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Torsional strengthening of RC beams using stainless steel wire mesh -Experimental and numerical study

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Abstract. Locally available Stainless Steel Wire Mesh (SSWM) bonded on a concrete surface with an epoxy resin is explored as an alternative method for the torsional strengthening of Reinforced Concrete (RC) beam in the present study. An experiment is conducted to understand the behavior of RC beams strengthened with a different configuration of SSWM wrapping subjected to pure torsion. The experimental investigation comprises of testing fourteen RC beams with cross section of 150 mm×150 mm and length 1300 mm. The beams are reinforced with 4-10 mm diameter longitudinal bars and 2 leg-8 mm diameter stirrups at 150 mm c/c. Two beams without SSWM strengthening are used as control specimens and twelve beams are externally strengthened by six different SSWM wrapping configurations. The torsional moment and twist at first crack and at an ultimate stage as well as torque-twist behavior of SSWM strengthened specimens are compared with control specimens. Also the failure modes of the beams are observed. The rectangular beams strengthened with corner and diagonal strip wrapping configuration exhibited better enhancement in torsional capacity compared to other wrapping configurations. The numerical simulation of SSWM strengthened RC beam under pure torsion is carried out using finite element based software ABAQUS. Results of nonlinear finite element analysis are found in good agreement with experimental results.

Keywords: reinforced concrete beams; torsional strengthening; stainless steel wire mesh; tensile strength; bond strength; torque-twist behavior

1. Introduction

Concrete structures experience a convoluted variety of internal stresses and strains, when subjected to external loading. Bending moment, Axial force, Shear force and Torsion are four key internal actions. Generally reinforced concrete (RC) elements are designed for axial force, shear force and bending moment. In many cases, connection between RC elements is detailed in such a way that torsion is eliminated from them. But, torsion cannot be neglected while designing the members having cross sections such as box, inverted *L*-shape, *T*-shape and subjected to eccentric loading. Members curved in plan, curved box girders in bridge and circular girder supporting Intz shape water tank are structural elements primarily subjected to torsion.

Repair and rehabilitation of concrete structures is necessary for all deteriorated or damaged structural elements to restore and enhance the load carrying capacity as well as to increase the life span of structure. A number of strengthening and rehabilitation techniques for a variety of structural elements have been proposed and studied. The use of Fiber Reinforced Polymers (FRP) has become the popular strengthening technique due to its high tensile strength, light weight, ease of application and durability (FIB Bulletin 14 2001, Hii and Al-Mahaidi 2006). Patel *et al*. (2016a), carried out at an experimental investigation to enhance the torsional resistance of RC beams using different wrapping configuration of Glass Fiber Reinforced Polymer (GFRP) and found RC beam strengthened with diagonal strip wrapping of GFRP is more efficient in resisting the torsional moment. Researchers carried out experiments to study the behavior of Carbon Fiber Reinforced Polymer (CFRP) and GFRP to enhance the torsional capacity of RC beams (Ameli *et al*. 2007, Panchacharam and Belarbi 2002, Tibhe and Rathi 2016). Researchers also observed different types of failure that reduced the performance of CFRP and GFRP when used for strengthening of the structural elements (Esfahani *et al*. 2007, Teng *et al*. 2003). These failures are often brittle and include debonding of FRP. Thus it is necessary to find an alternative material for FRP, which is more ductile and have better bond characteristic.

Stainless Steel Wire Mesh (SSWM) is explored for strengthening of RC elements in current research work. SSWM is a durable, strong, and corrosion resistant material (Kumar and Patel 2016a, Banaraswala Metal Crafts (P) Ltd, Coimbatore). It is locally available material with different wire thicknesses and opening size. SSWM is made of high strength steel cords. Chemical compositions of SSWM consists mainly carbon, manganese, silicon, chromium and nickel (Banaraswala Metal Crafts (P) Ltd, Coimbatore). Kumar and Patel (2016a), explored locally available SSWM to strengthen circular concrete column of grade M15, M20

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and M25. Based on tensile strength and bond strength of various SSWM, they found 40× 32 SSWM more effective to enhance the axial load carrying capacity of column without debonding when applied with epoxy Sikadur 30 LP. Successful application of the SSWM for strengthening of column motivated researcher to use SSWM as an alternative material to GFRP and CFRP. Further use of SSWM for flexural and shear strengthening of RC beam was carried out by Patel and Raiyani (2017, 2018). They found SSWM an effective material for strengthening of RC beams with flexural and shear deficiency.

Owing the fact that experimental investigations are costly and time consuming, the finite element analysis (FEA) for numerical simulation are generally adopted to supplement experimental study. Ganganagoudar *et al*. (2016), presented analytical and finite element studies on behavior of FRP composite strengthened RC beams under torsional loading. Basic equations to develop analytical model for FRP strengthened beams were based on Softened Membrane Model for Torsion (SMMT) derived by Jeng and Hsu (2009). For validation of analytical and experimental data, numerical model was also developed using finite element based software ABAQUS. Coronado and Lopez (2007), discussed numerical study of structural behavior of concrete strengthened with FRP sheets using ABAQUS software. Finite element analysis showed good agreement in terms of load displacement, failure pattern and post failure behavior with experimental result.

This paper reports the results of the experimental study conducted on fourteen RC beam specimens subjected to torsion. Two control beams without SSWM strengthening and twelve beams with six different configuration of external strengthening using SSWM are considered for the study. The experimental results of RC beams in terms of torque-twist behavior and the failure modes of the beams are studied. The results of experimental study are further verified through numerical simulation using finite element based software ABAQUS. The present experimental and numerical investigation will provide valuable information to both the researchers and professionals.

2. Experimental investigation

SSWM has been used for torsional strengthening of RC beam specimens. The aim of present investigation is to evaluate torque and twist behavior of SSWM strengthened RC beams with different wrapping configuration.

2.1 Test beams and wrapping configuration

Total 14 RC beams are prepared with M25 grade of concrete. The mix design of M25 grade of concrete is carried out as per IS: 10262 - 2009. Proportion of various ingredient used for preparing RC beams is shown in Table 1.

