multistoried buildings. The torsional capacity of these members needs to be maximized due to several factors, including structural damage, deterioration, and increased loading. Strengthening materials can be applied in two ways to (RC) structures: (1) externally reinforcement (ER) method, where the strengthening materials are applied externally to the concrete surface; and (2) near-surface mounted (NSM) method, where the strengthening materials are incorporated into the concrete cover in pre-cut grooves [1]. The NSM strengthening technique, considered an adequate alternative to the ER technique, involves cutting grooves in the concrete cover and edge beams. Other advantages of the NSM approach over the ER technique include increased bonding and better protection. The NSM methodology can also solve the ER method's peak strain restriction, which is below the ultimate strain owing to premature debonding. The main advantage of the NSM technology is the significant confinement provided by the glue and the surrounding concrete. [2], which prevents debonding and exhibited that the NSM bar enhanced the ultimate strength beside the control of the cracking pattern. This approach of strengthening RC

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beams has previously been proven to be efficient for combined shear and flexural strength. Many research investigations have employed steel and CFRP rebar instead of FRP materials for flexural and shear strengthening using the NSM approach, as well as column confinement. Nevertheless, only a few previous researches (Al- Bayati et al. 2016 [3], 2018 [4]; Askandar and Mahmood 2019 [5]) investigated the use of the NSM technique in strengthening Rc beams for torsion. Askandar and Mahmood [6] tested 10 samples of beams: two beams were used as controls, and the other eight beams were strengthened using CFRP laminates to their four sides. CFRP laminates were inserted into grooves using the NSM method. An adhesive epoxy was used in four strengthened beams, and a modified cement-based adhesive was applied as an alternative for epoxy in the four other beams which showed that the strengthening increased the efficiency of the RC beams to resist the torque and considered a good choice which use of strips at lower spacing enhanced the ultimate torsional strength capacity. Gowda et al. [7] investigated torsional behavior of thin-walled tubular RC beams strengthened by near-surface mounted CFRP bars in which Six beams were fabricated. The research showed that the addition of a Carbon rebar was so effective in enhancing the torsional strength, stiffness, and ductility of the twisted beam. During the testing of the beam, it was found that the tensile strength in carbon bar reached the limits of 89% of its tensile strength. This proved the effectiveness of the method in resisting torsion. Also, the deformation and the cracks propagation are controlled by the NSM CFRP bars. With the usage of strengthening, cracks spread increased but crack breadth reduced. They applied the same strengthening technique for the two strengthened beams to verify the accuracy of their findings. (Askandar and Mahmood [5]), examined four beams: one beam was used as control, and the other three beams were strengthened by inserting a U-shaped welded steel bars into grooves by using the NSM method. An adhesive epoxy was used in all strengthened beams. The NSM strengthening approach has been used in several works to increase the flexural and shear strength of RC beams. Only a few of these studies have focused on torsional strength (Al-Bayati et al. [3]; and Askandar and Mahmood [5]), and the usage of NSM steel and CFRP bar for torsion strengthening of RC beams has not received significant attention. For the purpose of filling the gap, a theoretical study was conducted that deals with different variables using strengthening with steel and FRP rebar mounted under the surface of the concrete.

## 2. Finite Element Modeling

In the present work a nonlinear finite element analysis of RC beams with torsion failure as the governing failure mode is performed using ANSYS. Material nonlinearities are considered to properly simulate the behavior of such beams. In the pre-processing stage, geometry and boundary conditions, element types, material properties, and nonlinear analysis solutions are defined. Finite element simulation of the complex behavior of concrete as a non-homogeneous and anisotropic material is a challenge in the finite element analysis of reinforced concrete structures and their components. Numerical modeling of RC beams calibrated by experimental results of other researcher is the main strategy of this study. To verify the model, three RC beams are selected and simulated. The numerical modeling is first calibrated by the experimental results of Kim et al. [8].

