EXPERIMENTAL INVESTIGATION OF GFRP STRENGTHENED RC BEAMS UNDER PURE TORSION

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ABSTRACT. Fiber Reinforced Polymer (FRP) as an external reinforcement is used extensively for axial, flexural and shear strengthening in structural systems. The strengthening of members subjected to torsion is recently being explored. The loading mechanism of beams located at the perimeter of buildings which carry loads from slabs, joists and beams from one side of the member generates torsion that are transferred from the beams to the columns. In this paper an experimental investigation on the improvement of the torsional resistance of reinforced concrete beams using Glass Fiber Reinforced Polymer (GFRP) is presented. Total ten beams of dimension 150mm × 150mm × 1300mm are cast. Two beams are designated as control specimen and eight beams are strengthened by GFRP wrapping of different configuration. All beams are subjected to pure torsion using specially fabricated support mechanism and universal testing machine. Measurements of angle of twist at regular interval of torque, torsion at first crack, and ultimate torque, are obtained for all specimens. Results of different wrapping configurations are compared and the effective GFRP wrapping configuration is suggested.

Keywords: Reinforced Concrete beam, Glass Fiber Reinforced Polymer composites, Torsion.

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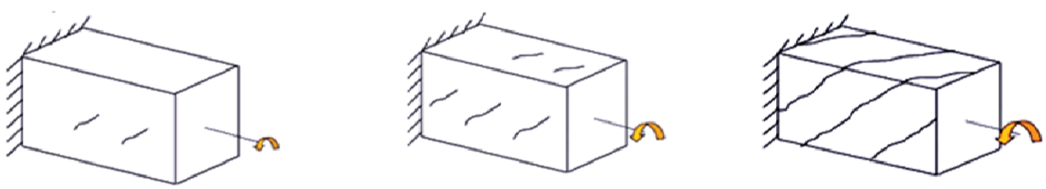
INTRODUCTION

In the design of many concrete structural elements, torsion is significant and has to be considered. Structural elements subjected to torsion experience diagonal tension and compression and fails in a brittle manner. Brittle failure of elements is undesirable and could lead to a non-ductile seismic behaviour of structures during earthquake. There are various structural elements like beam supporting cantilever slab, beam curved in plan, skew bridges, spandrel beam, box girder, inverted T-beam supporting pre-cast slabs etc. that are primarily subjected to torsional moment.

In reinforced concrete design, depending on the load transfer mechanism the torsion is classified as 'equilibrium torsion' and 'compatibility torsion'. Equilibrium torsion is induced in beams supporting lateral overhanging projections, and is caused by the eccentricity in the loading. In compatibility torsion, torsion is induced in a structural member by rotations (twists) applied at one or more points along the length of the member and their analysis necessarily involves compatibility conditions.

The cracks generated due to pure torsion follow the principal stress trajectories. The first crack is observed at the middle of the longer side. Next crack is observed at the middle of the shorter side. Subsequently, the cracks get connected and circulate themselves along the periphery of the beam as shown in Fig.1.



(a) Initiation of torsional crack in longer side

(b) Initiation of torsional crack in shorter side

(c)Spiral torsional crack

Figure 1 Formation of cracks in a beam subjected to torsion

The structural elements subjected to torsion show cracking if they are not designed and detailed properly. Further, change in loading or deterioration of structural element cause the deficiency in torsional resistance. Also, in recent past earthquakes, it has been seen that structures showed failure and some have been severely damaged. Such disasters have demonstrated the need for retrofitting of seismically deficient structures. Retrofitting allows strengthening of elements to resist the strength demands predicted by the analysis, without significantly affecting the overall response of the structure. Fiber Reinforced Polymer (FRP) composites can be effectively used as an external reinforcement for upgrading such structurally deficient RC structures [1]. The main objective of the present work is to study improvement in torsional resistance of RC beam with different configuration of GFRP wrapping. The behaviour and performance of RC members strengthened with externally bonded GFRP sheets subjected to pure torsion is presented in this paper.