Table 1 Concrete mix proportioning for RC beam specimen

Concrete grade	Cement	Fine aggregate	Coarse aggregate	Water
M25	1	1.76	3.12	0.49

Table 2 Nomenclature of beam specimens and specifications

Sr No.	Specimen identification	Number of beam Specimens	Description of SSWM wrapping configuration
1	CON	2	CONtrol specimen
2	CE300S	2	CEntral 300 mm Strip wrapping
3	CO&100SAS	2	COrner and 100 mm Strip wrapping Above Stirrups
4	CO&100SIS	2	COrner and 100 mm Strip wrapping In between Stirrups
5	D45W	2	Diagonal of SSWM strip at 45° Wrapping
6	CO&DS	2	COrner and Diagonal Strip wrapping
7	FW	2	Full Wrapping by SSWM

Table 3 Typical 40×32 wire mesh properties

Woven type	Mesh per inch	Standard Wire Gauge	Diameter of wire (mm)	Size of opening (mm)	Approx. Open area %
Square	40	32	0.25	0.365	36

Table 4 Boding material Sikadur 30 LP properties as per manufacture's specifications

Material	Sikadur 30 LP
Part A (resin)	White color
Part B (hardener)	Black color
Mixed density (kg/ltr)	1.8 ± 0.1
Mixing ratio (A:B)	3:1
Pot life	60 min

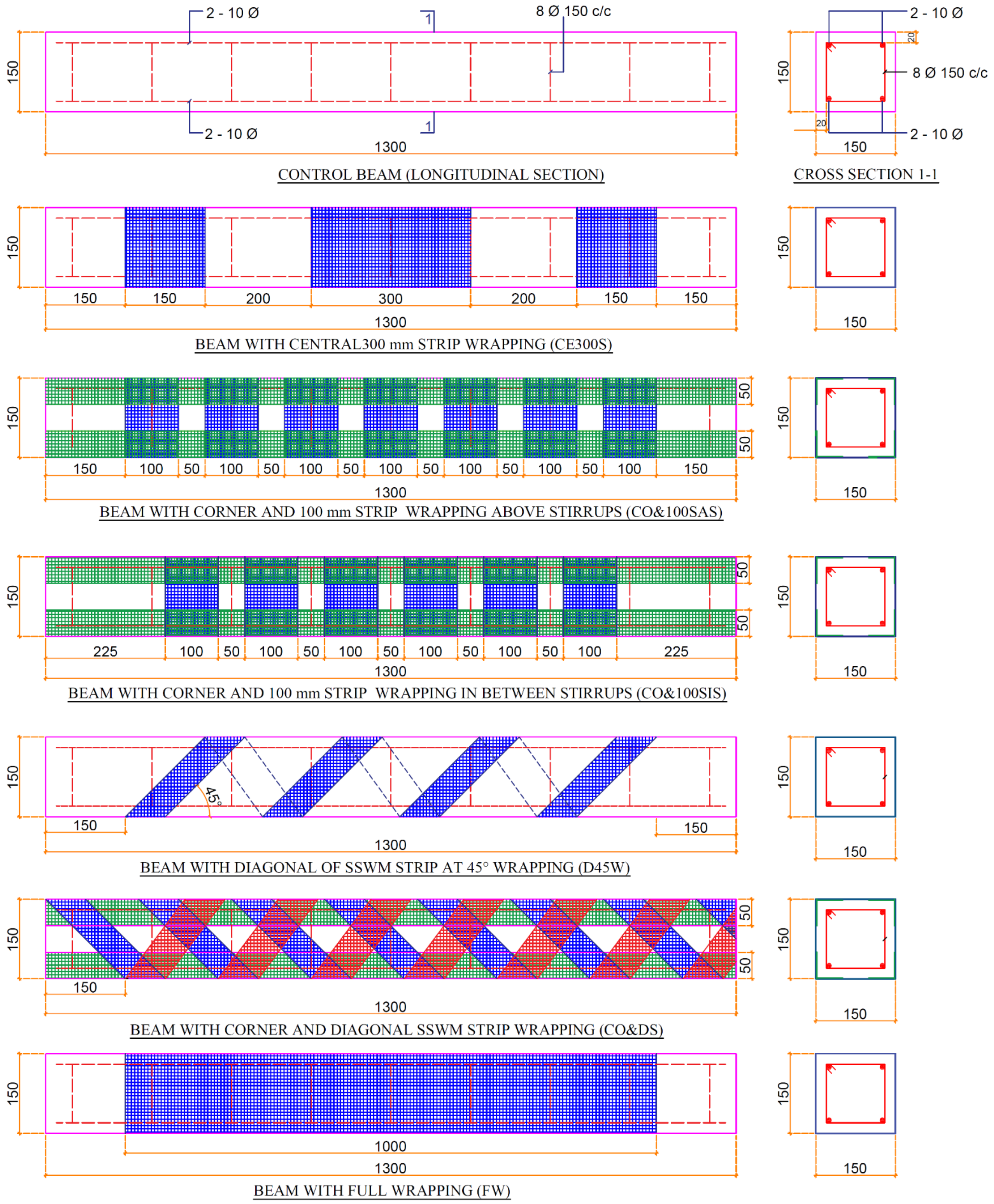
All the beam specimens are having the cross sectional dimension of 150 mm×150 mm with a length of 1300 mm. Beams are reinforced with 4-10 mm diameter longitudinal bars in four corners and closed stirrups in the transverse direction with 8 mm diameter bars at 150 mm center to center spacing. A clear cover of 20 mm to longitudinal reinforcement is provided for all the beams. Different wrapping configuration adopted in this study for specimens subjected to pure torsion is shown in Fig. 1. The nomenclature of beam specimens are given in Table 2.

2.2 Stainless Steel Wire Mesh (SSWM)

All RC beams are strengthened using SSWM supplied by M/s Banaraswala Metal Crafts (P) Ltd, Coimbatore. The advantages of using 40×32 SSWM are high tensile strength, bond strength, ease in application and cost-effectiveness (Kumar and Patel 2016a). The properties of 40×32 wire mesh are shown in Table 3. Sikadur 30 LP consist of hardener and resin for bonding SSWM on concrete surface. Typical properties of hardener and resin as supplied by manufacturer are shown in Table 4.

