



Study of torsional behavior of reinforced concrete beams strengthened with aramid fiber strips

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Abstract

This paper investigates the strengthening of reinforced concrete (RC) beams for its torsional behavior using aramid fiber strips. Most of the time aramid fiber is used as an externally bonded reinforcement to increase flexural and shear strength of RC beams. An attempt is made to use it for improving torsional moment carrying capacity of RC beam. Torsional failure mostly occurs in earthquake prone areas subjected to rapid failure. Brittle failure of structures occurs due to torsional moment. Different patterns of aramid fiber strips are selected to wrap around RC beams and torsional behavior of these strengthened beams is studied. RC beam of M30 grade of concrete is strengthened with aramid fiber strips and tested for torsional failure using lever arms subjected to torque. The beam size is 150 mm × 300 mm and of 1.3 m in length, designed as per IS456-2000. A total of 21 numbers of reinforced concrete rectangular beams were cast for the experimental study. Three are taken as controlled beams with normal reinforcement, 3 beams are designed with torsional reinforcement and other 15 beams with normal reinforcement have grouped in five sets. These five sets are strengthened using aramid fiber strips of 150 mm width with variable spacing of 100, 125, 150, 175 and 200 mm, respectively. The effect of different configuration of aramid fiber on torsional moment carrying capacity, angle of twist and failure mode of the beams is studied.

Keywords Aramid fiber · Strengthened beams · Torsional reinforcement · Angle of twist

Introduction

The civil engineering structures constructed around 50 years before are now reaching a critical stage, undergo deterioration and reduced functionality. Proper maintenance and strengthening of existing structures are necessary for their satisfactory performance. Strengthening reinforced concrete structures has become a popular technique in recent years.

The purpose of strengthening is to improve the defects in the structure due to the revision of design codes. Buildings designed by older codes are not sufficient to cater the present needs. In most of the cases behavior of strengthened and unstrengthened beam using different fiber reinforced

polymer (FRP) is studied. According to Mostofinejad and Talaeitaba (2014) reinforced concrete members need to be evaluated after superimposed with the loads and if few members are damaged to some extent, such members required immediate rehabilitation.

FRP material is able to wrap with any size and shape which is not possible with conventional materials like steel plates. FRP is composed of fibers and resins thereby costlier than other materials. But it consumes relatively less labor and equipment cost, and is easy to install. FRP can be installed in the areas of limited access where traditional techniques are impracticable (Ramakrishnan and Janarthanan 2016). FRP composites contain continuous carbon, glass or aramid fibers bonded together in a matrix of epoxy, vinyl ester or polyester. The load is taken by fibers in FRP, whereas transfer of shear is done by plastic and matrix materials. FRP can be used for retrofitting and strengthening in the form of laminates, sheets or in strips (Sarker et al. 2011). Extensive research is done on concrete beam and columns retrofitted with FRP composites to know the increase in strength, durability, ductility,

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confinement effect, etc. Few design guidelines are prepared based on experimental results.

Torsional strengthening of beams

Most of the research is done on RC beams strengthened with FRP subjected to shear and flexure. Many structural members such as curved girders, space frames, eccentrically loaded beams, spandrel beams in buildings, and spiral staircases are subjected to torsional moment. Beyond plane rectangular nature, structural member can be of T shape, L shape or box section. These various shapes create difficulty in understanding torsion in RC members (Panchacharam and Belarbi 2002). 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, behavior of RC beam subjected to torsion is different. Due to shear, crack propagates in the same direction on both sides of the beam, whereas due to torsion spiral cracks propagate in the opposite direction on opposite sides of the beam. Alabdulhady et al. (2017) used PBO-FRCM composites to improve torsional resistance of reinforced concrete beams. Zhang et al. (2001), Hii and Al-Mahaidi (2006), Jing et al. (2007), Mohammadzadeh and Fadeel (2009) and Deifalla et al. (2013) worked on the torsional behavior of different types of reinforced concrete beam externally strengthened with carbon fiber reinforced polymer (CFRP).

In this research an attempt is made to strengthen the reinforced concrete beam using aramid fiber. The effectiveness of various wrapping configurations indicated that the increase in the spacing of aramid fiber strips increases the deformation of beam under torsion.

There are many methods of strengthening such as,

1. enlargement of sections
2. FRP wrapping
3. external post tensioning
4. addition of fiber to concrete, etc.

Fiber

Fiber is an integral part of FRP composites occupying major volume fraction in composites. Fiber is able to take only tensile forces. If used as a fiber reinforced composite, it can contribute to a major part of tension, compression, shear, flexural strength and stiffness (Mukhopadhyay 2004).

