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Torsional Behavior of Strengthened Reinforced Concrete Beams by CFRP Sheets: Parametric study

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ABSTRACT

This paper presents a nonlinear finite element analysis of reinforced concrete beams subjected to pure torsion. A verification procedure was performed on three specimens by finite element analysis using ANSYS software. The verification with the experimental work revealed a good agreement through the torque-rotation relationship, ultimate torque, rotation, and crack pattern. The studied parameters of strengthening by CFRP sheets included strengthening configurations and number of CFRP layers. The confinement configuration methods included full wrapping sheet around the beam, U-shaped sheet, ring strips spaced at either 65 or 130 mm, longitudinal strips at the top and bottom faces, U-shaped strips in addition to the number of layers variable. It was found that the performance of the beam for resisting a torsional force was improved by (33-49%) depending on the method of coating with CFRP sheets and the number of used layers. A change in the angle of twist, as well as the shape of the spread of cracks, was also noticed from the predicted results.

1. Introduction

Usually structural concrete elements are subjected to a torsion moment that may cause total or partial failure of these elements. Many techniques have been used around the world with regard to strengthening the structural elements, especially the external reinforcement, which includes adding structural materials to the concrete members to ensure a higher resistance to loads, the most important of which is the strengthening by using polymeric carbon fibers, which has proven highly effective in resisting torsional and bending loads, as this material consists of fibers Continuous in a matrix of polymers used to transfer stresses through these fibers. One of the most important benefits of this material is its light weight compared to its high resistance, in addition to poor thermal conductivity, ease of use and abundance [1-4]. Many researchers investigated the effect of strengthening of

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the concrete beam under torsional loads but the studies regarding the strengthening by the CFRP were few although these studies were limited in terms of the used parameters and didn't demonstrating the torsional behavior. In 2019, Askandar and Mahmood [5] investigated the effect of wrapping the concrete beams by CFRP fabric which revealed an improvement in the ultimate torque, cracking torque beside the twist angle. The torsional behavior of strengthened RC beams by FRP was demonstrated by Kandekar [6], the study shows that the torsional strength enhanced by wrapping the concrete beam by FRP beside enhancing the initial cracking capacity. Saad et al. [7] investigated the behavior of the strengthened beams by CFRP under bending and torsion which showed that the CFRP enhanced the ultimate strength beside the control of the cracking pattern. Different FRP wrapping configuration were implement to predict the most effective way to strengthen the concrete beams. The strengthening configuration included the fibers orientation, number of FRP layers, in addition to the sheets form (full wrap, U-shaped, strips..etc). Similar work was presented by Panchacharam and Belarbi [8] and Deifalla and Ghobarah et al. [9]. The mentioned researchers illustrated that the wrapping by the full wrapping configuration was more effective than the strips method. As presented by Al-Rousan and Abo-Msamh [10], the use of the CFRP strips to increase the efficiency of the RC beams to resist the torque was a good choice in which the use of strips at lower spacing enhanced the ultimate torsional strength capacity. Allawi [11] in 2006, casted twelve wrapped beams strengthened with several wrapping configuration such as full sheet and strips with three and four sided strengthening. The results had shown an enhancement in the torsional strength in case of the full wrapping higher than the strips method. Also, the four sided method was more effective in comparison with the three sided scheme. A limited studies investigated the full behavior of the strengthened beam under pure torsion with an extensive study deals with the stress distribution [12]. The presence of the CFRP around the beam resists the torsional stresses according to the orientation of the FRP sheets as revealed in Fig. 1 [13]. The stress When investigating the establishment of an experimental and investigations in the engineering laboratories, it was found that it drains time and cost, so it is possible to resort to numerical analysis by finite element method by using some analytical programs such as ANSYS software, which can predict the patterns of failure, cracking and stress distribution. The aim of the present study is to analyze 12 models of reinforced concrete beams that are strengthened using carbon fibers in various strengthening methods. These are carried out after verifying the analytical model with the available experimental works.

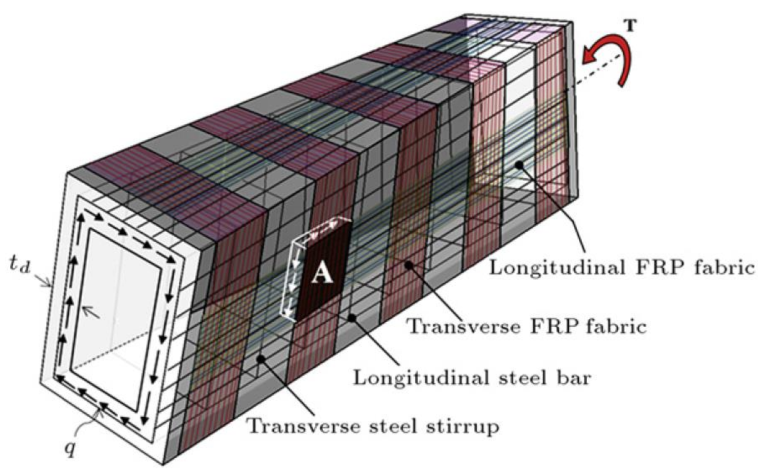


Figure 1. Stresses of twisted strengthened RC beam by CFRP sheets [13

2. Finite Element Modeling

The computer program ANSYS V15 is a powerful and impressive engineering finite element package that may be used to solve a variety of problems, and it has been used in the present work. SOLID65 was used to represent the concrete, LINK180 for steel, SOLID185 for steel plate, and SHELL 41 for CFRP sheets. SOLID65 is utilized to model the concrete material with and without rebar. The element is defined by eight nodes having three degrees of freedom at each node. The most significant feature of SOLID65 is that it can represent the non-linearity of the used material. SOLID65 has the ability to cracks, crush, plastic deformation, and creep. LINK180 is a truss element that has two nodes with three degrees of freedom in each node. This element capable of carrying out both compressions and tension stresses. SHELL41 is a 3D element having membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. The CFRP sheets modeled by using membrane41 (SHELL 41) having four nodes and each node has three degrees of freedom. This element can be modeled by the use of adhesive material such as epoxy in addition to the possibility for direct wrapping without adhesive material and this case considered the full perfect bond between the concrete and the CFRP sheet.

Regarding the properties that are used to model the concrete beams with different strengthened materials (full and partial carbon fiber Wrapping), the beam (S08-3-65) that was presented by Kim et al. [14] was chosen as a reference sample for strengthening with CFRP sheet, it had a rectangular cross-section of 400 x 600 mm, and a length of 2,000 mm with compressive strength of concrete = 35.4 MPa and Yield strength of longitudinal and transverse reinforcement are equal to 313 MPa and 334 MPa respectively. Poisson's ratio for concrete is 0.2 and 0.3 for steel. For CFRP sheet a linear orthotropic material with 240000 MPa modulus of elasticity and 0.3 Poisson's ratio. The steel reinforcement behavior was defined by a bilinear relationship. The elastic linear behavior was utilized to define the element (SOLID185) to represent steel plate which modeled in the support zone to prevent the stress concentration at this zone. Concerning the adopted behavior of the concrete beam, the data of concrete compressive strength, yield stress of the steel reinforcement, and steel plate were quoted from the experimental research of Kim [14]. Regarding the CFRP sheets, the material data quoted from the experimental research of Askander et al. [5].

3. Verification

Three models presented in an experimental study by Kim [14] are selected for the validation process. The modeled beams have the same geometry, boundary conditions, and material properties. The validation results showed a good agreement compared with the experimental ones (Fig. 2), 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 (10%) which showed an acceptable predicted value. Regarding the difference in the specimens (S0), the behavior of the plain concrete without reinforcement showed less rotation capacity as revealed in Fig. 3. The Details of the three beams are given in Ref. [14] which described in the previous section and in Fig. 2 and Table 1.

Table 1: Analyzed beams details.

