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Torsional behaviour of reinforced concrete beams retrofitted with aramid fiber

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Abstract. Retrofitting is an alteration of existing member or component of the structure. In civil engineering point of view, it is called strengthening of the old structure. Deterioration of structures may be due to aging, corrosion, failure of joints, earthquake forces, increase in service loads, etc. Such structures need urgent repair, retrofitting and strengthening to avoid collapse, cracking and loss in strength or deflection. Advanced techniques are required to be developed for the repair of structural components to replace conventional techniques. This paper focuses exclusively on torsional behaviour of Reinforced Concrete (RC) beams and retrofitted RC beams wrapped with aramid fiber. Beams were retrofitted with aramid fiber by full wrapping and in the form of 150 mm wide strips at a spacing of 100 mm, 150 mm, 200 mm respectively using epoxy resin and hardener. A total 15 numbers of RC beams of 150 mm×300 mm×1300 mm in size were cast, 3 beams are tested as control specimens, and 12 beams are tested for torsion up to the failure and then retrofitted with aramid fiber. Experimental results are validated with the help of data obtained by finite element analysis using ANSYS. The full wrapping configuration of aramid fiber regains 105% strength after retrofitting. With the increase in spacing of fabric material, torsional strength reduces to 82% with about 45% saving in material.

Keywords: retrofitting; strengthening; RC beams; torsional behaviour; aramid fiber

1. Introduction

1.1 General

The rehabilitation of existing structures is necessary due to growing engineering challenges like increase in service load, modification in structures, deterioration of structural members, changes in design code regulations, seismic retrofitting, etc. (Panchacharam and Belarbi 2002). Reinforced concrete beams were strengthened initially and compared with unstrengthened beams by most of the researchers. However, the behavior of RC members must be assessed after the structure has been loaded and, at least, some of the members have been damaged to a certain extent, and therefore, may need to be rehabilitated for further use (Mostofinejad and Talaeitaba 2014). It is required to identify the reliable method which accomplishes assessment of structure in terms of aging, evaluate the needs of intervention and design strengthening or retrofit measures (Ferreira *et al*. 2015). Retrofitting is a modification of an existing structure or its member by adding new components of the members. It is necessary to provide the most cost-effective and structurally efficient rehabilitation scheme. Many intervention techniques used earlier have been revised and developed in the light of the new seismic code requirements and new methods often based on new materials (e.g., fiber reinforced polymers FRPs) have been proposed (Thermou and Elnashai 2006). Strengthening of the beam with U wrap (three sides) or strengthening in the web and flange individually is more useful because of the inaccessibility of the entire cross-section by the addition of flange in the construction of uniform beam and slab. (T section of the interior beam) (Atea 2016). Such a type of wrapping is acting as confinement from all three sides. The ‘U’ wraps are having good torque carrying capacity for all states of torsion while reinforced concrete beam having better toughness when subjected to torsion (Beheraa *et al*. 2016). The study was further extended to use ferrocement jacketing as an alternative to CFRP and GFRP (Beheraa and Dhal 2018). Deifalla *et al*. (2013) deliberated the behavior of flanged beam sections externally strengthened with FRP and subjected to torsion. T- shaped and L- shaped RC beams are strengthened by such U wrapping and evaluated for torsion. In this research, jacketing of the beam is done with fiber-reinforced polymer i.e., aramid fiber (Kevlar fiber).