## 3. Concrete, Steel and Carbon Reinforcement

Concrete is considered a semi-brittle material and has a different compressive behavior than its tensile behavior. Concrete usually exhibits linear elastic behavior for about 30-35% of its maximum compressive strength (fc’). Following the yielding point, the tension progressively increases until it reaches maximum stress. The gradual increase in the load cause increase in the curve reaching the ultimate compressive strength, then the curve begins to drop and reach the point of failure in which the crushing of the concrete occurs at its highest strain value as revealed in Fig. 1. The tension case included an increase of the curve to the ultimate value of the tensile strength after this point, the concrete loses its stiffness and begins to crack [9]. To define the concrete material in ANSYS, there are essential values that must be input in the software such as Young modulus, Poisson ratio, stress-strain curve, compressive and tensile strength values, besides the open and closed shear cracks coefficient [9]. The constitutive stress-strain curve of the concrete model presented by Kim [8] was defined in the concrete depending on the Kachlakev [9] and ACI 318M-19 [10]. To imitate concrete behavior, plasticity-based damage is employed. Regarding the modelling of the concrete beam in ANSYS, elements of SOLID65, LINK180, and SOLID185 were used to simulate the concrete, steel rebar, steel plate, and CFRP bar. SOLID65 is the solid element with 8 nodes that has three degrees of freedom in each node and it can simulate cracking of concrete. Steel reinforcement and CFRP bar are represented by LINK180 with two nodes and three degrees of freedom at each node. The steel reinforcement behavior is defined in ANSYS by a bilinear relationship. The CFRP is defined as a linear-orthotropic material. The SOLID185 (steel plate) has the same nodes number and element faces of the concrete element (SOLID65) but with linear behavior. Concerning the adopted behavior of the concrete beam, the data concrete compressive strength, yield stress of the steel reinforcement, and steel plate were quoted from the experimental research of Kim [8] beside that, model geometry and methodology is shown in Fig. 2. All used properties of the concrete and the other concrete beam materials are presented in Table 1.

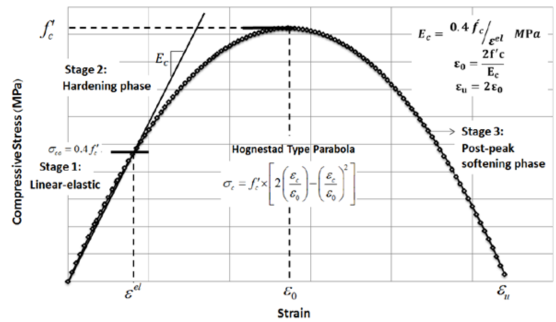


**Figure 1.** Stress-strain relationship of the concrete [9].

**Table 1.** material Properties of analyzed beams.

| Material | Yield strength [MPa] | Used element | Poisson ratio | Adopted stress-strain curve |
|---|---|---|---|---|
| Concrete | 35.4 | SOLID65 | 0.2 | Multilinear isotropic |
| Steel bar | 313 | LINK180 | 0.3 | Bilinear isotropic |
| CFRP bar | 1100 | SHELL41 | 0.3 | Linear orthotropic |
| Bearing plate | E= 2 x $10^5$ | SOLID185 | 0.3 | Linear isotropic |

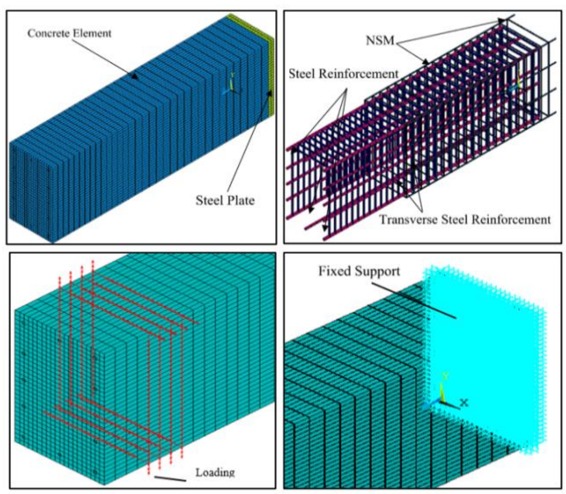


**Figure 1**: The finite element model shows the mesh and boundary conditions in ANSYS.

## 4. Verification

Three models presented in an experimental study by Kim [8] selected for the validation process. The modelled beams have the same geometry, boundary conditions, and material properties that were used in the experimental study. The validation results showed a good agreement compared with the experimental ones, where the comparison was made in terms of the torque-rotation relationship as given in Fig. 3 and Table 2. The average percentage difference in ultimate torque values was about (19%) and the values of maximum rotation was (8.26%) which showed an acceptable predicted value.

