

## Research Article

# Torsional Behavior of High Strength Concrete Members Strengthened by Mixed Steel Fibers

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Twelve mixing steel fibers-reinforced high strength concrete beams were experimentally tested under pure torsion to investigating the concrete member torsional behavior. The first cracking torque, ultimate torsional resistance, crack patterns, effect of steel fiber ratio, effects of shape and size of hollow cross-section, and effect of stirrups reinforcement were discussed. The ratio of mixing steel fiber, different shape and size of hollow cross-section, and ratio of stirrups reinforcement were considers as major parameters. The results are shown that the width of cracks decreases and the cracks number increases with mixing steel fibers ratio increased. The first cracking torque and ultimate torsion load increased with decrease in the hollow cross-section area of high strength concrete members strengthened by steel fibers.

## 1. Introduction

The study of reinforced concrete structural member behavior under pure torsion can be divided into two different parts: (1) before concrete cracking, the concrete behavior is considered as elastic response, which is predicted by the Saint Venant's torsion theory. (2) After concrete cracking, the material behaves as inelastic, and then the theory of elasticity becomes unusable and the interpretation of inelasticity mechanism is required in this part [1]. There are two very different theories used to design a structural element's resistance to twisting: the first theory depended on a skew bending theory. The ACI Code [2] was based on this theory in the 1971 through 1989 for the torsion design. This theory assumes in postcracking stage that the concrete contributes in resistance to some of the shear forces and torsion strength and the rest forces resisted by reinforcement of shear and torsion. The failure mode is assumed that the bending skew surface resulting from the torsional spiral cracks consists around three of the member four sides [3]. The second theory of torsion design depended on a thin-walled tube/plastic space truss model. This theory considers a basic of the torsion design provisions in the modern

European design codes for structural concrete and the ACI Code since 1995 [4]. Before 1960s, engineers ignored torsion design for structural members. They adopted the principle of increasing the bending safety factor, which can avoid slight torsion effects. After 1950s the design of torsion began, considered as interesting topic because of some important factors [5] such as the following: firstly, the ultimate design method is used rather than the working design method. Here, the bending analysis of the reinforced concrete elements is enhanced and the factors of safety are more accurate, and the torsion effect neglecting was unacceptable. Secondly, the design safety factors are investigated more precisely due to the rapid developments in electronic computer applications that engineers use in structural analysis. Thirdly, the developments of structural buildings and the adoption of vertical buildings instead of the plane buildings and the expansion of modern architectural concepts led to taking the effect of torsion into account. Some researches were conducted by others on the behavior of high strength concrete elements strengthened by steel fiber. Giridhar and Kumar [6] studied the behavior of high strength steel fiber-reinforced concrete members under pure torsion. Two types (crimped and straight) of steel fibers were

used with varying steel fiber ratios. In both previous steel fiber types, the first cracking torque and ultimate torque continuously increase with increase in the steel fiber ratios for varying the member cross-section. Hao-Jan et al. [7] experimentally investigated the behavior of normal and high concrete strength. Thirteen beams with low torsion reinforcement ratios were studied. Cracks pattern, widths of crack at service and failure torsional load, and torsional ductility were discussed. The ratio of torsional reinforcement and concrete strength and beams cross-section aspect ratio were considered as main parameters. The experimental test results show that after the first cracking occurs, reserve strength for members with relatively low torsional reinforcement ratio is primarily related to the ratios of the transverse and longitudinal reinforcement factors in addition to the total amounts of torsional reinforcement. Karayannis Chris [8] developed an analytical model for the increasing torsion of concrete members. This model was based on special numerical techniques that employ relations expressed in terms of cracks width and normal stresses. Consider the cracks width process zone as a material property and show good estimation through comparison of experimental and analytical results. The proposed model was applicable to concrete members under combined torsion with shear, flexure, and axial forces. Also, the model not restraint by the member crosses section shapes. There are many techniques to enhance the main concrete characteristics such as stiffness, toughness, ductility, tensile properties, and cracking control one of the techniques is addition of steel fibers to concrete matrices [9, 10]. The main effect of the steel fibers is observed in the postcracking stage when they restrict the cracks propagation in the matrix. At this stage, the contribution of steel fibers is principally dictated by the steel fibers pullout mechanisms.

