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Torsion of steel fiber reinforced concrete members

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Abstract

Addition of steel fibers in concrete improves the mechanical properties of the basic matrix as they slow down the growth of crack and creates pinching forces at the tips of the cracks. Thus, the steel fiber reinforced concrete becomes a better energy absorbing material and is best material for the seismic resistant structures and blast resistant structures. Relatively little research work has been done on the behavioural aspects of this material under pure torsion compared to its behaviour under flexure or shear or under combined loading. Earlier researchers [Int. J. Cem. Compos. Lightweight Concr. 4 (1982) 45, Indian Concr. J. 55 (1981) 222–232, Int. J. Cem. Compos. 2 (1980) 85] reported that addition of fiber in concrete improves the torsional strength and ductility. However, the enhanced properties of SFRC in particular the ductility of the matrix can be achieved when a minimum volume fraction of fiber content is maintained. This investigation aims at understanding the behavioural aspects of plain SFRC members under pure torsion. An empirical formula has been proposed to predict the ultimate torsional strength of the SFRC members under pure torsion.

Keywords: Composite-fiber reinforcement; Torsional toughness; Tensile properties; Shear strength

1. Introduction

Torsion occurs more frequently in most structures but rarely occurs alone. However, torsion forms one of the basic structural actions besides flexure, shear and axial compression/tension. Torsional failure of concrete members is initiated by the tensile stress developed due to a state of pure shear, which arises due to torsion. Inclusion of steel fibers principally may increase the tensile strength of the matrix to a moderate level but the toughness will be enhanced to a greater extent. This particular advantage of fiber reinforced concrete inspired the researchers to study its mechanical properties under different conditions of loading. But little information is available on the to behaviour of fiber reinforced concrete members under pure torsion. Earlier investigations indicated that the addition of fibers improves the torsional strength and ductility of member [1–4]. In this investigation an attempt has been made to quantify the effect of fibers in resisting torsional loads. Also a semiempirical formula for predicting the ultimate torsional strength of the SFRC members has been presented.

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2. Experimental investigation

The investigation consisted of short-term tests on plain steel fiber reinforced concrete members of same cross-sectional area varying the volume fraction of fibers and strength of concrete. The volume fraction of the fiber varied from 0% to 1.2% at an equal interval of 0.3%. The grades of concrete considered for the study are 20, 30, 40 and 50 MPa). Thus, 20 beams of size $100 \times 200 \times 2000$ mm were cast for testing under pure torsion. During the casting of each beam three companion cube specimens and three cylindrical specimens for assessing the compressive strength and split tensile strength of the matrix were cast and cured along with the corresponding beams under same conditions of environment. The details of the mix proportions of the beams along with the corresponding cube compressive strengths and split tensile strengths are presented in Table 1.

3. Materials

Ordinary Portland cement giving a 28 days mortar (1:3) compressive strength of 53 MPa and fine aggregate confirming to the requirements of ASTM-C-33 was used in the entire investigation. Crushed granite aggregates of maxi-

Table 1
Details of the plain fibrous beams tested under pure torsion

Designation of the beam	Mix proportion	Percentage volume fraction of fiber	Cube compressive strength (MPa)	Split tensile strength (MPa)
P20-P	1:1.8:3.4	0	22.00	2.35
P20-F1	1:1.8:3.4	0.3	22.41	2.54
P20-F2	1:1.8:3.4	0.6	23.26	2.75
P20-F3	1:1.8:3.4	0.9	24.15	2.82
P20-F4	1:1.8:3.4	1.2	25.41	3.00
P30-P	1:1.5:2.5	0	31.86	2.70
P30-F1	1:1.5:2.5	0.3	32.41	3.05
P30-F2	1:1.5:2.5	0.6	33.16	3.29
P30-F3	1:1.5:2.5	0.9	34.21	3.71
P30-F4	1:1.5:2.5	1.2	35.01	3.89
P40-P	1:1.3:2.4	0	38.99	2.95
P40-F1	1:1.3:2.4	0.3	41.54	3.39
P40-F2	1:1.3:2.4	0.6	42.20	3.52
P40-F3	1:1.3:2.4	0.9	43.02	3.81
P40-F4	1:1.3:2.4	1.2	44.31	3.99
P50-P	1:1.1:2.0	0	51.31	3.06
P50-F1	1:1.1:2.0	0.3	52.38	3.45
P50-F2	1:1.1:2.0	0.6	53.91	3.80
P50-F3	1:1.1:2.0	0.9	54.75	3.98
P50-F4	1:1.1:2.0	1.2	55.05	4.33