LITERATURE REVIEW

Ghobarah et al. [2] evaluated the effectiveness of FRP strengthening of steel-reinforced concrete beams and columns subjected to torsion. They conducted experiment on 11 beams with different orientation of CFRP and GFRP wrap. Complete wrap of torsional zone of RC beam was found to be more effective. The 45^0 orientation of the fibers showed more efficiency of material. Chalioris [3] experimentally evaluated the effectiveness of the use of epoxy-bonded carbon FRP fabrics as external transverse reinforcement to under-reinforced concrete beams with rectangular and flanged cross-section subjected to pure torsion. 14 rectangular and T-shaped beams having length 1.6 meter were casted and tested under pure torsion. They reported that FRP fabrics could effectively be used as external torsional reinforcement in under-reinforced concrete elements without steel transverse reinforcement. Santhakumar et al. [4] presented the numerical study on un-retrofitted and retrofitted reinforced concrete beams subjected to combined bending and torsion using finite element method. They reported improvement in behavior by the addition of FRP laminate being effective only after initial cracking of the beam but no significant effect on the initial stiffness of beams. The laminates with ±45° fiber orientation were more effective for higher values of twisting to bending moment ratios. Behavior and performance of reinforced concrete members strengthened with externally bonded Glass FRP (GFRP) sheets subjected to pure torsion is presented by Panchacharam and Belarbi [5]. Total eight beams were included in the investigation and different strengthening schemes were adopted. Combined FRP sheets in the longitudinal direction of the beam followed by all-around wrapped strips, showed an increase in both the ultimate strength and ductility of the beam. Ameli et al. [6] carried out experimental and numerical study of twelve rectangular RC beams strengthened by Carbon (C) FRP / GFRP wrap with different configuration. Numerical modeling of FRP strengthened beam was done with ANSYS. Significant improvement in ductility was observed with GFRP wrapping as compared to CFRP wrapping. Analytical method for evaluating torsional capacity of FRP strengthened RC beams was presented by Ameli and Ronagh [7] by considering interaction of concrete, steel and FRP. The method was in close agreement with experimental results of fully wrapped beams.

EXPERIMENTAL PROGRAMME

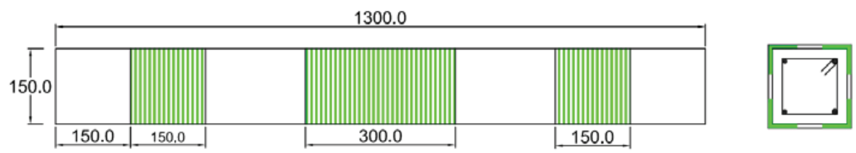
The experimental work carried out in this study comprises pure torsion test on R.C. beam wrapped with different configuration of GFRP. Special test set up is fabricated to apply torsion moment on RC beam.

Experiment Design

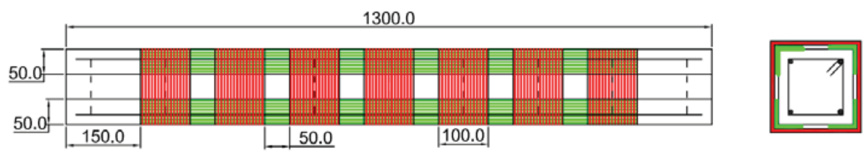
Total 10 beam specimens are prepared with M25 grade concrete. All beams are having 150 mm × 150 mm cross section and 1300 mm length. The beams are reinforced with 4–10 mm diameter bars in longitudinal direction and 8 mm diameter stirrups in the transverse direction spaced at 150 mm c/c. GFRP sheets with different configurations are applied to 8 beams and 2 beams are not wrapped to serve as control beams. The physical and mechanical properties of the E-glass fiber provided by the manufacturer are listed in Table 1. Different wrapping configuration adopted in the present study are shown in Figure 2.

Table 1 Fiber Properties as per Manufacture’s Specifications

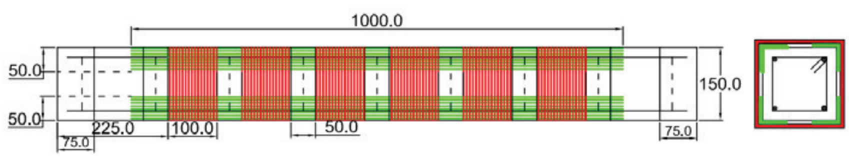
Appearance	MOE (N/mm^2)	Total wt. (g/m^2)	Thickness (mm)	Tensile Strength (N/mm^2)
White	74500	900	0.324	3400