**Table 2.** Verification results of adopted specimens.

| Specimen | Tcr | | $\frac{Tcr}{Exp.}$ Num | Tu | | $\frac{Tu}{Exp.}$ Num | Properties Øcr | | Øcr $\frac{Exp.}{Num}$ | Øu | | Øu $\frac{Exp.}{Num}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EXP | Num | % | EXP | Num | % | EXP | Num | % | EXP | Num | % |
| S 0 | 52 | 59 | 88% | - | - | - | 0.0015 | 0.001249 | 80% | - | - | - |
| S08-3-65 | 68 | 66.9 | 99% | 123 | 126 | 97.6% | 0.0018 | 0.0016 | 87.5% | 0.0243 | 0.022 | 90.74% |
| S12-5-72.5 | 63 | 64.7 | 97.3% | 129 | 107.7 | 81% | 0.0014 | 0.001418 | 98.7% | 0.0261 | 0.0268 | 97.3% |

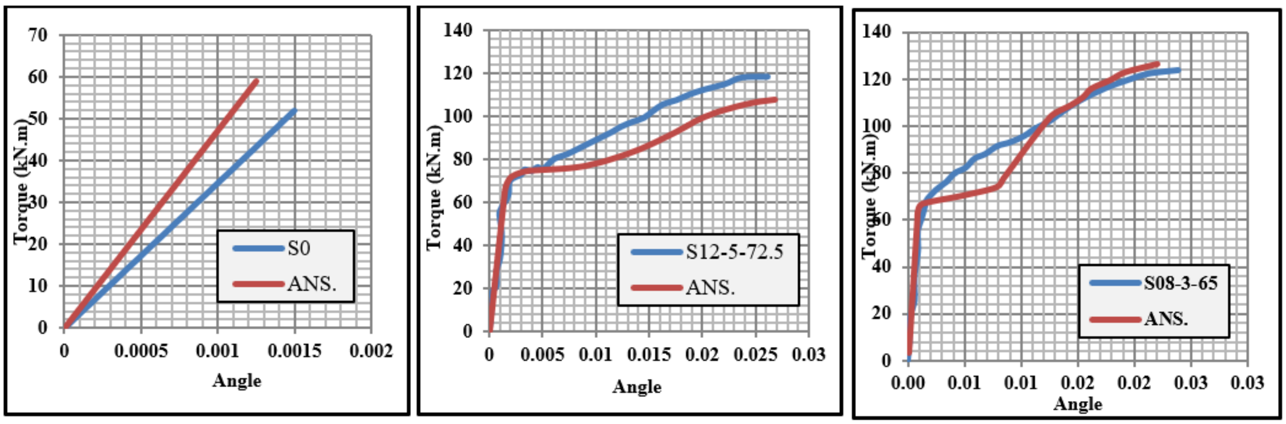


**Figure 3.** Torque- Rotation Curves Clarify the Verification Work.

## 5. Parametric Study

After validating the adopted modelling of the beam in ANSYS, a parametric study was carried out to investigate their effect on the behavior of the concrete beam. The reference beam details are presented in Fig. 4 which is the similar specimens presented by Kim [8]. The beam dimensions were (400 x 600 x 2000) mm reinforced with 4Ø16 mm as main reinforcement and 8 Ø13 mm as skin reinforcement beside Ø10 mm @50 and 65 mm as shear reinforcement. A total of 13 beams (one of them is a reference beam while the remaining 12 are strengthened beams) are investigated in this series. The beams with the same dimensions and reinforcement details were modelled by ANSYS and strengthened by steel and CFRP rebar as a near-surface mounted bar in different schemes, these are the external ring @ 65, 130, 195, and 260 mm, and the use of external longitudinal rebar with a variable number.

### *5.1. Strengthening Process*

The reinforcement was modelled as a NSM where the strengthening bars are mounted under the concrete surface at a distance of 2 cm, where the strengthening bars was fully connected to the shared nodes, which provides a full bond with the concrete.