Specimen	$f'c$	Longitudinal Reinforcement		Transverse Reinforcement		
		Al (mm^{2})	*fy* (MPa)	At (mm^2)	S (mm)	*fy* (MPa)
S 0	35.4	-	-	-	-	-
S08-3-65	35.4	1808	313	71.3	65	334
S12-5-72.5	35.4	1805	565	71.3	72.5	595

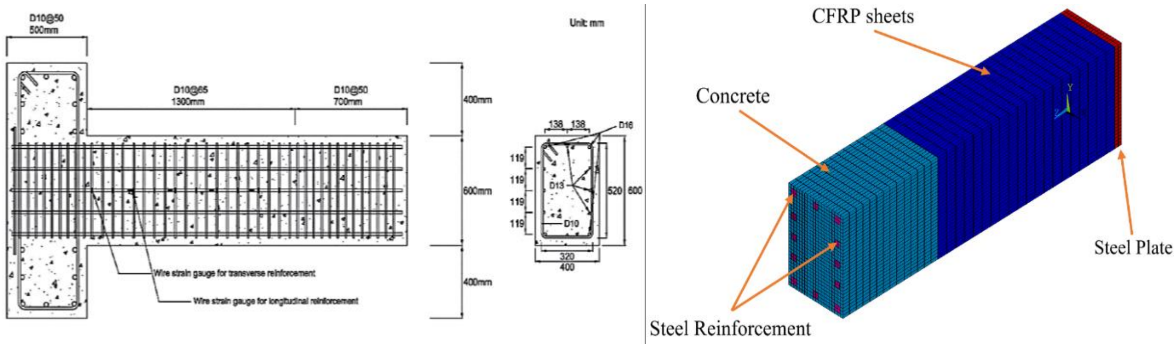


Figure 2. The experimental details and the finite element model used in ANSYS.

Table 2: Verifications results.

Specimen	Tcr kN.m		Tcr Exp./Num	Tu kN.m		Tu Exp./Num	Øcr rad./m		Øcr Exp./Num	Øu rad./m		Øu 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%

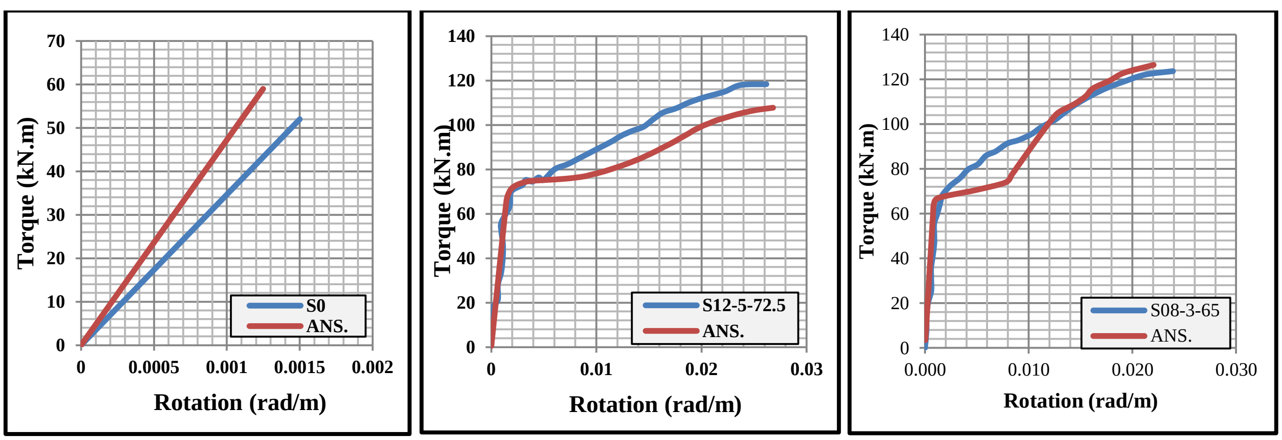


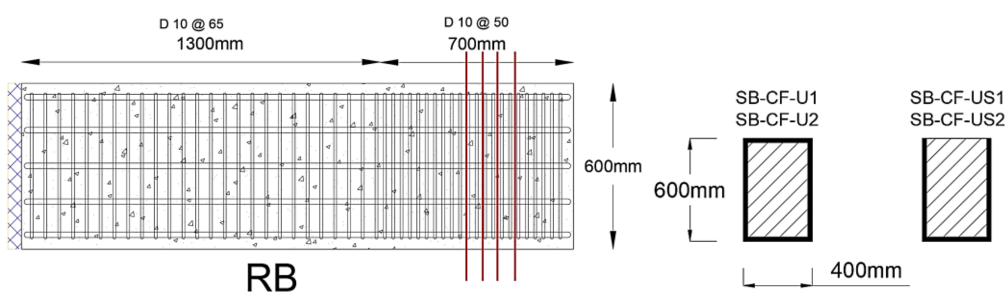
Figure 3. Torque - rotation curves clarifying the verification work

4. Parametric Study:

After validating the modeling process of the RC beams under pure torsion, a parametric study was carried out to investigate the effectiveness of different strengthening schemes on the torsional behavior of RC beams under pure torsion. The reference beam details presented in Fig. 4 which is the similar specimens tested by Kim [14]. The beam dimensions were (400 x 600 x 2000) mm reinforced with 4D16 mm as main reinforcement and 8 D13 mm as a skin reinforcement beside D10 mm @ 65 mm as shear reinforcement the sample (S08-3-65) was chosen as a reference sample for strengthening with CFRP sheet, with compressive strength of concrete = 35.4 MPa. Twelve beams with the same dimensions and reinforcement details were modeled by ANSYS and strengthened by CFRP sheets in different configuration schemes such as use of full wrapping, horizontal strips, and vertical strips. The parameters that are studied in the present work included the effect of using different wrapping procedure such as (full wrapping sheet around the beam, U-shaped sheet, ring strips 65 and 130 mm, longitudinal strips at the top and bottom faces, U-shaped strips) in addition to the number of CFRP layers as presented in Table 3 and Fig. 4.

Table 3: Details of specimens.

ID	$f'c$ MPa	Strengthening Method
REF	35.4	Reference beam
SB-CF-F(1)	35.4	Full strengthening in one layer
SB-CF-F (2)	35.4	Full Strengthening in two layers
SB-CF-U (1)	35.4	Strengthen in the form of single-layer U jacket
SB-CF-U (2)	35.4	Strengthen in the form of two layers of U jacket
SB-CF-US(1)	35.4	Strengthen in the form of single-layer U slices
SB-CF-US(2)	35.4	Strengthen in the form of two layers of U slices
SB-CF-65(1)	35.4	Strengthen with Surround Slides 65mm Width with Single Layer
SB-CF-65(2)	35.4	Strengthen with Surround Slides 65mm Width with Two Layers
SB-CF-130(1)	35.4	Strengthen with Surround Slides 130 mm Width with Single Layer
SB-CF-130(2)	35.4	Strengthen with Surround Slides 130 mm Width with Two Layers
SB-CF-2Tb (1)	35.4	Strengthen with Two CF sheet on top and bottom with one layer
SB-CF-2Tb (2)	35.4	Strengthen with Two CF sheet on top and bottom with two layer



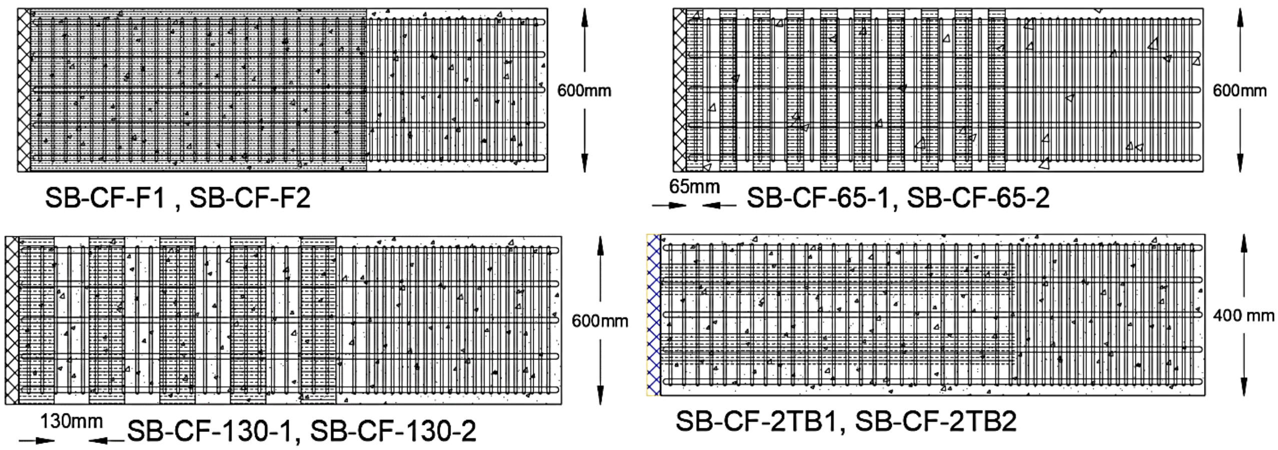


Figure 4. Details of the Analyzed beams.