Types of fibers

1. Glass fibers
2. Carbon fibers
3. Ceramic fibers
4. Aramid fibers

Aramid fiber

Under cyclic loading aramid fibers are good to resist abrasion. When compared on equal weight basis, it gives five times more strength than steel. These fibers are strong in heat resistance, weight of fiber is 300 g/m² and width is 1 m. The tensile strength ranges from 2400 to 3600 N/mm² with percentage elongation of 2.2–4.4%. Tensile modulus is 60–120 GPa. Kevlar which is a type of aramid fiber was selected by Granata and Parvin (2001) as the FRP material and Shell Chemical epoxy was chosen as the adhesive. Tensile strength of Kevlar fabric is 55% greater than E-glass and shear strength 180% stronger than E-glass. The bulk density (mass per unit of volume) and linear density (mass per unit of length) of the fabric are 1.44 g/cm³ and 1.656×10³ g/cm, respectively (Pereira and Revilock 2009). The plain-woven 1414 aramid fabric made by Hindoostan Technical Fabrics Limited is used in this study.

Experimental investigation

The specimens of RC beams are prepared as per Table 1. This includes casting RC beams, with and without torsional reinforcement. Aramid fiber of 150 mm strip is wrapped around the normally reinforced beams at variable spacing.

Table 1 Casting program for RC beam

Sr.No.	Beam designation	Beam type	Remark
1.	C	Controlled beam	Beam with normal reinforcement
2.	T	Beam designed for torsion	Beam with torsional reinforcement
3.	P	Wrapped with 150 mm aramid fiber strips for spacing 100 mm	Beam with normal reinforcement
4.	O	Wrapped with 150 mm aramid fiber strips for spacing 125 mm	
5.	Q	Wrapped with 150 mm aramid fiber strips for spacing 150 mm	
6.	R	Wrapped with 150 mm aramid fiber strips for spacing 175 mm	
7.	S	Wrapped with 150 mm aramid fiber strips for spacing 200 mm	



These specimens are tested for pure torsion and torsional moment, and the corresponding angle of twist is recorded. All the beams are 150 mm wide and 300 mm deep in cross section. Length of the beam is 1.3 m. Each beam is designed with longitudinal reinforcement of three bars of 8 mm diameter at bottom and two bars of 8 mm diameter at top. Shear reinforcement of 8 mm diameter two-legged stirrups is provided at 150 mm center to center throughout the span. For beams designed with torsional reinforcement, two bars of 8 mm diameter are provided longitudinally at mid-depth of beam as shown in Fig. 1.

Casting of specimen

The concrete mix design is prepared for M30 grade of concrete with the proportion of cement, sand and aggregates of 1:2.1:2.85, respectively, with the water:cement ratio 0.45. A total of 21 numbers of reinforced concrete rectangular beams were cast for the experimental study. Three are taken as controlled beam with normal reinforcement. Three beams are designed with torsional reinforcement and other 15 beams having normal reinforcement are strengthened using aramid fiber strips of five different patterns. Seven sets of beam were cast for this experimental program. The details of these sets are shown in Table 1.

Fabrication of aramid fiber

There are two basic processes for molding: hand layup method and spray-up method. The hand layup process is one of the oldest and simplest methods of fabrication. The process is most common in aramid fiber marine construction (Aiello et al. 2007). In hand layup method, liquid resin is placed along with aramid fiber beside finished surface. Chemical reaction of the resin hardens the material to a strong light weight product.

The following constituent materials were used for fabricating the beams:

1. aramid fiber
2. epoxy as resin
3. hardener

Strengthening of beams

As the FRP material is to be wrapped around structural members for external strengthening, surface characteristics of concrete are very important to furnish proper bond in the contact area. The fabric material is cut as per the requirement of area to be covered. Instructions need to be given by manufacturers regarding surface preparation. These instructions include removing the cement paste, and using primer putty to coat the surface. Epoxy resin and hardener are mixed together with the ratio of 100:30, and applied to the aramid fiber and on the surface of the beam. Finally, the aramid fiber strips with five different patterns were applied to the beams. Air bubble entrapped, if any, is removed in between fabric and beam surface.

Experimental setup

A torsion test setup attached to universal testing machine is shown in Fig. 2. Channel section is used to form a bracket. This bracket is attached to RC beam by bolted connection and lever arm of 1.12 m is created by bracket at farther end. Torsional moment is created by an I Section flange beam laid diagonally on the lever arms. A twist is created at the both ends with the middle part of RC beam in pure torsion. The RC beam is supported by roller support at both the ends as shown in Fig. 3. Deflection of dial gauge is noted with the least count of 0.02 mm and converted to angle of twist. As each lever arm is superimposing with equal load, moment is calculated by product of force and perpendicular distance. Crack propagations are marked on the surface of beam as shown in Figs. 3 and 4.

