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EXPERIMENTAL AND THEORETICAL STUDY FOR SOLID AND BOX-SECTION CONCRETE BEAMS STRENGTHENED WITH CFRP LAMINATES UNDER PURE TORSIONAL LOADS

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ABSTRACT

The present experimental and theoretical investigation deals with the torsional strengthening of solid and box section plain concrete beams using epoxy-bonded CFRP strips. Also, compares the effectiveness and efficiency of two strengthening techniques viz. FRP bars as NSM reinforcement and CFRP strips as external reinforcement. Plain concrete beam strengthened with CFRP strips as transverse and longitudinal reinforcement were tested under pure torsion. For this analysis, a system of computer program (ANSYS V.14.5) is used for this study. The concrete beam was modeled by 8-node isoparametric brick elements. The CFRP strips were modeled by shell elements. The interface elements were modeled by contact element to represent slip and uplift separation between the concrete beams and CFRP-reinforcement. The results showed that the torsional capacity of the strengthened beams can be increased by either decreasing the spacing of the CFRP, or replacing of CFRP strips by NSM FRP.

Keywords: concrete beam, torsional strengthening, NSM reinforcement, CFRP strips.

INTRODUCTION

Recently, utilizing carbon fiber reinforced polymer (CFRP) materials as a strengthening technique gain wide range of attention due to their excellent strength- to-weight and stiffness-to-weight ratios These supreme characteristic attract researchers and engineers to use this material in the repairing of damaged reinforced concrete (RC) members in addition to other kind of structural members i.e. masonry and steel members.

Over the past decade, most research in CFRP strengthening technique has emphasized the use of this technique in upgrading of RC beams using FRP fabrics and laminates. The vast majority of researchers have covered the flexural strengthening, while less attention was paid for the using of this scheme in strengthening of RC members vulnerable to shear force. For instance, **Li LJ et al. [1]** undertake an experimental study to investigate the effectiveness of CFRP strengthening scheme for members under flexural, **Li LJ et al. (2006) [1]** and shear **Triantafillou (1982)[2]**.

The experimental investigation that was carried out the torsional strengthening of concrete beams without stirrups using FRP sheets and strips as external transverse reinforcement were presented by **Constantin E. Chalioris (2008) [3]**. In the experimental program, 14 rectangular and T-shaped beams were tested under pure torsion. They found that CFRP can improve the torsional moment at cracking and at ultimate, the corresponding twists and the behavioral curves. It was also proved that the beams strengthened with a full wrapping CFRP sheet exhibited better performance in enhancing the torsional resistance than those strengthened with FRP strips. Moreover, it was reported that a premature de-bonding failure was captured for the U-jacketed flanged beams which then led to a reduction in the potential torsional capabilities of these beams.

The effectiveness of carbon and glass FRP sheets and strips in strengthening rectangular beams under torsion was experimentally carried out by **Ghobarah et al. [4]**. Another study was conducted by **Salom et al. [5]**, in which the torsional behavior of six CFRP strengthened spandrel beams was experimentally and analytically investigated. Both studies revealed that the CFRP strengthening scheme can effectively improve the torsional resistance of the tested beams. However, the using of NSM FRP reinforcement technique has not seriously been covered in previous studies.

The strengthening of RC members using NSM technique can be undertaken by making a cut onto the member surface to apply the FRP bar in it. Afterward, an appropriate binding agent can be applied in the groove in order to paste NSM to surface concrete. . It should be noted here that the grooves are created on the sides of the member at a required angle to beam axis in the case of shear strengthening with the NSM technique, **De Lorenzis** and **Teng (2007) [6]**.

MATERIALS

• Cement:

Ordinary Portland cement (OPC) according to (ASTM C150-Type I) was used in this research. The cement are conforming to **(IQS N0. 5/1984) [7].**

• Fine Aggregate:

Al-Ekhaider natural sand was used as fine aggregate. Results indicate that the grading and sulfate content are conformed to the requirements of **(IQS No.45/ 1984) [8].**

• Coarse Aggregate:

Crushed coarse aggregate was brought from Al-Nibaey region with maximum size of

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10mm. the coarse aggregate was washed, and then stored in air to dry. The grading and the physical properties of this aggregate content conformed to the Iraqi specification **(IQS No.45/ 1984) [8].**

• Water:

Tap water is used throughout this work for both mixing and curing of concrete.