## 2. Research Significance

The crack patterns, cracking torsional strength, ultimate torsional strength, cracking, and ultimate twist angle for steel fiber-reinforced high strength concrete beams subjected to pure torsion were studied. The steel fiber ratio and shape and size of hollow cross-section are considered as main parameters. The mixing steel fiber (50% corrugated and 50% end hooked) with approximately same aspect ratio, yield strength, and length was used in this study.

## 3. Torsion Design Development in the ACI 318-08 Code

It should be noted that the ancient ACI Codes of practice do not include detailed rules and are specific for design of reinforced concrete beams under torsion [11]. At the first time, ACI 318-63 Code provision mentioned one sentence, which recommended using the closed stirrups and in each corner of the closed stirrup, one longitudinal bar should be used. The torsion design provisions were introduced in 1968 and 1969 through a series of papers by the ACI Committee and were consequently adopted in the ACI 1971 and late [12]. The torsion design methods for combined shear, torsion, and bending in concrete

members were reviewed in ACI 318-95 Code provision and remain fundamentally unchanged since then. The torsion design methods of solid and hollow sections are based on two theories: thin-walled tube and space truss analogy. The space truss analogy equations of torsional strength relatively to the amount of longitudinal reinforcement are

$$T_n = 2A_0 \frac{A_t f_{yl}}{P_h} \tan \theta. \quad (1)$$

The basic space truss analogy equation of torsional strength relative to quantity of transverse reinforcement is

$$T_n = 2A_0 \frac{A_t f_{yv}}{s} \cot \theta. \quad (2)$$

The ACI design provisions for torsional concrete cracking strength is specified as follows [6]:

$$T_{cr} = \frac{\sqrt{f'_c}}{3} \left( \frac{A_{cp}^2}{P_{cp}} \right) \text{ for solid section,} \quad (3)$$

$$T_{cr} = \frac{\sqrt{f'_c}}{3} \left( \frac{A_{cp}^2}{P_{cp}} \right) \left( \frac{A_g}{A_{cp}} \right) \text{ for hollow section,}$$

where  $T_n$  is the nominal torsional strength under pure torsion,  $T_{cr}$  is the torsional cracking strength under pure torsion,  $A_0$  is the gross section area enclosed by perimeter of the wall within the path of shear flow, ACI-Code section 11. 6. 3. 6 permit to be taken as  $0.85 A_{0h}$ ,  $A_{0h}$  is the area enclosed by the perimeter of center line of closed stirrups,  $P_h$  is the outside perimeter of concrete cross-sections,  $A_t$  is the cross-sectional area of longitudinal reinforcement,  $A_t$  is the cross-sectional area in one leg of stirrup reinforcement,  $f_{yl}$  is the yield strength of longitudinal reinforcement,  $f_{yv}$  is the yield strength of transverse reinforcement, and  $\theta$  is the angle of inclination. ACI-Code section 11. 5. 3. 6 allows any twist angle value between 30 and 60 degrees. The commentaries by the obtained analysis suggest to be taken equal to 45 degrees [13].  $s$  is the stirrups spacing,  $A_{cp}$  is the area enclosed by the outside perimeter of concrete cross-section, and  $A_g$  is the gross section area of concrete. For a hollow cross-section, the area of the concrete only considers without including the area of void(s).  $P_{cp}$  is the outside perimeter of the concrete cross-section and  $f'_c$  is the specified compressive strength of concrete.

## 4. Experimental Study

**4.1. Concrete Mixing.** To achieve the required high strength, several trial mixes were used. The trial mixtures were designed to achieve cube high strengths of 60 MPa at 28 days. The test results show the optimum mixture was (1 cement, 1.3 sand, 2.3 gravel, 0.3 water, 1.5% Sika ViscoCrete, 10% Sika fume, by weight). Testing molds (150φ \* 300 mm cylinders, and 150 mm cubes), as shown in Figures 1(a) and 1(b), were prepared for testing the concrete splitting tensile strength and compressive strength tests, respectively. The slump test was nearly 100 mm. After 24 hrs, the test samples

