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Torsional response of fibrous reinforced concrete members: Effect of single type of reinforcement

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Abstract

Studies on the torsional behaviour of reinforced concrete members in general and fiber reinforced members in particular are of interest to several researchers as torsional rigidity, torsional stiffness and torsional toughness of the members play a vital role in the analysis of structures subjected to Seismic loads and Wind loads. In the present paper an investigation of the behaviour of steel fiber reinforced concrete members having single type of reinforcement, viz., longitudinal reinforcement or transverse reinforcement, has been presented. Torsion tests on 10 reinforced SFRC members revealed that single type of reinforcement, either longitudinal or hoop reinforcement, can not improve the torsional strength of the member beyond the torsional strength of the plain member without any reinforcement. However, single type reinforcement improved the ductility of the member. Steel fibers improved the cracking torque of the members noticeably.
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Keywords: Torsional strength; Steel fibers; Cracking torque; Torsional toughness; Torque twist response

1. Introduction

Torsion forms one of the basic structural actions besides axial force, shear force and flexure. Generally torsion occurs as combined loading. Torsion in reinforced concrete structures arises as a result of primary or secondary action. Primary torsion occurs when the external load has no alternative to being resisted but by torsion. This torsion can be found from equilibrium equations. Hence, it is referred to be Equilibrium torsion. In statically indeterminate structures also torsion occurs as secondary action from the requirements of compatibility or continuity of the structure. This torsion is referred as compatibility torsion or secondary torsion.

Torsional rigidity and torsional stiffness of the members play an important role in the three-dimensional analysis of the concrete structures. Because the three-dimensional analysis of concrete structures is obligatory in the design of earthquake resistant structures. Thus, studies on the torsional response of reinforced concrete members are as essential as the studies of the other forces, viz., bending, shear and axial force. Significant studies on the pure torsional behaviour of reinforced concrete members were reported earlier by Rausch (Space truss theory), Hsu (Skew bending theory, Softened truss theory) [1,2], Paundit [3] and Collins [4], etc. The pure state of shearing stresses due to torsional load induces the principal diagonal tensile stress. The diagonal tensile stress thus developed is principally responsible for the failure of the plain concrete member under pure torsion. In reinforced concrete members, after initial cracking, the longitudinal reinforcement and transverse reinforcement and concrete present between spiral cracks share the torsional loads, with reduced torsional stiffness. Hsu [1] has conducted torsion test on rectangular beams without stirrup steel and showed that the behaviour of such beams is practically

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same as that of the corresponding plain concrete beams. It was recommended that a concrete beam with longitudinal reinforcement alone may be considered as plain concrete member.

The addition of steel fibers improves the tensile strength of the matrix to a marginal extent and ductility and energy absorbing capabilities of the basic matrix to a significant extent. The better qualities of Steel fiber reinforced concrete (SFRC) make it a suitable material for blast resistant/earth quake resistant structures. Narayan [5], Hafeez Khan et al. [6], Mansur [7], John Craig et al, [8,9], Batson et al. [10] reported the effectiveness of the fibers in resisting the torsional loads.

Narayan [5] reported tests on SFRC beams under pure torsion and combined bending and torsion. Steel fibers of aspect ratio 150 were used. Three square beams were tested for pure torsion and concluded that the torsion capacity of plain beams increases with increase in the tensile strength of concrete. The angle of twist at ultimate load was approximately same for plain and fibrous beams. It was mentioned that plain beam under torsion failed immediately when peak load was reached, while the fibrous beams sustained loads even after ultimate load. Sand heap analogy for ultimate torque appears to be sufficient. Tensile strength of fibrous concrete was assumed as $0.36\sqrt{f_c}$.

Mansur [7] conducted tests under pure torsion on 21 plain SFRC beams. Galvanized steel fibres of aspect ratio, 26, 38.6, 54.5 and 80 were used. Volume fraction varied as 1%, 2% and 3%. The conclusions were, inclusion of fibres in concrete improves ultimate torsional strength and imparts significantly to the ductility and toughness of beams is pure torsion. The torsional strength increased with increasing volume fraction and aspect ratio of fibres. Elastic and skew bending theories appear to be unsatisfactory for SFRC beams. Plastic theory seems to estimate the torsional strength of the beams reasonably. The increase in torsional strength with increasing beam depth is approximately linear.