2.2.1 Tensile strength of SSWM

To find unidirectional tensile strength of SSWM, preparation of specimen and further testing are carried out



Note: All dimensions are in mm

Fig. 1 Schematic representation of different wrapping configuration by SSWM

as per ASTM D3039/D3039M (ASTM 2008). SSWM strip is cut in 100 mm × 500 mm in size. SSWM strip is fixed at the end by 100 mm wide and 150 mm long steel plate. Sikadur 30 LP as bonding agent is applied between steel plates and SSWM strip. Sufficient weight is placed on steel plates, to eliminate voids and to achieve adequate bond between plate and SSWM. The specimens are kept for curing up to 7 days in ambient temperature. Schematic plan and section of specimen and prepared specimen for tensile test are shown in Fig. 2(a). This sample is subjected to tensile force in universal testing machine (UTM) and ultimate tensile strength and elongation are measured as shown in Fig. 2(b). Fig. 3 shows the Stress v/s Strain curve obtained from the tensile test of SSWM and it is used as property definition of SSWM for numerical simulation in ABAQUS software. Tensile test results of SSWM is shown in Table 5.

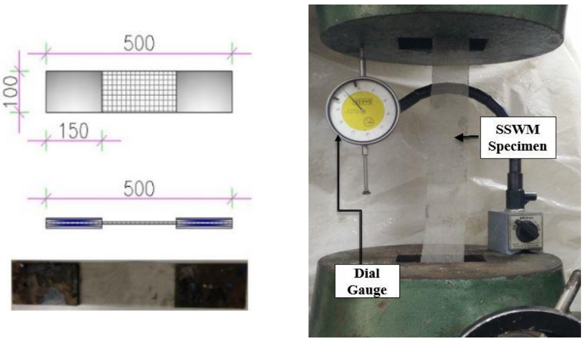
2.2.2 Bond behavior of SSWM with concrete

Bond between concrete and SSWM plays an important

Table 5 Tensile test of SSWM sample

Wire mesh Type	Width of Mesh	Wire Gauge	Diameter of wire	Number of wire	c/s of wire	Total c/s area	Ultimate strength	Rupture strain	Modulus of elasticity
40 × 32	100	32 SWG*	0.25	158	0.049	7.76	770.78	0.047	14305
SSWM	mm		mm		mm^2	mm^2	MPa		MPa

* SWG - Standard Wire Gauge



(a) (b)

Note: All dimensions are in mm

Fig. 2 (a) Schematic diagram and sample of SSWM specimen for tension test (b) Tensile test set up for SSWM

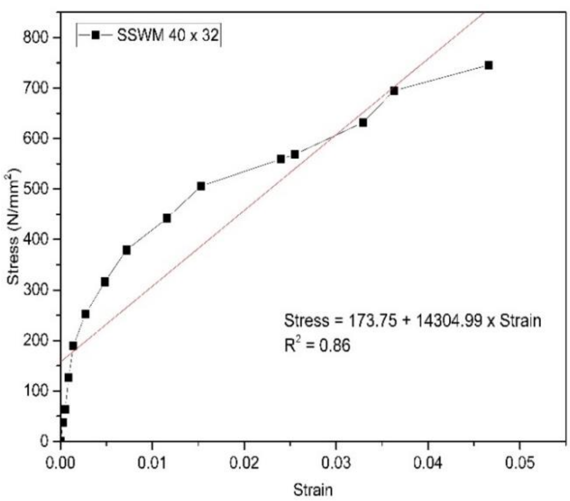
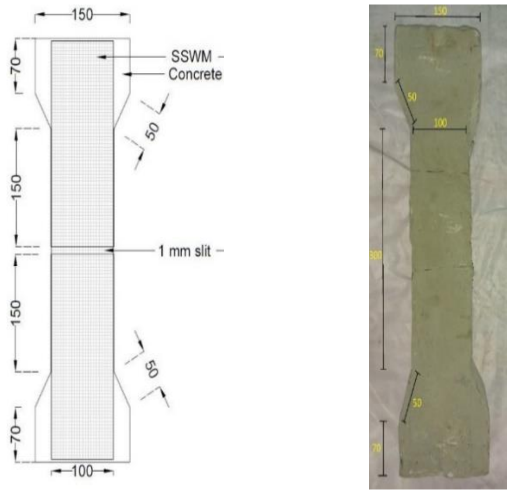


Fig. 3 Stress v/s strain behavior of SSWM specimen



Note: All dimensions are in mm

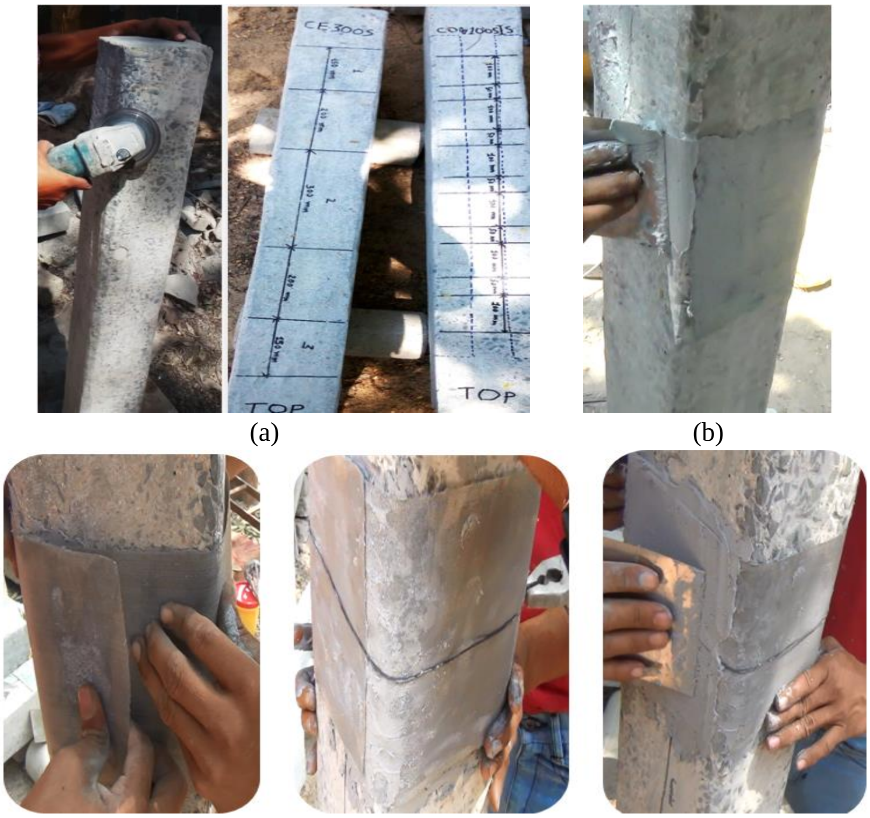
Fig. 4 Schematic diagram and SSWM wrapped dumbbell Specimen

