Research Article

Experimental Study of Hollow RC Beams Strengthened by Steel Fiber under Pure Torsion

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This paper examines the effectiveness of pure torsional loads on hollow reinforced concrete high-strengthened beams. Engineers need to know how much twist a structural member generates when exposed to torsional loads to design it properly. This is done through an experimental investigation of the torsional behavior of reinforced concrete (RC) beams using twelve hollow rectangular beams with varying parameters, such as the spacing of the stirrups, the influence of the steel fiber fraction, and the main reinforcement amount. Four values of fiber volume fractions (0, 0.5%, 0.75%, and 1%), three spacings of transverse reinforcements (60,100, and 150 mm), and various longitudinal reinforcements (8Φ12 mm, 6Φ12 mm, and 4Φ12 mm) have been used. The tested beams had the same length (1000 mm), cross-sections, concrete mixture, and quality control. In the hollow beams, the interior dimensions were 180 mm × 180 mm, while the exterior dimensions were 300 mm × 300 mm. Torsional loads were applied to all the beams using custom-built test equipment. This study highlighted that the structural characteristics of hollow RC beams could be improved by increasing the fiber volume, lowering the stirrup spacing, and increasing the longitudinal reinforcement. Torsion moments rose by 132% when the fractional volume of fiber was increased from 0% to 1%, while they rose by 71.27% when the longitudinal reinforcement was increased from 4 to 8 bars for beams with fractional volumes of fiber of 0.5 percent and the same transverse reinforcement ratios.

1. Introduction

Hollow cross-section (HCS) models are being used more frequently in structures nowadays, including bridges and buildings. This is primarily because they have advantages over traditional open section members in terms of both structural and aesthetically pleasing design elements. The most well-known use of hollow cross sections is to provide an economic, lightweight, and long-span member.

For RC beams, premature torsion failure may occur if a torsional moment is supplied to a reinforced concrete beam without transverse reinforcing before its flexural strength reaches its limit. As this failure occurs suddenly and without prewarning, it is generally catastrophic; therefore, stirrups and steel fibers have traditionally been used to prevent the torsional failure of concrete beams.

Since steel fibers' effects on hollow beam torsion behavior with stirrup reinforcement are not well understood, it is difficult to design properly. This research addresses the use of steel fibers in hollow concrete beams under pure torsion. This research is looking for ways to improve the torsional strength of hollow reinforced concrete beams by altering the stirrup spacing, adding reinforcement along the longitudinal axis, and adding steel fiber. This experimental study tests eleven beams with different steel fiber aspect ratios, stirrup spacing, and various numbers of longitudinal reinforcements.

2. Background

In most structures, the torsion action occurs more frequently, but it rarely occurs by itself. Torsion, on the other hand, is regarded as one of the crucial structural activities,

alongside shear, flexure, and axial tension compression. Torsion causes the failure of the concrete member, which is caused by tensile stress. This failure was caused by a pure shear state. The model's tensile strength was significantly increased with the inclusion of steel fibers. This property of reinforced concrete with steel fibers led to various examinations of it under various loading techniques. Limited data were provided about the performance of steel fiber reinforced concrete members with hollow sections under pure torsion. Prior tests demonstrated that the use of steel fiber increased the torsional strength of members.