Gunneswara Rao and Seshu [12] conducted pure torsional tests on 20 rectangular un reinforced steel fiber reinforced concrete members. A semi empirical formula was proposed to estimate the ultimate torsional strength of the member as:

$$T_u = \left[0.5 - 0.223\frac{b}{d}\right]b^2 d f'_t,$$

$$f'_t = \frac{f_c f_{ct}}{f_c + f_{ct}},$$

where b is the shorter dimension of the rectangular cross-section; d is the longer dimension of the rectangular cross-section; f_c is the cylinder compressive strength of SFRC; f_{ct} is the split tensile strength of SFRC; f'_t is the effective tensile strength.

The present investigation aims at exploring the beneficial prospects of steel fibers in reinforced concrete members with either longitudinal reinforcement or transverse reinforcement. It is also aimed to know the potential of fibers in concrete to act as longitudinal reinforcement or transverse reinforcement in a beam where any one of the aforementioned reinforcements is absent.

2. Methodology

Steel fiber reinforced concrete rectangular beams of size 100 mm × 200 mm × 2000 mm with either longitudinal reinforcement or transverse reinforcement are tested under pure torsion. The volume fraction fiber content in the concrete was varied from 0% to 1.2% at regular intervals of 0.3%. Thus, five beams with longitudinal reinforcement and without web reinforcement varying volume fraction of fiber content 0%, 0.3%, 0.6%, 0.9% and 1.2% and five more beams with transverse reinforcement and without longitudinal reinforcement varying volume fraction of fiber content 0%, 0.3%, 0.6%, 0.9% and 1.2% were tested under pure torsional loading. Companion cylinders were prepared and tested for each and every beam cast to serve as representative cube compressive strength and split tensile strength of the corresponding beam. The design mix adopted for concreting is 0.47:1:1.5:2.5. For the mix design Erntroy and Shack lock method was adopted and method of trial mixes has been used to adjust the proportions. The same proportioning has been adopted for all beams. The mix proportions were presented in the Table 1.

3. Materials

Ordinary Portland cement having a compressive strength of 53 MPa and fine aggregate (sand) satisfying the requirements of ASTM-33C was used in the entire

Table 1
Mix proportions

Mix designation	Water content (kg/Cu m)	Cement content (kg/Cu m)	Fine aggregate	Coarse aggregate	Steel fibres (kg/Cu m)
RL/RT-P	206.19	438.70	658.05	1096.76	0
RL/RT-F1	206.19	438.70	658.05	1096.76	23.55
RL/RT-F2	206.19	438.70	658.05	1096.76	47.10
RL/RT-F3	206.19	438.70	658.05	1096.76	70.65
RL/RT-F4	206.19	438.70	658.05	1096.76	94.20

investigation. Crushed granite aggregates of maximum size 12 mm were used. Forty-one mm long straight Galvanized Iron wires of diameter 0.546 mm were used as fibers, maintaining an aspect ratio of 75. The aspect ratio of the fiber was maintained constant throughout the investigation. The details of reinforcement in each series of the beam, along with Compressive strength and split tensile strength of the mix are presented in Table 2. Each beam is designated by specifying the type of reinforcement (RL-longitudinal reinforcement alone, RT-transverse reinforcement alone) along with the volume fraction of fiber (P-0%, F1-0.3%, F2-0.6%, F3-0.9%, and F4-1.2%). Thus, a beam having a designation of RL-F2 refers to a longitudinally reinforced concrete beam with 0.6% of fibers in the concrete mix. In RL series of beams the web reinforcement is absent, however to hold the longitudinal bars 3 mm diameter galvanized wires at 1000 mm c/c were provided. In RT series of beams the transverse reinforcement is only present. To keep the transverse reinforcement in position, discontinuous bits of discrete galvanized bars of 4 mm diameter bars were used.

4. Casting and testing of beams

Rigid M.S. channel moulds were used for casting the beams. The required quantities of the materials for casting one beam, the companion cubes and cylinders were mixed in an electrically operated mixer. The fiber was added to the mixer manually in small quantities intermittently to avoid balling of fibers. The mix was placed in the mould carefully in three layers and each layer has been compacted fully. In a single casting one beam of size 100 mm × 200 mm × 2200 mm, six cylinders of standard size were cast. The time taken for completing the concreting was well within the initial setting time of the cement. After 24 h of casting, the specimens were kept in the curing pond for curing. During the testing one end of the beam was supported on rollers, while the other end was supported on rigid support. This type of test setup facilitates free rotation of roller end. Specially made twist arms are placed at either supports of the beam having an arm length of 1.5 m. Load on the twist arm was applied through a mechanical screw jack. Absolute care has been taken, such that, the plane of loading and twisting arm were perpendicular to the longitudinal axis of the beam. This avoids any possibility of bending of the beam instead of twisting. Thus, the beam between the two supports was subjected to pure torsion. To avoid local crushing of concrete near the supports, neoprene pads were placed between the sides of the beam and the steel plates of the twisting arms. The complete test-setup has been presented in the Figs. 1 and 2. Load was applied at an eccentricity of 1.47 m from the