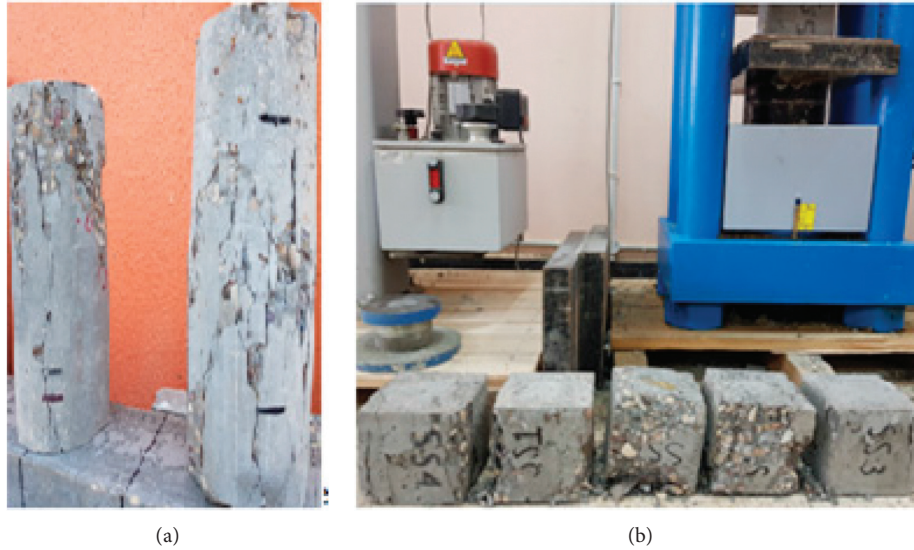


FIGURE 1: Concrete mixing properties.

were removed from the molds and cured in pure water for 28 days until the testing. Table 1 shows the mixture details. The optimum concrete mixture used in this study was consistent, without segregation, and has acceptable workability. The testing samples were given high compressive strength (average of 6 cubes) 60.12 at 28 days for trail mixture of 60 MPa.

**4.2. Details of Specimens.** Twelve beams, having rectangular hollow cross-sections of 250 mm \* 250 mm outer dimensions, with different shape and size of hollow dimensions, and 1000 mm length for all specimens, were mixed, casted, and tested under pure torsion in the laboratory, as shown in Figure 2. The dimension details of testing specimens, including the steel fibers and reinforcement volumetric ratios, are shown in Table 1.

**4.3. Testing Methodology.** The experimental study aims to investigate the behavior of mixing steel fibers high strength concrete members under pure torsion. Also, choose the steel fiber ratio and the shape and size of hollow cross-section which give the highest torsional strength without concrete segregation and acceptable workability. To prevent the first cracking failure of the members, all test members were reinforced with 4#10 mm longitudinal steel bars; three closed stirrups #12 mm at each specimen ends were used to prevent the end failure during testing.

**4.4. Test Procedure.** The system details of test machine are shown in Figure 3. The test beam ends are clamped with U-section steel channel arms of 750 mm length, which are centrally loaded through I-section steel girder by the universal machine system to create a pure torsion. The end support is located on a roller to ensure free rotation and contraction or extension during testing. At both beam ends, digital angle measure gauges were fixed on the beam top surface to measure the angle of twist at beam ends during the

TABLE 1: Proportions of concrete mixture.

Parameter	Material quantity (60 MPa)
Water/cement ratio	0.3
Water (kg/m <sup>3</sup> )	150
Cement (kg/m <sup>3</sup> )	500
Fine aggregate (kg/m <sup>3</sup> )	650
Coarse aggregate (kg/m <sup>3</sup> )	1150
Sika ViscoCrete (kg/m <sup>3</sup> )	7.5
Sika fume (kg/m <sup>3</sup> )	50



FIGURE 2: Casting of concrete specimens.

testing, as shown in Figure 4. The testing specimen is hinged to the upper main steel I-section girder and plates, which are tight together by bolts, and fixed to the end roller supports by welding. The torsional moment is created by applying a concentrated point load to the center of the main steel I-section girder. In order to create a pure torsional moment, the stiff girder is used to transfer concentrated applied loads of the testing hydraulic machine to the beam end arms. The transmitter I-section girder is directly loaded by the piston of a testing hydraulic machine. Steel fiber-reinforced concrete beams are tested under monotonically increasing load up to failure. During testing, the applied torsion loads are in a controlled manner with low rating applied torsion load until