1.2 Aramid fiber

The origin of aromatic polyamide (aramids) is dependent on para-phenylene terephthalamide, which combines the idea of introducing the amide group and benzene rings into polyamide molecules. The molecules are highly oriented with strong inter-chain bonding and high level of crystallization, resulting in high modulus and high tenacity of the fiber (Chen and Zhou 2016). Aramid fiber is also having high tensile strength, tough and highly oriented organic fiber manufactured from polyamide (Abdel-Jaber *et*

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Fig. 1 Texture of aramid fiber

Table 1 Properties of aramid fiber

Description	Test Method	Specification
Weave style	--	Plain
Areal Weight of Fabric (g/m^2)	ASTM D 3801	300
Standard width (mm)	ASTM D 3774	1000
Dry Fabric Thickness(mm)	ASTM D 1777	0.25
Density (g/cm^3)	--	1.45
Tensile Strength (Mpa)	ASTM D 3039	2400 to 3600
Tensile Modulus (Gpa)	ASTM D 3039	60 to 120
Elongation Percentage (%)	--	2.2 to 4.4

al. 2007). Aramid fiber is extensively used in the field of civil and construction engineering nowadays. Use of aramid fiber pre-tensioned wrap increased the ductility of structure and reduces collapse (Tarfan *et al*. 2019). The word Aramid is a universal term for a manufactured fiber in which fiber-forming substance is a long-chain synthetic polyamide, in which about 85% amide linkages are attached directly to two aromatic rings. Compared with synthetic fiber, aramid fiber has 5-10% higher mechanical properties. These are displacing metal wire and inorganic fiber from the market of high performance uses like various composite structures for application in aircraft, marine and automobile, rope for offshore oil rigs, and bulletproof vests (Jassal and Ghosh 2002). Refer Table 1 for various properties of aramid fiber. The texture of aramid fiber is shown in Fig. 1.

1.3 Torsional strengthening of beams

Most of the researches on the RC beam using design guide (ACI 440. 2R-08, and CSA-S806-02) covers external strengthening using FRP systems subjected to flexure and shear. Abdel-Kareem (2014) investigated the behaviour of the reinforced concrete beam in shear with a rectangular web opening. These rectangular web openings are provided with different dimensions and at various locations in the shear zone. These openings are externally strengthened with FRP. Elwan (2017) worked on flanged beams retrofitted with FRP system subjected to torsional moment. Though shear and torsion both produced diagonal cracks in RC beam, yet the behaviour of RC beam subjected to torsion is different. Due to shear, the crack propagates in the same direction on both sides of beam whereas due to torsion spiral cracks propagate in the opposite direction on opposite sides of the beam. The assumptions made for modeling of RC beam in shear are different when compared with the assumptions for modeling in torsion. For shear forces, stresses are considered in the plane of the applied shear and

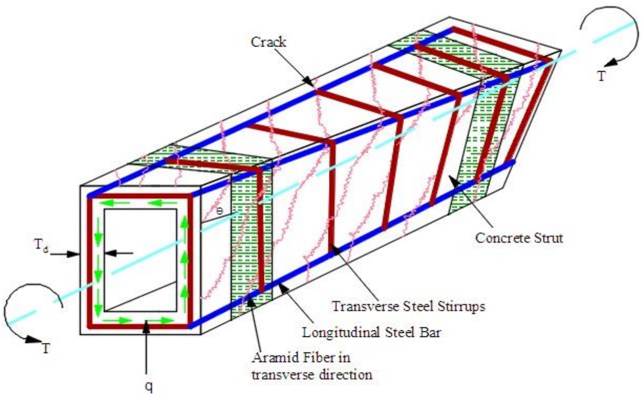

Fig. 2 Torsion of beam

are acting uniform across the perpendicular plane to it (Deifalla and Ghobarah 2014). Alabdulhady *et al*. (2017) carried investigation on the improvement of the torsional resistance of reinforced concrete beams using PBO-FRCM composite. When fiber orientation of 0°, 45°, and 90° was tested, 90° fiber orientation was found more suitable for torsional strengthening of beams (Alabdulhady and Sneed 2018). There are many methods of retrofitting such as; 1) Section enlargement 2) Stirrup spacing decreasing 3) External post-tensioning method 4) Addition of fiber to concrete 5) Use of FRP for external strengthening etc. Fig. 2 shows schematic of RC beam strengthened with aramid fiber along transverse direction subjected to pure torsion at both the ends. Longitudinal and transverse reinforcement is provided for bending and shear. When such a beam is subjected to torsional moment, spiral cracks get initiated. These beams are retrofitted with aramid fiber wrapping, and their torsional strength can be gained.