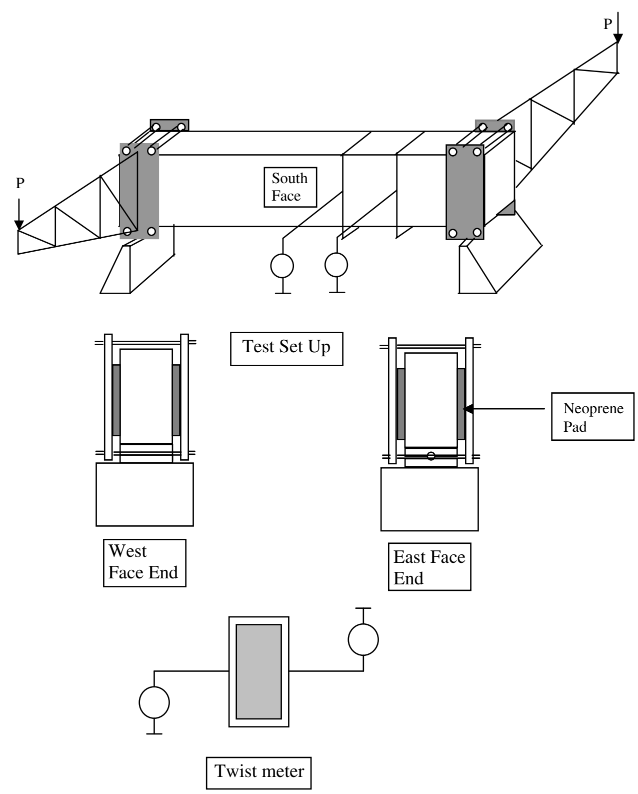

Fig. 1. Overall test setup with different views.

Table 2
Reinforcement details of the reinforced SFRC beams

Beam designation	Longitudinal reinforcement	Transverse reinforcement	Cylinder compressive strength (MPa)	Split tensile strength (MPa)
RL-P	4 No. of 10 mm diameter	3 mm diameter two legged stirrups at 1000 mm c/c	33.60	2.25
RL-F1	4 No. of 10 mm diameter	3 mm diameter two legged stirrups at 1000 mm c/c	35.20	2.81
RL-F2	4 No. of 10 mm diameter	3 mm diameter two legged stirrups at 1000 mm c/c	37.04	3.27
RL-F3	4 No. of 10 mm diameter	3 mm diameter two legged stirrups at 1000 mm c/c	37.70	3.81
RL-F4	4 No. of 10 mm diameter	3 mm diameter two legged stirrups at 1000 mm c/c	38.40	4.12
RT-P	4 No. of 3 mm diameter	8 mm diameter two legged stirrups at 60 mm c/c	32.48	2.20
RT-F1	4 No. of 3 mm diameter	8 mm diameter two legged stirrups at 60 mm c/c	33.85	2.46
RT-F2	4 No. of 3 mm diameter	8 mm diameter two legged stirrups at 60 mm c/c	34.44	3.35
RT-F3	4 No. of 3 mm diameter	8 mm diameter two legged stirrups at 60 mm c/c	34.95	3.75
RT-F4	4 No. of 3 mm diameter	8 mm diameter two legged stirrups at 60 mm c/c	35.25	3.95

Fig. 2. Test setup.

center of the beam. Load measurement was monitored with the help of a proving ring. At the restraining end also a proving ring was placed to verify the reaction torque. The beam was gradually loaded by slowly rotating the mechanical jack. For every increment of load, the corresponding dial gauge readings were noted for computing twist per unit length. The beams were loaded up to the ultimate.

4.1. Twist measurement

Twist meters were used to measure the twist of the beam. The twist meters consist of steel frames as shown in Fig. 1 and can be attached to the beam by means of transverse screws. The steel frames were welded with steel arms of length 200 mm on vertical sides of the frame. Dial gauges placed under the steel arms of the twist-meter allow the measurement of rotation of the cross-section of the beam. Such two frames were spaced at a gauge distance of 300 mm. This facilitates the measurement of twist per unit length.