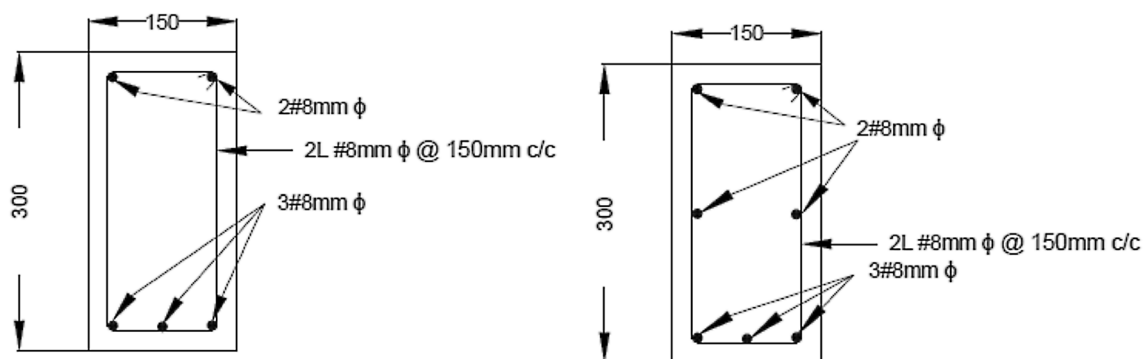


Fig. 1 Cross section of controlled beam (normal reinforcement) and beam designed for torsion

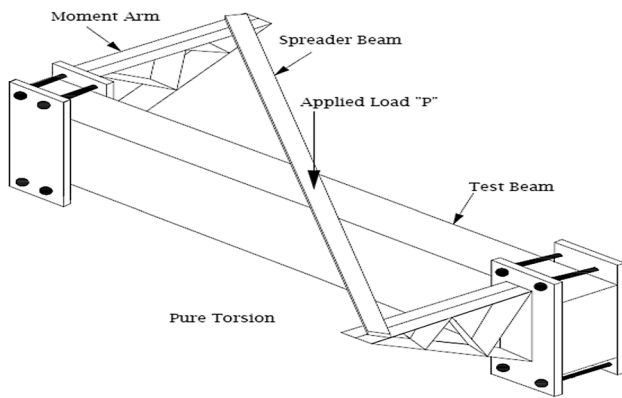


Fig. 2 Schematic of torsion test setup



Fig. 3 Beam no. T1 after cracking

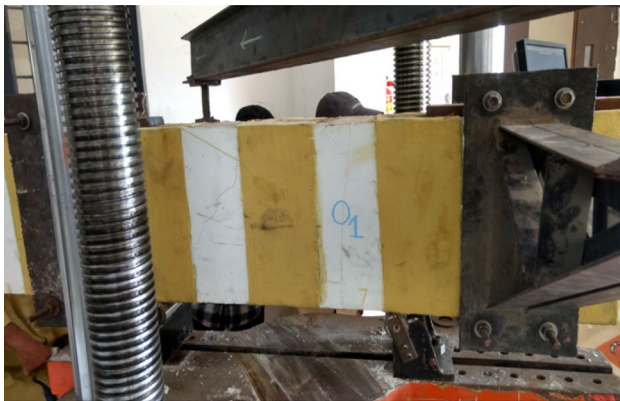


Fig. 4 Beam no. O1 after cracking

Test results and discussions

A total of 21 beam specimens are tested and torsional moment and angle of twist are observed. 15 beams were strengthened with aramid fiber strips of five different

spacings and are compared with controlled beam (normally reinforced) and torsionally reinforced beam. Figure 5 shows torsional moment and angle of twist for controlled beam (normal reinforcement) and torsionally designed beam. The average torsional moment at first crack is found to be 2.47 kN m at which angle of twist was 0.0026 rad. The ultimate torque taken by controlled beam is 3.06 kN m with the angle of twist 0.0034 rad. For beam designed with torsional reinforcement, first crack appears at about 7.15 kN m where angle of twist was 0.018 rad approximately. At the ultimate torque of 8.525 kN m, twisting angle was about 0.022 rad.

When beams with normal reinforcement was strengthened by aramid fiber strips of 150 mm width at spacing 100 mm, average first crack moment was 6.5 kNm with a twist of about 0.016 rad. Ultimately it fails at 7.97 kNm where the angle of twist was 0.018 rad. Now spacing of 150 mm wide strips is increased to 125 mm and the average torque at first crack was 6.32 kNm and angle of twist was 0.014 rad. Such beam fails at 7.42 kNm at which the twisting angle is found to be 0.017 rad. Refer Fig. 6.

Figure 7 shows that, with the increase in spacing of strips to 150 mm, the first crack appears at 5.77 kNm with angle of twist 0.0133 rad. The ultimate twisting moment was 7.19 kNm and twisting angle 0.0178 rad. Spacing of strips is further increased to 175 mm the average torque at first crack and ultimate point was 5.4 kNm and 6.78 kNm, whereas angle of twist at these two points are 0.013 rad and 0.017 rad, respectively. Finally at 200 mm spacing of aramid fiber strips, the first crack torque was about 4.95 kN m with the average angle of twist of 0.0125 rad. At an ultimate torque of 6.41 kNm, beam fails with a twist of 0.015 rad as per Fig. 8.