mum size 12 mm were used. Plain galvanized iron wires (0.546 mm diameter and 41 mm long) were used as fibers, maintaining an aspect ratio of 75. The aspect ratio of the fiber was maintained constant throughout the investigation. The yield strength of the fiber was found to be 275 MPa.

4. Details of testing

The cured beams were white washed and a grid of size 50 × 50 mm was drawn with the pencil on the four sides of the beams to facilitate the crack inclination measurements. The beams were then mounted on two rigid supports simulating simply supported end conditions. A spherical roller was placed on one of the support in the longitudinal direction of the beam to facilitate the twisting of the beam. The other support was partially restrained to twist about the longitudinal axis of the beam. 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 was 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 is presented in Fig. 1. Load was applied at an eccentricity of 1.47 m from the center of the beam. Load measurement was monitored with the help of a proving ring. At the restraining end a proving ring was also placed to verify the reaction torque. Twist meters specially prepared in structures laboratory 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, as shown in Fig. 1, allow the measurement of rotation of the cross section of the beam. Two such frames were spaced at a gauge distance of 300 mm. This facilitates the measurement of twist per unit length.

5. Discussion of test results

The beams mounted in East–West direction on two simply supported rigid supports were tested under pure torsion by gradually applying transverse load through the mechanical jack. Utmost care was taken while applying the load so that the plane of loading does not fall out of the plane of twist arms. Thus, any possible bending of the test specimen was avoided. For every increment of load the corresponding twist per unit length was measured until the failure of the specimen. After completion of the test the beams were taken out from the test platform and inclination of potential crack was noted. Immediately after the

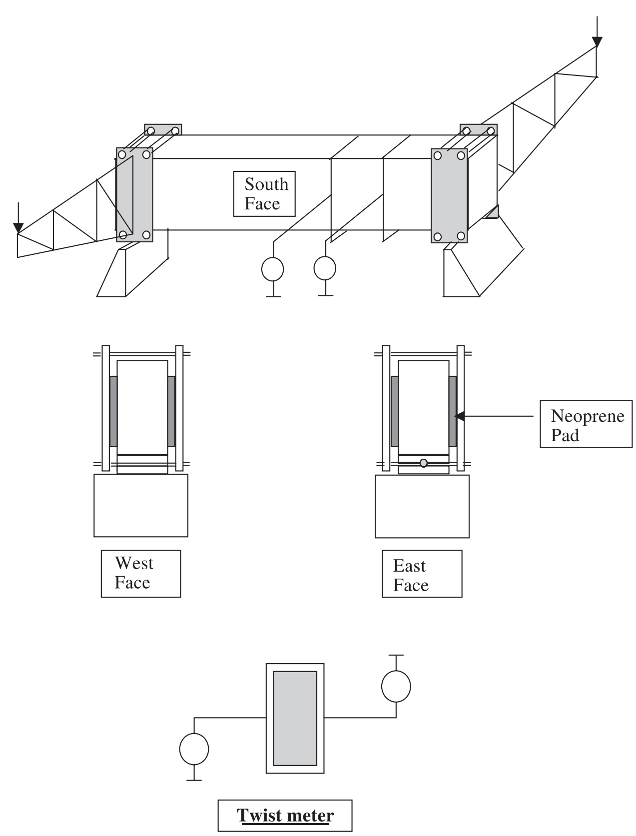

Fig. 1. Test setup with different views.