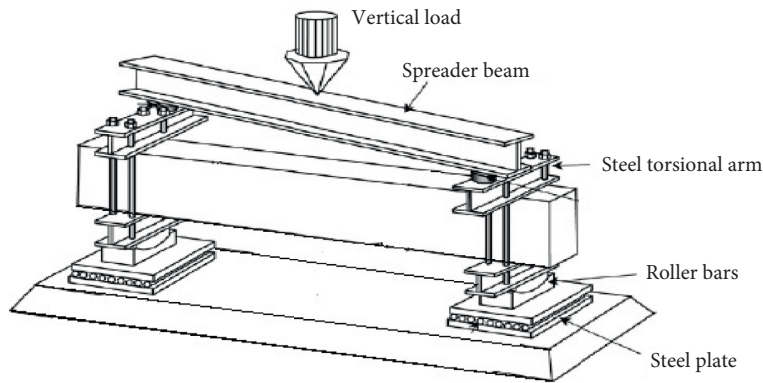


FIGURE 3: Testing setup.



FIGURE 4: Twist angle measurement.

first cracks appeared on the beam surfaces. For each load step, the cracking torsion  $T_{cr}$  and the corresponding angle of twist  $\theta_{cr}$  are recorded. Here, the load is applied automatically 5 kN at each step with the use of control panel. After each 5 kN applied load, the control panel turns off the loading engine automatically; for the cumulative applied load again, the loading engine must be restarted again through the control panel.

## 5. Test Results and Discussion

Table 2 shows the experimental results of twelve square beams were tested under pure torsion to study the influence of different shape and size hollow cross-section on high strength steel fiber-reinforced concrete member torsional behavior. One of the specimens was a plain concrete beam without fiber. The other specimens were reinforced by various ratios of steel fibers. All specimens were reinforced by 4#10 mm longitudinal reinforcement and 3#12 mm closed stirrups at each end. The obtained results are discussed in this paragraph based on torsional behavior.

**5.1. Crack Patterns.** When a member is under effect of torsion loads, the shear stresses are developed on the front and top member sides [14], as shown in Figures 5(a)–5(c). The principal tensile stresses propagation is equal to the principal compression stresses, and both principle stresses are equal to the shear stresses [9]. The helical cracking

around the perimeter of members is mainly caused by the principal tensile stresses. From experimental testing results of the plain concrete member BM0, the crack patterns was one major inclined helical crack initiated from front side upward top side of the tested member, then toward to the back side and the bottom side with approximately angle of twist  $45^\circ$ , as shown in Figure 6. In this approximate experimental testing, the crack patterns are corresponding to that assumed in the theory of skew bending [13]. On the other hand, the test of mixing steel fiber-reinforced concrete beams shows many smeared inclined cracks are distributed on the beam sides, as shown in Figure 7. After the first crack's occurrence, the steel fiber is developed to resist the postcracking torque. The enhancement of torsional strength is dependent on the steel fibers' shape and cohesion between steel fibers and the surrounding concrete paste. According to theory of elasticity, when structural members are subjected to a pure torsion, the first crack mostly initiates inclined on the wider side of the member [10]. The results of experimental tests display that the crack width of members which have low ratios of steel fibers was less than crack width of the control beam; the number of cracks of the mixed steel fiber beams was more than the number of cracks of the control beam. In the mixed steel fiber specimens, the first crack shape appeared as smeared cracks.

**5.2. Effects of Steel Fiber Content.** The experimental test results show that the first crack torques and ultimate

TABLE 2: Experimental study results.

Specimen symbol	$T_{Cracking}(Spec.)$ (kN m)	$T_{Ultimate}(Spec.)$ (kN m)	$T_U(Spec.)/T_{Cr}(Spec.)$	$T_{Cr}(Spec.)/T_{Cr}(B0)$	$T_U(Spec.)/T_U(B0)$	$\theta_{Cracking}$ (rad/m)	$\theta_{Ultimate}$ (rad/m)
BM0	6.7	7.8	1.16	1.00	1.00	0.0036	0.0351
BM0.5	7.1	10.8	1.52	1.05	1.38	0.005	0.048
BM1	7.7	13	1.8	1.15	1.66	0.005	0.061
BM1.5	7.8	15	2.05	1.16	1.92	0.0052	0.069
BM100	7.75	27.75	3.58	1.15	3.55	0.0055	0.0675
BM150	7.3	20.2	2.76	1.09	2.58	0.0056	0.0624
BM200	7	15.5	2.14	1.04	1.98	0.0065	0.0525
BMS100	9.3	16.8	1.74	1.38	2.15	0.0047	0.069
BMS50	10.1	19	1.69	1.5	2.43	0.0045	0.074
BMD150	7.7	16.5	2.14	1.15	2.11	0.0051	0.071
BMD100	9.1	17.8	1.89	1.36	2.28	0.0051	0.072
BMD50	11.2	20.9	1.69	1.67	2.67	0.0056	0.078

\*B, beam; M, fiber mixing (50% corrugated and 50% end hooked); (0, 0.5, 1, and 1.5), steel fiber ratio; (S100 and S50), square hollow cross-sections; (D150, D100, and D50), circular hollow cross-sections.