Comparative graphs are drawn, and comparisons are made based on torsional moment at first crack and ultimate torsional moment as shown in Figs. 9, 10 and 11. Also the corresponding angle of twist is observed.

Modeling using ANSYS

For validation of experimental program, same beams are modeled in ANSYS software as shown in Figs. 12 and 13. During modeling 1 mm size of mesh is selected with standard deviation of 0.17 mm. The beam is applied with the torque at both ends. Displacement in all direction is restrained, whereas rotation in all directions is allowed with six degrees of freedom. A bonded joint interface is created in aramid fiber and RC beam. This study considers bilinear relationship (elastoplastic) as experimental investigation is up to yield point and breaking point. Controlled beam fails at an angle of twist of 0.0026–0.0034 rad. Torsionally designed beam fails at an angle 0.018–0.022 rad. In normally reinforced beam when wrapped with aramid fiber strips, the

Fig. 5 Torsional moment and angle of twist for controlled beam and torsionally designed beam

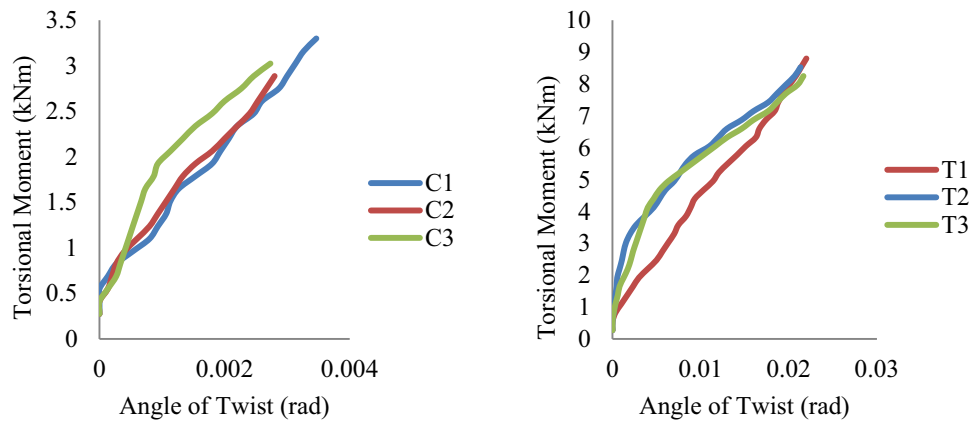


Fig. 6 Torsional moment and angle of twist for 150 mm wide strips at spacing 100 mm and 125 mm

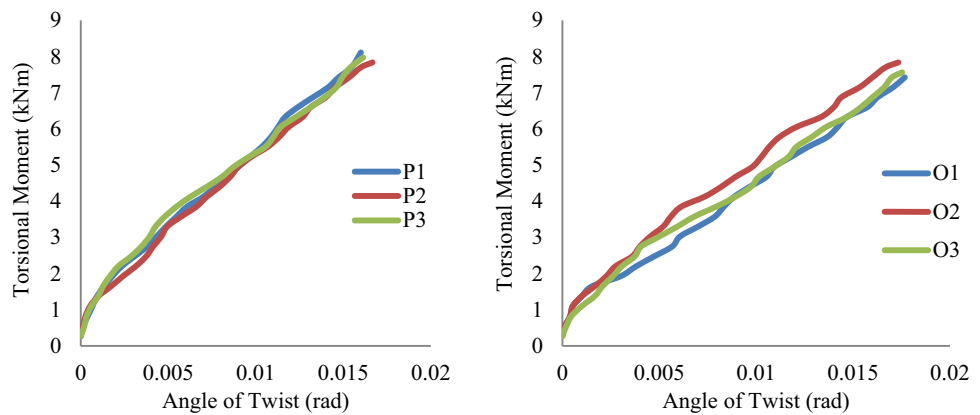
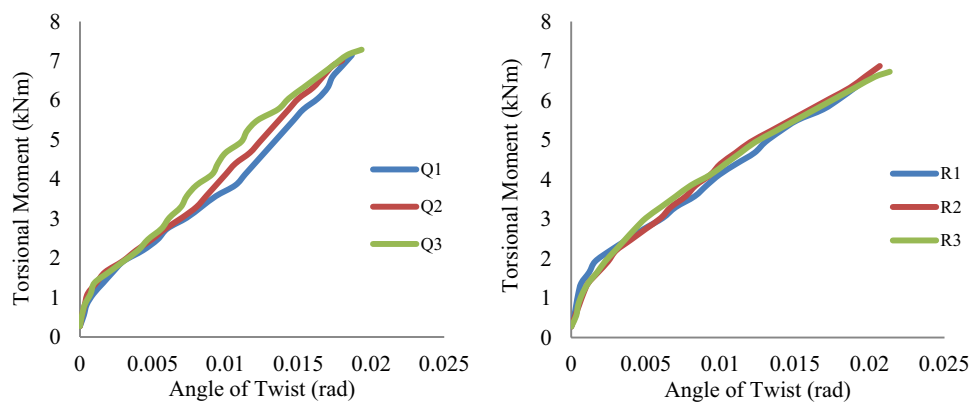