Experimental Program:

Two of concrete beams with dimensions (200*200*1200) mm were tested under pure torsion in the laboratory of the civil engineering department of the Babylon University. Test span of beams was measured at (1000) mm. The first beam (SF) was strengthened using CFRP strips as external transverse and longitudinal. The beam was wrapped by full vertical strips around the perimeter of the section, one layer of CFRP strips spaced (100) mm center to center with development length of (200) mm and additional continuous CFRP strips of (40) mm width parallel to the longitudinal axis of the beam on the two long faces were used as shown in Plate (1). The second beam (SC) was unstrengthened concrete beams. A summary of the specimen details can be found in Table (1).

The load was imposed consistently and measured by a load cell shown in Plate (2). The twist angle of the beam was calculated from the displacement of the end cross-section. The beams were tested in monotonically increasing torque moment until the ultimate torsional strength (total failure of the specimen).

Test Results and Discussion:

The torque twist behavior of the strengthened beam (SF) in comparison with the reference beam (plain concrete beam (SC) is shown in Fig. (1). Strengthened beam (SF) showed initial cracks at approximately the same torque as the unstrengthed beam (SC). However, the presence of CFRP strips prevented the cracks from widening and propagating on the vertical face. The beam (SF) failed at ultimate torque of (20.7) kN.m with an increase of about 48% compared to control beam. The mode of failure of beam (SF) was extensive concrete cracking between strips followed by the rapture of the FRP strips as shown in Plate (3), while the beam (SC) failed very suddenly after reaching its ultimate torque and divided into two parts.

Finite Element Representation of Reinforced Concrete beam with NSM FRP Reinforcement:

One of the common methods which using in determining the stresses and deformations, it is the finite element method. In order to represent any element within the whole structure, therefor, three-dimension solid element will be need it. ANSYS computer program contains on many elements.

• Concrete Brick Element:

In this research represented the R.C. beams by brick element, this element has eight

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nodes. ANSYS program contain on a solid 65 capable to simulate the concrete. Fig. (2) explain the proprieties of this element.

• Finite Element Idealization of Reinforcement:

Link 8 in ANSYS program, capable to represent the FRP-rods. Assume the steel reinforcement is capable to transmit axial force only, therefor; the bond between concrete and steel bars was perfect. Fig. (3) explain the proprieties of this element.

As the element is capable of carrying axial loads only, then the strain-displacement relationship is as follows:

$$\varepsilon = \varepsilon_{x'} = \frac{\partial u'}{\partial x'} \qquad \text{.................................(1)}$$

Where: U' local displacement, X' local coordinate.

• SHELL181 Element (Membrane shell):

In ANSYS computer program the 3-D element (SHELL 181), this element is capable to represent CFRP-sheet, Fig. (4) explain the proprieties of this element. This element is capable to transmit the deformations in three-dimensions.

• Steel Plates Representation:

In ANSYS computer program the Solid element (SOLID 185) used in this study to represent steel plate, this element can transmit the deformations in x, y, and z direction, Fig. (5).

• Interface Finite Element Idealization:

A three-dimensional point-to-point contact element (**Contact 187) ANSYS 14.5 [9]**, is used to model the nonlinear physical contact behavior of the surface between the CFRP-reinforcement and the ordinary concrete beam in a composite concrete beam. This model also includes the definition of the stress transfer. Fig. (6) explain the proprieties of this element.

Concrete Modeling:

• Stress-Strain Relationship:

Linear isotropic and multi-linear isotropic must be given to solid 65 in order to represent concrete model. **ACI Code (2008) [10]** suggested the following equation to calculate modulus of elasticity.

$$Ec = 4730\sqrt{f_c'} \qquad \text{............................(2)}$$

In this study was depended on stress-strain curve that suggested by **Gere et al., (1997) [11]** as shown in Fig. (7).

Modeling of FRP Reinforcement:

The FRP reinforcement can be assumed as a linear-elastic material. As a result of that, the FRP reinforcement can be classified as a brittle material, while steel material was modelled as a ductile material. For a comparison reason, the yield strain of grade 60 steel is approximately 0.002, which represents about 10% of the ultimate strain of FRP material. Fig. (8) explain the proprieties of this element.