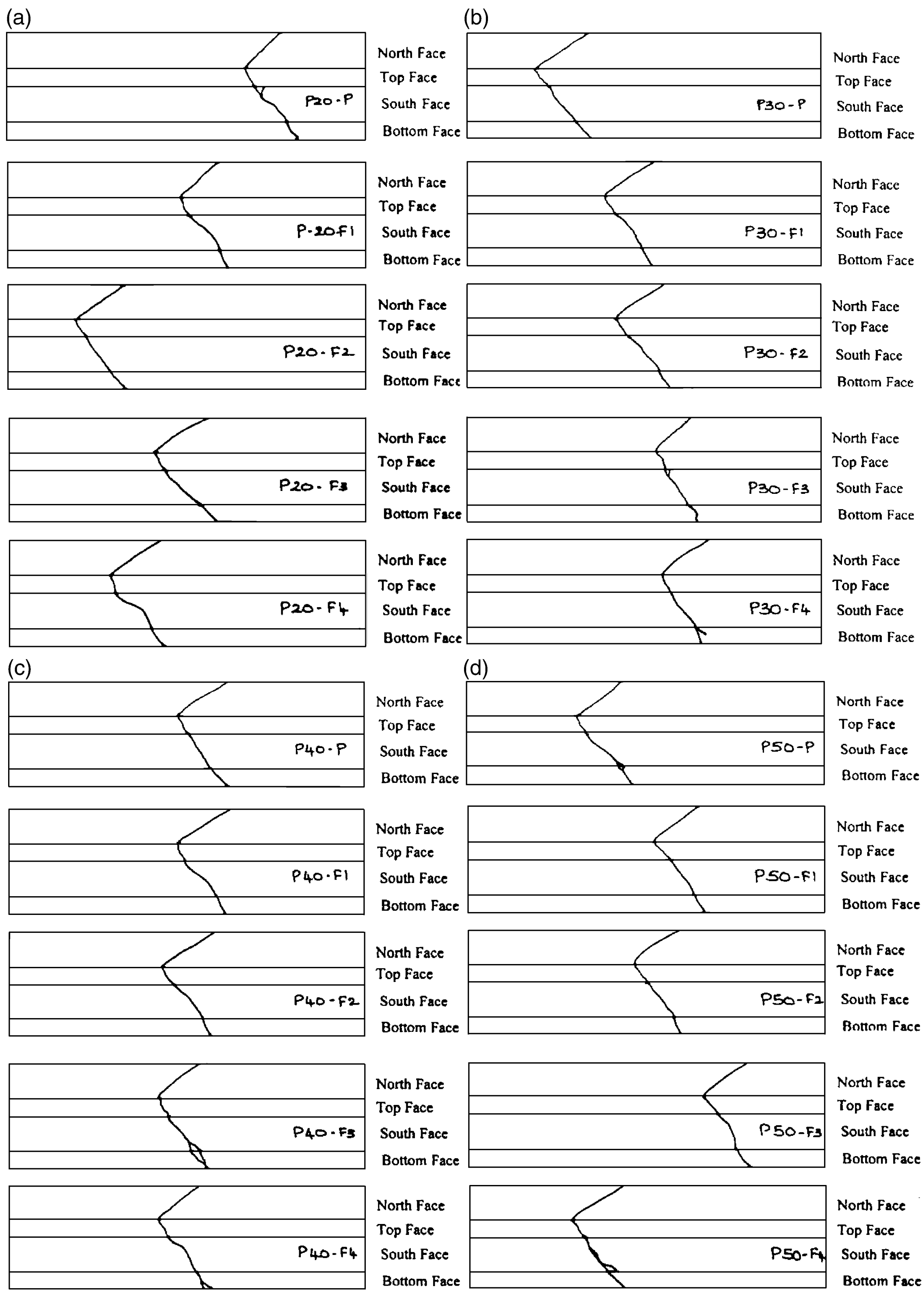

Fig. 2. (a) Crack pattern of fibrous beams with concrete strength 20 MPa. (b) Crack pattern of fibrous beams with concrete strength 30 MPa. (c) Crack pattern of fibrous beams with concrete strength 30 MPa. (d) Crack pattern of fibrous beams with concrete strength 50 MPa.