5. Results and Discussion

5.1. Torque-Rotation Relationship

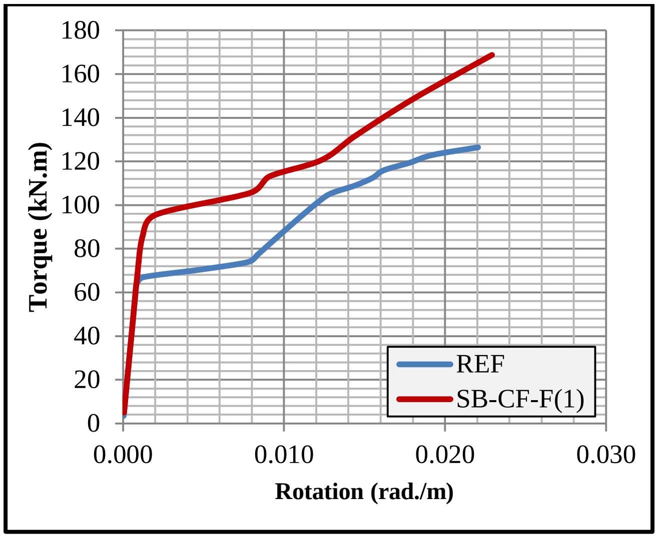
From the predicted results, the behavior of the reference beams has shown a linearly elastic behavior up to about (53%) of the ultimate torsional capacity. The torque increases gradually up and reaches the ultimate capacity as shown in Fig. 5. Table 4 summarized the predicted results of the analyzed beams. The strengthening by CFRP sheet provided a good confinement to the beam against the torsion which enhanced the ultimate torque capacity when compared with the reference unstrengthen beam.

Table 4. Test results of the analyzed beams.

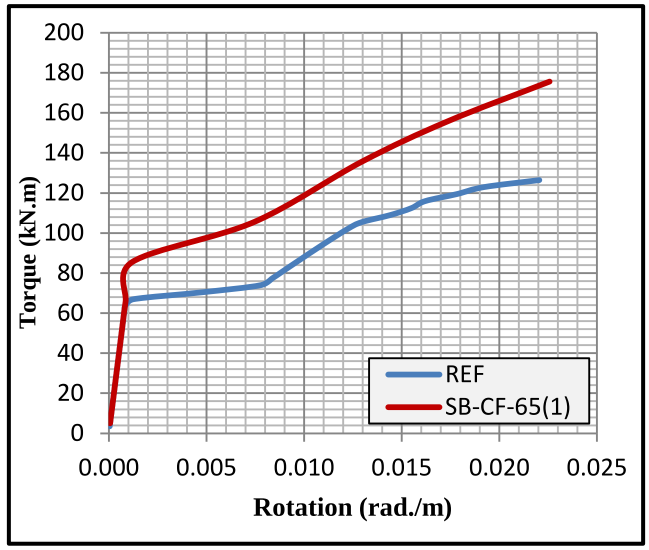
Sample	Tcr (kN.m)	Øcr (rad./m)	Tu (kN.m)	Øu (rad./m)	%Tu Increase	%Øu Increase	% Tcr increase	%Øcr Increase
REF	66.9382	0.00125	126.4	0.02205	-	-	-	-
SB-CF-F(1)	85.624	0.00121	168.8	0.02292	33.46%	3.93%	27.92%	-2.93%
SB-CF-F(2)	85.624	0.00121	188.8	0.02606	49.28%	18.17%	27.92%	-2.93%
SB-CF-U(1)	85.624	0.00121	175.6	0.02274	38.90%	3.13%	27.92%	-2.93%
SB-CF-U(2)	85.624	0.00121	187.8	0.02634	48.54%	19.46%	27.92%	-2.93%
SB-CF-65(1)	85.624	0.00121	175.6	0.02257	38.90%	2.37%	27.92%	-2.39%
SB-CF-65(2)	85.624	0.00121	185.6	0.02735	46.81%	24.03%	27.92%	-2.39%
SB-CF-US(1)	74.454	0.00100	169.5	0.02864	34.02%	29.87%	11.23%	-20.31%
SB-CF-US(1)	74.454	0.00099	184.5	0.03265	45.88%	48.09%	11.23%	-20.77%
SB-CF-130(1)	85.624	0.00121	175.6	0.02384	38.90%	8.13%	27.92%	-2.93%
SB-CF-130(2)	85.624	0.00121	175.6	0.02350	38.90%	6.58%	27.92%	-2.93%
SB-CF-2Tb(1)	85.624	0.00121	168.8	0.02660	33.46%	20.63%	27.92%	-2.93%
SB-CF-2Tb(2)	85.624	0.00121	173.8	0.02694	37.5%	22.18%	27.92%	-2.93%

5.2. Effect of the Wrapping method

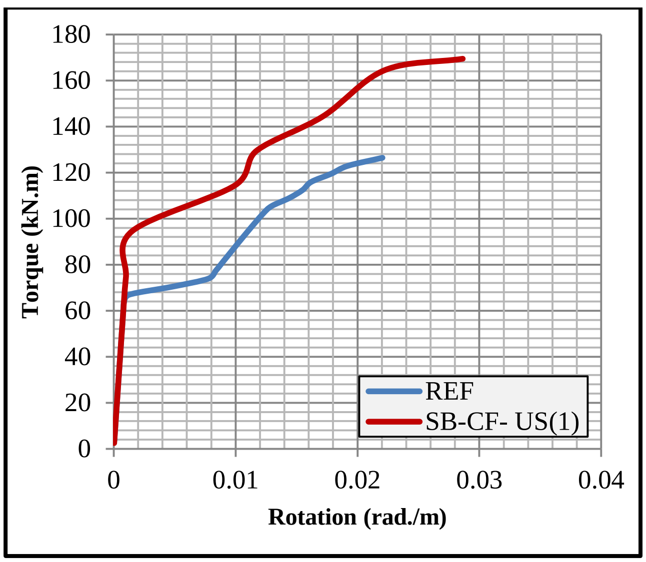
After the first stage of loading (linear phase), the non-linear phase of concrete starts at the appearance of the first crack (at 53% of the ultimate torsional capacity). The behavior of the strengthened beams was approximately similar to that of the control one. Use of full wrapping with one layer enhanced the ultimate torque by (33.46%) when compared with the control beam (REF). The predicted ultimate rotation has shown enhancement by approximately (3.9%) when compared with the control specimen as shown in Fig. 5 a. Although the complete wrapping method is considered one of the best ways to enhance the resistance of the beams against torsion. Regarding the other strengthening method with one layer such as using U-shaped jacket and strips, the use of U-shaped jacket provided enhancement in the ultimate torque by 39% and reduction in ultimate rotation by (3%) when compared with the control beam (REF) as shown in Fig. 5 b. Replacing the U-jacket by U-shaped strips (beam SB-CF-US1) revealed improvement in the ultimate torque by (34%) less than the U-jacket by about (5%) as shown in Fig. (5 c). The use of 65- and 130-mm strips (SB-CF-65(1) and SB-CF-130(1)) upgraded the ultimate torque by equal value for both of these methods by approximately (40%) but showed dissimilar behavior in term of the rotation which showed an enhancement in the rotation by (8.13%) when the strip width increased to 130 mm as shown in Fig. (5 d and e). Strengthening the beam by top and bottom longitudinal strips (SB-CF-2TB(1))) also increased the strength by (33.4%) but showed higher rotation in comparison with all strengthening methods by (20.63%) when compared with the control beam (REF) as depicted in Fig. (5 f). Because of the linear behaviour of the CFRP, its restriction negatively affects the possibility of greater rotation of the concrete beams, despite its high efficiency in enhancing the concrete resistance of the beam against torsion.