Finite Element Idealization:

The load was represented in the finite element model by 4 equivalent nodal forces across the width of the beam, as shown in Fig. (9).

Found load-displacement relationship from ANSYS program and by using curve fitting by GRAF4WIN program obtained on angle of twist.

Results of the finite element model:

Relationship between the results of numerical analysis and experimental results, shown in Fig. (10 and 11). The analytical angle of twist (0.5 and 2.6) is detected quite well compared with that experimentally observed (1.6 and 2.72) for beam (SC and SF) respectively.

PARAMETRIC STUDY: -

1- Effect of the spacing between CFRP.

Different values of spacing for the same amount of reinforcement ratio (by CFRP strips) were considered in this study to investigation the influence of the spacing between CFRP strips on the torsional strengthening efficiency of plain concrete beams. Decreasing the spacing between CFRP strips will lead to increase the torsion strength Fig. (12). The effect of spacing decrease on the behavior of the concrete beams are significant until the value of (80) mm. Decreasing the spacing of the CFRP from (180 to 80) mm led to increase in capacity of 34.3% for SF.

2- Effect of Variation of CFRP strips to NSM FRP.

To study and compares the effectiveness and efficiency of two strengthening techniques viz. steel rebar's as NSM reinforcement and CFRP strips as externally bonded reinforcement (with the same area of polymer material), in improving the torsion strength of concrete beams. Fig. (13) show torsion strength of the beams strengthened with CFRP strips decreased by 10% for SF.

3- Effect of Variation of Cross Section of Beams.

To study the effect of the cross section of the beam on the behavior of the strengthened and unstrengthened concrete beams. The following cases are considered:

1) The original case has solid cross section (SC and SF).

2) The second case has box cross section (BC (unstrengthened beam) and SF (strengthened beam)).

Fig. (14&15) shows the effect of the cross section of the beam on torque-angle of twist behavior of strengthened and unstrengthened concrete beams. It can be noted that the

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solid cross section is more efficient and give significant results behavior than the box cross section.

CONCLUSIONS

1- The test results confirm that the strengthening technique of CFRP system is applicable and can increase the torque capacity of concrete beams. In general, FRP fabrics could effectively be used as external torsional reinforcement.

2- The three-dimensional nonlinear finite element model presented in this study by using the computer program (ANSYS V.14.5) is able to simulate the analysis of solid and box-section concrete beams strengthened in torsion with CFRP reinforcement. The numerical results were in good agreement with experimental torque-twist curves throughout the entire range of behavior.

3- The near surface mounted (NSM) technique presents a good method for external strengthening of beams torque capacity of the beams strengthened with NSM increased by 10% for solid and 14% for box section when compared with CFRP beams.

4- The spacing of CFRP strips also affects the torque capacity of the strengthened beams. For the same amount of reinforcement ratio (by CFRP), decreasing the spacing between the CFRP strips was more effective than increasing the width of the strips.

5- It was found that the variation of cross section shape has a real effect on the predicted and ultimate torque of beam concrete members. It can be noted that the solid cross section is more efficient and give significant results behavior than the box cross section.

Table (1): Summary of specimen details.

Beam	Section type	No. of CFRP layers	Inclined of CFRP
SC	Control beam (solid)	None	90
SF	Full strips (solid)	2	90
BC	Control beam (box)	None	90
BF	Full strips (box)	2	90

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Plate (1): Strengthening Scheme.

Plate (2): Test setup.