Chalioris and Karayannis [1] studied the behavior of reinforced concrete beams with steel fibers under torsion. 35 beams with T-shaped, L-shaped, and rectangular cross-sections with steel fibers with an aspect ratio of $lf/df = 37.5$ are presented and discussed. To assess the efficacy of fibers as a prospective stirrup replacement, steel fibers were used as the only shear torsional reinforcement the results showed that fibrous concrete beams had better torsional performance than the corresponding non-fibrous control beams. Okay and Engin [2] found that adding steel fiber reinforcement to RC beams changed their torque capability. Chalioris and Karayannis [3] reported an experimental study using eleven RC beams with rectangular spiral reinforcement subjected to torsion; according to test results, torsional capacity was enhanced for beams with rectangular spiral reinforcement. Lopes and Bernardo [4] examined sixteen hollow beams with concrete compressive strengths ranging from 46.2 to 96.7 MPa and torsional reinforcement ratios ranging from 0.3 to 2.68%. They found a novel failure type where the beam corners break off at a specified reinforcement ratio, which prevents the beam from reaching its predicted maximum strength and ductility. Enthuran and Sattainathan [5] reported that crimped steel fibers with 1.5% and 2.0% volume fractions resulted in increased torque and twist angles. Therefore, the results suggested that RC beams with a greater volume proportion of steel fibers exhibit superior torsional performance. Sudhir and Keshav [6] investigated the effect of adding 1.5% steel fibers on improving concrete torsional strength. The inclusion of steel fibers enhanced the torsional strength, concrete crack resistance, and the combined torsional shear bending strength while decreasing the deflection. Kandekar and Talikotiþ [7] investigated the torsional behavior of RC beams strengthened using aramid fiber strips. They constructed twenty-one RC beams: three with normal reinforcement, three with torsional reinforcement, and the remaining fifteen with normal reinforcement and with aramid fiber strips of 150 mm width and varied spacings of 100, 125, 150, 175, and 200 mm. All beams with aramid fiber strips were found to have increased torsional moment bearing capability. With modest changes in the twist angle, torsional moment carrying capacity improves as strip spacing decreases. Hameed and Al-Sherrawi [8] found that under pure torsion tests, adding steel fibers to RC beams improves the ultimate torsion strength for three specimens up to 28.55%, 38.09%, and 49.46% compared to RC beams without fibers. These enhancements are dependent on the increment in fiber content. Facconi et al. [9] showed that steel fiber reinforced

concrete beams exhibit stable torsional behavior after cracking in terms of improved crack control, increased torsional resistance, and cracked stiffness. AlKhuzaie and Atea [10] evaluated the impact of adding steel fiber on the behavior of reactive powder concrete beams with hollow T-sections under pure torsion. The researchers determined that a beam with a 2% fiber volume fraction raised the cracking torsional moment by 184% and the final torsional moment by 66%. Nitesh et al. [11] studied the effect of adding 0.5% hook steel fiber to self-compacting concrete beams with recycled coarse aggregate. To test the strength of the concrete using natural and recycled coarse material, 32 beams were constructed. The results showed a large increase in the ultimate torque, torsional stiffness, angle of twist, and torsional toughness in self-compacting concrete compared with vibrated concrete for natural and recycled coarse aggregates with steel fibers. Ibrahim et al. [12] studied the effects of spacing and type of stirrup. The investigation comprised ten reinforced concrete beam specimens: seven hollow sections with various ratios of rectangular spiral stirrups, two solid beams with spiral and closed rectangular stirrups, and one hollow beam with closed rectangular stirrups. Compared with standard closed stirrups, the findings revealed that inclined spiral rectangular stirrups in beam reinforcement enhanced the torsional capacity and strained energy by 16% and 27%, respectively, for solid beams, and 18% and 16%, respectively, for hollow beams. Kim et al. tested eleven RC beams with various torsional reinforcement amounts and different cross-sectional properties. The results indicated that solid and hollow sections have the same levels of torsional strength. Furthermore, regardless of cross-sectional properties, specimens with less arranged torsional reinforcement exhibited ductile behavior compared with the ACI 318 − 19 building code [13]. Kim et al. [13] investigated six steel fiber reinforced concrete (SFRC) beams under torsion. The tested beams were divided into three groups; beams with no stirrups, beams with a minimum transverse reinforcement amount (according to Euro code 2), and beams with hooked steel fibers (25 or 50 kg/m^3). The results indicate that the addition of steel fibers increases the maximum resisting torque and maximum angle of twist compared with the same specimen without fibers. Moreover, SFRC has a relatively high post-cracking stiffness compared to the RC elements [14]. Hadi and Mohammed [15] studied the behavior of reinforced concrete beams with straight and hooked steel fibers under combined torsional-flexural load. The experimental study involved three fixed supported beams with dimensions of 250 mm ∗ 300 mm ∗ 1800 mm and different types of fibers with a volume percentage of 1.5%. The beam with hooked steel fibers has a 33.37% increase in compressive strength and a 55.08% increase in tensile strength. It was also concluded that the use of hooked fiber had the greatest influence on improving the cracking behavior of beams. Using hooked and straight fibers, beams are able to sustain larger loads at the same rate of deflection/twisting, with a 128.13% and 74.76% increase in ultimate load, respectively. Despite the fact that the applied load was torsional-flexural, all tested beams failed due to excessive twisting. Abdulkadir et al. [16]

