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Steel fiber reinforced concrete beams under combined torsion-bending-shear

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Abstract

An experimental investigation is carried out to assess the torsional behavior of steel fiber reinforced concrete (SFRC) rectangular beams subjected to combined torsion-bending-shear with longitudinal and web reinforcement. The tests were conducted on twenty samples of prototype and studied for their torsional resistance for combined loading under torsion-bending-shear. For the tested prototype beams, all the parameters were maintained identical except the three chosen parameters viz. torsion to moment ratio (T/M), torsion to shear ratio (T/V) and percentage of web reinforcement. The values of aspect ratio and volume fraction are kept uniform to 60 and 0.6% respectively for all the beams. The study involved the influence of web reinforcement on the ultimate torsional strength of SFRC beams under variable values of T/M and T/V ratios. The test results are compared with Mansur's model for SFRC beams without reinforcement. The comparison reveals that though the ultimate torsional strength is independent of longitudinal reinforcement, it depends on the spacing (thereby the percentage) of web reinforcement.

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Keywords: Steel fiber reinforced concrete (SFRC), ultimate torsional strength, modulus of rupture, torsion to moment ratio, torsion to shear ratio, web reinforcement

Notations:
T_u = ultimate torsional strength of SFRC beams under combined torsion-bending-shear in N-mm
T_p = ultimate torsional strength of plain concrete beams in N-mm
T_{u1} = ultimate torsional strength of SFRC beams for Mode I failure in N-mm
T_{u2} = ultimate torsional strength of SFRC beams for Mode II failure in N-mm
T = ultimate torque applied in N-mm
M = applied bending moment in N-mm
V = applied vertical shear in N
f_{cu} = cube strength of plain concrete in N/mm^2
f_{cuf} = cube strength of SFRC in N/mm^2
b = overall width of the beam section in mm
h = overall depth of the beam section in mm
f_r = modulus of rupture of fiber reinforced concrete.
Ψ = T/M ratio
α = T/V ratio

1. Introduction

The well-known inherent deficiencies of concrete are its tensile strength and its brittleness. These weaknesses of concrete lead to immediate collapse of plain concrete beams after formation of the first crack and its propagation, at very low values of tensile stress developed in the cross section due to direct (axial) and / or indirect (flexural, shear or torsional) nature of loading. These deficiencies are overcome by reinforced concrete and pre-stressed concrete systems. These systems are not improving the weaknesses of the concrete matrix but are aiding the concrete with tensile reinforcement for sharing almost totally the tensile load on the elements. The new concept was then introduced to overcome these deficiencies of concrete by Romualdi and Mandel [1]. They and many other investigators have well established that the inclusion of high strength, high elasticity modulus steel fibers of short length and small diameter enhances the tensile strength, ductility and other properties of concrete significantly and also acts as crack arrestors [2-8]. Concrete with steel fibers is known as steel fiber reinforced concrete (SFRC). Closely spaced steel fibers effectively arrest the cracks but due to practical difficulties short, randomly oriented steel fibers are preferred.

It has been established by many researchers [10-19] that the inclusion of steel fibers in concrete improves the torsional strength of the elements in pure torsion as well in combined loading [20-23]. Some of them proposed analytical models and empirical formulae to estimate the ultimate torsional strength of the steel fiber reinforced rectangular concrete beams. Some of the formulae are independent of the properties of steel fibers and depend only on the cube strength of fiber reinforced concrete [11] and [22]. Few of the researchers [15] have proposed a combined effect of steel fiber properties and cube strength of fiber reinforce concrete in a single combined term of the expression. R. Narayanan and Kareem Palanjian [16] proposed an analytical model, based on space truss concept, which provides two separate terms to estimate the torsional strength of beam, one for the contribution of plain concrete and the other for contribution of steel fibers.

The members of a reinforced concrete structures are subjected to shear forces, axial forces, bending moments and torsional moments. Many researchers carried out tests on reinforced concrete beams under bending-shear-torsion, bending-torsion and shear-torsion and proposed modes of failure, empirical formulae and interaction curves. The investigations made in the field of the analysis of behavior of SFRC rectangular beams in combined loading, available in the literature [19-23], are fewer as compared with that in the field of pure torsion. In the present investigation twenty reinforced concrete beams with steel fibers were tested under combined torsion-bending-shear at different values of torsion to moment ratio (T/M) and torsion to shear ratio (T/V) and spacing of web reinforcement to correlate the test results.