Fig. 5 Test Setup and failure pattern of specimen after test

role in strengthening of reinforced concrete members. Direct tension test gives bond characteristic of SSWM with concrete and failure pattern such as tension failure of SSWM or debonding of SSWM. Specimen is prepared and test set up is developed as described by Kumar and Patel (2016a). Schematic diagram and SSWM wrapping of dumbbell specimen is shown in Fig. 4. Dumbbell specimen of M25 grade of concrete is prepared with 1 mm gap between two parts of dumbbell. Sikadur 30 LP is used for bonding mesh to the dumbbell shaped concrete specimens. Sikadur 30 LP (Part A and Part B) in proportion of 3:1 by weight mixing is applied on dumbbell surface. After one coat of adhesive, strip of SSWM is applied and then after final coat of Sikadur 30 LP is applied on dumbbell specimen as shown in Fig. 4. Specimen is kept for curing up to 7 days in ambient temperature to get sufficient bond strength. Dumbbell specimen is put in special type of frame and is tested under UTM. With the help of dial gauge elongation is measured. Test set-up and failure pattern of specimen is shown in Fig. 5. During the test debonding is not observed and only tearing of SSWM is observed. From the test bond strength of SSWM with concrete is observed as 723.3 MPa. On the basis of this test, Sikadur 30 LP is selected as bonding material for the strengthening of beams.

3. Experimental programme

To study the effectiveness of SSWM under pure torsion, wrapping configuration is adopted based on study of Patel *et al*. (2016) for torsional strengthening of beams using GFRP.



(a) (b) (c) (d) (e)

Fig. 6 (a) Grinding of beam specimen (b) Application of first layer of adhesive Sikadur 30 LP (c) Wrapping of SSWM strip at proper location (d) Binding of mesh by using binding wire (e) Final coat of adhesive Sikadur 30 LP

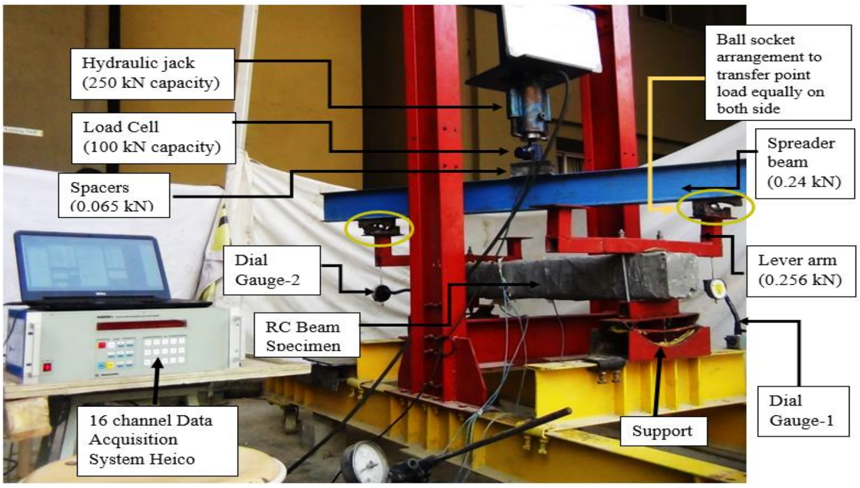


Fig. 7 Test set-up for applying pure torsion

3.1 Strengthening procedure

Strengthening of beams is carried out by bonding SSWM on RC beam using Sikadur 30 LP epoxy material. SSWM is wrapped on surface of beams after 28 days of curing of concrete beams. The concrete specimens are grinded for smoothening of surface and making curved corners as shown in Fig. 6(a). Sikadur 30 LP is a solvent-free and thixotropic two part adhesive. Two parts, A (resin) and B (hardener) are mixed together for at least 3 minutes with a mixing spindle attached to a slow speed stirrer, until the material become smooth in consistency and a uniform grey color is achieved. First layer of adhesive is applied on prepared surface as shown in Fig. 6(b) by using steel plates. SSWM strips are applied on concrete surface and pressed gently into the first layer of adhesive as shown in Fig. 6(c). For the proper contact between SSWM and concrete, SSWM is held tight to concrete surface with the help of binding wire to avoid the air voids in between wire mesh and concrete surface as shown in Fig. 6(d). Subsequently, a final coat of Sikadur 30 LP is applied on mesh and finished smooth as shown in Fig. 6(e).

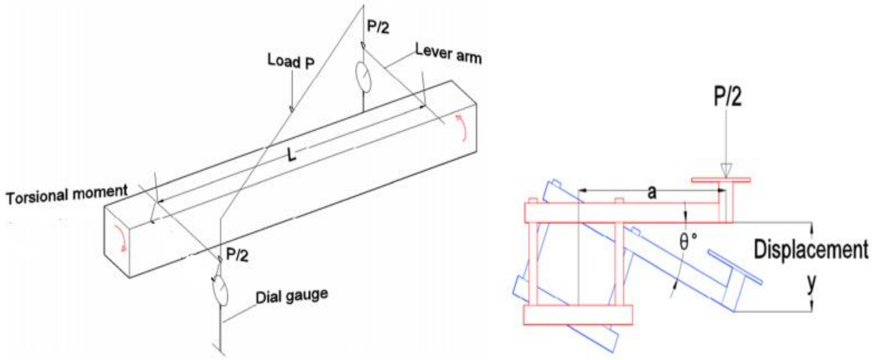


Fig. 8 Measurement of angle of twist and torque

$$\text{Torque } (T) = \frac{P}{2} \times a \text{ kN.m} \quad (1)$$

$$\text{Angle of twist } (\theta) = \tan^{-1}\left(\frac{y}{a}\right) \text{ Degree/m} \quad (2)$$

3.2 Test set up and instrumentation

Test set up is developed to apply pure torsion as shown in Fig. 7. Supports of RC beams are such that they allow rotation about longitudinal axis of beam. Lubricant is applied on sliding surface of support to ensure the free rotation of beam at supports. Ball socket arrangement is provided on lever arm to transfer equal point load on both the end of spreader beam. Both lever arms are placed on the beam such that distance between center of support and end of lever arm is 400 mm. A steel spreader beam (ISMB150) is diagonally placed resting on hinge end supports on top of the lever arms. Load cell having capacity of 100 kN is placed below the hydraulic jack. Electrical resistance strain gauge are attached to beam specimen surfaces to measure strain and two dial gauges are placed under the lever arm for measuring vertical displacement. Point load is applied by hydraulic jack on the center of the spreader beam.