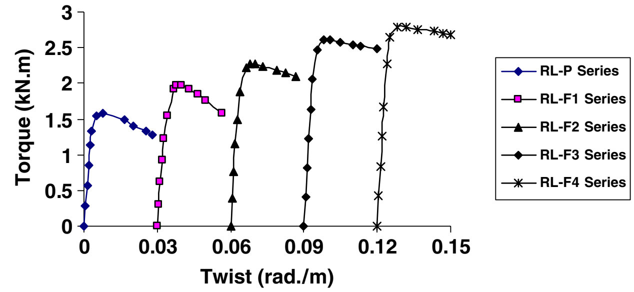

Fig. 3. Torque–twist response of SFRC beams with longitudinal reinforcement only.

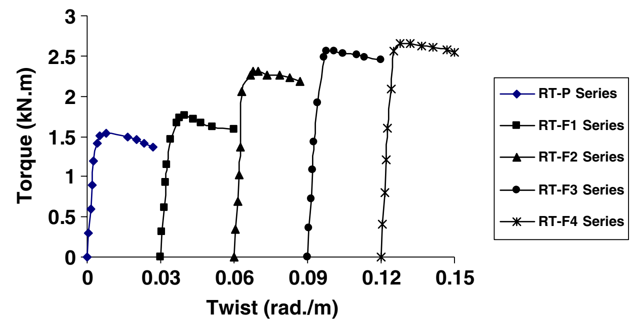

Fig. 4. Torque–twist response of SFRC beams with transverse reinforcement only.

5. Test results and discussions

The first visible cracking torque, corresponding twist, and ultimate torque, corresponding twist of each beam tested were recorded. Torque twist responses of the beams are presented in Figs. 3 and 4. Torsional toughness of the members as indicated by the area under torque twist response of the corresponding beam and torsional stiffness of the members taken as the initial slope of the torque twist response of the corresponding member were also evaluated. The test results were

Table 3
Experimental results of reinforced fibrous beams

Designation of the beam	Cracking torque (kN m)	Twist at cracking torque Φ_{cr} (rad/m)	Ultimate torque (kN m)	Ultimate twist Φ_u (rad/m)	Torsional toughness (kN m/m)	Initial torsional stiffness (kN m^2)
RL-P	1.582	0.009	1.582	0.0267	0.038	423.249
RL-F1	1.952	0.010	2.010	0.0233	0.044	461.770
RL-F2	2.254	0.010	2.266	0.0267	0.054	577.158
RL-F3	2.596	0.011	2.608	0.03	0.071	615.636
RL-F4	2.791	0.012	2.822	0.03	0.076	628.461
RT-P	1.546	0.008	1.570	0.008	0.037	448.900
RT-F1	1.721	0.009	1.753	0.0233	0.046	461.727
RT-F2	2.290	0.010	2.309	0.0267	0.055	513.030
RT-F3	2.540	0.012	2.566	0.03	0.069	538.681
RT-F4	2.664	0.012	2.694	0.028	0.072	602.810

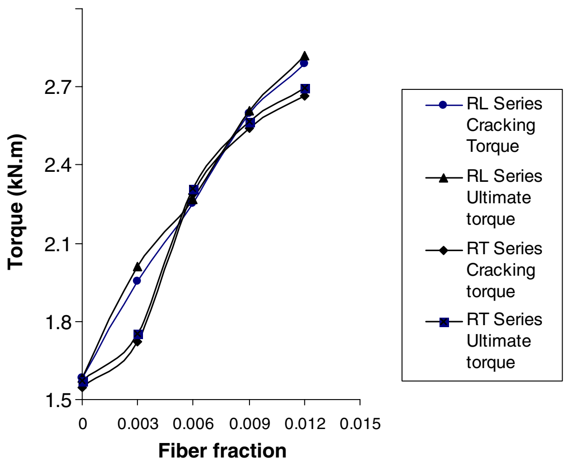

Fig. 5. Variation of cracking torque and ultimate torque of RL series beams with fiber content.

presented in Table 3. The variation of cracking torque and ultimate torque of both series of beams with fiber content was presented in Fig. 5. The variation of torsional stiffness and toughness of both series of beams with fiber content was presented in Figs. 6 and 7.