Table 2
Ultimate torque, twist at ultimate torque, initial torsional stiffness and torsional toughness of the tested fibrous beams

Beam designation	Ultimate torque (kNm)	Twist at ultimate torque (10^{-3} rad/m)	Initial torsional stiffness (kNm^2)	Torsional toughness (10^{-3} kNm/m)
P20-P	1.753	5.65	454.03	6.32
P20-F1	1.881	5.93	469.17	7.15
P20-F2	1.924	6.10	479.26	7.75
P20-F3	2.095	6.27	504.48	8.64
P20-F4	2.266	6.44	540.51	9.68
P30-P	1.967	4.75	504.48	5.44
P30-F1	2.180	5.88	518.89	8.00
P30-F2	2.351	5.90	540.51	8.53
P30-F3	2.522	6.78	562.13	11.23
P30-F4	2.651	7.68	583.75	13.75
P40-P	2.266	5.65	544.84	7.87
P40-F1	2.394	6.55	554.93	10.17
P40-F2	2.522	6.67	562.13	10.81
P40-F3	2.608	8.76	583.75	16.19
P40-F4	2.907	9.32	605.37	19.57
P50-P	2.138	4.41	605.37	5.52
P50-F1	2.309	6.67	635.64	10.82
P50-F2	2.651	8.31	648.62	15.96
P50-F3	2.950	8.59	670.24	18.12
P50-F4	2.993	8.64	691.86	18.69

testing of each beam the corresponding companion cubes and cylinders were tested for cube compressive strength and split tensile strength. All beams including fibrous beams failed with a single potential crack. The plain beams and fibrous beams with volume fraction 0.3% and 0.6% failed suddenly and violently. These beams got separated into two pieces. Fibrous beams with volume fraction of fibers 0.9% and 1.2% also failed with a single crack but were not separated into two pieces showing better ductility over plain beams and beams with low volume fraction of fiber. This is due to the better interlocking of additional fibers available in the given volume. Debonded fibers were noticed on the failure face of the broken beams. This is perhaps due to the medium aspect ratio (75) of the fiber adopted. The inclination of the crack with longitudinal axis of the beam varied between 42° and 48° for all plain and fibrous beams of all grades of concrete. From this, it is clear that addition of fibers does not change the inclination of the crack angle. The failure pattern of all the beams was skew bending type of failure. The tension crack formed on the longer face extended to the top and bottom of the beam and joined on the forth face of the beam as a compression hinge leading to the collapse of the beam. The crack patterns on all four sides of the beams tested under pure torsion were presented in Fig. 2. The ultimate torsional strength of the tested beams was presented in Table 2. Fiber addition found to increase the torsional strength of the beam. This increase is mainly due to the improvement of the tensile strength of the matrix due to fiber addition. The interesting point to be observed is that the torsional strength of fibrous concrete beam with 25.41 MPa cube compressive strength having 1.2% volume fraction of fiber showed better torsional strength of plain concrete member