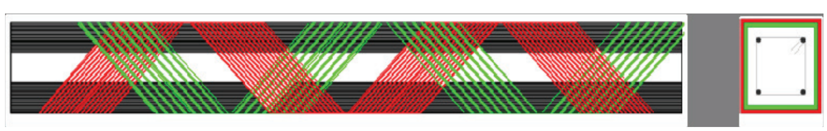
(a) 300 mm central strip wrapping (CE300S)



(b) Corner and strip wrapping above stirrups (CO&100SAS)



(c) Corner and strip wrapping in between stirrups (CO&100SIS)



(d) Corner and diagonal strip wrapping (CO&DS)

Figure 2 Schematic representations of different wrapping configurations for pure torsion

Experimental Test Set-up

Universal Testing Machine (UTM) is used for testing specimens under pure torsion. A special support system is fabricated, which allows the rotation about longitudinal axis of the beam. The advantage of the test setup is that, a single vertical load induces pure torsion on RC beam. The load is applied on concrete beam through lever arm via spreader beam as shown in Figure 3. Two Dial gauges are used each below the lever arm, for measuring vertical displacement. The lever arm is providing an eccentricity of 470 mm to vertical load normal to the longitudinal axis of the beam. Box section is used as lever arm and ISMB150 is used as spreader beam which rests diagonally on hinged end supports at top of the lever arms.

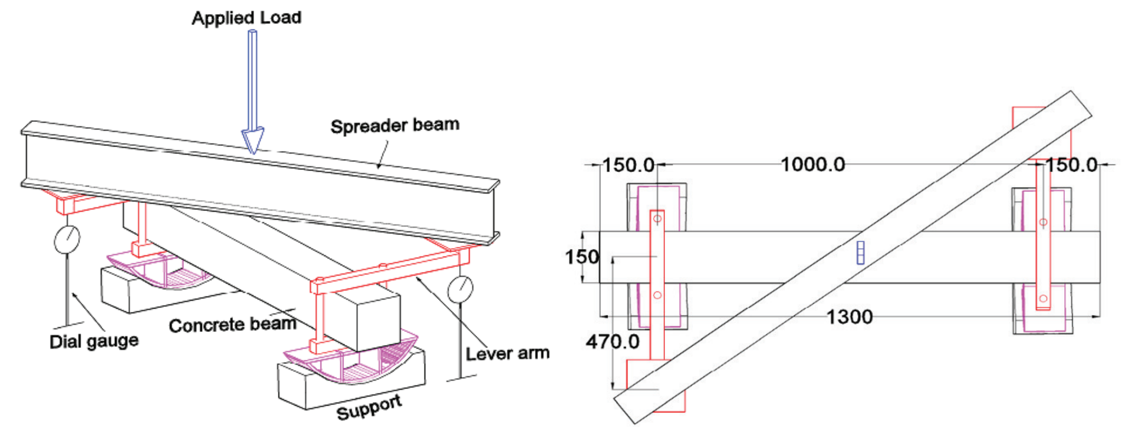


Figure 3 Schematic diagram of test set-up

A spreader beam is loaded at its center by a 1000 kN capacity Universal Testing Machine (UTM). The applied load and vertical displacement of both the lever arms are continuously recorded.

Test Procedure

Beams to be tested under pure torsion are placed on Universal Testing Machine (UTM). Arrangement of test set-up for the beams under pure torsion is shown in Figure 4.