2. Methodology

2.1 Analytical torsional moment in reinforced concrete beam

The torsional moment in the main beam is obtained by distributing unbalanced joint moment in proportion to the ratio of torsional stiffness of the main beam to the sum of the torsional stiffness and bending stiffness of the members at the joint.

The beam is reinforced with Fe500 grade of steel rebars as shown in Fig. 3. Assuming moderate exposure,

$$b\text{=150 mm, } D\text{=300 mm, } d\text{=270 mm, } fck\text{=30 MPa,}$$
$$fy=fyt\text{=500 MPa}$$

As the area of reinforcement of top steel is less than bottom steel and beam is subjected to pure torsion, torsion resistance is governed by top steel.

$$Ast=2\times\frac{\pi}{4}d^2=2\times\frac{\pi}{4}8^2=100.5\text{ mm}^2$$

$$M_{e2}=0.87f_yA_{st}d\left(1-\frac{f_yA_{st}}{f_{ck}bd}\right)$$

$$M_{e2}=0.87\times500\times100.5\times270\left(1-\frac{500\times100.5}{30\times300\times270}\right)$$

$$M_{e2}=11.56\text{ kNm}$$

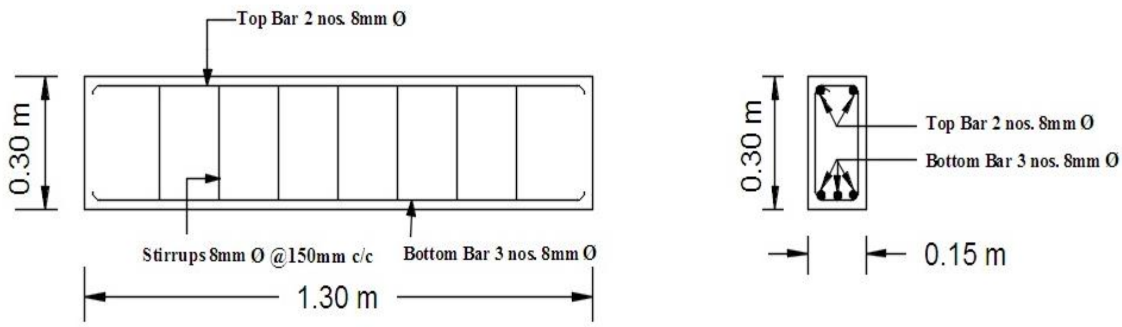

Fig. 3 Beam dimensions

Table 2 Design mix proportion (M30)

Description	Cement	Fine Aggregate	Coarse Aggregate	Water
Mix proportion	1	1.35	2.49	0.45
Quantities of materials (in kg/m^3)	438.13	591.47	1090.95	197.16

$$Mt = Mue2 - Mue1$$

$Mue1 = 0$ as beam is in pure torsion

$$\therefore Mt = Mue2$$

$$M_{ue2} = M_t = \frac{Tu\left(1+\frac{D}{b}\right)}{1.7}$$

$$Tu = \frac{1.7Mt}{1+\frac{D}{b}} = \frac{1.7 \times 11.56}{1+\frac{300}{150}}$$

$$Tu = 6.55 \text{ kNm}$$

Analytically the beam is able to carry 6.55 kNm ultimate torsional moment.

2.2 Material used

Concrete mix design is prepared for the M30 grade of concrete. Reinforced concrete beams of length 1300 mm are prepared with cross-section 150 mm×300 mm as shown in Fig. 3. These specimens are tested for a torsional moment. The corresponding angle of twist is noted. After the failure of beam, retrofitting is done by using various patterns of aramid fiber and again tested for a torsional moment. The effect of retrofitting on torsional moment carrying capacity of beam is studied.