5.1. Behaviour of RL-series members

The variation of cracking torque and ultimate torque of non-fibrous beams and fibrous beams of this series presented in Fig. 5 shows that the longitudinal reinforcement in the beams without fiber content could not improve the torque carrying capacity of the beam beyond first crack. Hsu [11] based on the tests on reinforced concrete members under pure torsion without web reinforcement also reported that longitudinal reinforcement alone improves the torsional strength of the un-reinforced concrete member to a marginal extent. All the tested beams failed with a single potential crack, similar to the failure of plain beams without reinforcement, under pure torsion. But the reinforcement provided ductility to the members by not allowing the beam to break in to two pieces, which is mostly observed in plain concrete members without any reinforcing steel [12]. Thus, the longitudinal reinforcement alone could provide better ductility to the member and could not enhance the torsional strength of the member beyond the first visible cracking torque. However, addition of fiber improved the cracking torque of the member, as presence of steel fibers delays the crack propagation or alters the crack propagation path. Addition of steel fibers could not impart noticeable improvement beyond first crack. Presence of fibers in this category of beams improved the torsional toughness of the members to a greater extent showing the potentiality of the fibers in improving the torsional toughness of the members. Addition of steel fibers at 1.2% increased the torsional toughness of the non-fibrous beam by about 200%. Steel fibers also improved the torsional stiffness of the beams to a larger extent. Addition of fibers at 1.2% increased the torsional stiffness of the non-fibrous beam by 148%. From the torque twist response of this series of beams (Fig. 3 and Table 2); it is clear that the addition of steel fibers improves the twist at cracking torque as well as ultimate torque.

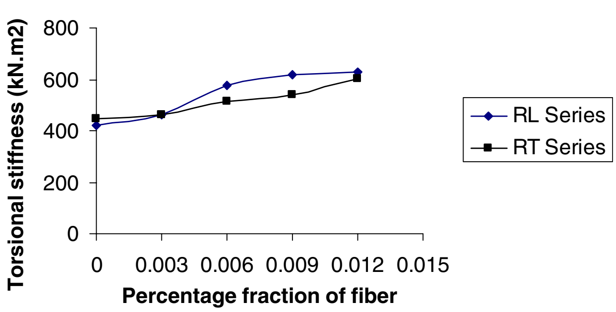

Fig. 6. Variation of torsional stiffness of RL&RT Series beams with fiber content.

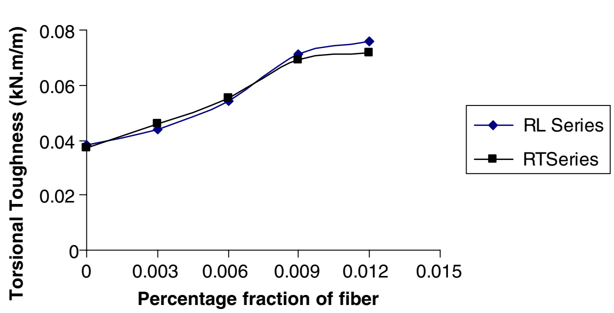

Fig. 7. Variation of torsional toughness of RL&RT Series beams with fiber content.

5.2. Behaviour of RT-series members

In this series of beams with transverse reinforcement alone, behaviour similar to that of RL-series of beams was observed. Addition of steel fibers improved the cracking torque to a noticeable extent and initial torsional stiffness and torsional toughness to a greater extent. Even with the addition of fibers no improvement in torsional strength beyond first visible crack was observed.

This indicates that the single type of reinforcement does not help in improving the torsional strength of beams beyond the first visible cracking torque. Thus, it can be inferred that the ultimate torsional strength of the beams with single type of reinforcement may be limited to the torsional strength of un-reinforced fibrous or non-fibrous members. The presence of fibers makes the beam to behave in a ductile manner to some extent by delaying the progress of the crack. However, fibers present in the matrix improve the torsional toughness and torsional stiffness of the members.

6. Conclusions

Based on the limited test results the following conclusions have been drawn:

1. Steel fibers improve the cracking torque of the members to a noticeable extent, which improves the performance of the member in aggressive environments.
2. Single type of reinforcement, i.e., either longitudinal reinforcement or web reinforcement alone does not improve the torque carrying capacity of the members beyond first crack torque.
3. Steel fibers enhance the torsional toughness of the members to a greater extent, which imparts better resistance to the structure in resisting blast/dynamic forces.
4. Steel fibers provide better torsional stiffness to the members.

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