Fig. 7 Torsional moment and angle of twist for 150 mm wide strips at spacing 150 mm and 175 mm



angle of twist improves significantly. Small variations in the angle of twist is seen with variable spacing of aramid fiber strips.

Failure modes

Controlled beam specimen shows torsional cracks developed in spiral direction at a very small value of torsional moment and angle of twist.

Strengthened beam shows torsional shear failure due to aramid fiber rupture and debonding. Aramid fiber strips may fail in rupture if fabric material reaches ultimate strain before concrete. If force in aramid fiber is not transferred to strengthened beam, debonding may occur between fabric material and RC beam. The torsional moment at which first crack is initiated and the ultimate torsional moment before failure is tabulated in Table 2.

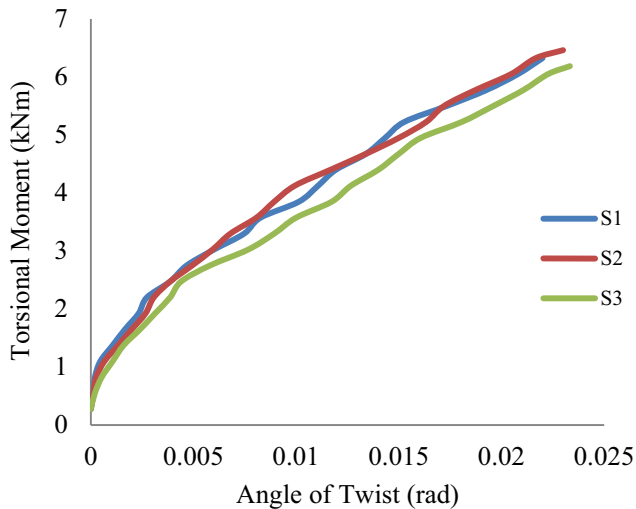


Fig. 8 Torsional moment and angle of twist for 150 mm wide strips at spacing 200 mm

Torsional moment and angle of twist analysis

Here the angle of twist of each beam is analyzed. The angle of twist of each beam is compared with the angle of twist of controlled beam (normal reinforcement). Also the torsional behavior is compared between different wrapping schemes having the same reinforcement.

All the beams are tested for same type of loading arrangement. It was noted that the behavior of the beams strengthened with aramid fiber is better than the controlled beams (normal reinforcement) and nearly equivalent to the beam designed for torsion. The angle of twist enhances when beam was wrapped externally with aramid fiber. The use of aramid fiber had an effect in delaying the growth of crack formation. Beams wrapped with aramid fiber strips increases torsional

moment carrying capacity. When spacing of strips increases, torsional moment carrying capacity decreases with a small effect on angle of twist.

Figures 14 and 15 show the graphical representation of various sets of aramid fiber strips and corresponding torsional moment at first crack as well as ultimate torsional moment taken by the RC beam. The effect of increase in spacing size on torsional moment carrying capacity of beam indicates that, more the spacing of strips less will be the moment carrying capacity and angle of twist as shown in Fig. 16. Each specimen of 100 mm and 125 mm spacing required 0.56 m^2 aramid fibers. For 150 mm and 175 mm spacing, material required is 0.5 m^2 . When spacing increases to 200 mm the fabric required is 0.45 m^2 in a single specimen.

Conclusions

In this experimental investigation, 150 mm wide aramid fiber strips are wrapped around the reinforced concrete beams with variable spacing. The effect of different spacings of strips on torsional moment carrying capacity and angle of twist is studied.