**Table 3.** Details of the analysed specimens

| ID | *ƒc* MPa | Strengthening Method |
|---|---|---|
| **REF** | ***35.4*** | **Unstrengthened reference beam** |
| SB-NS 65 | ***35.4*** | **Strengthen with external steel ring at a spacing of 65 mm** |
| SB-NS 130 | ***35.4*** | **Strengthen with external steel ring at a spacing of 130 mm** |
| SB-NS 195 | ***35.4*** | **Strengthen with external steel ring at a spacing of 195 mm** |
| SB-NS260 | ***35.4*** | **Strengthen with external steel ring at a spacing of 260 mm** |
| SB-NS-2Lb | ***35.4*** | **Strengthening with longitudinal steel 2 in each face** |
| SB-NS- 4Lb | ***35.4*** | **Strengthening with longitudinal steel 2 in each face** |
| SB-CFB-65 | ***35.4*** | **Strengthen with external CFRP ring at a spacing of 65 mm** |
| SB-CFB-130 | ***35.4*** | **Strengthen with external CFRP ring at a spacing of 130mm** |
| SB-CFB-195 | ***35.4*** | **Strengthen with external CFRP ring at a spacing of 195mm** |
| SB-CFB-260 | ***35.4*** | **Strengthen with external CFRP ring at a spacing of 260mm** |
| SB-CFB-2Lb | ***35.4*** | **Strengthening with longitudinal steel 2 in each face** |
| SB-CFB-4Lb | ***35.4*** | **Strengthening w ith longitudinal steel 4 in each face** |