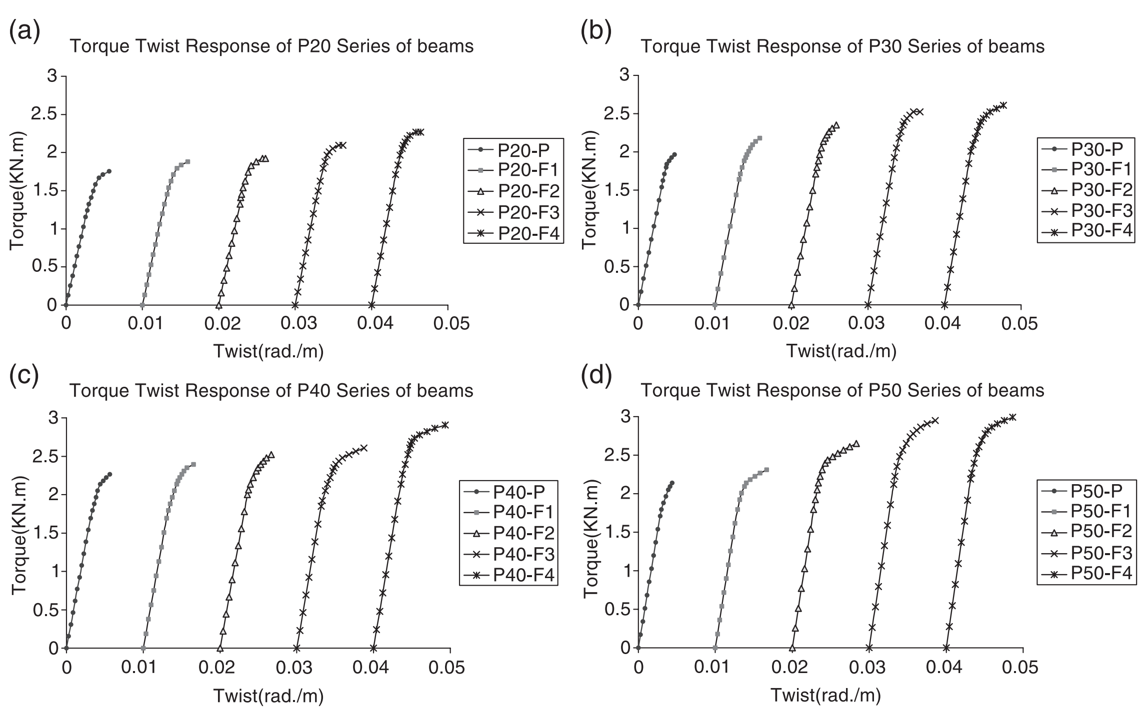

Fig. 3. (a) Torque–twist response of SFRC beams of concrete strength 20 MPa. (b) Torque–twist response of SFRC beams of concrete strength 30 MPa. (c) Torque–twist response of SFRC beams of concrete strength 40 MPa. (d) Torque–twist response of SFRC beams of concrete strength 50 MPa.

possessing 55.05 MPa cube compressive strength without fibers. This indicates the potentiality of steel fiber reinforced concretes in resisting torsional loads. The twist at ultimate torque in the case fibrous beams was found to be more than that of the plain beams. This improvement in ultimate twist can be attributed to the crack-delaying property of the fibrous matrix. The torque–twist response of the tested beams were presented in Fig. 3. The initial torsional stiffness (slope of the initial tangent of torque–twist curve) of the beams was also found to increase with the addition of fibers. Reason for this improvement is mainly due to increase in the modulus of the matrix with the addition of the fibers. Pronounced improvement in torsional toughness of the member, as indicated by the area under torque twist response, was observed with the addition of steel fibers. The test results indicated that structural performance of the concrete members can be enhanced by incorporating steel fibers in the matrix. The improvement in torsional toughness in the case of beams with higher grades of concrete (50 MPa) was found to be greater compared to the improvement for members with low-grade concrete (20 MPa). This shows that the fiber addition improves the torsional toughness better in brittle matrix phase.

6. Ultimate torsional strength

Fiber addition improved the tensile strength of the SFRC mix to a larger extent compared to the improvement in the compressive strength. This improvement in tensile strength of the matrix led to the increase in the torsional strength of the beam. Pure torsion creates a state of pure shear, which develops principal compressive and tensile stresses of the same intensity. Shearing stresses induced in the member can be found using the linear elastic theory, assuming the concrete to be an elastic material. However, at the ultimate torque level computation of shearing stresses becomes difficult as concrete develops inherent micro cracks. The maximum principal tensile stress thus developed is mainly responsible for the cracking and failure of the beam under pure torsion. The torsional strength of the beam, based on elastic analysis proposed by Saint Venant for rectangular sections, is given by

$$T_e = \alpha b^2 d f_t \quad (1)$$

Where α = Constant depends on b/d ratio, b = breadth of the beam (smaller dimension), d = depth of the beam (larger dimension), f_t = Tensile strength of the concrete.