1. The torsional moment carrying capacity of strengthened beams is increased as compared to the controlled beam.
2. Initial cracks appear for higher moments in case of strengthened beams. The moment carrying capacity of the strengthened beam wrapped with 150 mm aramid fiber strip for 100 mm spacing was found to be maximum compared to all the beams.
3. Strengthening with 100 mm spacing enhances the ultimate moment carrying capacity of beams by 140% com-

Fig. 9 Experimental results for beam no. C1, T1, P1, O1, Q1, R1, S1

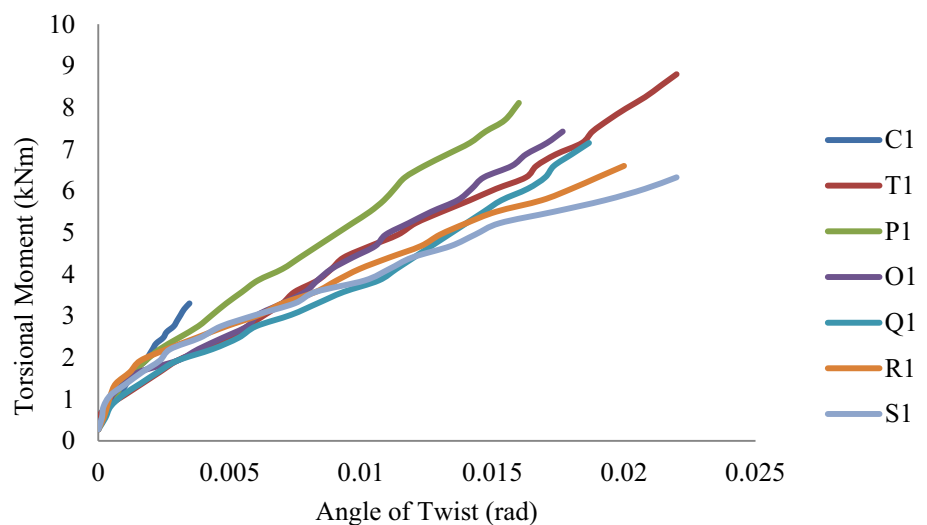


Fig. 10 Experimental results for beam no. C2, T2, P2, O2, Q2, R2, S2

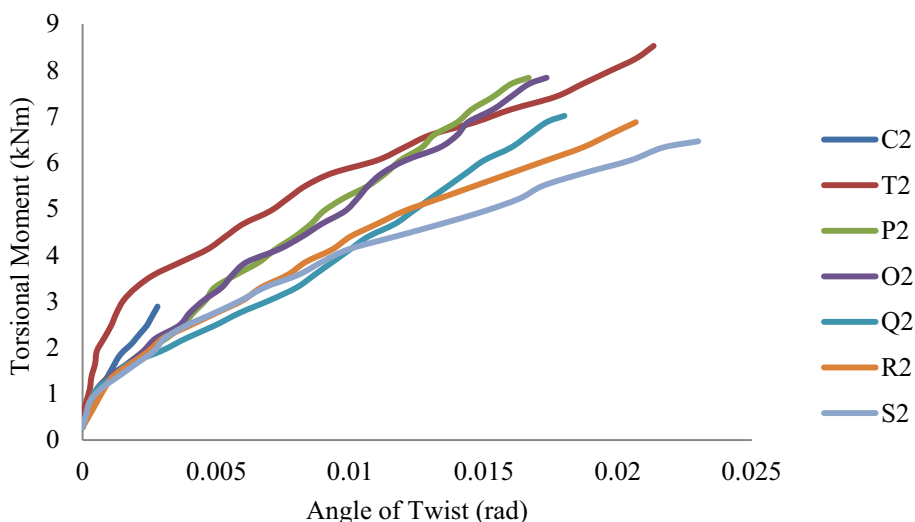
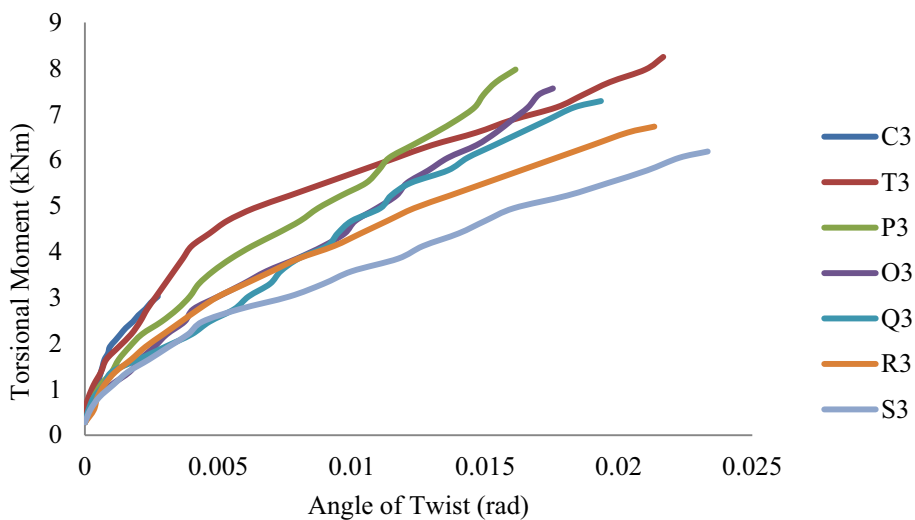