180
160
140
120
100
80
60
40
20
0
Torque (kN.m)
0.000
0.010
0.020
0.030
Rotation (rad./m)
REF
SB-CF-F(1)

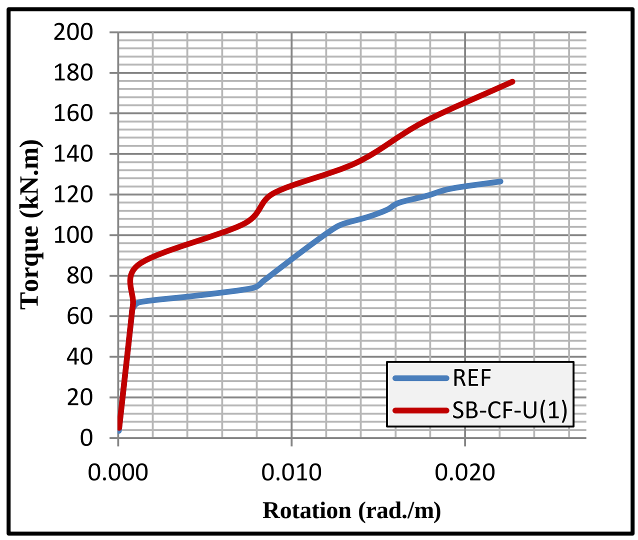
(a)


200
180
160
140
120
100
80
60
40
20
0
Torque (kN.m)
0.000
0.005
0.010
0.015
0.020
0.025
Rotation (rad./m)
REF
SB-CF-65(1)

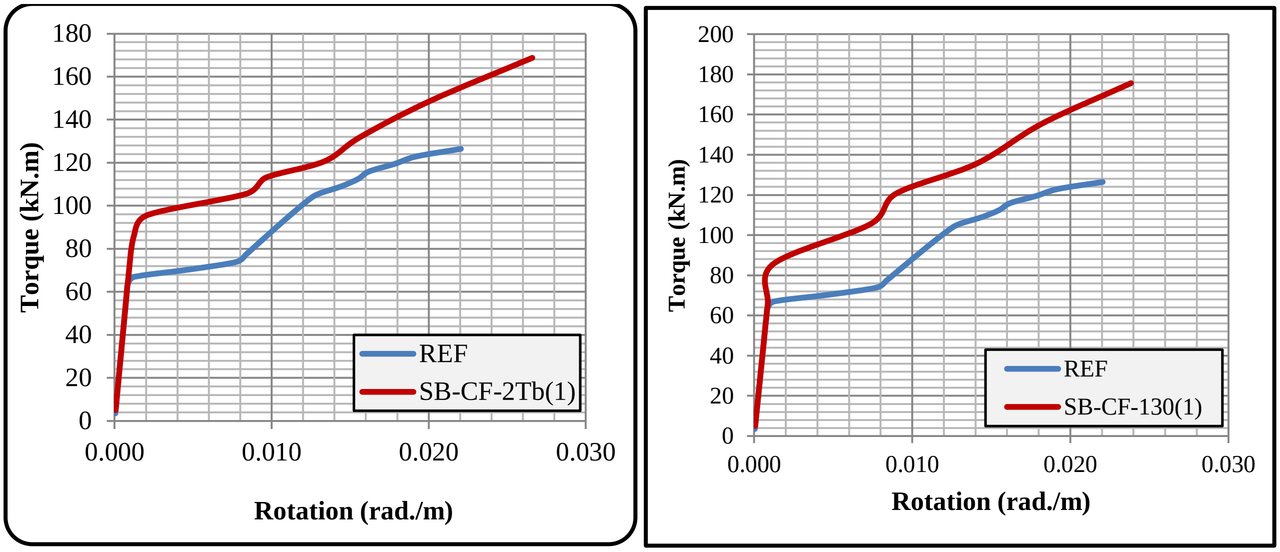
(b)


180
160
140
120
100
80
60
40
20
0
Torque (kN.m)
0
0.01
0.02
0.03
0.04
Rotation (rad./m)
REF
SB-CF- US(1)

(c)


200
180
160
140
120
100
80
60
40
20
0
Torque (kN.m)
0.000
0.010
0.020
Rotation (rad./m)
REF
SB-CF-U(1)

(d)

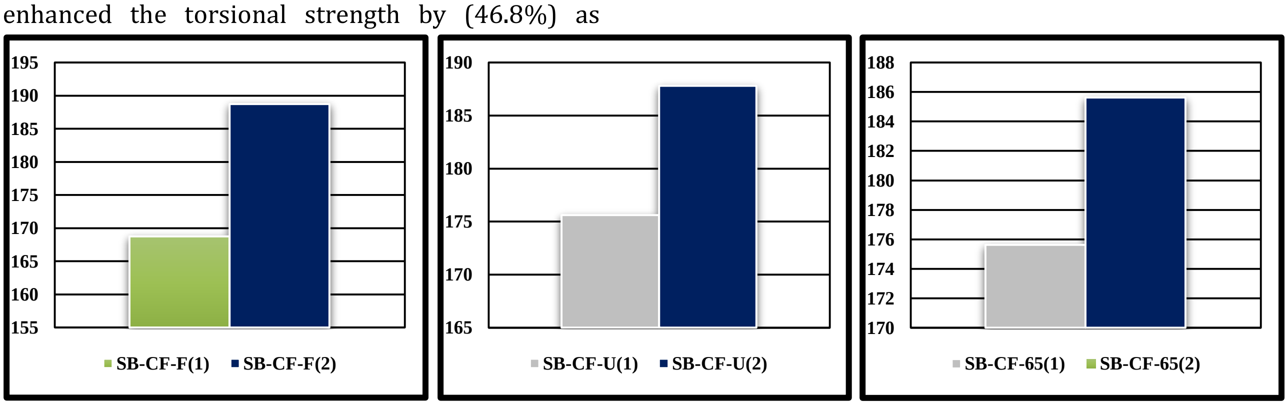


(e) **(f)**

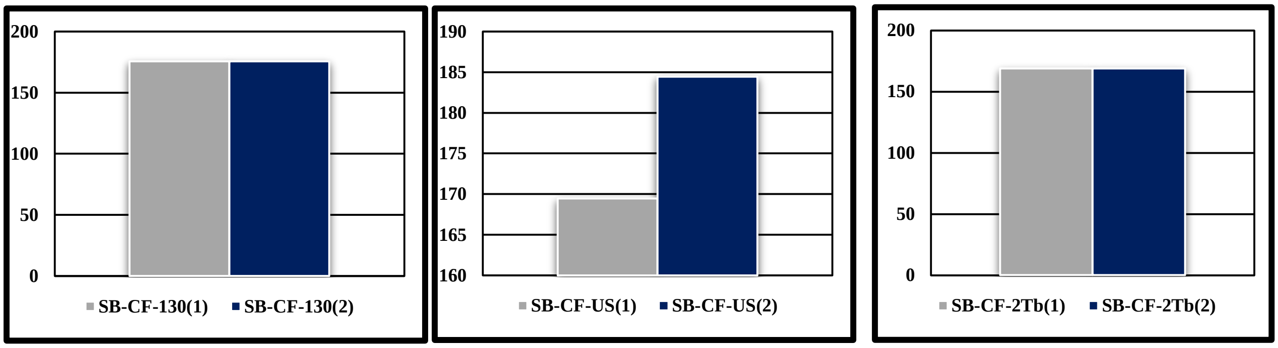
Figure 5. Torque-Rotation Relationship of Strengthened Beams.