experimented with RC members with 0, 30, and 60 kg/m^3 steel fibers under shear, torsion, and axial load. The results indicate that increasing the ratio of steel fibers increases the torsional moment capacity and decreases the shear strength capacity. Moreover, increasing the steel fiber content increases the moment capacity and axial load of RC columns. Hussain et al. [17] experimented with the structural performance of ten flat slabs with and without a square opening using four types of fibers to gain a better understanding of how the variance of fiber type and shape affects the flexural behavior of two-way slabs. Results revealed that the existing fiber in concrete improved the mechanical properties of the hardened concrete mix, the compressive strength, flexural behavior of the reinforced concrete slab, and flexural strength capacity.

Most of the experimental and theoretical studies that were mentioned above corresponded to concrete beams with solid sections under pure torsion. A few studies on hollow reinforced concrete beams under pure torsion are available in the literature. The present study attempts to investigate the behavior and load-carrying capacity in torsion for hollow RC beams to show the effects of adding different steel fiber ratios, different longitudinal reinforcements, and stirrups that influence the torsional strength capacity and the behavior of the beam. The angle of twist, cracking torsional moment, and ultimate torsional moment were measured.

3. Materials and Methods

The beam specimens in this study were cast using plywood molds constituted from a single part (external parts). The fallen were used to make the tested beams' hollow shape, as shown in Figure 1. A 1 cm square stock was placed inside the molds to maintain the proper concrete cover to hold the reinforcement throughout the construction process. A typical poker vibrator was employed during the concrete casting to facilitate consolidation and precise concrete placement within and around the reinforcement.

Portland cement, natural sand, and aggregate were used in the concrete mixture to meet the IQS (5/1984) [18, 19] and ASTM 33-03 [20] specifications. Tables 1 and 2 represent the cement's chemical and physical characteristics, whereas Tables 3 and 4 provide the properties of sand and aggregate, respectively. The maximum size of the used aggregate was 10 mm, and the percentages used in the concrete mix design were (1 : 1.31 : 2.8/0.32 by weight) for (cement: sand: gravel/water), respectively, Test beams' compressive strength was determined using three 150-millimeter concrete cylinders, each 300 mm high. The compressive strength of the cylinder in 28 days was designed to be 65 MPa according to ACI 218 [21]. Steel with a yield strength of 547 MPa was used. Steel fiber ratios of 0.5%, 0.75%, and 1% of the concrete weight were used. The design of RC beams was done by using ACI 318 [21].

3.1. Specimen Details.
The factors evaluated in this work include the fiber volume percentage, the main reinforcement quantity, and the spacing of the stirrups, all of which impact the torsional capacity of the beam. Twelve hollow reinforced concrete beam specimens with an overall length of 1000 mm are shown in Figure 2 with exterior and interior dimensions of 300 × 300 mm and 180 × 180 mm, respectively. As shown in Table 5, this work consists of three groups:

Group A is used to study the influence of stirrup spacing and fiber volume fraction (Vf) on the torsional strength of beams. The impact of adjusting the stirrup spacing on the torsional strength of these beams under pure torsion was investigated using six reinforced hollow concrete beams. The stirrup spacing for these beams is 60, 100, and 150 mm, and the VF range is 0.5% to 0.75%.

Group B deals with the effect of fraction volume of fiber on the behavior of hollow reinforced concrete beams. Four RC beams were presented to find the fiber's ratio (Vf) impact on the beam's torsional strength. These beams have a varied volume fraction of fibers (0, 0.5%, 0.75%, and 1%).

Group C deals with calculation of torsional displacement and studies the effect of changing the amount of main reinforcement and fiber volume fraction (Vf) for the same reinforcement. Six reinforced concrete beams were used to find the effect of the longitudinal reinforcement amount on the beam torsional strength. The main reinforcement includes 8Φ12 mm, 6Φ12 mm, and 4Φ12 mm, and Vf ranged between 0.5 and 0.75%.