Load is distributed to both the lever arm as shown in Fig. 8. Experimentally torque and angle of twist is calculated from the Eqs. (1) and (2) respectively. The specimens is tested under pure torsion load until the specimen failed. The application of load is discontinued when the hydraulic jack showed reversal of load i.e., specimen reaches to ultimate limit and cracks are observed on the specimen.

4. Numerical programme

Finite element modelling of RC beams strengthened with FRP is difficult as it should respond to different nonlinear behaviors such as cracking and crushing of concrete, yielding of steel, FRP debonding and rupture (Ganganagoudar *et al*. 2016). A nonlinear finite element model is proposed in this study to simulate the torsional behavior of SSWM strengthened RC beams using finite element based software ABAQUS.

Concrete is modeled using three dimensional solid element. Concrete Damaged Plasticity (CDP) model is selected for nonlinear analysis. The stress strain relationship proposed by Jeng and Hsu (2009) is used for uniaxial

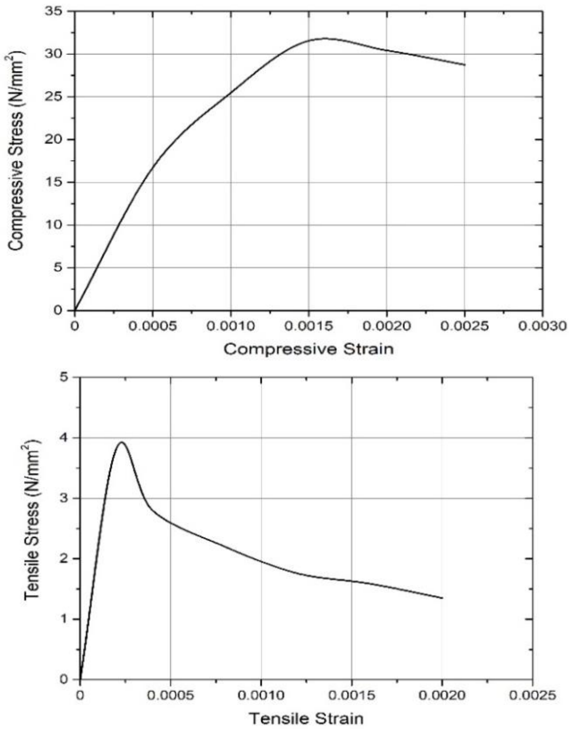


Fig. 9(a) Stress-strain relationship of concrete (Jeng and Hsu 2009)

Table 6 Failure ratio for concrete

Dilation angle	Eccentricity	Biaxial to uniaxial compressive strength ratio ($\frac{f_{b0}}{f_{c0}}$)	K	Viscosity parameter
36	0.1	1.16	0.68	0

compressive and tensile stress-strain curve for concrete. Stress strain relationship of concrete is derived as shown in Fig. 9(a). Concrete beam is modeled with C3D8 - an 8-node linear isoparametric 3D stress element. Failure ratios for concrete used in the model are shown in Table 6 (Ganganagoudar *et al*. 2016, Kumar and Patel 2016b).

Longitudinal and transverse reinforcements are

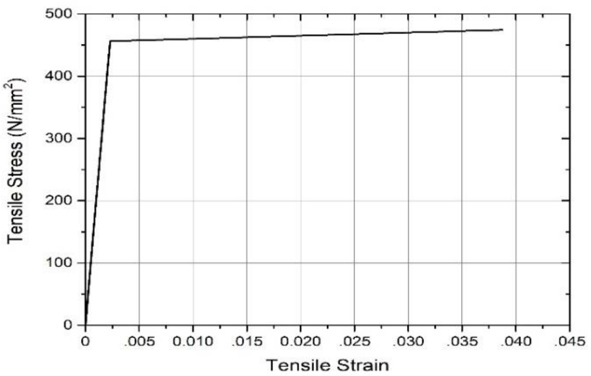


Fig. 9(b) Stress-strain relationship of Steel (Jeng and Hsu 2009)

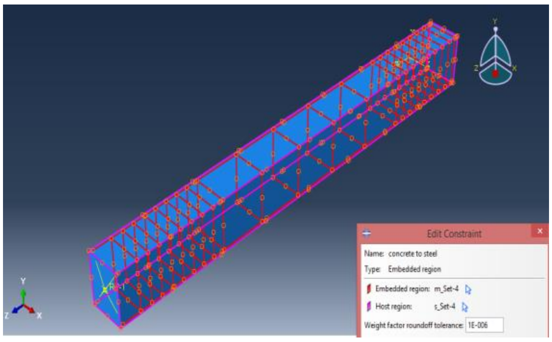


Fig. 10(a) Reinforcement embedded in concrete

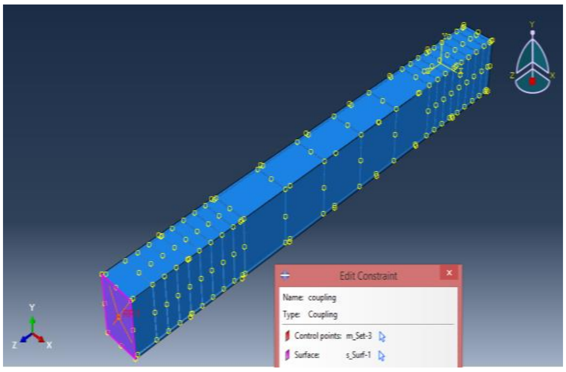
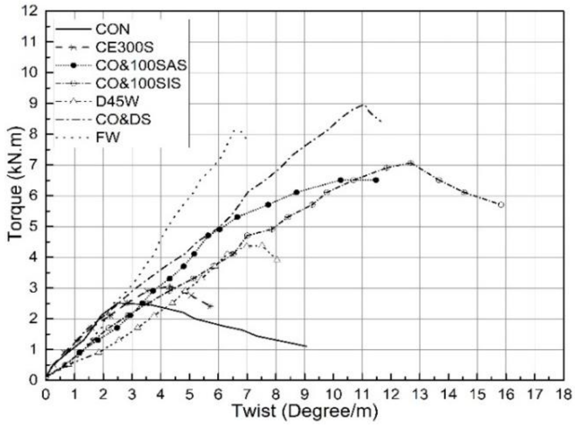