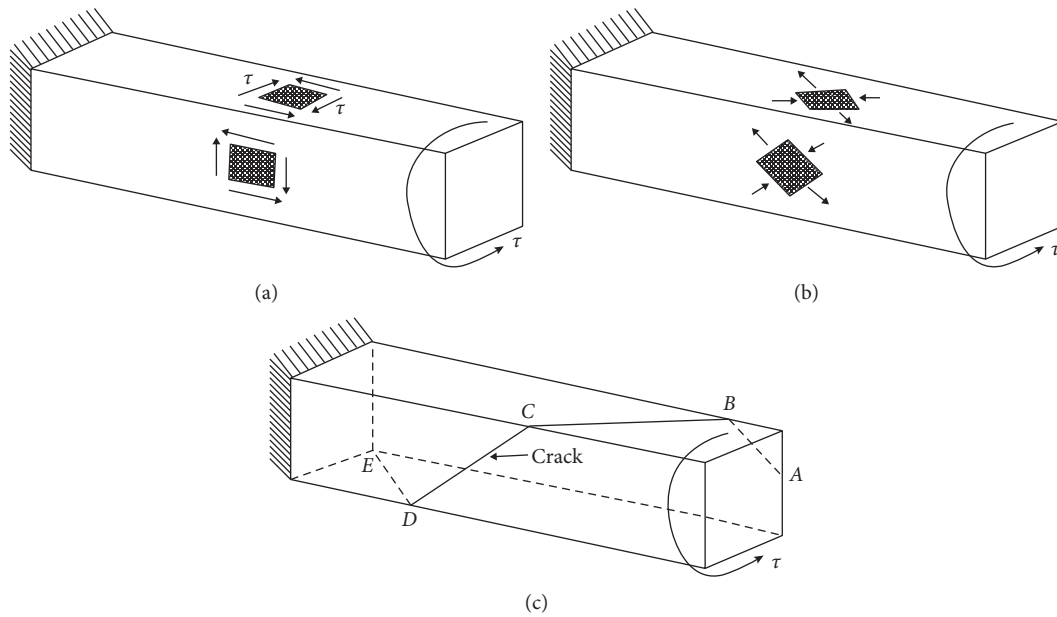


FIGURE 5: Principal stresses and helical crack patterns due to pure torsion. (a) Shear stresses. (b) Principal stresses. (c) Crack.



FIGURE 6: Crack pattern of beam BM0.



FIGURE 7: Crack pattern of steel fiber beam.

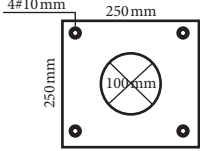
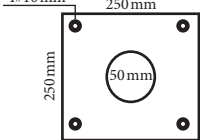
torsional strength incessant increase with the mixing steel fiber ratios increased for the (0.5%, 1%, and 1.5%) ratios. When the steel fiber concrete members are subjected to high applied torque, appreciable relative increase in the angle of twist magnitudes is observed which shows the torsional ductility of members increased with the increase of mixing steel fiber ratios. For all test specimens for mixing steel fiber concrete members (50% corrugated and 50% end hooked) with different cross-section shape and size given higher first crack torques, ultimate torsional resistance and torsional ductility with steel fiber ratios increased. The first crack torques of mixing steel fiber concrete members were as follows: BM0.5, BM1, BM1.5, BM100, BM150, BM200, BMS100, BMS50, BMD150, BMD100, and BMD50 were found to be 6%, 15%, 16%, 16%, 9%, 5.5%, 39%, 51%, 15%, 36%, and 67% more than the first cracking torque of plain concrete member BM0. The ultimate torque of mixing steel fiber concrete members were as follows: BM0.5, BM1, BM1.5, BM100, BM150, BM200, BMS100, BMS50, BMD150, BMD100, and BMD50 were found to be 34%, 59%, 82%, 215%, 129%, 70%, 84%, 94%, 87%, 95%, and 115% more than the first cracking of the plain concrete member BM0. The ultimate torques of members BM0, BM0.5, BM1, BM1.5, BM100, BM150, BM200, BMS100, BMS50, BMD150, BMD100, and BMD50 were found to be 31%, 66%, 82%, 100%, 258%, 176%, 114%, 74%, 69%, 114%, 89%, and 69% more than their first crack torques. From the previous results, we noticed that the higher ratios of the mixing steel fibers gave a relatively great torsional resistance. Consequently, the increase of adding mixing steel fibers causes increase in both cracking and ultimate torsion. From the previous discussion, the 1% mixing steel fiber ratio gave relatively high first cracking torque and ultimate torsional torque with acceptable workability and without segregation. The use of mixing steel fibers (50% end hooked and 50% corrugated) gives higher first cracking torque, ultimate torque, and torsional ductility than both the corrugated and end hooked if used separately [15].