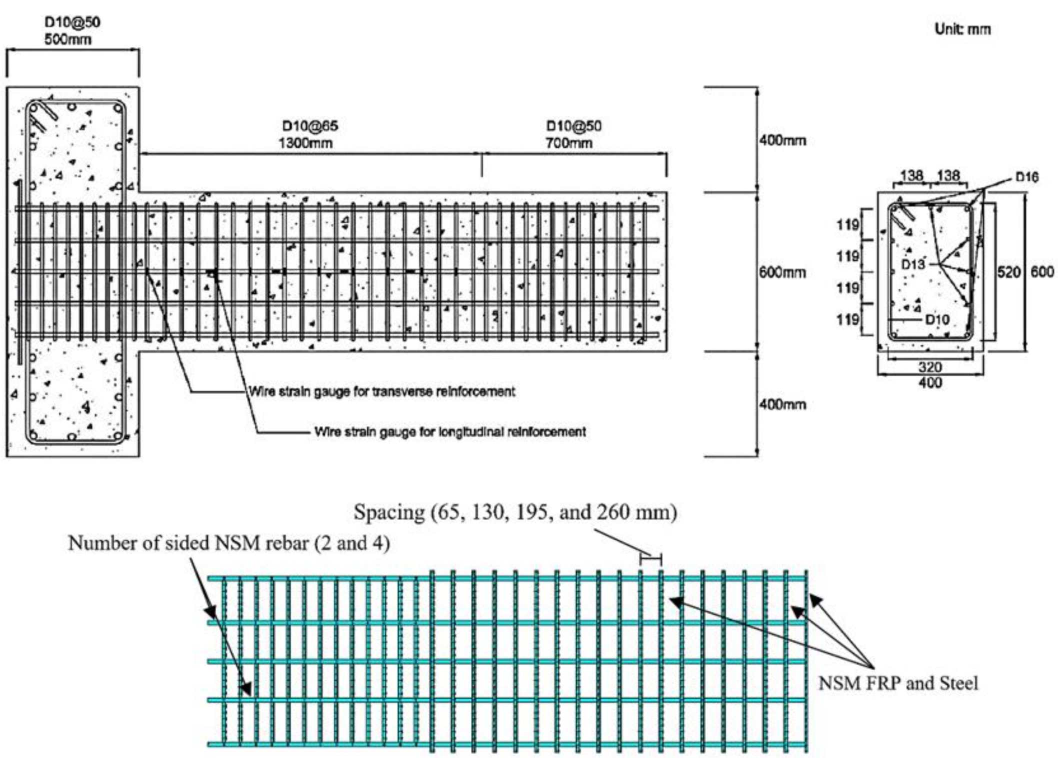


**Figure 4:** Reference and strengthened beams details.

## 6. Test Results

### *6.1. Failure and Cracking mode*

The predicted cracking showed approximately similar cracking mode for most of the analysed beams as follows; the first cracking appeared at torque that is (53%) of the control beam and an average of (48.2%) for the strengthened beams which the first cracking was slightly affected by the existence of NSM. Most of the strengthened beams revealed the appearance of the cracks at a phase less than the reference beam by an average of (9%). The cracks started at the support region, the cracks widened and extended in an inclined direction reaching the final stage of the loading which included crushing the concrete and the crack occupied most of the twisted beams. The crack propagation showed more spread when the beam was strengthened by the NSM as revealed in Fig. 5.

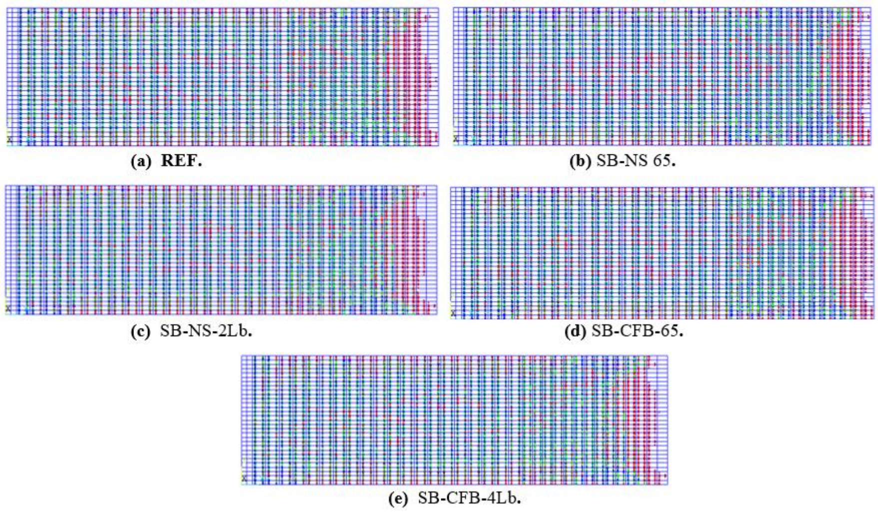


**Figure 5.** Crack pattern for reference and strengthened beams.

### *6.2. Torque-Rotation Relationship*

The predicted results have shown that strengthening by NSM bar provided good confinement to the beam against the torsion and led to enhance the ultimate torque capacity when compared with the reference strengthened beam as revealed in Table (5). The main variables offered an ultimate torque ranged between the (126.4 – 185.6) kN.m and rotation ranged between (0.0176 – 0.0221). The ductility and energy absorption are presented in Table (5).

### *6.3. Effect of NSM on the Torsional Strength*

The strengthening by NSM steel rebar in ring form spaced at 65 mm offered a decrement in the cracking load by about (29.2%) when compared with the reference beam. The ultimate torsional strength increased by about (46.8%) and rotation decreased approximately by (3%) when compared with the reference beam as presented in Fig. (6 a). Regarding the same strengthening way but at a spacing of 130 mm, the ultimate torsional strength increased by (23.1%) and rotation decreased approximately by (3%) when compared with the reference beam as presented in Fig. (6 b). The use of 195 mm spacing of steel ring showed less enhancement in the torsional strength than beams (SB-NS 65 and SB-NS 130) which was (17.6%) as revealed in Fig. (6 c). The last ring beam (SB-NS 260) exposed an enhancement by (23%) as revealed in Fig. (6 d). Use of two and four longitudinal near-surface mounted rebar exhibited less decrease in the cracking torque when compared with the other strengthened beams. The ultimate torsional strength exhibited an enhancement by (33.50% and 31%) for beams (SB-NS-2Lb) and (SB-NS-4Lb) respectively as revealed in Figs. (6 e). Concerning the NSM strengthening by CFRP bars, it was found that it provided a higher enhancement ratio when compared with the beams that were strengthened by NSM steel bars especially when the bars space at 130 mm and more. The ultimate torsional strength increased by (3.5%) and rotation decreased by (4%) approximately when the steel rebar was replaced by the carbon fibre bars as exhibited in Fig. (6 a to 6 e). Regarding the same strengthening way but at a spacing of 130 mm, the difference in the ultimate torsional strength was by about (23.1%) and rotation was by (41%) for the beam with the CFRP bars. Use of 195 mm ring showed less enhancement in the torsional strength than beams (SB-CFB 130) which was (13.4%) and increase in rotation by (39.7%). The last ring spacing of 260mm beam (SB-CFB 260) exposed an enhancement by (4.6%).