Fig. 10(b) Coupling constraint to apply torque

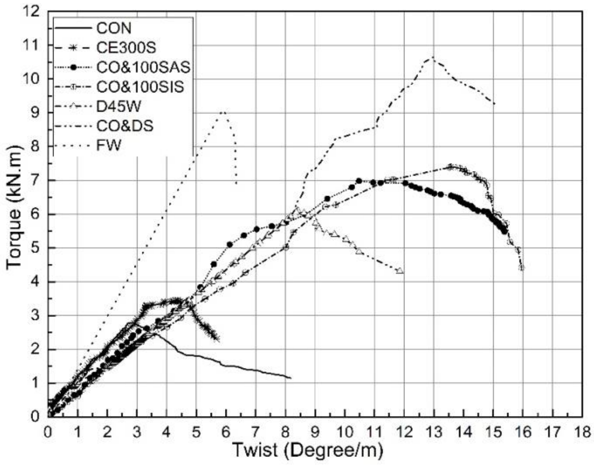
modelled with three dimensional, three node truss elements. Young's modulus of elasticity for steel is 200000 N/mm^2 and Poisson's ratio is 0.3. Stress strain relationship of reinforcement is derived as shown in Fig. 9(b). Reinforcement is modeled with T3D3 - a 3-node quadratic 3D truss element.

SSWM is modeled as 3D shell extrusion type of element. Thickness of SSWM is relatively small compared to dimensions of other parts. Therefore shell element is selected for modelling SSWM. Stress strain relationship of SSWM is derived based on tension test as shown in Fig. 3. For modeling of SSWM, S4R - a 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite element is used.

For connecting reinforcement to concrete embedded constraint option is selected. In embedded constraint, reinforcement is selected as embedded region and concrete



(a) By experimental results



(b) By FE analysis

Fig. 11 Torque v/s twist response

is selected as host element. Perfect bond tie constraint is used to model interface between concrete and SSWM (Ganganagoudar *et al*. 2016, Kumar and Patel 2016b). For tie constraint, concrete is considered as master surface and SSWM is considered as slave surface as shown in Fig. 10(a). Coupling constraint is selected to apply twist about longitudinal axis. Reference point is selected as control point and side surface of beam is selected as surface as shown in Fig. 10(b). Monotonic Static load in step is considered. To consider the geometry nonlinearity and the enable higher order terms in strain NLgeom option is selected while modelling in ABAQUS. Loading is applied in terms of displacement in static general step. Twist obtained from experiment is applied about longitudinal axis of beam as reference point in terms of radian. Boundary condition is provided in predefined initial step. Fixed support is provided at one end of beam.

5. Results and discussion

In order to understand the behavior of SSWM strengthened RC specimens under pure torsion, angle of twist of specimens are measured at regular interval of torque up to failure. Also, torque at first crack and ultimate torque for all specimens are observed. Failure mechanism

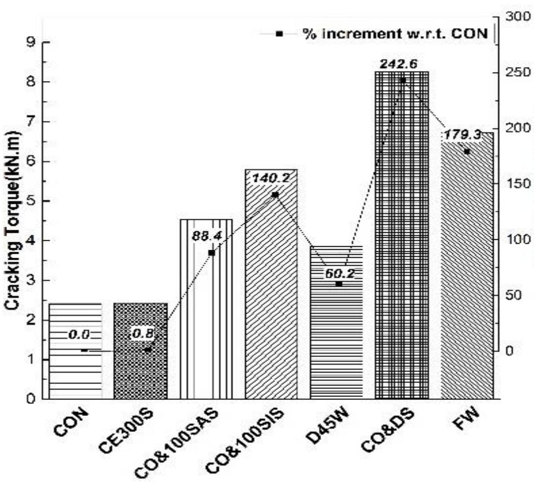


Fig. 12 Cracking torque

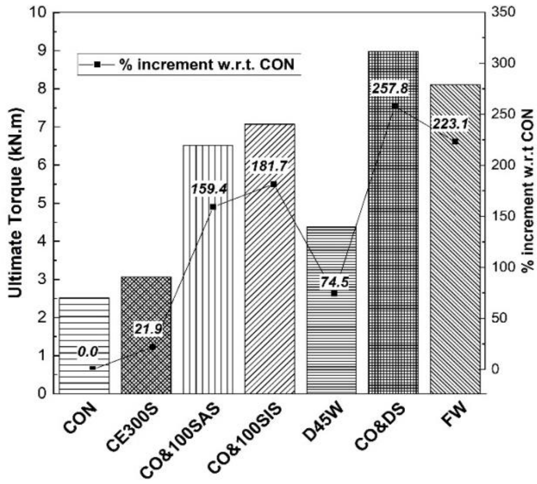


Fig. 13 Ultimate torque

of each specimens is observed to understand the role of SSWM in torsional strengthening.

5.1 Torque-twist comparison

Two specimens are cast in each category for experimental study. Average torque and twist are considered for comparison of results. Torque-Twist behavior of beams under pure torsion as obtained from experimental study and from FE analysis is shown in Fig. 11(a) and Fig. 11(b) respectively. Fig. 11 shows that behavior of strengthened beams observed from experiment is in close agreement with that obtained from FE analysis. All specimens strengthened by SSWM exhibit better torque resistance compared to the controlled specimen. The ultimate torque of specimen CO&DS (COrner and Diagonal Strip wrapping) is maximum compared to other wrapping configuration. CO&100SIS (COrner and Strip wrapping In between Stirrups) resisted less torque compared to FW(Full Wrapping) but experienced larger angle of twist and thus presents better ductility than other wrapping configurations. Better confinement to concrete using SSWM is obtained in specimen CO&100SIS as indicated by better torsional resistance than specimen CO&100SAS. CE300S (CEntral 300 mm Strip wrapping) and D45W (Diagonal strip Wrapping at 45°) have more torsional resistance compared to controlled specimen. Torsional resistance of FW specimen is very much high as compared to D45W specimen but has experienced small angle of twist.