For plastic analysis the value of $\alpha = .5 - (b/6d)$.

However, concrete is neither perfectly elastic nor perfectly plastic. Elastic analysis underestimates the torsional strength of the beam, whereas plastic analysis overestimates the same. Hence, the ultimate torsional strength of the beam lies in between these two values.

7. Tensile strength of concrete

Split tensile strength was used by Narayanan et al. [2] and Mansur and Paramasivam [1] as representative of the tensile strength of concrete. Hsu [5] used the modulus of rupture value as the failure of the beam, which is of skew-bending type failure. As the state of stress is pure shear accompanied by the same intensity of compressive and tensile stresses in orthogonal directions the apparent tensile strength drops a little less than the actual tensile strength of concrete. Hence, in the present investigation tensile strength of concrete is taken as the value dependent on both compressive strength (f_c) and tensile strength of concrete. For conservative results the interaction between these two stresses was taken as linear. The tensile strength of concrete was considered as split tensile strength (f_{spt}). So the effective tensile strength of concrete (f_t) in pure torsion is taken as

$$1/f_t = 1/f_c + 1/f_{spt.} \quad (2)$$

Using this value as effective tensile strength of concrete, the torsional strength of the fibrous beams can be found. Regression analysis revealed the value of α as (.5 − .223b/d) [6]. The experimental ultimate torques of the tested members were compared with the theoretical values for both plain and SFRC beams and is presented in Table 3. From this table it can be concluded that the semiempirical formula proposed fairly estimates the torsional strength of the fibrous beams.

Table 3
Comparison of experimental ultimate torque with ultimate torque using proposed semiempirical equation

Designation of the beam	Ultimate torque (kNm.)				$T_{exp.}/T_{th.}$
	Elastic analysis	Plastic analysis	Proposed semiempirical equation ($T_{th.}$)	Experimental ($T_{exp.}$)	
P20-P	1.045	1.769	1.648	1.753	1.063
P20-F1	1.122	1.901	1.771	1.881	1.062
P20-F2	1.210	2.049	1.909	1.924	1.008
P20-F3	1.242	2.104	1.961	2.095	1.069
P20-F4	1.320	2.236	2.083	2.266	1.088
P30-P	1.225	2.074	1.933	1.967	1.018
P30-F1	1.372	2.323	2.164	2.180	1.007
P30-F2	1.473	2.494	2.324	2.351	1.012
P30-F3	1.647	2.789	2.599	2.522	0.971
P30-F4	1.722	2.918	2.718	2.651	0.975
P40-P	1.349	2.285	2.129	2.266	1.064
P40-F1	1.542	2.612	2.433	2.394	0.984
P40-F2	1.599	2.707	2.523	2.522	1.000
P40-F3	1.722	2.917	2.717	2.608	0.960
P40-F4	1.801	3.050	2.842	2.907	1.023
P50-P	1.421	2.406	2.242	2.138	0.953
P50-F1	1.593	2.697	2.513	2.309	0.919
P50-F2	1.746	2.958	2.756	2.651	0.962
P50-F3	1.825	3.092	2.881	2.950	1.024
P50-F4	1.975	3.345	3.117	3.206	1.029

8. Conclusions

Based on the torsion tests on 20 steel fiber reinforced concrete beams, the following conclusions have been drawn:

1. Addition of steel fibers improves the ultimate torsional strength, torsional toughness and torsional stiffness of the beams.
2. The proposed equation reasonably predicts the ultimate torsional strength of the fibrous beams subjected to pure torsion.
3. A minimum volume fraction of fiber content of 0.9% is required to impart noticeable ductility to the SFRC beams under torsion.
4. Addition of steel fibers is more beneficial in high-strength concretes as they are brittle in nature.

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