5.3. *Effect of Shape and Size of Hollow Cross-Section.* All the specimens used in the experimental study were of the same external dimensions, but they differed in the dimensions and shapes of the hollow cross-sections, as shown in Table 3. The results obtained showed that whenever the hollow cross-

TABLE 3: Properties of specimens.

Symbol of specimens	Shape of specimens	Steel fiber ratios (%)
BM0 BM0.5 BM1 BM1.5		0 0.5 1 1.5
BM100		0
BM150		0
BM200		0
BMS100		1.5
BMS50		1.5
BMD150		1.5

TABLE 3: Continued.

Symbol of specimens	Shape of specimens	Steel fiber ratios (%)
BMD100		1.5
BMD50		1.5

\*B, beam; M, fiber mixing (50% corrugated and 50% end hooked); (0, 0.5, 1, and 1.5), steel fiber ratio; (S100 and S50), square hollow cross-sections; (D150, D100, and D50), circular hollow cross-sections.

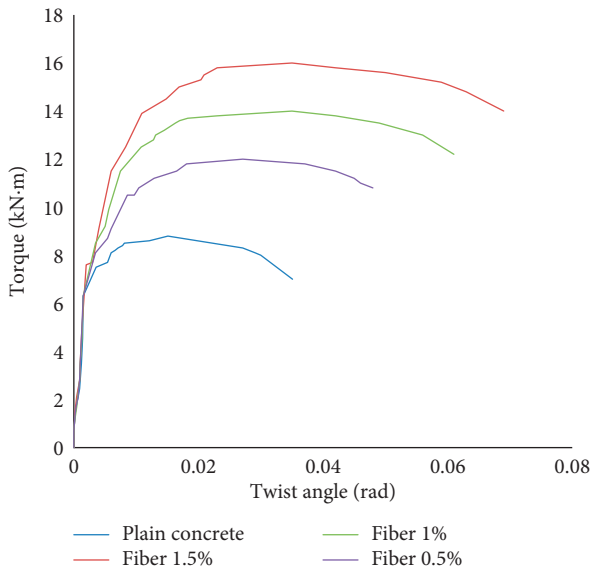


FIGURE 8: Torque-twist angle relationship of mixing steel fibers.

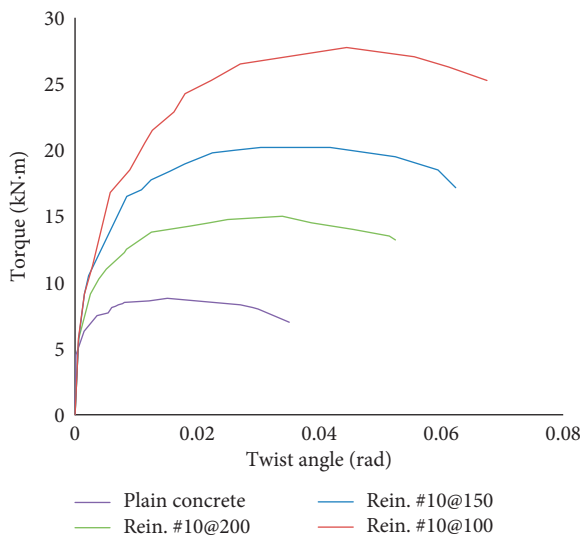


FIGURE 9: Torque-twist angle relationship of stirrup reinforcement.