**Table 5.** Test results of analysed beams

| Sample | Tcr (kN.m) | Tu (kN.m) | Øcr (rad./m) | Øu (rad./m) | %Tcr | % Øu Increase | Ductility | Energy Absorption |
|---|---|---|---|---|---|---|---|---|
| REF | 66.938 | 126.43 | 0.00125 | 0.0221 | - | - | 17.7 | 42.33 |
| SB-NS 65 | 70.3 | 185.62 | 0.001212 | 0.0176 | 5.02% | -20.16% | 14.5 | 62.32 |
| SB-NS 130 | 68 | 155.62 | 0.001212 | 0.01862 | 1.59% | -15.56% | 15.4 | 37.76 |
| SB-NS 195 | 74 | 148.75 | 0.001212 | 0.02002 | 10.6% | -9.21% | 16.5 | 40.1 |
| SB-NS260 | 70 | 155.62 | 0.001212 | 0.01891 | 4.6% | -14.24% | 15.6 | 44.35 |
| SB-NS -4Lb | 86.4 | 165.62 | 0.001212 | 0.02202 | 29.1% | -0.13% | 18.2 | 44.92 |
| SB-NS-2Lb | 84.3 | 168.75 | 0.001212 | 0.01739 | 26% | -21.12% | 14.3 | 64.2 |
| SB-CFB-65 | 84.7 | 179.376 | 0.00078 | 0.02152 | 41.87% | 97.64% | 27.5 | 59.82 |
| SB-CFB-130 | 86 | 168.75 | 0.00115 | 0.02482 | 33.46% | 12.58% | 21.6 | 66.92 |
| SB-CFB-195 | 89.4 | 168.75 | 0.00121 | 0.02569 | 33.46% | 16.55% | 21.2 | 68.32 |
| SB-CFB-260 | 94.5 | 162.812 | 0.00078 | 0.01956 | 28.77% | 88.75% | 25.0 | 45.85 |
| SB-CFB-2Lb | 73.6 | 168.75 | 0.00121 | 0.02565 | 33.46% | 16.35% | 21.1 | 68.23 |
| SB-CFB-4Lb | 84.2 | 188.34 | 0.00100 | 0.0201 | 48.96% | 91.16% | 20.2 | 46.1 |