Cement: - OPC 53 Grade

Fine aggregate: - Natural river sand of specific gravity 2.65 kg/m^3

Coarse aggregate: - Nominal size of 20 mm having specific gravity 2.75 kg/m^3

Aramid fiber- The plain-woven 1414, bidirectional aramid fabric of plain weave style.

Steel reinforcement:-High yield strength deformed bar (Fe 500).

2.3 Mix proportion

Concrete mix design for M30 grade of concrete is prepared according to the guidelines of IS 10262 (2009). The mix proportion for cement, sand, and aggregates with water: cement ratio is used as given in Table 2.

Table 3 Casting program

Sr.No.	Beam Type	Designation	No. of beams
1	Controlled beam	C	3
2	Beam retrofitted with full wrapping	F	3
3	Beam retrofitted with 150 mm strips of fiber at 100 mm spacing	S	3
4	Beam retrofitted with 150 mm strips of fiber at 150 mm spacing	T	3
5	Beam retrofitted with 150 mm strips of fiber at 200 mm spacing	U	3

2.4 Casting procedure of all beams

Total 15 under-reinforced beams were cast. 3 beams are controlled specimens and remaining 12 beams are tested for torsion until failure occurs. After failure 3 beams were retrofitted with the full wrapping of aramid fiber. 9 beams are wrapped with aramid fiber strips of 150 mm width with variable spacing of 100 mm, 150 mm, and 200 mm respectively in a group of three. Details of casting program are given in Table 3.

2.5 Pre- retrofitting technique

First of all 3 controlled beams C1, C2, and C3 are tested for a torsional moment and the corresponding angle of twist is noted down up to the failure of beam. After this, all 12 beams were tested for a torsional moment. This moment was at pre-cracking of the beam specimen and about 45% less than the designed torsional moment. The corresponding angle of twist was noted. Fig. 4 shows the pre-cracking of the beam before retrofitting. After the failure of beam retrofitting was done by using continuous wrapping and strip wrapping with aramid fiber and again tested for a torsional moment. The effect of retrofitting on torsional moment carrying capacity and angle of twist of the beam was studied.

2.6 Retrofitting

Retrofitting of all the beams is done by U-shaped jacketing i.e., jacketing on 3 sides with aramid fiber having different patterns like 1) full wrapping 2) strips of width 150 mm at a spacing of 100 mm 3) strips of width 150 mm at a spacing of 150 mm 4) strips of width 150 mm at spacing 200 mm.

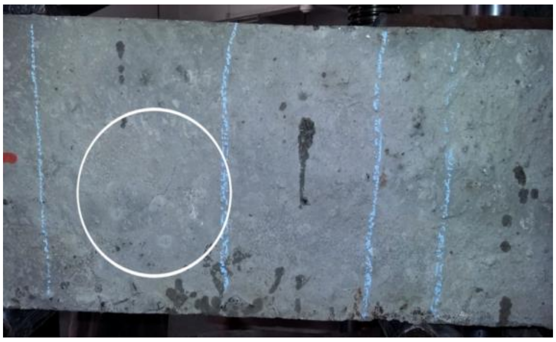

Fig. 4 Pre-cracking of beam before retrofitting

Fig. 5 Full wrapping using aramid fiber

The dirt and debris were removed from the beam surface using coarse sandpaper. Resins and hardeners were mixed together as per the manufacturer’s instructions. The fabric material was cut into the required size. The epoxy coating was applied to the concrete surface and fabric material is placed on it. Air bubble entrapped in concrete and fabric was removed out. Fig. 5 shows the full wrapping of RC beam.