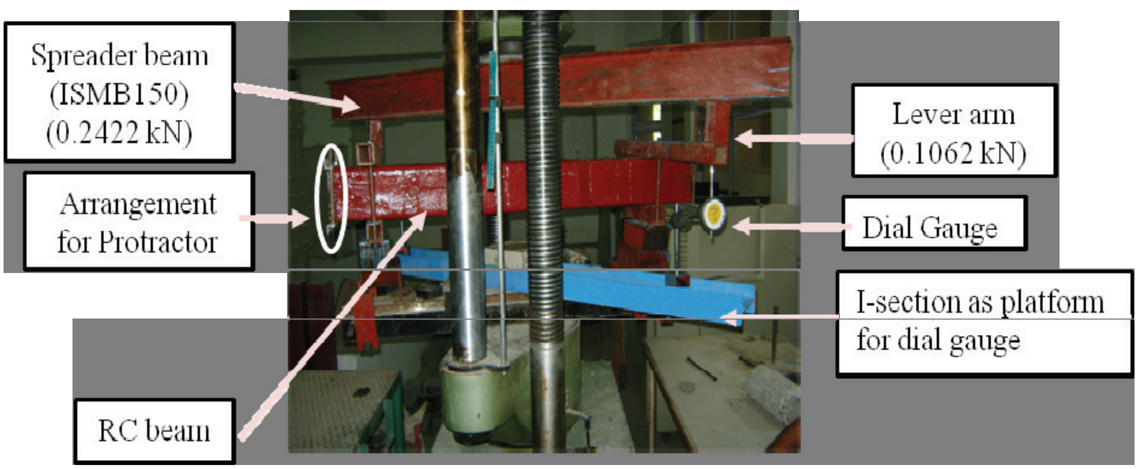


Figure 4 Test set-up for beams to be test under pure torsion

Length of lever arm is adjusted as 470 mm. Dial gauges are placed exactly below the lever arm in such a way that it touches the bottom of lever arm at 470 mm apart from centre of the RC beam. Two dial gauges are used for measuring vertical displacement of the lever arm. Point to be noted is that, UTM is applying the load by raising its base. Hence, the dial gauges are placed on the platform prepared by placing an I-section on the base of the UTM such that dial gauges also moves in upward direction as lower cross head of UTM moves and can measure the vertical displacement of lever arm only. To cross check the results of angle of twist, special arrangement of protractor is also done. The Point load applied by UTM on the centre of the spreader beam is transfer equally on both the lever arms which will tend the beam to rotate and ultimately, pure torsional moment is applied on the beam. The torque on the specimen is load at the end of lever arm (half the applied load) multiplied by length of lever arm from the center of specimen. The angle of twist at each lever arm is obtained from vertical displacement and length of lever arm. The total angle of twist of specimen is sum of angle of twist at both the lever arm.

TEST RESULTS

Comparative performance of RC beams strengthened with different wrapping configurations in pure torsion is presented in this section.

Torque-Twist Comparison

Torque-twist behavior for beams tested under pure torsion is plotted in Figure 5.