5.3. Effect of The Numbers of Wrapping Layer

The effect of the numbers of wrapping layers of the CFRP was significant on the behavior of the twisted strengthened beam. Maximum enhancement occurred at the full jacket wrapping of beam (SB-CF-F(2)) which scored improvement by (49.3%) when the number of the CFRP sheet doubled as revealed in Fig. (6 a). As depicted in Fig. 6 b, wrapping by double U-shaped jacket increased the ultimate strength by 48.5% in comparison with the control beams while the single U shaped jacket which offered improvement of 38.9%. Doubling the number of strips as presented in beams (SB-CF-65(2)) and (SB-CF-130(2)) showed that the doubling of CFRP layers in the 65 mm strips enhanced the torsional strength by (46.8%) as depicted in Fig. 6 c but for the 130 mm strips, doubling the number of CFRP layers does not affected the ultimate strength of the beam as depicted in Fig. 6 d. The enhancement percent when doubling the 65 mm strips was less than the full jacketing by (5%). Using double U shaped slices as in beam (SB-CF-US(1)) causes an enhancement by (45.9%) while the percentage increase when using a single U shaped jacket was 38.9% as depicted in Fig. 6 e. Regarding the remaining strengthening method (SB-CF-2Tb(2)), the enhancement was only marginal (2.9%) when compared with the strengthened beams by single layer as illustrated in Fig 6 f.



(a) (b) (c)

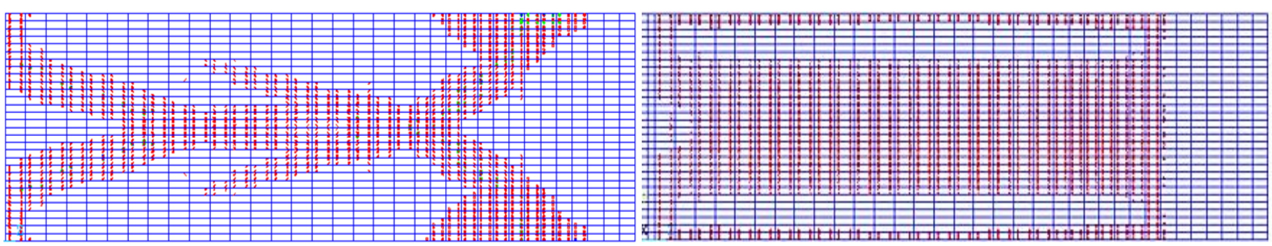


(d) (e) (f)

Figure 6. Effect of the number of CFRP layers on the ultimate torsional capacity.

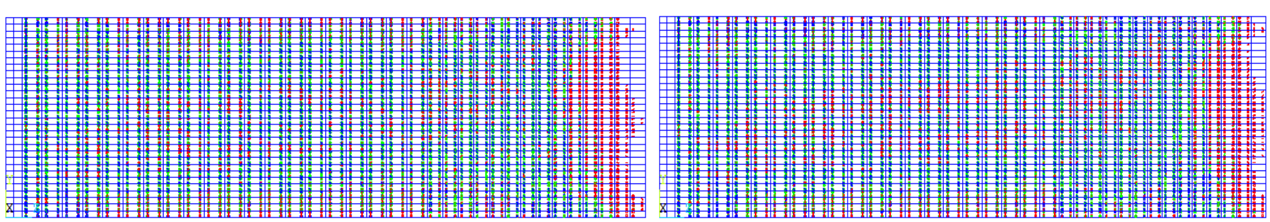
5.4. Failure and cracking mode

The cracking mode showed approximately similar cracking mode for most of the analyzed beams as follows; the cracking started at (53%) of the ultimate torque for the control beam and at average of (48.2%) for the strengthened beams. The cracking torque was affected by the wrapping method, where in the full jacketing the first cracking appeared at 45.4% of the ultimate torsional strength less than the control beam by (14.3%). Most of the strengthened beams had shown appearance of the cracks at loading less than the refence beam by an average of (9%) but the spread of cracks for the wrapped concrete was more than the reference beam as shown in Fig. 7 a. After the cracks started at the support region, the cracks widened and extended in inclined direction reaching to the final stage of the loading and the crack covered most of the twisted beams. Regarding the stress distribution, Fig. 8. Shows the damage in the concrete and CFRP sheets. The stress distribution affected by wrapping methods and number of layers in which the full jacketing method showed higher stress distribution than the other strengthening methods. The stress distribution in the CFRP sheets showed that confinement caused more distribution. Higher stress concentration occurred in the small strips and when the strips size increased, this led to a less stress concentration. The figure below shows the stress intensity in the steel reinforcement where the higher stress occurred near the support.

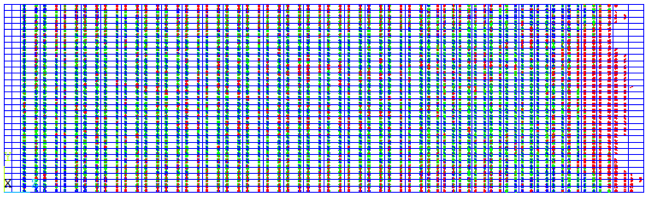


1st crack before Strengthening **1st crack after Strengthening**

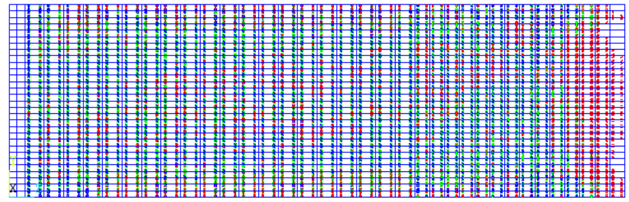
(a)



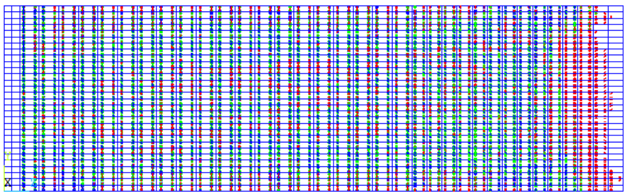
(b) REF. **(c) SB-CF-F(1).**



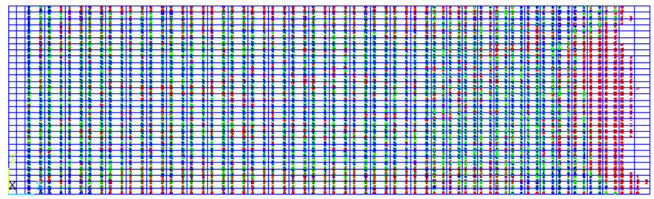
(d) SB-CF-U(1).



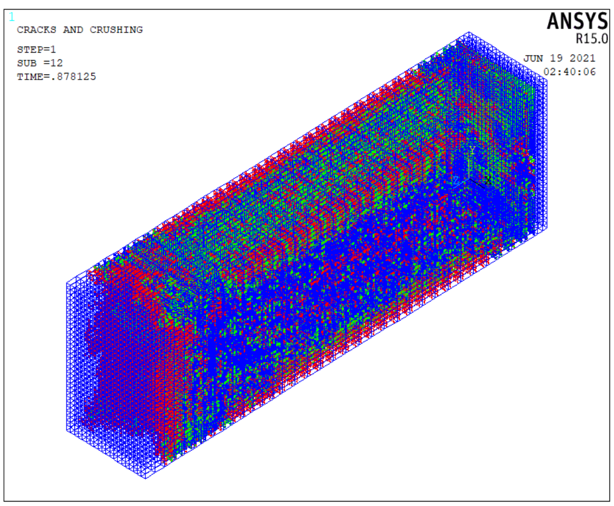
(e) SB-CF-U(2).