2. Literature review

Three theories that have been developed to estimate the ultimate torsional strength of plain concrete members are elastic theory, plastic theory and skew bending theory. However, tests have shown that elastic theory consistently underestimates the failure strength of a plain concrete beam. Plastic theory summarizes that extra strength is due to plastic property of concrete but failure is not plastic failure. The third method is the skew bending theory. This theory, based on observations of torsion tests, reveals similarity of the torsional failure with flexural failure of an under-reinforced concrete beam.

In SP 18, 1968 Detroit, Hsu [9] proposed the equation (1) based on skew bending theory to estimate the ultimate torsional strength of plain rectangular concrete beams on the basis of his extensive experimental work.

$$T_u = 0.13 b^2 h \sqrt{f_{cu}} \tag{1}$$

Mansur [21] and Mansur Paramasivam [22] carried out the tests on steel fiber reinforced concrete beams without reinforcement, in pure bending, pure torsion, torsion-bending, torsion-shear and torsion-bending-shear. Based on the experimental data, they have proposed two modes of failure viz. Mode I and Mode II.

Mode I: Fibrous concrete beams which are subjected to combined loading under torsion-bending- shear fail by bending about a skewed axis. The compression zone is getting formed at the top face in skewed bending for smaller values of torsion to moment ratio (T/M). Based on the observed failure modes a theoretical model has been proposed by Mansur for the estimate of the ultimate torsional strength of SFRC beams for the combined loading. The model is reflecting the torsional strength as independent of transverse shear as seen from the equation (2).

$$T_{u1} = \frac{1}{3} b h^2 \phi f_r \left(\sqrt{\frac{1}{\psi^2} + 1} - \frac{1}{\psi}\right) \tag{2}$$

Mode II: Mode II failure occurs when the torsional moment predominates the bending moment. The compression zone is getting formed at the side face in skewed bending for larger values of torsion to moment ratio. Based on the observed failure modes a theoretical model has been proposed by Mansur and Paramasivam to the estimate of ultimate torsional strength of SFRC beams for the combined loading under consideration. The model (3) is reflecting the torsional strength as independent of bending moment.

$$T_{u2} = \frac{0.71 b h^2 f_r}{3\left(1 + \frac{b}{6\alpha}\right)} \tag{3}$$

where

$$\phi = 1 + \left(\frac{0.29(1-R)}{(1+R)}\right)$$

$$R = \sqrt{1 + \left(\frac{\psi}{3K}\right)^2}$$

$$K = 0.179 \text{ for } \left(\frac{h}{b} = 1.5\right)$$

$$\alpha = \frac{T}{V}$$

The range of torsion to moment ratio decreases for mode I failure with increasing value of transverse shear.

Hsu's skew bending theory of plain concrete beams subjected to pure torsion happens to be a special case of Mode II model proposed by Mansur and Paramasivam [22]. Mode II model is modified as equation (4) to estimate the ultimate torsional strength of fiber reinforced concrete beams in pure torsion by assigning infinity as value of α (torsion to shear ratio).

$$T_u = \frac{0.71 b^2 h f_r}{3} \qquad (4)$$

The value of modulus of rupture is calculated by the formula proposed by Bakhsh, Faisal and Akhtaruzzaman [26].

$$f_r = 0.8\sqrt{f_{cuf}}$$

Ramakrishna and Vijayarangan [24] have established the model for the torsional strength of plain concrete beams without web reinforcement subjected to combined torsion and bending. The model is independent of the effect of flexural reinforcement on the torsional strength of beams. Authors [25] have conducted the tests on six number of SFRC beam prototypes without web reinforcement by keeping all parameters identical except the longitudinal reinforcement. The test results were compared with Models of Mode I and Mode II proposed by Mansur and Mansur-Paramasivam. The test results were compatible with the estimated values by models of Mode I and Mode II respectively. This comparison reveals that the ultimate torsional strength of SFRC beams is independent of the longitudinal reinforcement.