5.2 Cracking torque and ultimate torque comparison

Comparison of torsional moment at first crack is shown in Fig. 12. The cracking torque is increased in all the strengthened beams compared to control beam. The specimen CO&DS exhibit maximum (242.6%) increase in cracking torque. However, increase in cracking torque for specimen CE300S is only 0.8%. Increase in cracking torque for specimen D45W is 60.24%. It is observed that specimen CO&100SAS and specimen CO&100SIS exhibited 88.4% and 140.2% increment in torque at cracking state respectively. The specimen CO&100SIS is resisted 50% more cracking torque compare to CO&100SAS specimen due to confinement of SSWM strip in between the stirrups. Almost 180% increment is observed for FW specimen in cracking torque.

Comparison of ultimate torque obtained from experimental study is presented in Fig. 13.

From experimental results it is observed that specimen CO&DS has maximum (257.8%) increase in ultimate torque. In CO&DS strengthening of corner using SSWM strip has increased confinement and diagonal strip of SSWM has prevented failure of concrete due to torsional shear stress on all four faces. So, CO&DS shows maximum enhancement in torsional strength. Almost 223.1% increment in ultimate torque is observed for FW specimen. Full wrapping of SSWM helps in confinement of concrete but steel cords of SSWM are not normal to crack developed due to torsional moment. So its effectiveness is reduced compared to CO&DS wrapping configuration of SSWM. Further due to large surface area it is difficult to achieve full adhesion of SSWM on concrete surface. Increase in ultimate torque for specimen D45W is observed 74.5% higher compare to control specimen. Diagonal 45^o wrapping of SSWM prevented tension failure of concrete only on two faces, thus reducing effectiveness of SSWM wrapping compared to CO&DS and FW as it can be observed in Fig. 13. CO&100SAS and CO&100SIS configuration of SSWM shows 159.4% and 181.7% increase in ultimate torque. Vertical strips of SSWM adds to confinement of concrete similar to transverse reinforcement of beam. If SSWM strip is applied between stirrups, more confinement of concrete is achieved compared to SSWM strip applied at the location of stirrups. When concrete is covered either by transverse reinforcement or SSWM strip the cracks on concrete is prevented. Thus torsional resistance is increased in CO&100SIS. While incase of CO&100SAS, transverse reinforcement and SSWM strip both are located at same place and concrete between strip started cracking at lower torque and resisted less ultimate torque. Results of ultimate torque for specimen CE300S is slightly (21.9%) higher than the control specimen. In specimen CE300S, the spacing between SSWM strips is kept 200 mm. Cracks started on the concrete surface which is not covered by SSWM.

Table 7 Comparison of experimental and FEM data

Specimen identification/ parameters	CON		CE300S		CO&100SAS		CO&100SIS		D45W		CO&DS		FW	
	Exp.	FEM	Exp	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM	Exp.	FEM
Ultimate torque (kN.m)	2.51	2.79	3.06	3.46	6.51	6.99	7.07	7.41	4.38	6.10	8.98	10.65	8.11	9.08
Ultimate twist (degree/m)	2.50	2.84	4.31	4.35	10.25	10.48	12.69	13.56	7.52	8.42	11.09	12.98	6.54	5.88
$T_{u,\exp}/T_{u,\mathrm{FEM}}$	-	0.90	-	0.88	-	0.93	-	0.95	-	0.72	-	0.84	-	0.89
$\theta_{u,\exp}/\theta_{u,\mathrm{FEM}}$	-	0.88	-	0.99	-	0.98	-	0.94	-	0.89	-	0.85	-	1.11
% difference between Experimental & FEM torque	11.15%		12.07%		7.37%		4.81%		39.27%		18.60%		11.96%	

Further spacing of SSWM strips is 200 mm, which is greater than depth of specimen. As inclined crack propagation in concrete area cannot be prevented effectively by SSWM strips, there is not much advantage of SSWM in CE300S SSWM configuration.

Comparisons of ultimate torque and ultimate twist from FE model and experimental results is reported in Table 7.

Nonlinear finite element analysis of CO&DS specimen shows 282% increase in ultimate torque. Increase in ultimate torque for specimen CE300S and D45W are 24% and 118% respectively as observed from numerical study. The specimen FW has 225% increment in ultimate torque compared to control specimen. Results from nonlinear finite element analysis and experimental study are in close agreement with nearly 10% to 12% of difference except for specimens D45W and CO&DS. The higher difference between experimental and finite element analysis results for D45W and CO&DS configuration may be due to modelling of inclined strips of SSWM in numerical study.

Patel *et al*. (2016) explored torsional strengthening of RC beam using Glass Fiber Reinforced Polymer (GFRP). They reported all the specimens wrapped with GFRP resisted higher torque compared to control specimen. They also reported minimum efficiency of CE300S configuration of SSWM and maximum enhancement in torsional capacity about 238.5% with corner and diagonal wrapping (CO&DS) configuration of GFRP. So, behavior of RC beams strengthened with SSWM and GFRP are similar in nature.