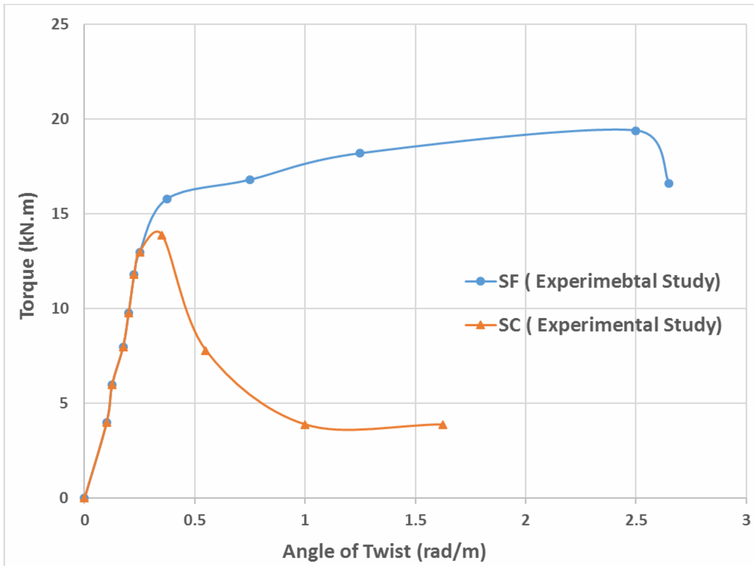

Fig. (1): Experimental behavior curve of beams.

Plate (4): Cracks pattern at failure of beam SF.

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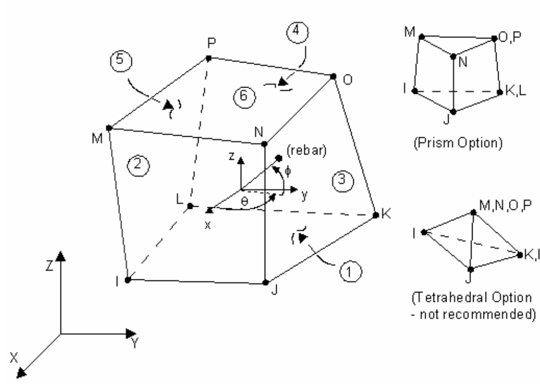

Fig. (2): Brick element with 8 nodes (SOLID65 in ANSYS 14.5).

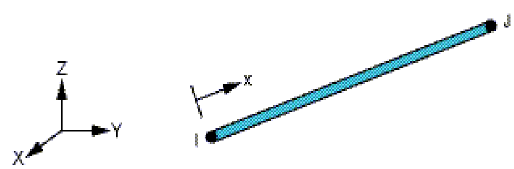

Fig. (3): Bar element (LINK 180 in ANSYS 14.5).

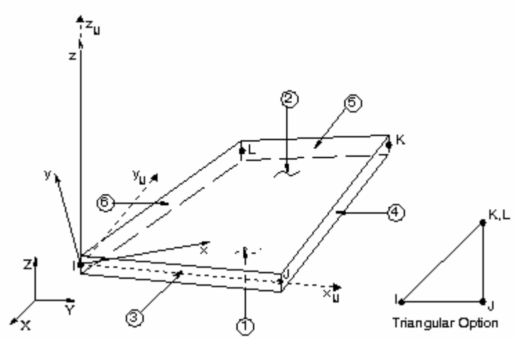

Fig. (4): Shell 181 geometry.

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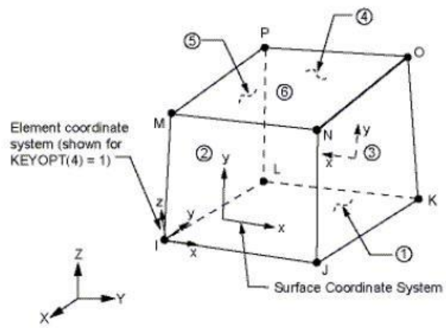

Fig. (5): Solid 185 geometry.

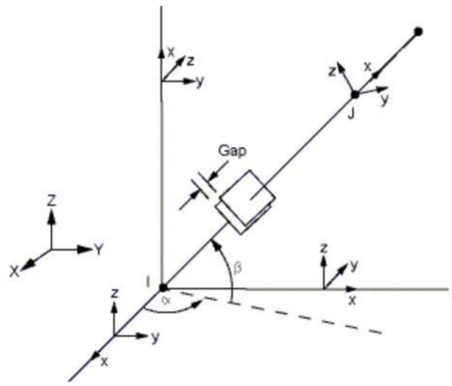

Fig. (6): 3-D Point-to-point contact element.