3.2. Test Setup and Devices.
Figure 3 shows the torsional testing machine used to test the hollow RC beams. This machine has been enhanced by adding an arm to apply pure torsion. A heavy steel plate of 45 mm in thickness in a wedge shape was used to make a torsion arm with a net length equal to 0.65 m. Four bolts were utilized to fasten two steel plates on the top and bottom sides of the tested beam to secure the test arm. The RC beams were built to be simply supported at two bearings, with the roller support located underneath the bearing to facilitate the movement of the beam specimens, allowing them to be readily rotated under the supplied torque, as shown in Figure 4. Figure 5 shows a schematic of applied loading.

3.3. Measurements of Angle of Twist.
Figure 6 shows the addition of linear variable differential transformers (LVDTs) at the beam ends to determine the twist angle. By averaging the deflections from the LVDTs on both sides of the tested beam, the twist angle was computed.

4. Results and Discussion

The load was applied at the ends of a 650 mm torsion lever arm from the beam center to achieve a pure torsional moment in the present investigation. The torsion moment was applied to the beam using a hydraulic testing machine with five kN increments, and the test continued until the beams failed. The torque produced after the appearance of the first crack is indicated as the cracking torsional moment (Tcr), whereas the torque that causes beam failure is known
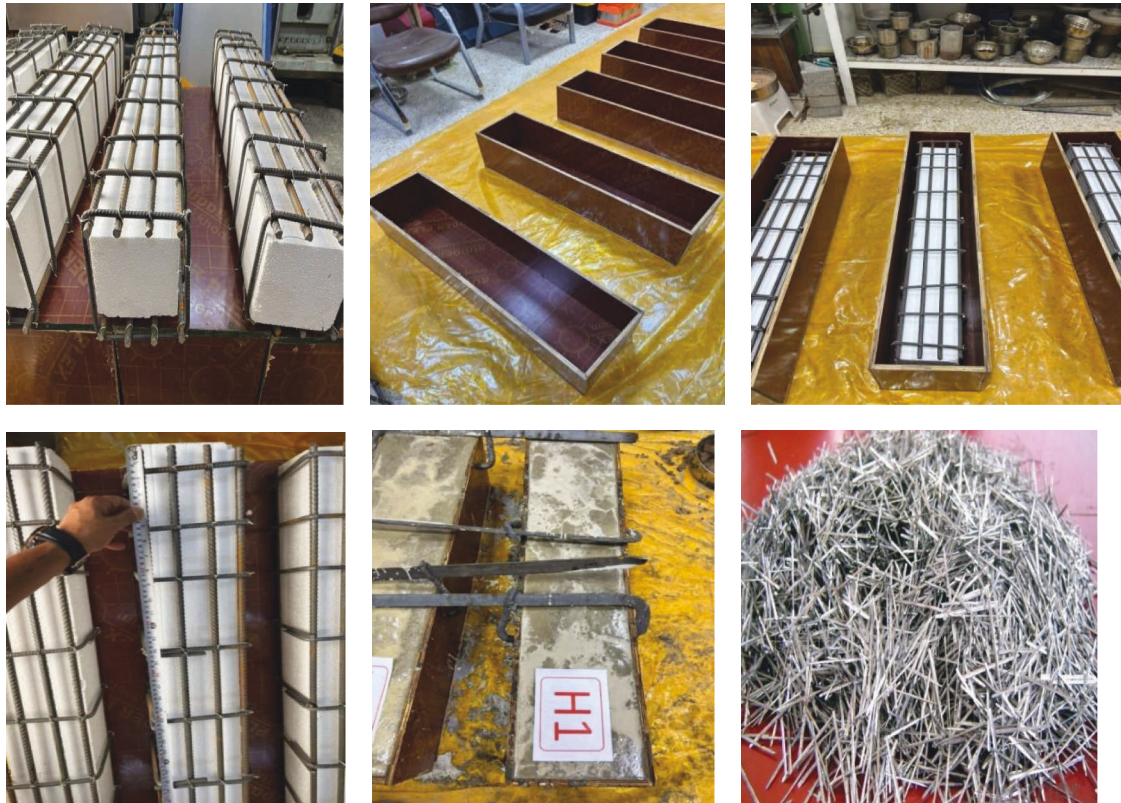
FIGURE 1: Concrete casting.