Fig. 11 Experimental results for beam no. C3, T3, P3, O3, Q3, R3, S3



Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
4/4/2017 12:08 PM

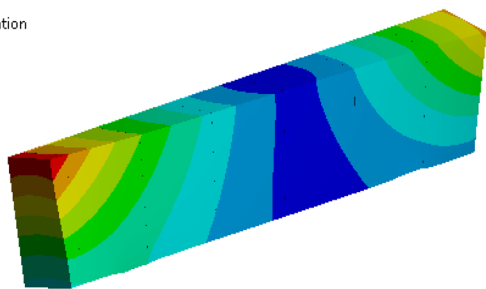
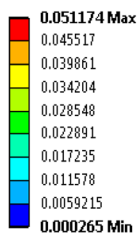


Fig. 12 Controlled beam model in ANSYS

Moment 2
Time: 1. s
4/4/2017 12:10 PM

A Moment: 5.5e+005 N-mm
B Moment 2: 5.5e+005 N-mm

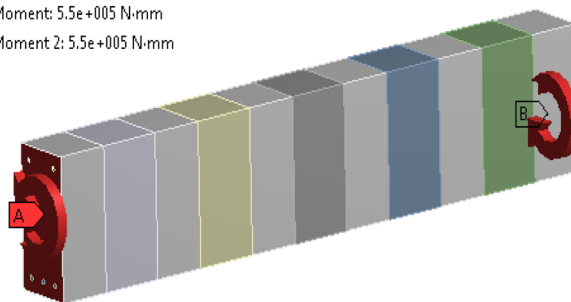
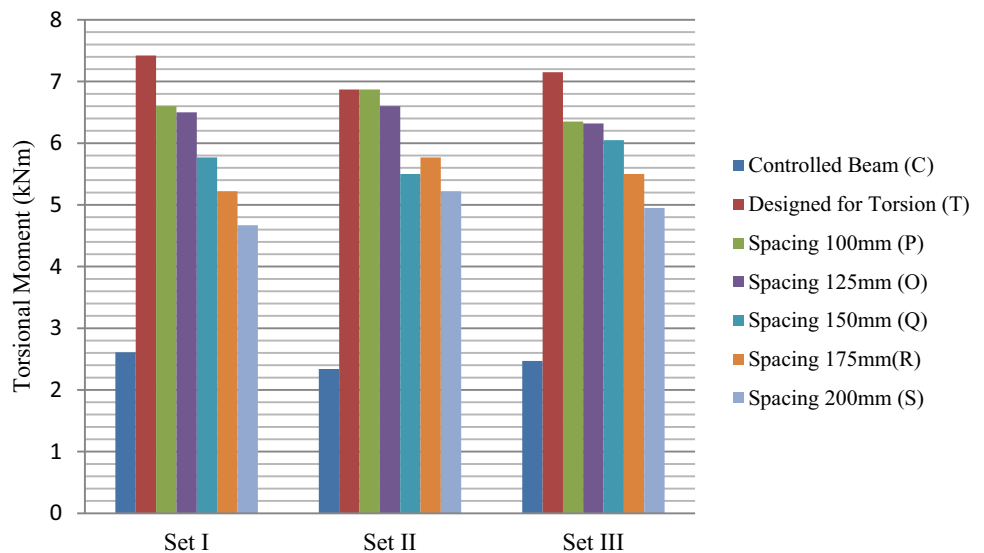


Fig. 13 Beam model in ANSYS wrapped with strips

Table 2 Ultimate load and nature of failure for beams

Set no	Type of beam	Beam designation	Torsional moment (kNm) experimental		Average angle of twist experimentally (rad)		Average angle of twist using ANSYS (rad)	
			At initial crack	Ultimate	At initial crack	Ultimate	At initial crack	Ultimate
I	Controlled beam	C1	2.61	3.3	0.002600	0.003467	0.003467	0.004400
		C2	2.34	2.88				
		C3	2.47	3.02				
II	Designed for torsion	T1	7.42	8.8	0.018800	0.022000	0.020333	0.024120
		T2	6.87	8.525				
		T3	7.15	8.25				
III	Wrapped with 150 mm strip for spacing 100 mm	P1	6.6	8.11	0.016400	0.018000	0.015334	0.018334
		P2	6.87	7.83				
		P3	6.35	7.97				
IV	Wrapped with 150 mm strip for spacing 125 mm	O1	6.5	7.42	0.01420	0.017667	0.014800	0.017900
		O2	6.6	7.83				
		O3	6.32	7.56				
V	Wrapped with 150 mm strip for spacing 150 mm	Q1	5.77	7.15	0.013334	0.017867	0.014334	0.018667
		Q2	5.5	7.01				
		Q3	6.05	7.28				
VI	Wrapped with 150 mm strip for spacing 175 mm	R1	5.22	6.6	0.013000	0.170000	0.012000	0.018000
		R2	5.77	6.87				
		R3	5.5	6.73				
VII	Wrapped with 150 mm strip for spacing 200 mm	S1	4.67	6.32	0.012500	0.015000	0.011664	0.016000
		S2	5.22	6.46				
		S3	4.95	6.18				