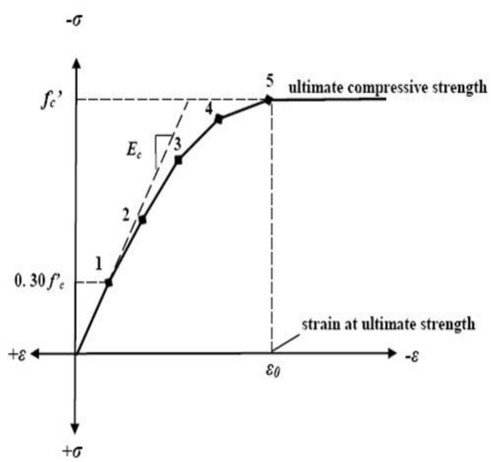

Fig. (7): Simplified compressive uniaxial stress- strain curve for concrete Kachlakev et al. (2001) [12].

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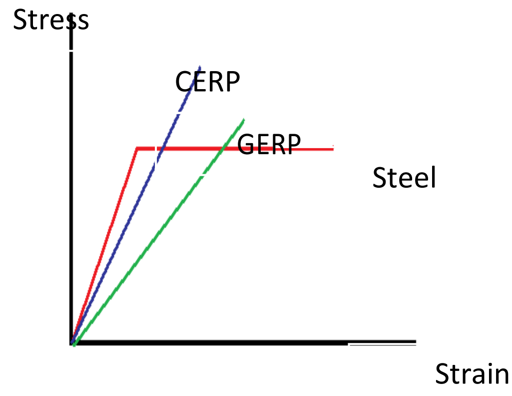

Fig. (8): Behavior of Typical Materials, John (2009) [13].

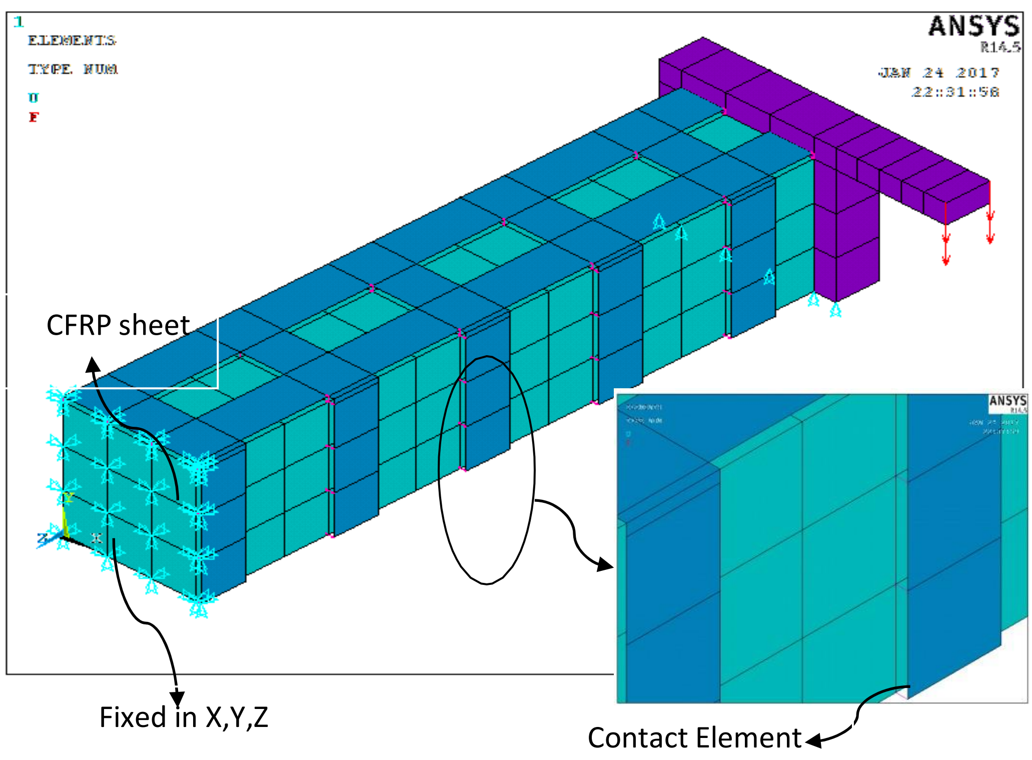

Fig. (9): Finite elements mesh and load simulation for beams used in ANSYS program [9].