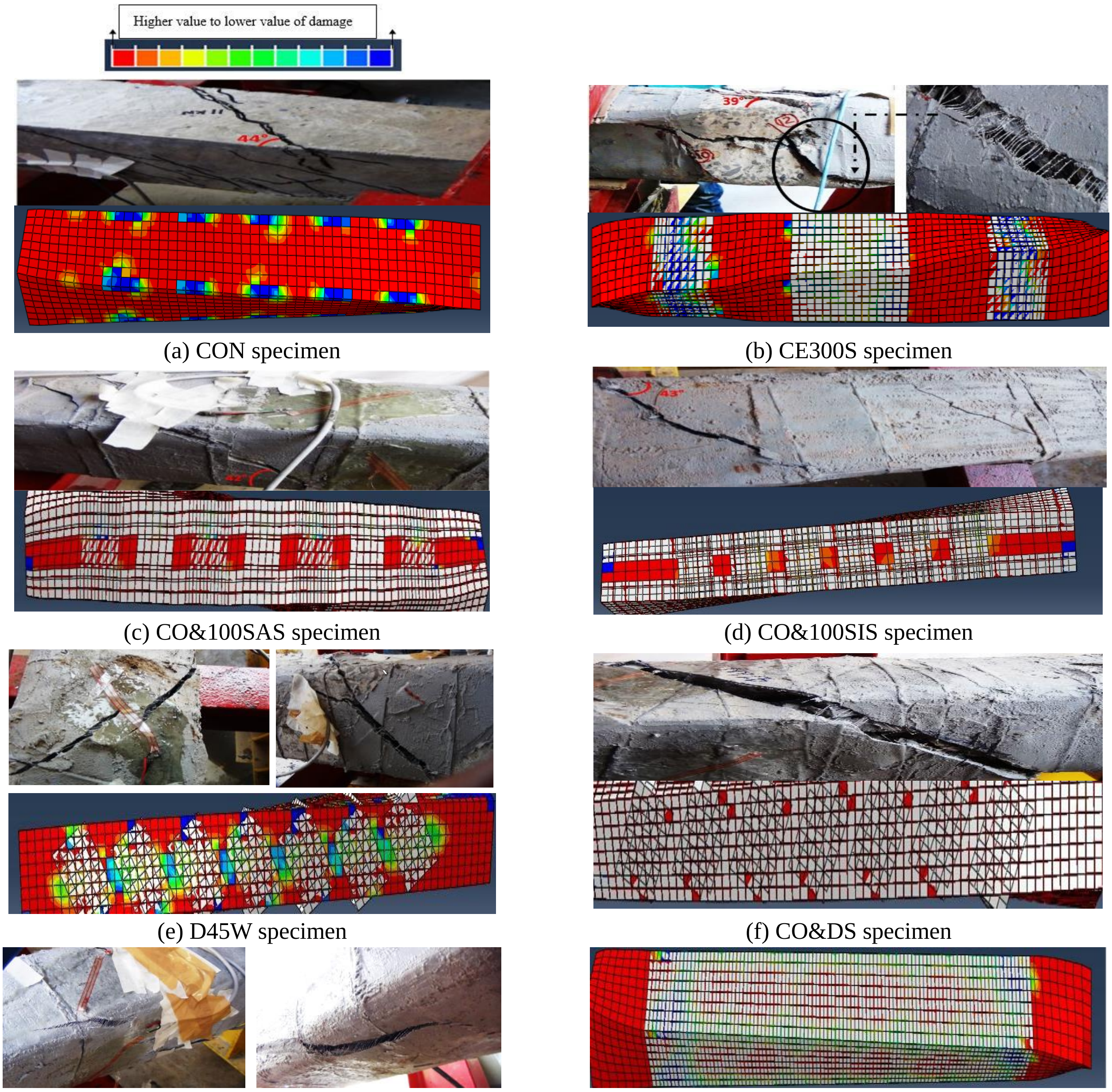
5.3 Failure mode and crack pattern

Fig. 14 shows the failure mode of each beam specimen observed during experiment. Damage distribution as obtained from FE analysis using ABAQUS software is also presented for comparison. In control specimens, the first crack is appeared on vertical faces and further propagated into the two horizontal faces. Diagonal cracks are observed at an inclination of 44° approximate1y. Moreover spalling of concrete is also observed at side surface and main reinforcement bars are twisted. In CE300S specimen, first diagonal crack at 39° inclination is observed on concrete surface where SSWM strip is not available. 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 concrete surface where there is no SSWM strip in specimen CO&100SIS. For D45W specimen, on all 4 sides of beam specimen cracks are observed at an inclination of 44°. Cracks are mainly observed on concrete surface in perpendicular direction of wrapping by SSWM strip. Through crack is observed at the center of the D45W beam specimen. Somehow, damage is observed on SSWM strips by doing FE analysis. For CO&DS specimen, failure is occurred by tearing of diagonal SSWM strip from center of the vertical beam face. Failure is prolonged considerably after formation of first crack. For FW specimen, cracks are observed on SSWM strips and furthermore failure is observed as tearing of SSWM strip.

6. Conclusions

An experimental study is carried out to explore the use of locally available Stainless Steel Wire Mesh (SSWM) for enhancing torsional resistance of RC beams. Further a numerical simulation is also carried out to validate the experimental results of torsional strengthening of RC beam with SSWM using finite element based software ABAQUS. Based on experimental study and numerical simulation following conclusions are derived.

- In bond test between SSWM and Concrete, no debonding is observed with Sikadur 30 LP and bond strength of SSWM with concrete is observed as 723.3 MPa.
- Ultimate tensile strength and rupture strain of 40×32 SSWM is observed as 770.78 N/mm^2 and 0.047 respectively.
- Stress-strain behavior of SSWM developed in present study is useful for numerical simulation of SSWM strengthened beam.
- Different configuration of SSWM wrapping on reinforced concrete beams significantly enhances cracking and ultimate torque as well as ultimate twist deformations.
- Corner and diagonal strip (CO&DS) wrapping of SSWM on RC beam shows maximum increase in cracking and ultimate torque compared to other wrapping configuration.



(a) CON specimen

(b) CE300S specimen

(c) CO&100SAS specimen

(d) CO&100SIS specimen

(e) D45W specimen

(f) CO&DS specimen

(g) FW specimen

Fig. 14 Failure pattern of each beam specimen

• Full wrapping (FW) of SSWM shows higher torque resistance of RC beam compared to diagonal 45^o wrapping (D45W) configuration but has smaller angle of twist.

• Corner and strip wrapping of SSWM in between stirrups (CO&100SIS) exhibits less increase in torsional resistance but shows larger angle of twist representing better ductility compared to other wrapping configurations.

• Comparisons of nonlinear finite element analysis results of SSWM strengthened RC beams with results of experimental study shows 10% to 12% difference in ultimate torque and twist. FE analysis results are closely matches with that of experimental data in pre-cracking stages but some deviations are observed in post-cracking behavior.

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