3. Experimental program

3.1 Torsional testing of beam

All the beams are cured in water for 28 days. Surface cleaning is done using sandpaper for the appearance of crack on beam. Control beams are tested until the complete failure occurs by crushing of concrete. For rest of the beams, loading is stopped as soon as the beam fails. Torque is created in both sides of the beam using two leaver arms of the bracket. The bracket is made up of two-channel section connected back to back. These lever arms are 1.12 m long, bolted on the beam by using a steel plate. A rolled steel I- section beam (spreader beam) is placed diagonally on end support of bracket distributing the load equally at both ends. Fig. 6 shows a typical setup for Torsion Test. The main advantage of this test setup is, it is applied with a single vertical load at the center of the RC beam creates pure torsion at both ends. Roller support is provided by using roller bearings creating a 50 mm gap at the end of the beam as shown in Fig. 7. The vertical load is given by the Universal Testing Machine of capacity 1000 kN. The applied load is converted to torsional moment and the corresponding angle of twist is calculated by dial gauge

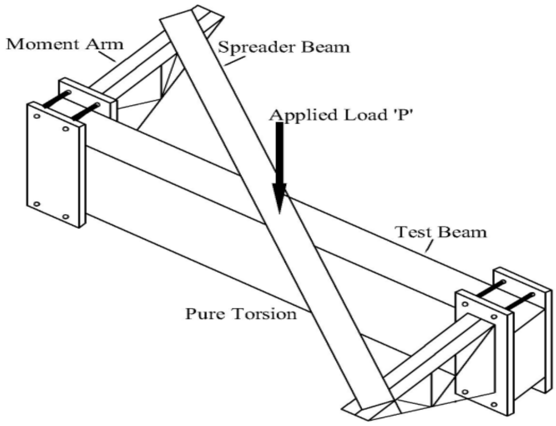

Fig. 6 Setup for Torsion Test

Fig. 7 Beam fully wrapped on 3 sides by aramid fiber

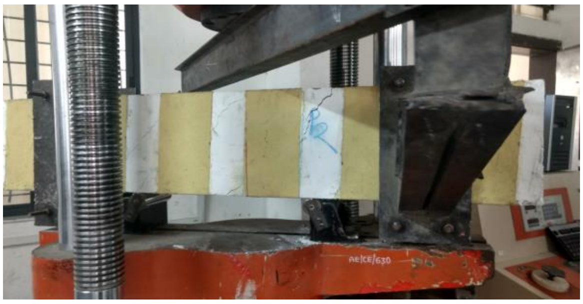

Fig. 8 Failure of beam after retrofitting with 150 mm strips at spacing 100 mm

reading having least count 0.02 mm (Kandekar and Talikoti 2018). Fig. 8 indicates failure due to crack propagation in beams wrapped with 150 mm strips at spacing 100 mm. Spiral cracks are formed from the bottom towards the top of the beam at the opposite side of RC beam. Due to the formation of cracks, debonding of beam surface and aramid fiber took place which causes the failure of the beam in torsion.

4. Results and discussions

Table 4 shows the torsional moment taken by RC beams when wrapped with different configurations of aramid fiber. After the failure of the beam, retrofitting is done with resins and hardener in the proportion of 100:30. The significant increase is torque carrying capacity of beams is found after retrofitting.

Table 4 Ultimate torsional moment and nature of failure for beams

Set No.	Type of Beam	Beam Designation	Torsional Moment (kNm) Before	Torsional Moment (kNm) After	Nature of failure
I	Controlled Beam	C1	4.675	-	Crushing of Concrete
		C2	5.005	-	
		C3	4.840	-	
II	For full wrapping with or without aramid fiber	F1	4.235	4.675	Crushing of Concrete
		F2	4.070	4.620	
		F3	4.097	4.207	
III	Wrapped with 150 mm strip for spacing 100 mm	S1	5.250	4.757	Crushing of Concrete
		S2	5.060	4.730	
		S3	5.170	4.647	
IV	Wrapped with 150 mm strip for spacing 150 mm	T1	4.840	4.180	Crushing of Concrete
		T2	5.060	4.290	
		T3	5.280	4.400	
V	Wrapped with 150 mm strip for spacing 200 mm	U1	4.675	3.875	Crushing of Concrete
		U2	5.060	4.207	
		U3	4.840	3.960	