TABLE 1: Chemical properties of cement [16].

Composition of cement	(%)	Specification limit
(CaO)	62.83	
SiO_2	22.54	
AL_2O_3	5.4	
Fe_2O_3	2.64	
MgO	3.23	5%
SO_3	2.45	2.8%
(Na_2O)	0.24	
(K_2O)	0.62	
(L.O.I)	0.71	4.00 (max.)
(I.R)	0.57	1.50 (max.)
(L.S.F)	0.91	0.66–1.02
Cement compound		
C_4AF	7.93	7.72–8.02
C_3A	10.21	11.96–12.3
C_2S	33.65	28.61–37.9
C_3S	38.51	31.03–41.05

TABLE 2: Physical properties of cement [16].

Physical property	Test results	Limit of IQS No. 5/1984
Setting time (Vicat apparatus), hr: min		
Initial	00 : 57	00 : 45 (min.)
Final	8 : 47	10 : 00 (max.)
Compressive strength (70.7 mm cube)	19.7	15 (min.)
3-day and 7-day MPa	26	23 (min.)

TABLE 3: Specification of used sand [18].

Sieve size	Passing %	Standard
No. 8	100	100
No. 4	95	95–100
No. 8	83	80–100
No. 16	67	50–85
No. 30	48	25–60
No. 50	17	5–30
No. 100	6	2–10
F.M.		2.7
M.A.S		No. 4
A.S.S.		No. 30
Sp. gr.		2.61

as the ultimate torsional moment (Tu). Two LDVTs are positioned at the maximum torsional moment sites to measure the twist angle. Table 6 shows the twist angle, cracking, and ultimate torsional moment.

4.1. Effect of Spacing of Stirrups. Tcr is the torque at which the applied stresses exceed the section's tensile strength and the cracks begin to appear. After the appearance of these cracks, rapid deformations, and a drop in the reading of the tested machine, the load-carrying capacity of the beam will decrease. In this case, it is referred to as the ultimate torsional moment (Tu). Two beams, H11 and H12, were selected to represent the control beams to study the effect of changing the spacing of the stirrups. Figure 7 indicates that

TABLE 4: Specification of used gravel [18].

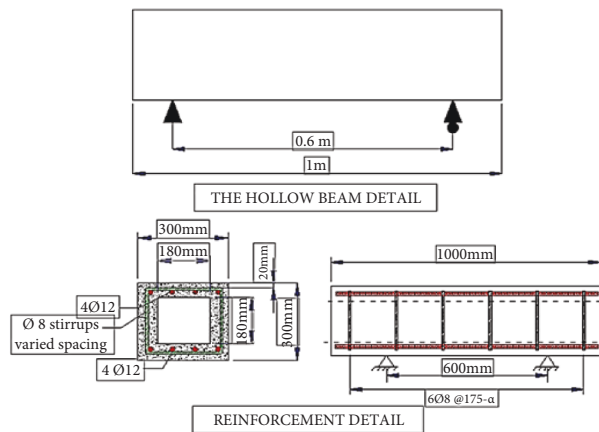| Sieve size (in)	Passing %	Standard %
2	100	100
1.5	98	95–100
3/4	65	35–70
3/8	12	10–30
3/16	2	0–5
Pan	0	
F.M.	7.1	
M.A.S	1.5 in	
Sp.gr.	2.61	

FIGURE 2: Details of reinforcement of hollow RC beams.

TABLE 5: Specimen group details.

Group	Beam number	Vf %	Spacing of stirrup	Longitudinal steel number	Case study
A	H11	0.5	150	4	Effect of stirrup spacing of on pure torsion
	H2	0.5	100	4	
	H9	0.5	60	4	
	H12	0.75	150	4	
	H3	0.75	100	4	
	H10	0.75	60	4	
B	H1	0	100	4	Effect of steel fiber ratio on pure torsion
	H2	0.5	100	4	
	H3	0.75	100	4	
	H4	1	100	4	
C	H2	0.5	100	4	Effect of amount of longitudinal steel reinforcement on pure torsion
	H5	0.5	100	6	
	H7	0.5	100	8	
	H3	0.75	100	4	
	H6	0.75	100	6	
	H8	0.75	100	8	