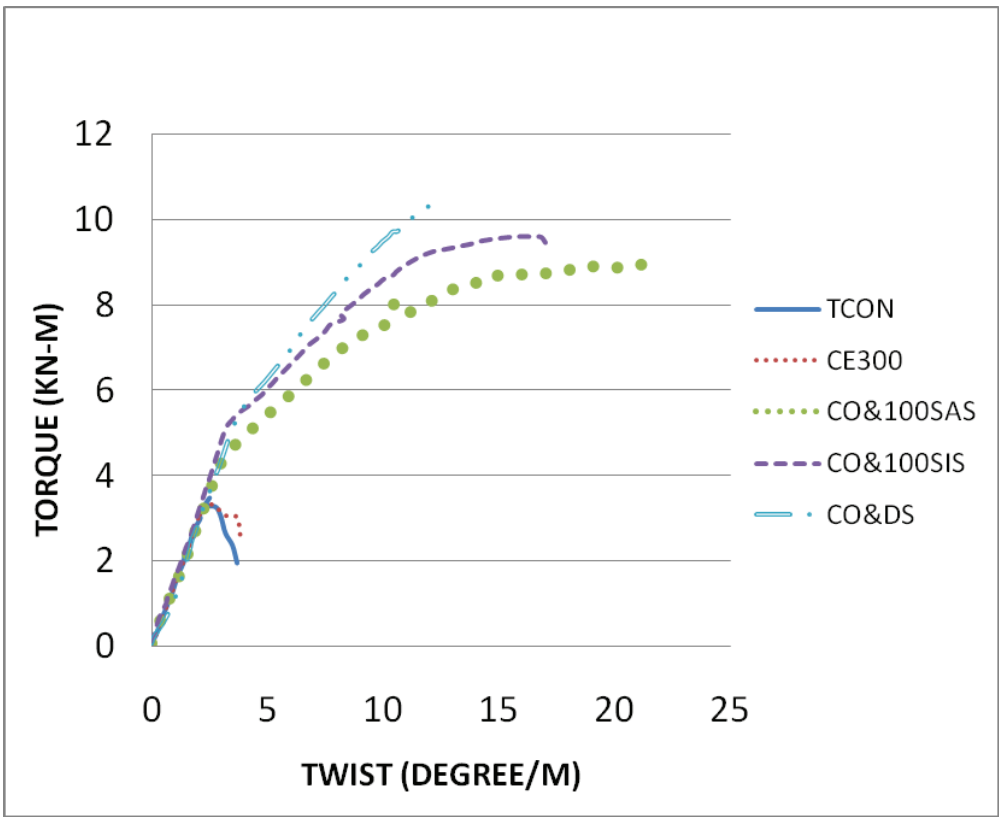


Figure 5 Comparison of Torque vs. Twist results for pure torsion specimens

The ultimate torque of specimen CO&DS (Corner and Diagonal Strip wrapping) is maximum compared to other wrapping configuration. Results of torque for specimen CE300S is slightly lower than the control specimen (TCON) which may be due to lower compressive strength of the concrete compared to the control specimen. Specimen CO&100SAS resist less torque but exhibit larger angle of twist and thus represent better ductility than other wrapping configurations. Specimen CO&DS is not allowing the beam to under gone large twist as the spiral wraps are preventing it and due to that, angle of twist for specimen CO&DS is lower than specimens CO&100SAS and CO&100SIS even though it has more torque at that point. Specimen CO&100SIS gives better confinement to concrete as indicated by better torsional resistance than specimen CO&100SAS.

Cracking Torque and Ultimate Torque Comparison

Comparison of torsional moments at cracking torque and at ultimate torque for RC beams tested in pure torsion are shown in Figure 6 and Figure 7, respectively. Table 2 provides a summary of cracking and ultimate torsional moment of all test beams along with their relative increase in cracking and ultimate torsional moments with respect to control beam (TCON).

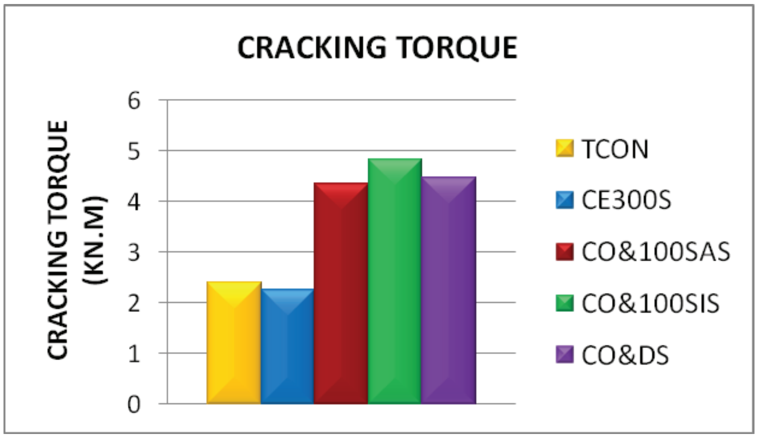


Figure 6 Comparison of cracking torque for specimens tested under pure torsion

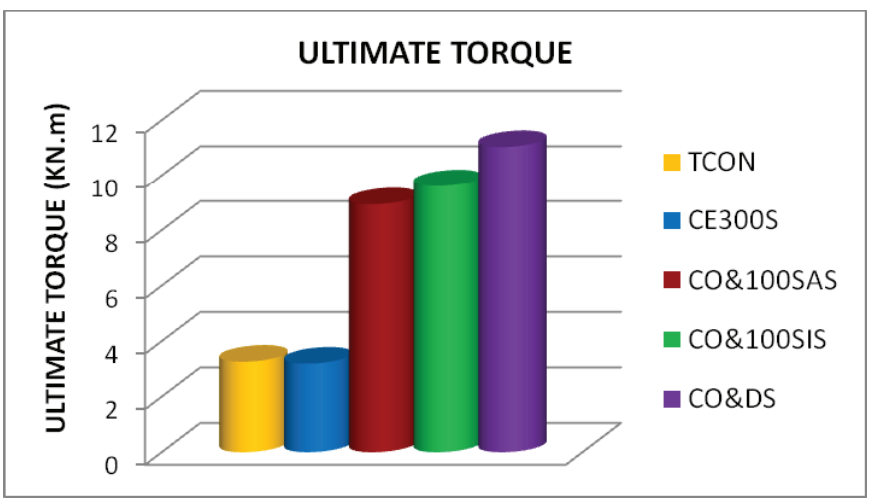


Figure 7 Comparison of ultimate torque for specimens tested under pure torsion

Even though the cracking strength is increased in all the strengthened beams except CE300S, the Test-beam CO&100SIS with corner and 100 mm strip wrapping in between stirrups exhibited a maximum (111.74 %) increase in cracking torque among all the test beams as shown in Table 2. However, the increase in ultimate strength is the largest (238.48 %) for the