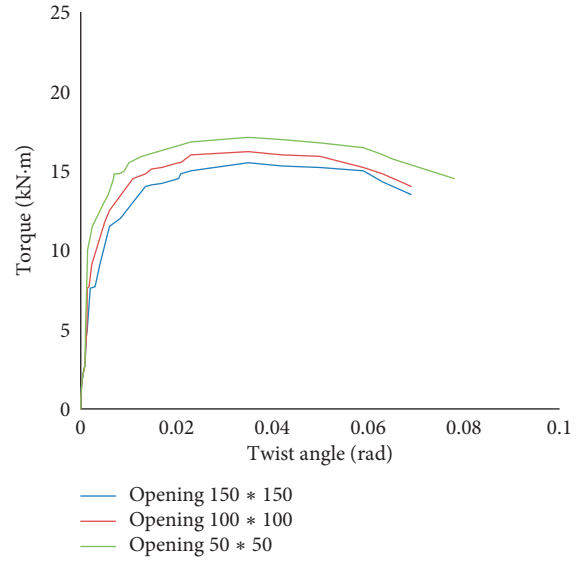


FIGURE 10: Torque-twist angle relationship of square hollow cross-section.

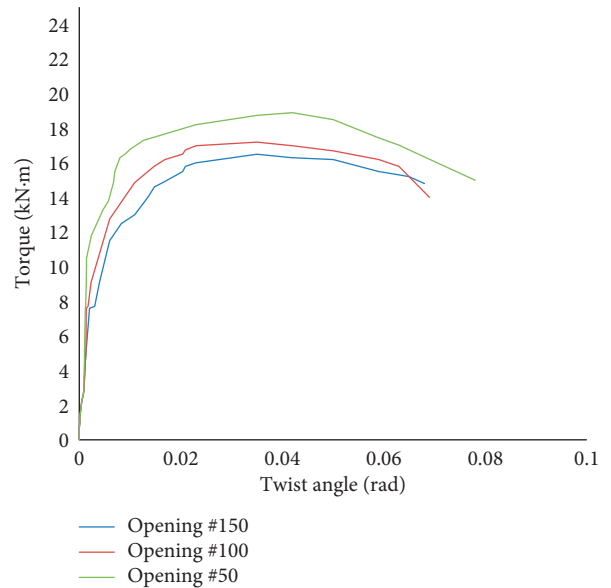


FIGURE 11: Torque-twist angle relationship of circle hollow cross-section.

section area decreased the cracking and ultimate torsional load increased with constant steel fiber ratio (1.5%). Here, reducing the area of square hollow section by 88% increases the cracking and ultimate torsional load by 30% and 19%, respectively. Also, reducing the area of circle hollow cross-section by 88% increased the cracking and ultimate torsional load by 45% and 27%, respectively.

**5.4. Effect of Reinforcement Steel.** The results showed that the use of stirrup steel reinforcement gives results of cracking torsional load approximately close to the results of steel fibers, but it gives much higher values in the ultimate

torsional load. The specimens of reinforcement steel (stirrups #10@200) give results approximately equal to the results of specimens of (1.5%) steel fiber in both cracking and ultimate torsional load. Figures 8–11 show the experimental results.

## 6. Conclusions

- (1) Use of mixing steel fiber in concrete paste has found to be very beneficial to increase the first crack torques and ultimate torsional torque of reinforced concrete members under pure torsion.
- (2) For equal net concrete cross-section areas and steel fiber ratios, the members of circle hollow cross-section gave higher torsional strength than the members of square hollow cross-sections.
- (3) The addition of mixing steel fibers to high concrete strength paste has succeeded enhancing the torsional ductility of concrete members by increasing the member angles of twist as compared with the control beam BM0.
- (4) The addition of mixing steel fibers (50% end hooked and 50% corrugated) gives relatively higher results than the corrugated or end hooked if used separately.
- (5) When the hollow cross-section area decreased, the cracking and ultimate torsional load increased with constant steel fiber ratio (1.5%). Here, reducing the area of square hollow cross-section by 88% increases the cracking and ultimate torsional load by 30% and 19%, respectively. Also, reducing the area of circle hollow cross-section by 88% increased the cracking and ultimate torsional load by 45% and 27%, respectively.
- (6) The test of specimens reinforced by stirrup steel reinforcement gives results of cracking torsional load approximately close to the results of test of specimens reinforced by steel fibers, but it gives much higher values in the ultimate torsional load.

## Data Availability

All required data are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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