Table 1
Properties of beams

Specimen	Beam group	Beam size	Fiber Cube strength f_{cuf} N/mm^2	Top (Compression) reinforcement	Bottom(Longitudinal) reinforcement	Web reinforcement
1 to 4	TMV/R C/B	100 X 150 X 1700	24.22	2 No.s 6mm bars (Mild steel) (yield stress 265 N/mm^2)	2 No.s 8 mm bars (HYSD) (yield stress 430 N/mm^2)	6mm (Mild steel) vertical stirrups at 90 mm c/c
5 to 8			23.19			
9 to 10			24.96			
11 to 12	TMV/R C/A		24.96			6mm (Mild steel) vertical stirrups at 60 mm c/c
13 to 16			19.85			
17 to 20			24.07			

3. Test rig and instrumentation

All the twenty beams were tested in a specially constructed test frame for the purpose. The essential component of the test rig is loading frame (for loading and restraining) through a set of trusses. The test set up is capable to test the beam specimen up-to 2.5 m length.

The beam, supported on simple supports at 100mm from both the ends, is subjected to combined action of torsion- bending- shear, using two trusses attached to the beam at two different points but in opposite directions to each other. One of the truss is attached at distance ‘a’ from left support and the load is applied at distance ‘e’ from the axis of the beam using a hydraulic jack against one of the loading frames. The load is applied through a 20 KN capacity proving ring. Restraint is provided by attaching other truss at the support at distance ‘e’ from the axis of the beam using other loading frame. The values of ‘a’, ‘c’ and ‘e’ are tabulated in Table 2 for different loading conditions. The sketch for the torsion-bending and shear is shown in Figure 1.

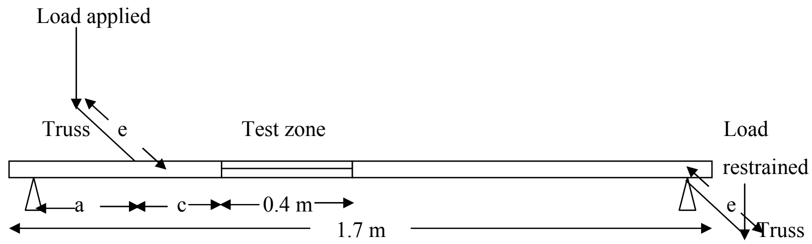

Figure 1. Test set up for bending, shear and torsion

3.1 Materials

The concrete mix was made with ordinary Portland cement, river sand and coarse aggregate of maximum size 20mm. Cement, sand and coarse aggregates were mixes in 1:2:2.4 proportion by weight. “Shaktiman” crimped steel fibers of 0.5 mm diameter and 30 mm length and volume fraction as 0.6% was used for the entire concrete mix. First dry mix was prepared from ordinary Portland cement, river sand and coarse aggregates (maximum 20mm size), and steel fibers were added to the dry mix of the materials. Water was then added to the mix to prepare the concrete. The W/C ratio for the mix was 0.58. After thorough mixing, beam specimens were casted along with companion cube moulds to measure the compressive strength of concrete. All the beams and companion cubes were compacted properly. The beam specimens were stripped off their moulds after 24 hours and submerged in water tank for 28 days for curing after casting. Before testing, the beams were coated with whitewash to facilitate the observation of cracking pattern.

4. Experimental program

Tests were conducted on twenty specimens of beams, of size 100mm wide X 150mm deep X 1700 mm long, cast in moulds. Steel fiber reinforced concrete beams and accompanying cubes were cast in the laboratory using the prescribed mix. Eight groups consisting two specimens each were tested for different loading combinations. The details of properties of beams are shown in Table 1. The aspect ratio of steel fibers as 60 and volume fraction as 0.6 were kept constant.

Table 2
Loading arrangement

Beam group	Beam dimensions (in mm.)	Loading parameters (in mm.)		
		a	c	e
TMV/RC/B-1	100 mm x 150 mm x 1700 mm	550	75	250
TMV/RC/B-2		500	75	480
TMV/RC/B-3		650	300	600
TMV/RC/B-4		650	420	600
TMV/RC/B-5		200	550	600
TMV/RC/A-1		550	75	250
TMV/RC/A-2		500	75	480
TMV/RC/A-3		650	300	600
TMV/RC/A-4		650	420	600
TMV/RC/A-5		200	550	600