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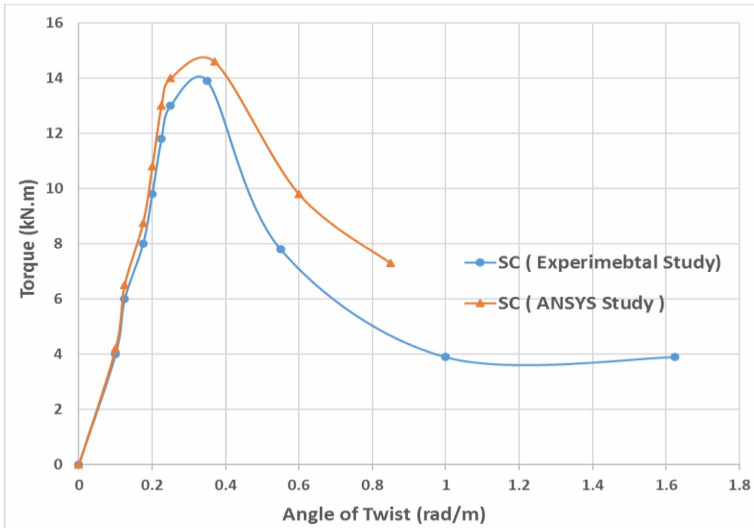

Fig. (10): Torque-twist curve for beam SC.

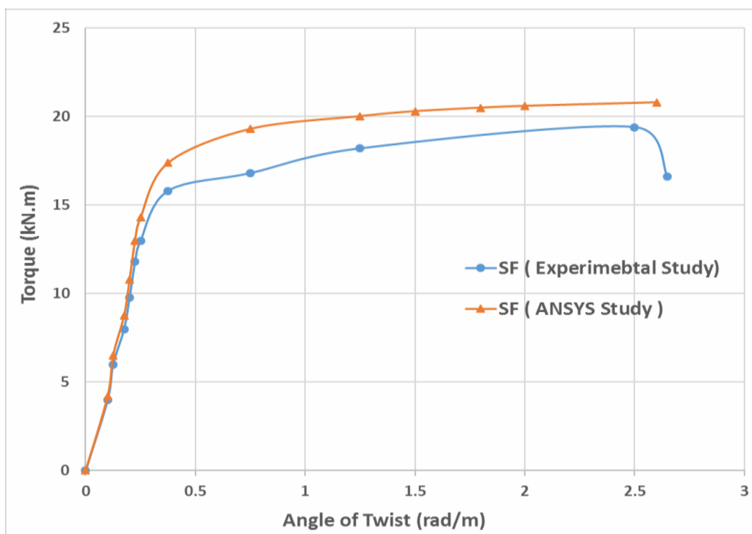

Fig. (11): Torque-twist curve for beam SF.

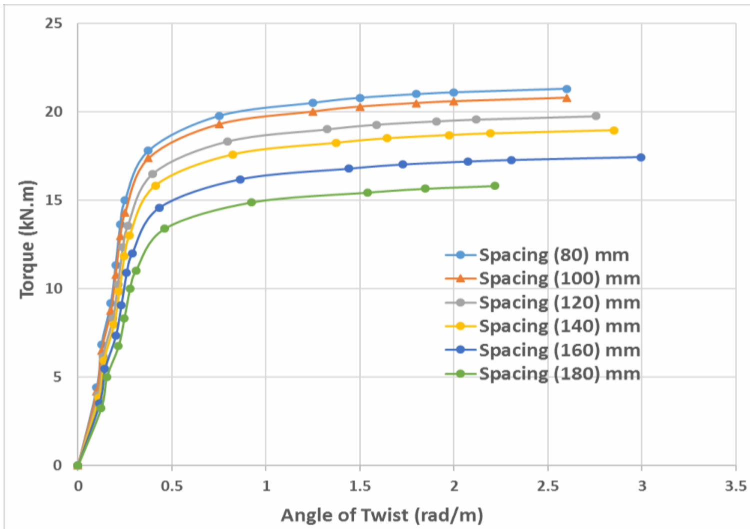

Fig. (12): Torque-twist curve for beam SF with variables spacing.