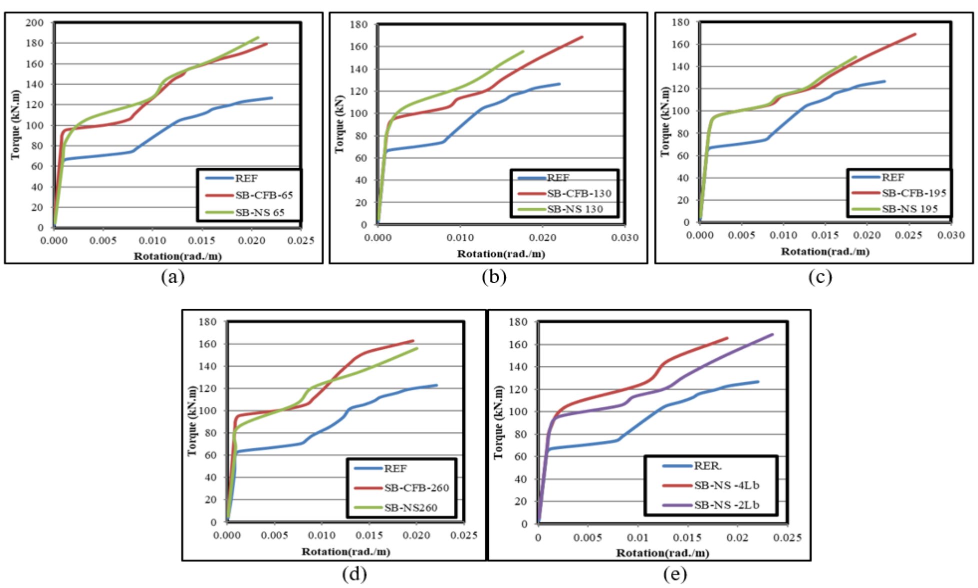


**Figure 6.** Torque rotation relationship of the tested beam

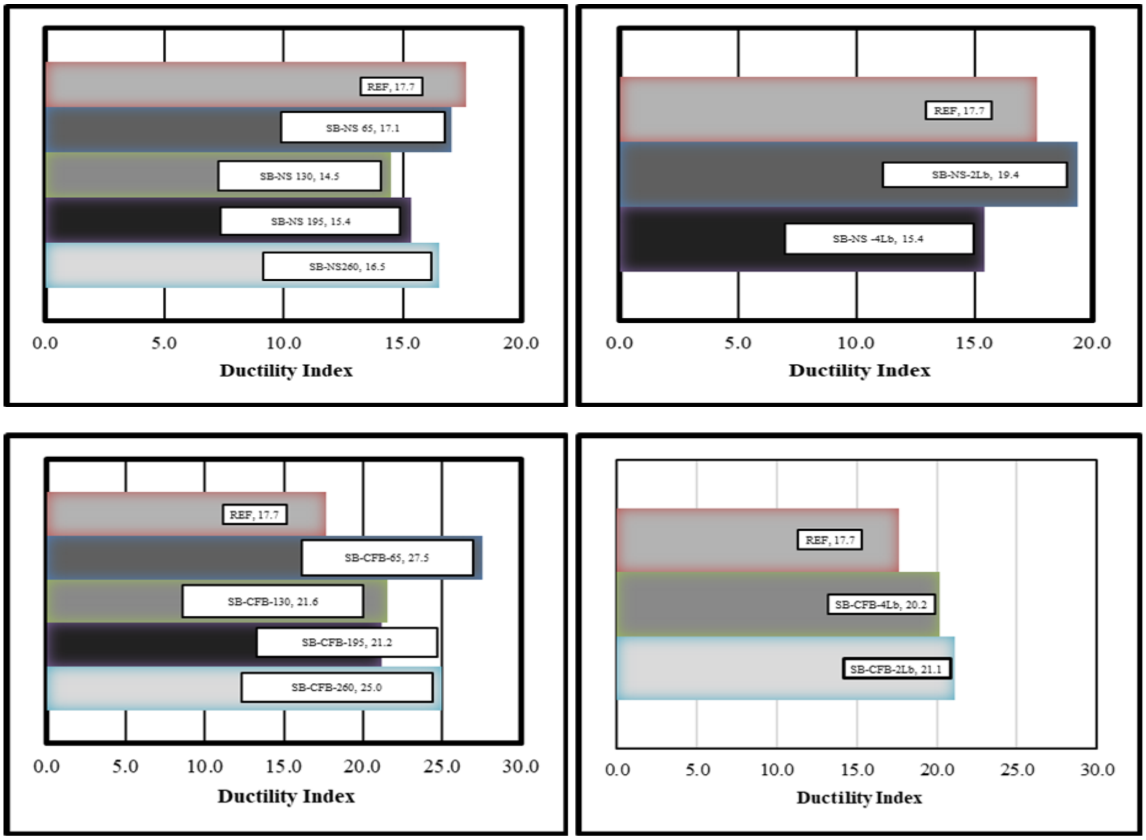


**Figure 7.** Ductility of the strengthened beams

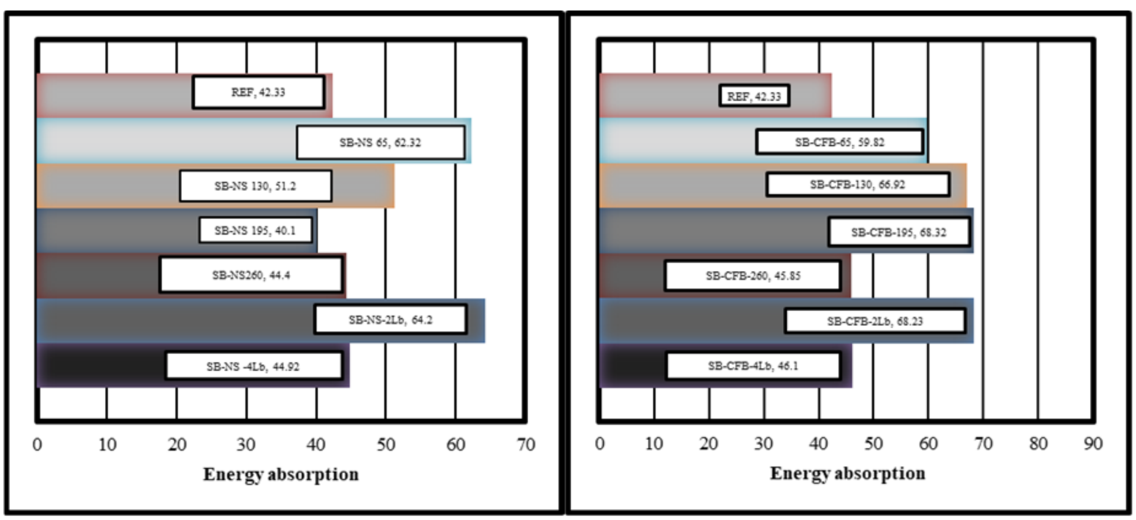


**Figure 8.** Energy absorption of the strengthened beams

*6.4. Ductility of Analyzed Beams*

The ductility of the tested beams showed that the strengthening enhanced the ductility of the twisted RCSBs The ductility values varied according to the method of strengthening, it was found that the highest values are predicted for the beam that was strengthening by steel rebar @ 65 mm, and the values dropped as the distance between the mounted rebar increased. Concerning the carbon fiber mounted rebar, it gave the highest value of ductility and its values ranging from (20.2 to 27.6) which was more effective than that for the beams reinforced with steel rebar. The ductility of both series (series two and three) are presented in Fig. (7) . *6.5. Energy Absorption in the Analysed Beam.*

As appeared in Table (5) and Fig (8), the energy absorption showed that the values are varied according to the strengthening procedure and more enhancements in the energy absorption was found for the strengthened beams with NSM carbon bars. Maximum enhancement occurred in the beams strengthened with NSM carbon bars was by (90%) for the beam (SB-CFB-4Lb). Strengthening by NSM rebar at variable spacing showed that the beams with 130 and 195 mm spacing offered more energy absorption.

## 7. Conclusion

In this manuscript, the analytical results of 12 RC strengthened RC beams were presented and discussed. Based on these studies, the following conclusions are drawn:

1) The addition of NSM rebar redistributed the internal stresses and enhanced the ultimate torsional strength, torque-rotation capacity, ductility, and energy absorption of the concrete beams.

2) The strengthening by external steel rebar in ring form at 65 mm spacing offered an enhancement in the cracking load by (129.2%) when compared with the reference beam. The ultimate torsional strength also increased by (46.8%) and rotation decreased by approximately (3%) when compared with the reference beam. Regarding the same strengthening way but at a spacing of 130 mm, enhancement in the cracking load was found to be (5%) when compared with the reference beam. The ultimate torsional strength increased by (23.1%) and rotation decreased by approximately (3%) when compared with the reference beam.

3) Concerning the NSM strengthening, the CFRP bar provided a higher enhancement ratio when compared with the beams that were strengthened NSM steel rebar especially for the bars spaced at 130 mm and more. The ultimate torsional strength increased by about (3.5%) and rotation decreased by approximately (4%) when the steel rebar was replaced by the carbon fibre bars.

4) The ductility of the analysed beams showed that the strengthening enhanced the ductility of these beams. The ductility values varied according to the method of adopted strengthening method and the highest values are for the beam that was reinforced with NSM CFRP bar more than the steel rebar.

5) The energy absorption showed variation in the values according to the strengthening method and the enhancement in the energy absorption was predicted for the beams strengthened with FRP carbon bars was higher than that offered by NSM steel rebar.

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