Table 3
Comparison of Test results with Mansur's models

Specimen	Beam group	T/M	T/V	T_{uo} (Experimental value) N-m	T_{u1} Estimated ultimate torsional strength by Mode I N-m	T_{u2} Estimated ultimate torsional strength by Mode II N-m	T_u Estimated Minimum of Mode I & Mode II N-m	% deviation of T_u Estimated w.r.t. T_{uo} $(T_{uo}- T_u)/T_u$
1	TMV/RC/B	0.99	0.68	2185.42	1089.65	1364.24	1089.65	100.56
2	TMV/RC/B	1.03	0.67	2098.12	1115.58	1363.75	1115.58	88.07
3	TMV/RC/B	1.94	1.38	1727.55	1497.82	1380.99	1380.99	25.10
4	TMV/RC/B	2.62	1.32	1849.46	1641.06	1380.25	1380.25	33.99
5	TMV/RC/B	2.28	1.28	1789.29	1544.53	1350.05	1350.05	32.54
6	TMV/RC/B	3.89	1.21	1808.33	1747.11	1349.05	1349.05	34.04
7	TMV/RC/B	1.87	1.47	1732.14	1446.54	1352.30	1352.30	28.09
8	TMV/RC/B	1.88	1.46	1789.29	1449.34	1352.19	1352.19	32.33
9	TMV/RC/B	5.69	3.75	1865.48	1912.24	1412.59	1412.59	32.06
10	TMV/RC/B	7.40	3.35	1808.33	1962.59	1411.84	1411.84	28.08
11	TMV/RC/A	1.01	0.68	2360.02	1119.47	1384.92	1119.47	110.82
12	TMV/RC/A	1.30	0.67	2431.45	1284.51	1384.43	1284.51	89.29
13	TMV/RC/A	4.83	1.24	1788.50	1670.88	1248.53	1248.53	43.25
14	TMV/RC/A	3.83	1.27	1879.93	1612.06	1248.92	1248.92	50.52
15	TMV/RC/A	2.19	1.29	1865.48	1411.49	1249.18	1249.18	49.34
16	TMV/RC/A	2.39	1.27	1827.38	1448.83	1248.92	1248.92	46.32
17	TMV/RC/A	1.89	1.33	1922.62	1479.41	1376.09	1376.09	39.72
18	TMV/RC/A	1.75	1.35	2017.86	1437.61	1376.35	1376.35	46.61
19	TMV/RC/A	11.71	3.11	1960.71	1987.81	1385.91	1385.91	41.47
20	TMV/RC/A	7.67	3.44	2017.86	1933.07	1386.62	1386.62	45.52

Figure 2. Typical failure patterns

4. Evaluation of torsional strength

The tests results were obtained of twenty SFRC beam prototypes with web reinforcement of 6mm mild steel stirrups at 90 mm c/c and at 60mm c/c distances respectively for ten beams each, keeping the longitudinal and anchor reinforcements identical. The beam prototypes were tested for the ultimate torsional strength for various combinations of

T/M and T/V ratios under combined loading of torsion-bending-shear. The test results show that though the ultimate torsional strength is independent of flexural reinforcement as established in references [24] [25], it depends on the spacing of shear stirrups. The torsional resistance was worked out by using Models of Mode I and Mode II failure and the lower value of these two was considered as estimated value of torsional resistance. The percentage increase in the ultimate torsional strength due to addition of web reinforcement is worked out by comparing the observed values with the estimated ones. As per the illustration given by Mansur [21] underlying the model for Mode I failure, the failure is indicated by formation of cracks in the compression zone in the upper half of the cross section, but the observations are contradicting. The cracking pattern clearly reveals the failure due to mode II for all the twenty samples tested. The samples of the cracked prototype beams are exhibited in photograph 1. The test results also reveal that the ultimate torsional strength depends on the web reinforcement, as seen from Table 3, it increases with decrease in spacing of web reinforcement.

5. Conclusions

The experimental values of the ultimate torsional strengths of steel fiber reinforced concrete beams with reinforcement are compared with that of the corresponding estimated values of the ultimate torsional strength of steel fiber reinforced concrete beams without reinforcement. The comparison reveals that the ultimate torsional strength depends on the web reinforcement and it increases with decrease in the spacing of stirrups (increase in the percentage of web reinforcement).

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