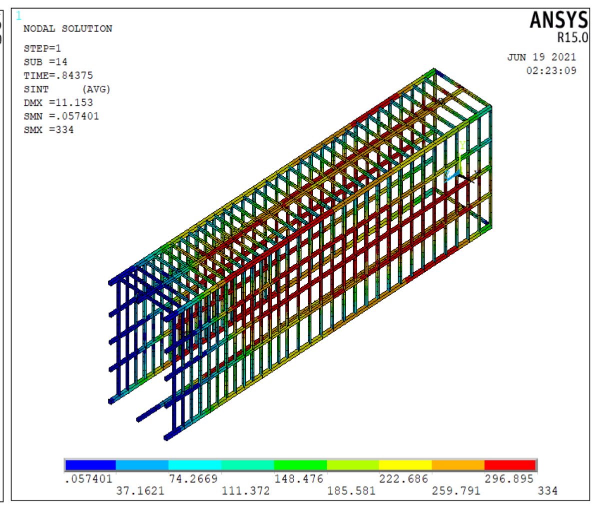


(f)SB-CF-US(1).



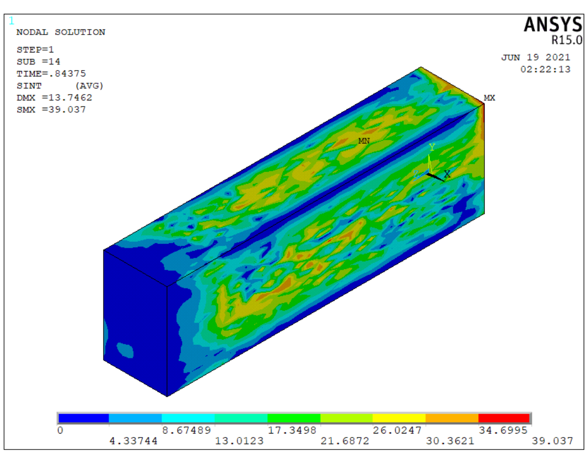
(g) SB-CF-US(2).

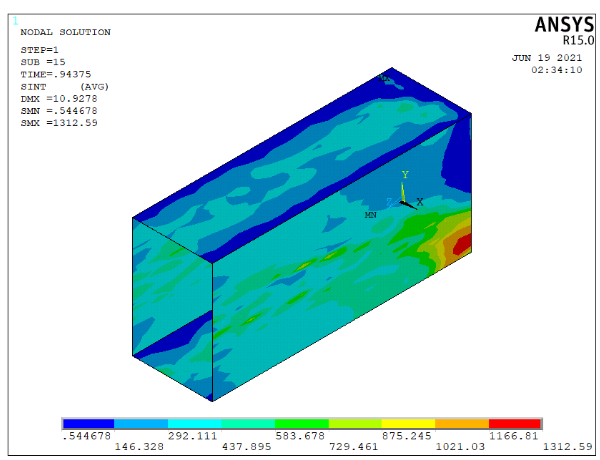




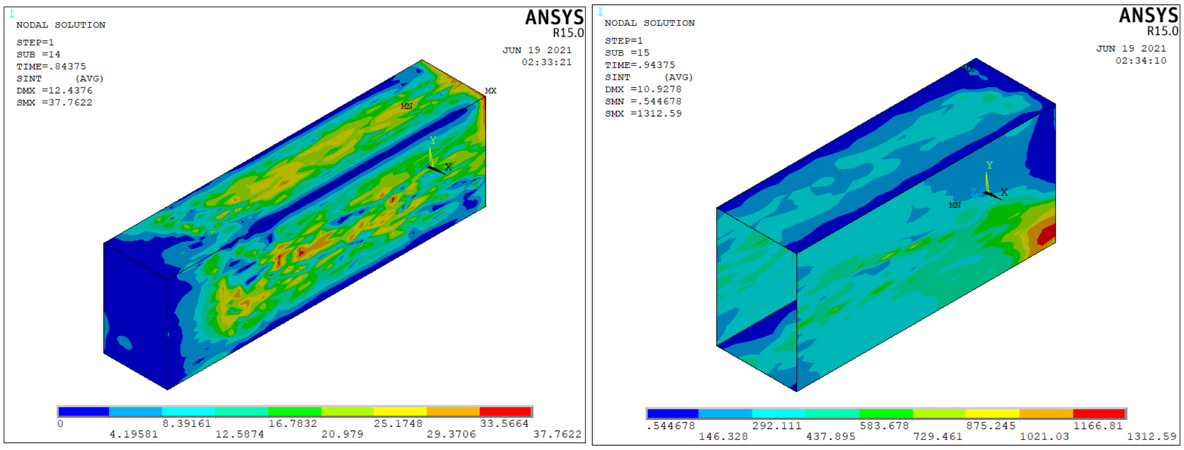
(h) REF

Figure 7. Crack Pattern and Stress Intensity of Steel Reinforcement .

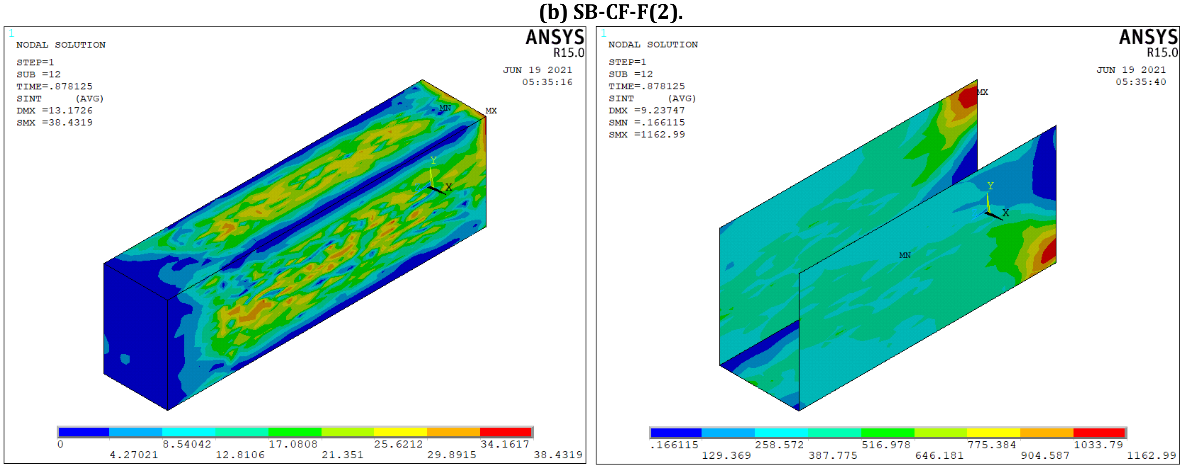




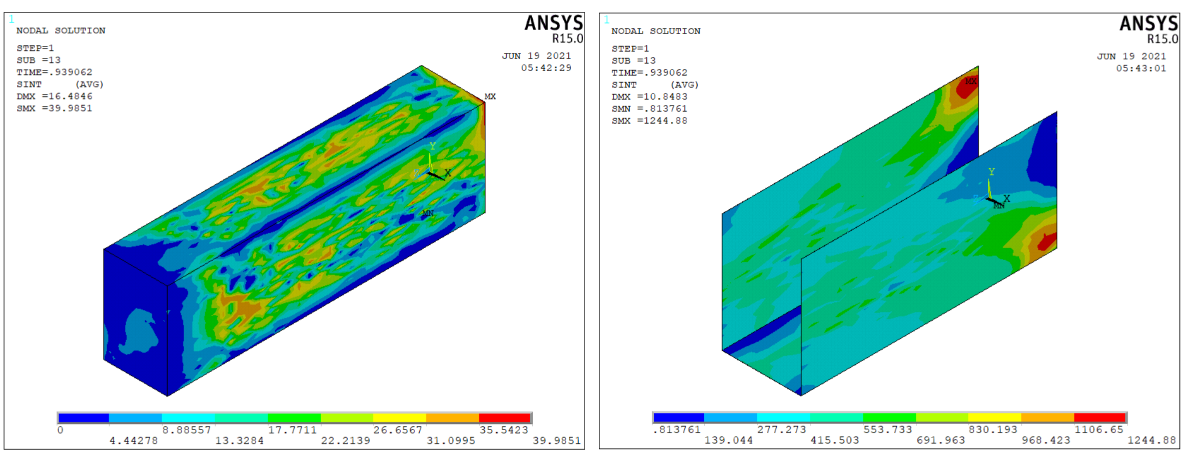
(a) SB-CF-F(1).