Test beam CO&DS strengthened with corner and diagonal strip wrapping. In specimen CE300S, the distance between GFRP strips is 200 mm. As the distance between GFRP strips is greater than the depth of beam, they are unable to prevent torsional cracking (cracks inclined at 45°). This indicates when GFRP strips provided at spacing greater than depth of beam, they may not be effective in resisting pure torsion.

Table 2 Test results for cracking and ultimate torsional moments

TEST BEAMS	CRACKING TORQUE (KN.M)	% INCREASE IN CRACKING TORQUE	ULTIMATE TORQUE (KN.M)	%INCREASE IN ULTIMATE TORQUE
TCON	2.313	-	3.259	-
CE300	2.313	0	3.189	-2.16
CO&100SAS	4.417	90.92	8.940	174.31
CO&100SIS	4.898	111.74	9.604	194.68
CO&DS	4.663	101.58	11.032	238.48

Crack Patterns and Failure Modes

Modes of failure for specimens tested under pure torsion are shown in Figure 8.

(a) Control specimen (TCON)

(b) 300 mm central strip wrapping (CE300S)

(c) Specimen CO&100SAS

(d) Specimen CO&100SIS

(e) Corner and Diagonal strip wrapping (CO&DS)

Figure 8 Modes of failure for specimens tested under combined torsion and bending

In **control specimen** cracks first appeared on one of the vertical faces and then propagated into the two horizontal faces. The cracks gradually widened as load increased with the two beam segments rotating relative to one another about centroidal axis of RC beam. Cracks started from mid span of the beam and finally failed between the two stirrups which has less confined region. Failure cracks are shifted to the region where there layer of GFRP sheet is not present in specimen **CE300S**. In specimen **CO&100SAS**, failure is partially delayed in respect to the failure of the control specimens, but eventually diagonal torsional cracks occurred and widened in the unwrapped concrete part of the beams between the strips. Similarly failure cracks are observed on every blank spot where there is an absence of GFRP sheet in specimen **CO&100SIS**. As the portion of concrete between vertical steel stirrup and GFRP strip is reduced, its torsional strength is increased compared to specimen with GFRP strips at location of vertical stirrups. In specimen **CO&DS** Failure cracks are developed on concrete surface perpendicular to the GFRP orientation. Failure is occured by tearing of diagonal GFRP strip from centre of the vertical beam face. Inclined diagonal cracks are observed inside the wrapping. Failure is prolonged considerably after formation of first crack.

CONCLUDING REMARKS

Based on the work carried out, following conclusions can be drawn.

- Reinforced concrete beams with different configuration of GFRP wrapping exhibited significant increase in their cracking and ultimate torque as well as ultimate twist deformations.
- Behaviour of all RC beams wrapped with GFRP sheet are almost similar upto cracking load. This indicates that upto elastic limit concrete is effective in resisting torsion after cracking reinforcement (steel and GFRP) becomes effective.
- Failure of RC beam with 300 mm central GFRP wrap (CE300S) is delayed but failure occurs in the unwrapped portion of specimen between the strips. So, when the strips of GFRP is provided at spacing greater than the depth of beam, it will not be effective for resisting torsional moment.
- Specimen with corner and 100 mm strips between stirrups (CO&100SIS) shows better confinement of concrete and exhibits higher torsional resistance compared to specimen with GFRP strip provided at the location of stirrup.
- In Corner and diagonal wrapping (CO&DS) maximum increase of 238.5% in ultimate torque is observed.
- Corner and diagonal strip wrapping (CO&DS) is much more efficient in enhancement of the torsional resistance of reinforced concrete beams compared to other wrapping configurations. In CO&DS the inclined fibers are in tension up to failure, indicating effectiveness of GFRP in resisting cracking.
- Corner and 100 mm strips above stirrups (CO&100SAS) gives better ductility compared to other wrapping configurations as it is evident from increased torsional resistance with large angle of twist.

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