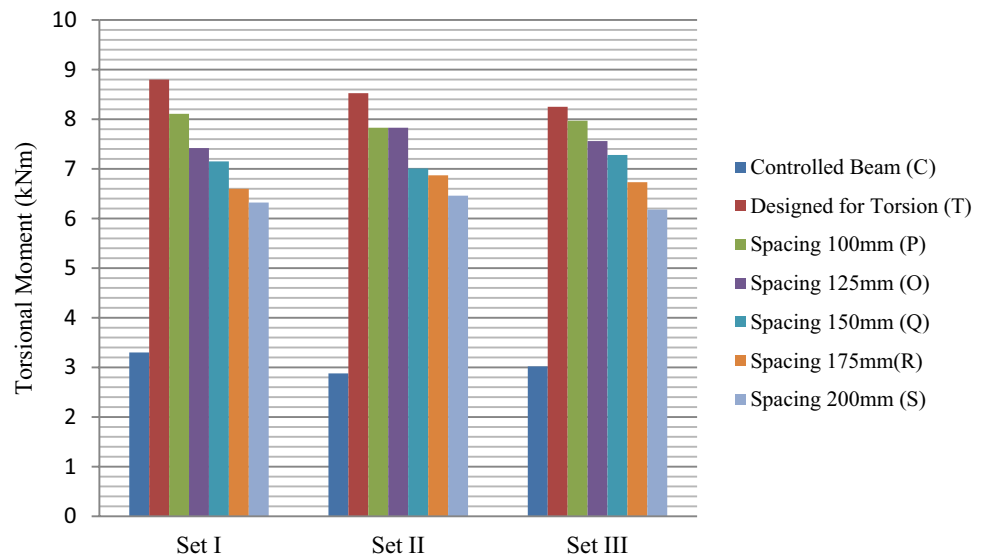
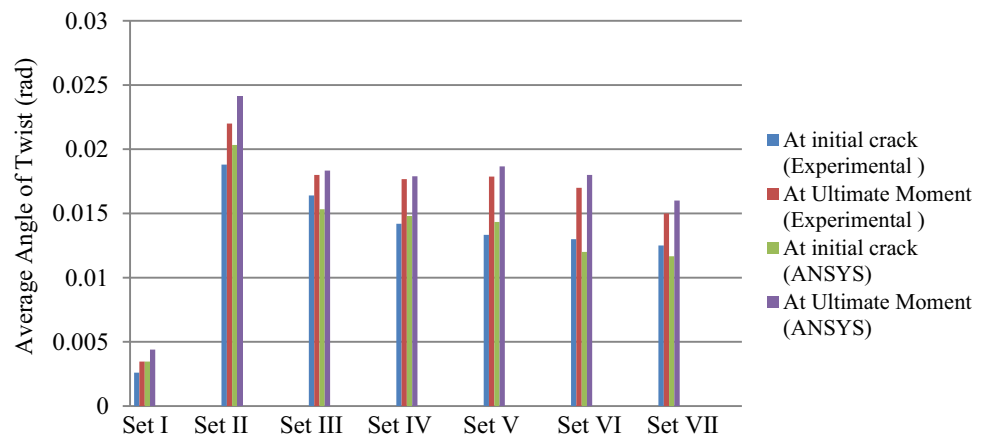
Fig. 14 Torsional moment at first crack

pared with controlled beam and is 11% less as compared to torsionally designed beam.

- For spacing of 125 mm aramid fiber strips the ultimate moment carrying capacity of beams are increased by 130% compared with controlled beam and 16% less compared to torsionally designed beam.

- Aramid fiber strips of spacing 150 mm increases the moment carrying capacity of beams by 120% compared with controlled beam and it is decreased by 19% as compared to torsionally designed beam.
- In case of 175 mm spacing, the ultimate moment carrying capacity of beam is increased by 110% compared



Fig. 15 Ultimate torsional moment**Fig. 16** Comparative graph for angle of twist

with controlled beam and 22% less compared to torsionally designed beam.

7. For spacing of 200 mm, the ultimate moment carrying capacity of beams is increased by 100% compared with controlled beam and it is 25% less as compared to the torsionally designed beam.
8. With the 100 mm and 125 mm aramid fiber spacing, 32% material can be saved. 150 mm and 175 mm spacing saves 40% material, whereas 200 mm spacing of aramid fiber strips holds 46% material saving.
9. It is seen that all the beams wrapped with aramid fiber strips increases torsional moment carrying capacity. When the spacing of strips increases the torsional moment carrying capacity decreases with small variations in the angle of twist.

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