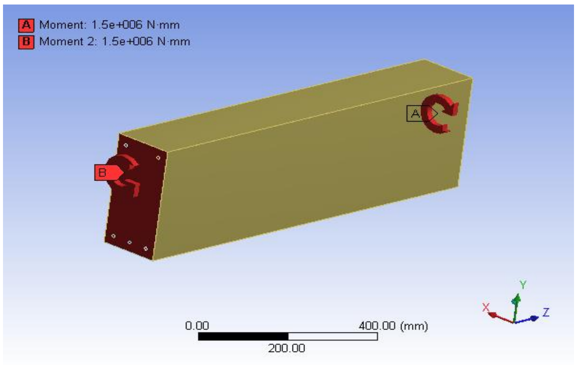

Fig. 9 ANSYS modeling for fully wrapped beam

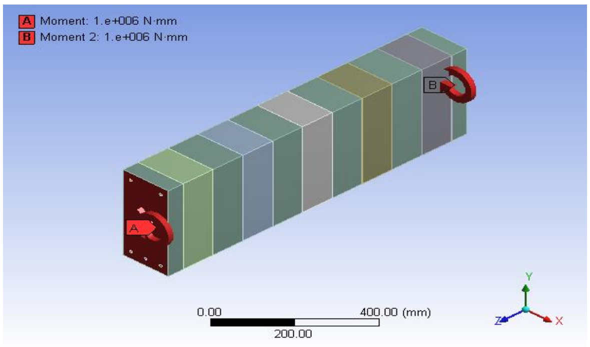

Fig. 10 ANSYS modeling for beam wrapped with strips

All experimental results are validated by finite element modeling using ANSYS 2017. Various elements used for modeling in ANSYS are solid 65 for concrete, beam 188 for reinforcing steel and shell 91 for aramid fiber. Mesh size was 1 mm and the standard deviation was 0.17 mm. The beam was subjected to simple support with torsional moment acting at both ends which were equal in magnitude and opposite in direction. The beam was restrained for displacement and allowed for rotation. Fig. 9 shows modeling of the fully wrapped beam in ANSYS and Fig. 10