FIGURE 3: The torsional test machine.
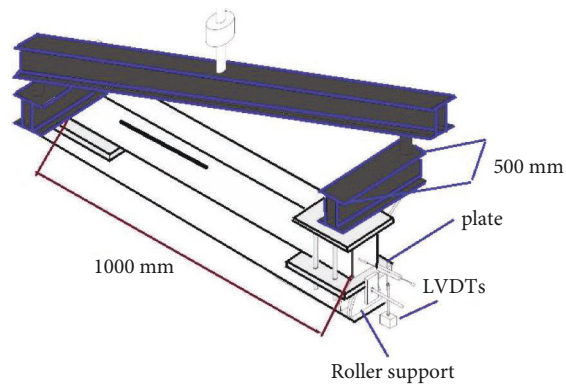
FIGURE 4: The support of the tested beam.

FIGURE 5: Typical cross section of the tested machine.

FIGURE 6: Location of LDVTs.

TABLE 6: The overall results of tested beams.

Beam number	Maximum twist angle (degree %)	Cracking torque (kN.m)	Ultimate torque (kN.m)
H1	9.40	8.3	21.1
H2	10.85	15.77	26.24
H3	12.87	17.59	29.51
H4	15.89	19.25	32.09
H5	12.06	16.35	44.37
H6	13.24	18.50	47.94
H7	14.3	17.18	44.94
H8	14.42	19.17	49.79
H9	14.04	18.42	30.87
H10	15.18	19.25	31.96
H11	9.80	8.50	20.30
H12	10.20	9.70	21.55

the values of Tcr and Tu are improved by minimizing the spacing of stirrups and increasing the fiber's ratio for the same stirrup spacing. The increments in the cracking moment of beams H2 and H9, which have a steel fiber ratio of 0.5% and stirrup spacing of 100 mm and 60 mm, were equal to 85.53% and 116.7%, respectively, compared to the control beam (H11). The increases in the ultimate torsional moment for the two beams (H2 and H9) are 29.26% and 43.25%, respectively. It was also discovered that increasing the steel fiber ratio from 0.5 percent in beam H11 to 0.75 percent in beam H12 enhanced the cracking torsional moment and ultimate torsional moment by 14.12% and 6.16%, respectively. The effect of the fiber fraction on both Tcr and Tu is decreased with the reduction of stirrup spacing. Therefore, to improve the behavior of the beams, the stirrups should be increased.

The angle of twist (∅) is measured by the deflection rate on both sides of the beam, which was measured using the previously described LDVTs. Increasing the number of stirrups with the corresponding fiber fraction and main reinforcement improves the beam stiffness and the twist angle. Figure 8 depicts the relationship between the difference in the twist angle and the Tu for each beam compared to the control beams.

It can be shown that increasing the stirrups improves Tcr, Tu, and ∅. The rate of increment in the torsional resistance of the tested beams to the corresponding spacing of stirrups was not proportional, as shown in Tables 7 and 8. Figures 9(a)–9(c) demonstrate that the cracking torsional moment increased by 116.7%, the twist angle improved by 48.82%, and the ultimate torsional moment improved by 48.31%.

4.2. Effect of Steel Fiber Ratio. According to Table 9 and Figure 10, increasing the fiber percentage increases the ultimate and cracking torque. The crack torsional moment of the beam increases by 90%, 112%, and 132%, respectively, as it increases from zero to 0.5, 0.75, and 1%, while the ultimate torque increases by 24.4, 45.6, and 62.7%, respectively, in comparison to the beam without steel fiber (H1). The addition of steel fibers enhances the concrete tensile strength and improves the ductility of the beams. The beam fails when the tensile stresses on the concrete raise and exceed the concrete tensile strength, the beam cracks, but the fibers continue to resist the raising tensile stresses until the steel fibers completely pull out at a critical crack. All of the tested beams failed owing to excessive torsional shear stress, resulting in a large diagonal torsional fracture.

Figure 11 depicts the relationship between the twist angle difference and the torsional moment of the tested beams. Increasing the fiber ratio while maintaining the same stirrup spacing and the number of main reinforcements increases the beam stiffness and twist angle.