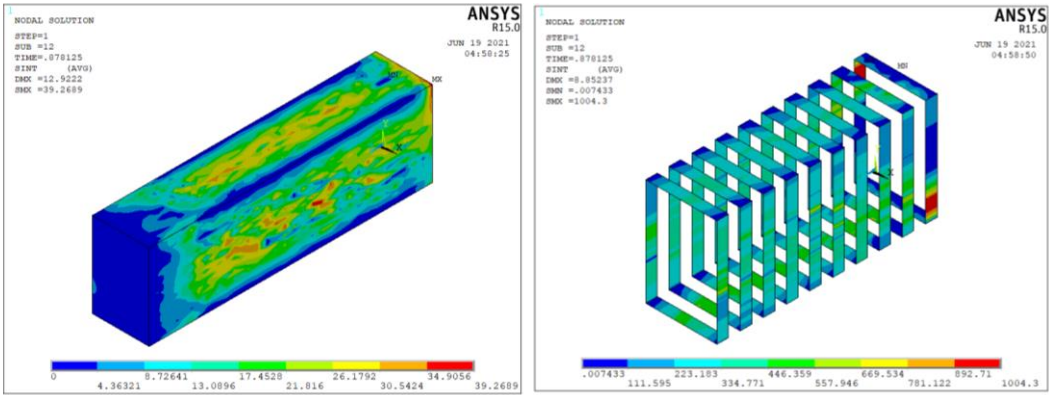
(b) SB-CF-F(2).



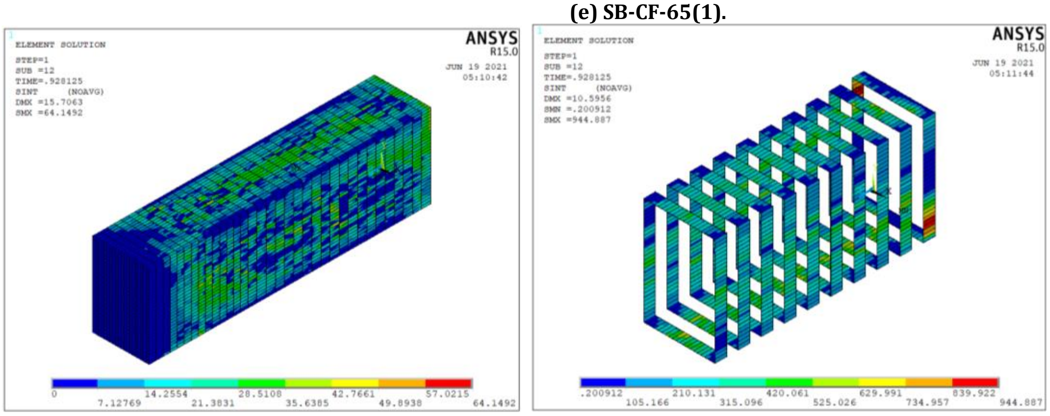
(c) SB-CF-U(1).



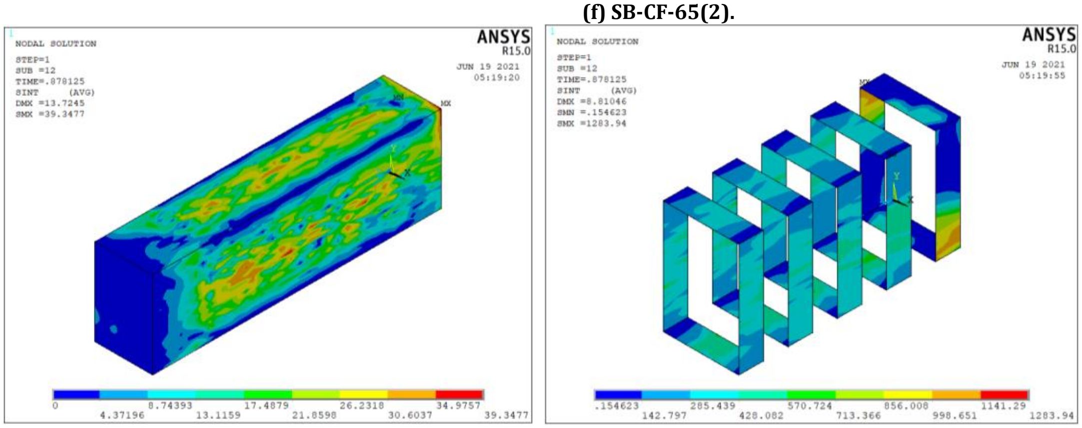
(d) SB-CF-U(2).



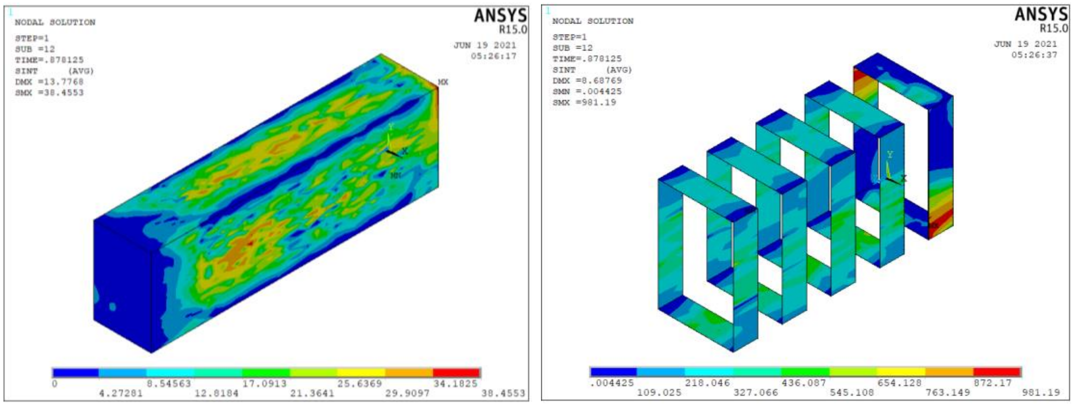
(e) SB-CF-65(1).



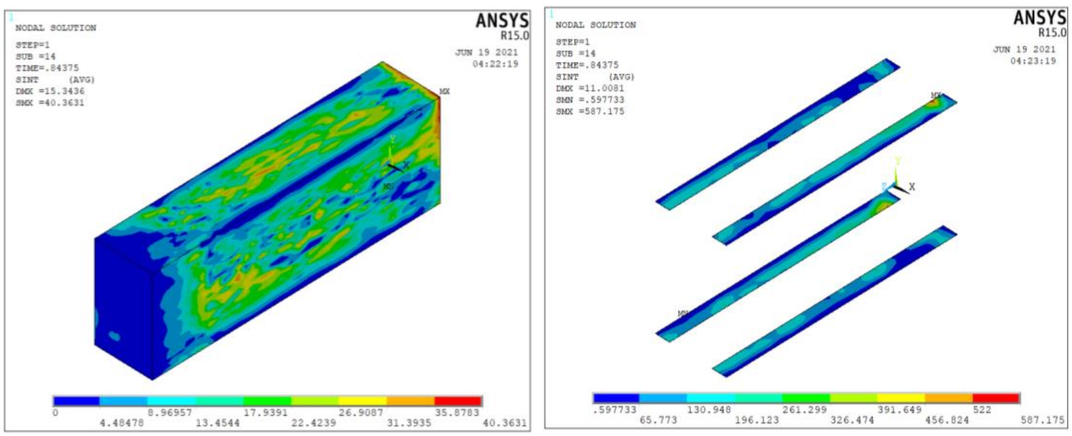
(f) SB-CF-65(2).