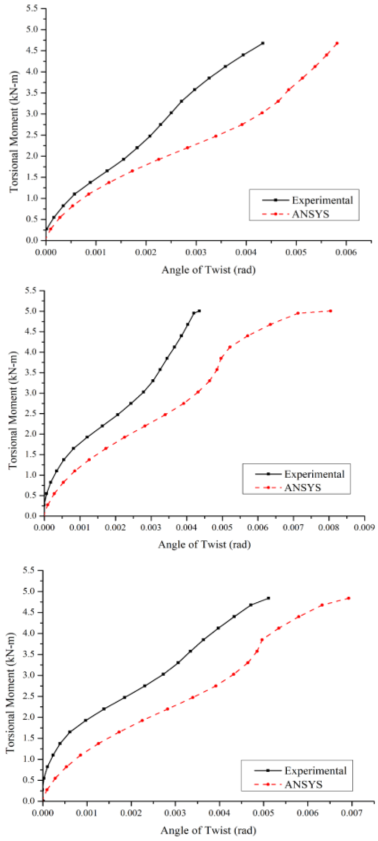

Fig. 11 Torsional moment vs Angle of twist curve for controlled beam C1, C2, C3

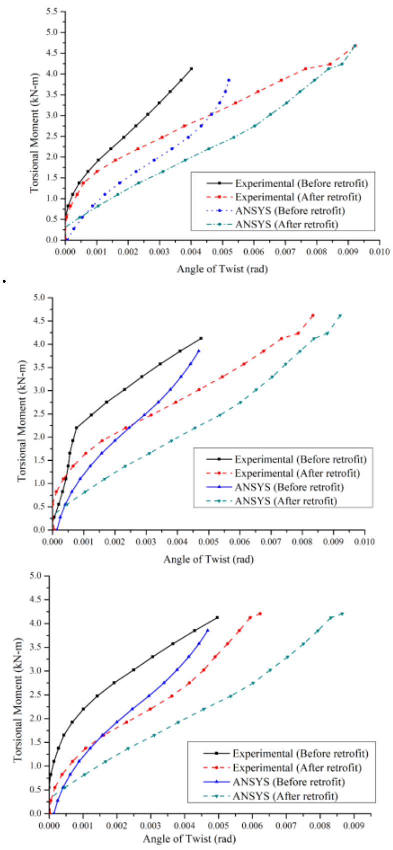

Fig. 12 Torsional moment vs Angle of twist curve for beam F1, F2, F3

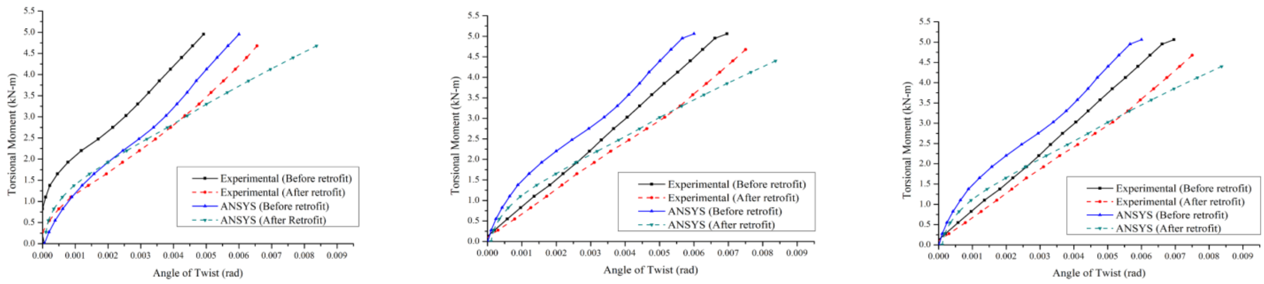

Fig. 13 Torsional moment vs Angle of twist curve for beam S1, S2, S3

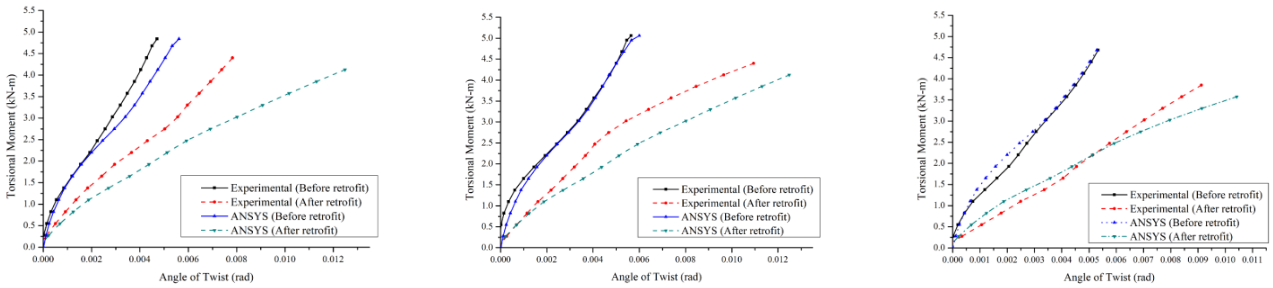

Fig. 14 Torsional moment vs Angle of twist curve for T1, T2, T3

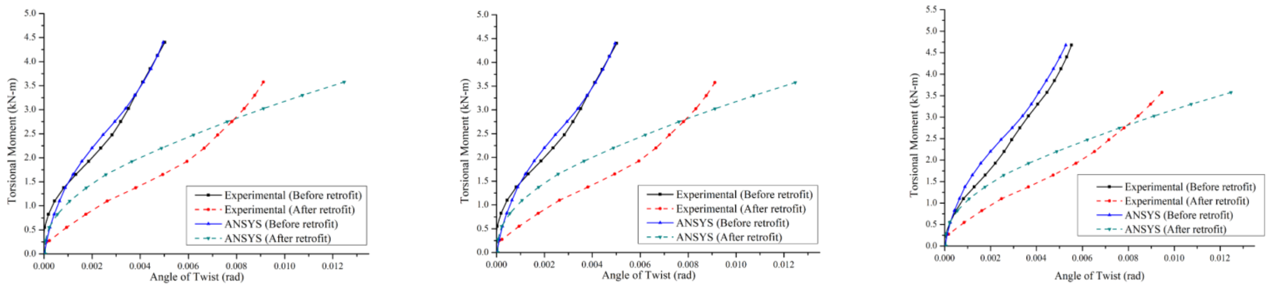

Fig. 15 Torsional moment vs Angle of twist curve for beam U1, U2, U3

is the modeling of beam wrapped with strips of aramid fiber. Experimental results are validated with the software results. Fig. 11 indicates that experimental and software results for a torsional moment and angle of twist are nearly the same in case of the control beam.

Before retrofitting RC beams are applied with torsional moment up to failure. Once failure occurs beams are fully wrapped and again tested for a torsional moment. Fig. 12 shows a graph of a fully wrapped RC beam before and after retrofitting. Fig. 13, Fig. 14 and Fig. 15 shows the nature of RC beam before and after retrofitted with 150 mm aramid fiber strips at a spacing of 100 mm, 150 mm and 200 mm respectively

The controlled beam fails at a torque of 4 kNm to 5 kNm where the angle of twist was about 0.01 rad (refer Fig. 11). Such beams when retrofitted with fully wrapped aramid fiber, it regains its original torsional moment carrying capacity and fails at the equivalent angle of twist. In case of full wrapping configuration, the average torsional moment before retrofitting was 4.13 kNm. After retrofitting, average torque taken by these specimens was 4.5 kNm as shown in Fig. 12. When 150 mm wide aramid fiber strips were used at 100 mm spacing, average torque before and after retrofitting was 5.16 kNm and 4.71 kNm respectively as per Fig. 13. For 150 mm spacing of strips, the torsional moment before retrofitting was 5.06 kNm and after retrofitting, it was 4.29 kNm as shown in Fig. 14. In case of 200 mm spacing of aramid fiber strips, torsional moments were 4.85 kNm and 4.01 kNm before and after retrofitting respectively (refer Fig. 15).