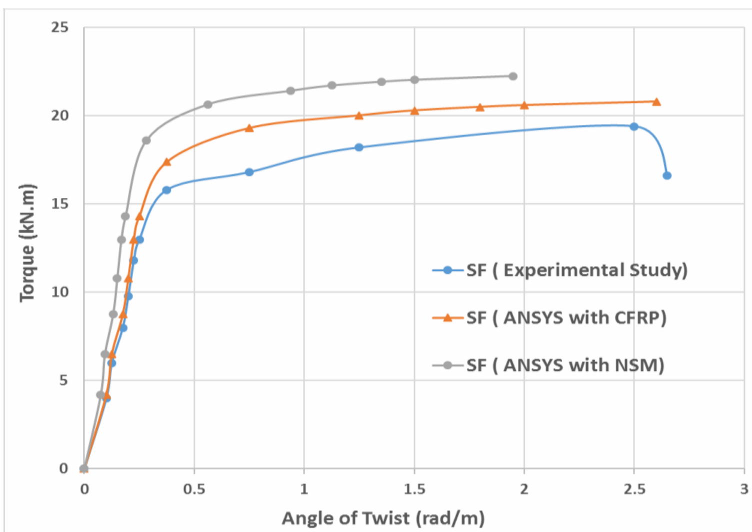

Fig. (13): Torque-twist curve for beam SF with NSM.

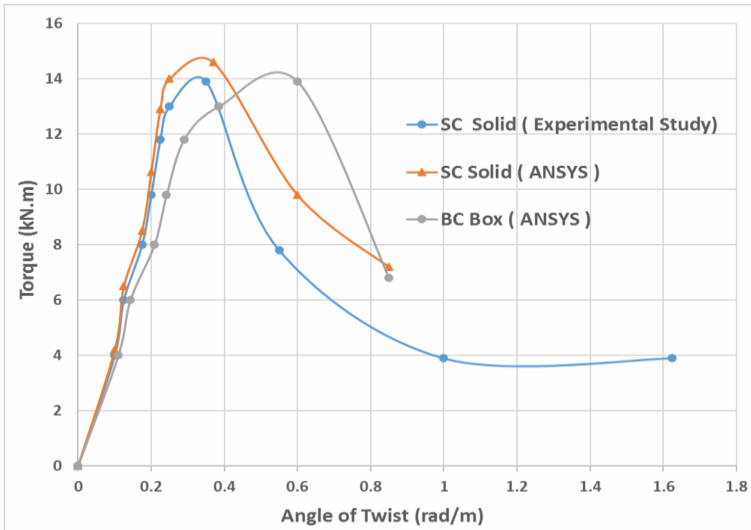

Fig. (14): Torque-twist curve for beam SC with variables cross section.

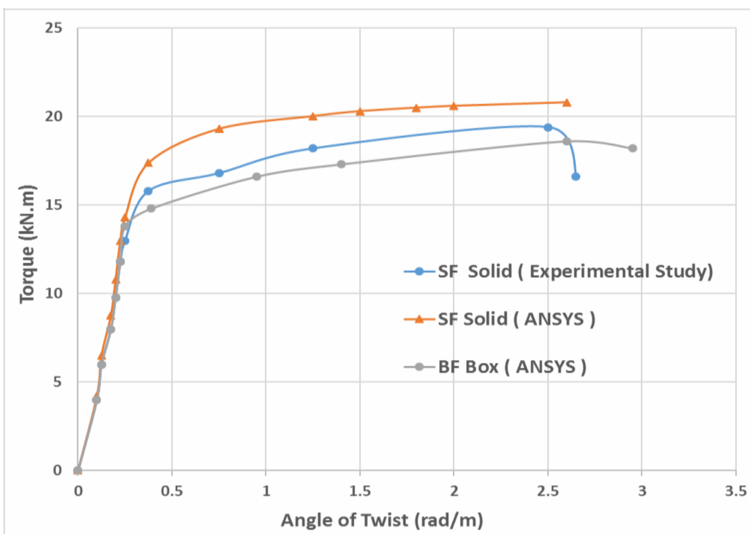

Fig. (15): Torque-twist curve for beam SF with variables cross section.

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