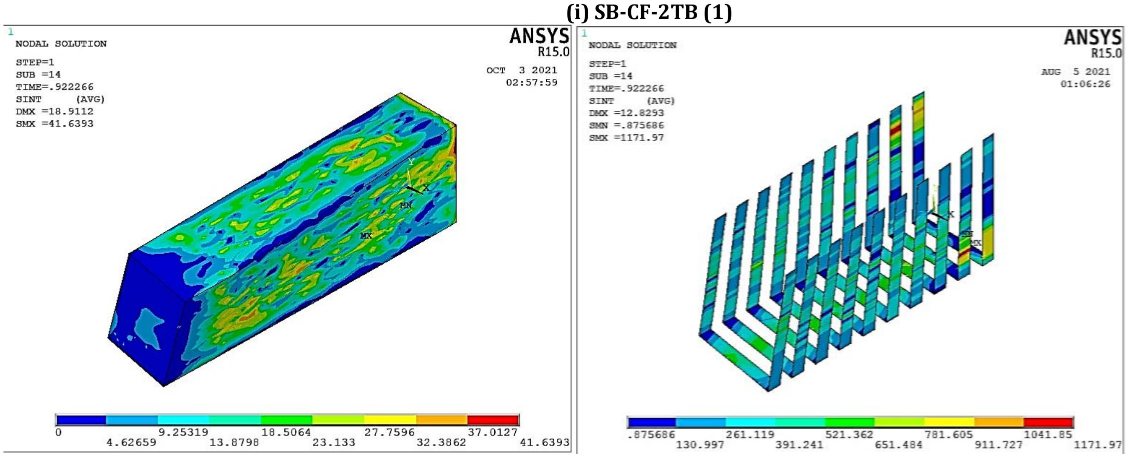
(g) SB-CF-130(1).



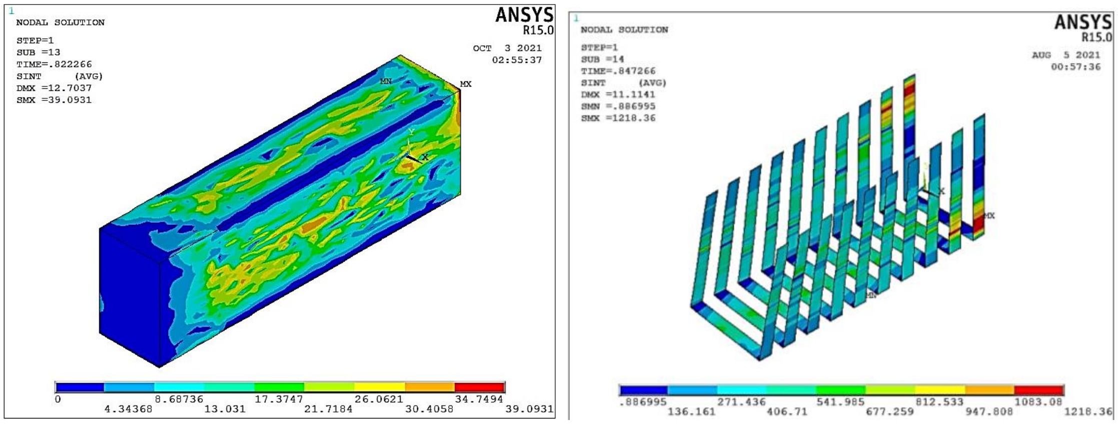
(h) SB-CF-130(2).



(i) SB-CF-2TB (1)



(j) SB-CF-US (2)



(k) SB-CF-US (1)

Figure 8. Stress Intensity of The Concrete and CFRP Sheet of Strengthened Beams.

6. Conclusion

The present paper focused on the torsional behavior of strengthened beams by CFRP sheets using different wrapping methods. Some factors have a significant effect on the torsional behavior of strengthened RC beams and their mode of failure, these effects can be summarized as follows:

1- Use of full wrapping with one layer enhanced the ultimate torque and rotation when compared with the control beam (REF). The average enhancement in the torque was about by (39. %) and the reduction in the value of ultimate rotation was in the order of (15.%). Regarding the other strengthening method with one layer such as the use of U-shaped jacket and strips, the use of U-shaped jacket provided enhancement in the ultimate torque by 39% and reduction in the rotation by (3.%) when compared with control beam. Replacing the U-jacket by U-shaped strips revealed improvement in the ultimate torque less than the U-jacket by about (5%).

2- The strengthening by strips at 65 and 130 mm, longitudinal strips at the top and bottom faces, U-shaped strips in addition to the number of CFRP layers revealed enhancement in values less than that of the full jacket by an average value equal to (22%).

3- The number of the used layers of CFRP significantly affect the ultimate behavior of the twisted strengthened beam. Maximum enhancement occurred at the full jacketed beam which scored improvement by (49.%) when the number of the CFRP sheet doubled.

4- The stress distribution affected by wrapping methods and number of CFRP layers.

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References

[1] Alabdulhady, M. Y., et al. (2019). "Analytical study on the torsional behavior of reinforced concrete beams strengthened with FRCM composite." Journal of Composites for Construction 23(2): 04019006.

[2] Tibhe, S. B. and V. R. Rathi (2016). "Comparative experimental study on torsional behavior of RC beam using CFRP and GFRP fabric wrapping." Procedia Technology 24: 140-147.

[3] Majeed, A. A., et al. (2017). "Behavior of CFRP strengthened RC multicell box girders under torsion." Structural Engineering and Mechanics 61(3): 397-406.

[4] Ma, S., et al. (2016). Behavior of reinforced concrete box beam strengthened with CFRP U-wrap strips under torsion. MATEC Web of Conferences, EDP Sciences.

[5] Askandar, N. and A. Mahmood (2019). "Comparative investigation on torsional behaviour of RC beam strengthened with CFRP fabric wrapping and near-surface mounted (NSM) steel bar." Advances in Civil Engineering 2019.

[6] Kandekar, S. and R. Talikoti (2018). "Study of torsional behavior of reinforced concrete beams strengthened with aramid fiber strips." International Journal of Advanced Structural Engineering 10(4): 465-474.

[7] [7] Said, A. M. I. and Q. H. Al-Shemmari (2020). Numerical Investigations on Behavior of Strengthened RC Beams with CFRP under Combined Bending and Torsion. Key Engineering Materials, Trans Tech Publ.

[8] [8] Panchacharam, S. and A. Belarbi (2002). Torsional behavior of reinforced concrete beams strengthened with FRP composites. First FIB Congress, Osaka, Japan.

[9] [9] Deifalla, A. and A. Ghobarah (2010). "Strengthening RC T-beams subjected to combined torsion and shear using FRP fabrics: Experimental study." Journal of Composites for Construction 14(3): 301-311.

[10] [10] Al-Rousan, R. and I. Abo-Msamh (2019). "Bending and torsion behaviour of CFRP strengthened RC beams." Инженерно-строительный журнал(8): 48-62.

[11] [11] Allawi, A. (2006). Nonlinear analysis of reinforced concrete beams strengthened by CFRP in torsion, Ph. D. Thesis, University of Baghdad.

[12] [12] Shen, K., et al. (2018). "Theoretical analysis on full torsional behavior of RC beams strengthened with FRP materials." Composite Structures 183: 347-357.

[13] [13] Atea, R. S. (2017). "Torsional behavior of reinforced concrete T-beams strengthened with CFRP strips." Case studies in construction materials 7: 110-117.

[14] [14] Kim, M.-J., et al. (2020). "Pure torsional behavior of RC beams in relation to the amount of torsional reinforcement and cross-sectional properties." Construction and Building Materials 260: 119801.