As soon as spacing of 150 mm wide aramid fiber strips increases small decrease in torque and an increase in the angle of twist is found. For a fully wrapped beam specimen, fiber jacketing required is 0.825 m^2. When 150 mm wide strips are wrapped at 100 mm spacing, it consumes 0.562 m^2 aramid fiber. For spacing of 150 mm and 200 mm, fiber required was 0.45 m^2.

5. Conclusions

From the above-discussed results, it can be concluded that:

- The fiber content in jacket increases the ultimate moment carrying capacity and decrease the angle of twist.
- Retrofitting with aramid fiber gives adequate strength to the beam hence; aramid fiber can be used as strengthening material for various structural members.
- Due to full wrapping configuration torsional moment

carrying capacity increases by 105% after retrofitting.

- When RC beam wrapped with 150 mm wide aramid fiber strips at a spacing 100 mm center to center, about 92% strength can be gained with a material saving of 32%.
- Aramid fiber strips of 150 mm width when draped around RC beam at a distance 150 mm beam salvaged 84% strength.
- When the spacing of 150 mm wide aramid fiber strips was 200 mm, about 82% strength is regained.
- Both 150 mm and 200 mm spacing saves the fabric material up to 45% but a significant decrease in torque carrying capacity is found.
- Retrofitting of RC beam can be done either by full wrapping or by strips of 150 mm width at a spacing of 100 mm without sacrificing strength and economy.
- The fiber content in jacket increasing the load-carrying capacity of the beam which simultaneously increases the torsional moment and corresponding angle of twist.
- With the increase in spacing of fiber strips, torsional moment carrying capacity of RC beam decreases with a small drop in the angle of twist.

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