These results reveal that Tcr, Tu, and ∅ are improved by increasing the fiber fraction. As evident in Tables 9 and 10, the rate of increment in the torsional properties to the steel fiber ratio was not the same for all tested beams. Figures 12(a)–12(c) demonstrate that the cracking torsional
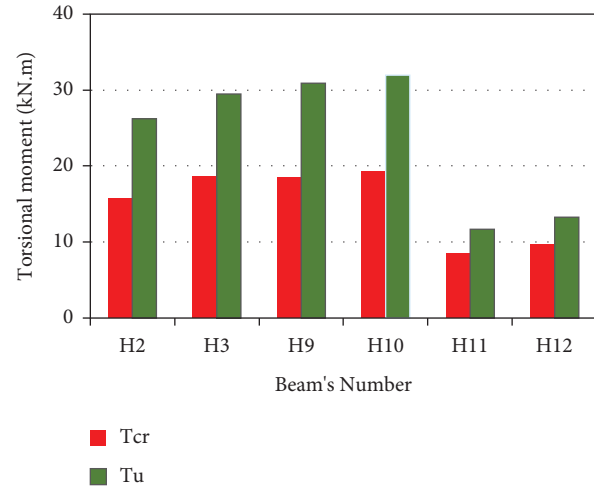

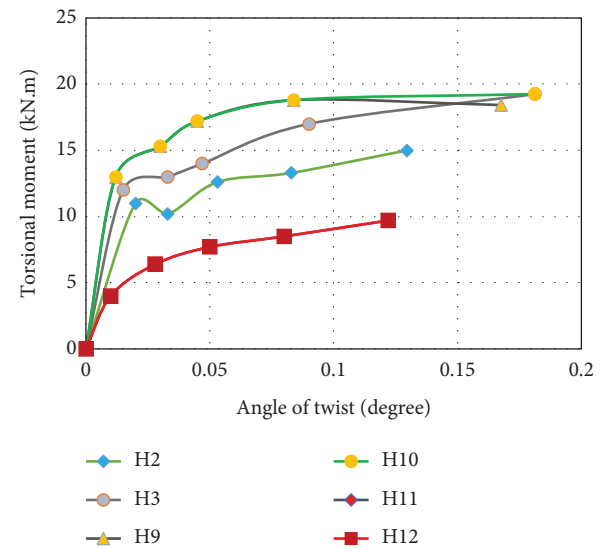
FIGURE 7: Torsional moment of the tested beams.

FIGURE 8: The twist angle and torque relationship.

moment increased by 132%, the twist angle improved by 69.04%, and the ultimate torsional moment improved by 62.1%.

4.3. Effect of Main Reinforcement. The impact of modifying the number of longitudinal reinforcements with the two distinct fiber ratios was investigated in this experimental study section by comparing two beams (H5 and H7) with the control beam (H2). The cracking and ultimate torsional moments rise by 3.68% and 69.09%, respectively, for beam H5, and by 8.94% and 71.27%, respectively, for beam H7, as the number of longitudinal reinforcement increases (see Table 11 and Figure 13). The increase in the fiber ratio from 0.5% to 0.75% resulted in an 11.5% increase in the cracking load and a 12.46% rise in the ultimate torsional moment for beams with the same longitudinal reinforcement (4 bars). Beam H8, which contains the largest main reinforcements (8 bares) and the

TABLE 7: Effect of spacing of stirrups on the beam torsional moment.

Beam no.	Stirrups spacing (mm) c/c	Vf %	Cracking torque (Tcr) (kN.m)	Increase in Tcr according to H11 and H12 (%)	Ultimate torque (Tu) (kN.m)	Increase in Tu according to H11 and H12 (%)
H11	150	0.5	8.5	—	20.3	—
H2	100	0.5	15.77	85.53	26.24	29.26
H9	60	0.5	18.42	116.7	30.87	43.25
H12	150	0.75	9.7	—	21.55	—
H3	100	0.75	17.59	81.34	29.51	36.94
H10	60	0.75	19.25	98.45	31.96	48.31

TABLE 8: Effect of stirrups spacing on the twist angle.

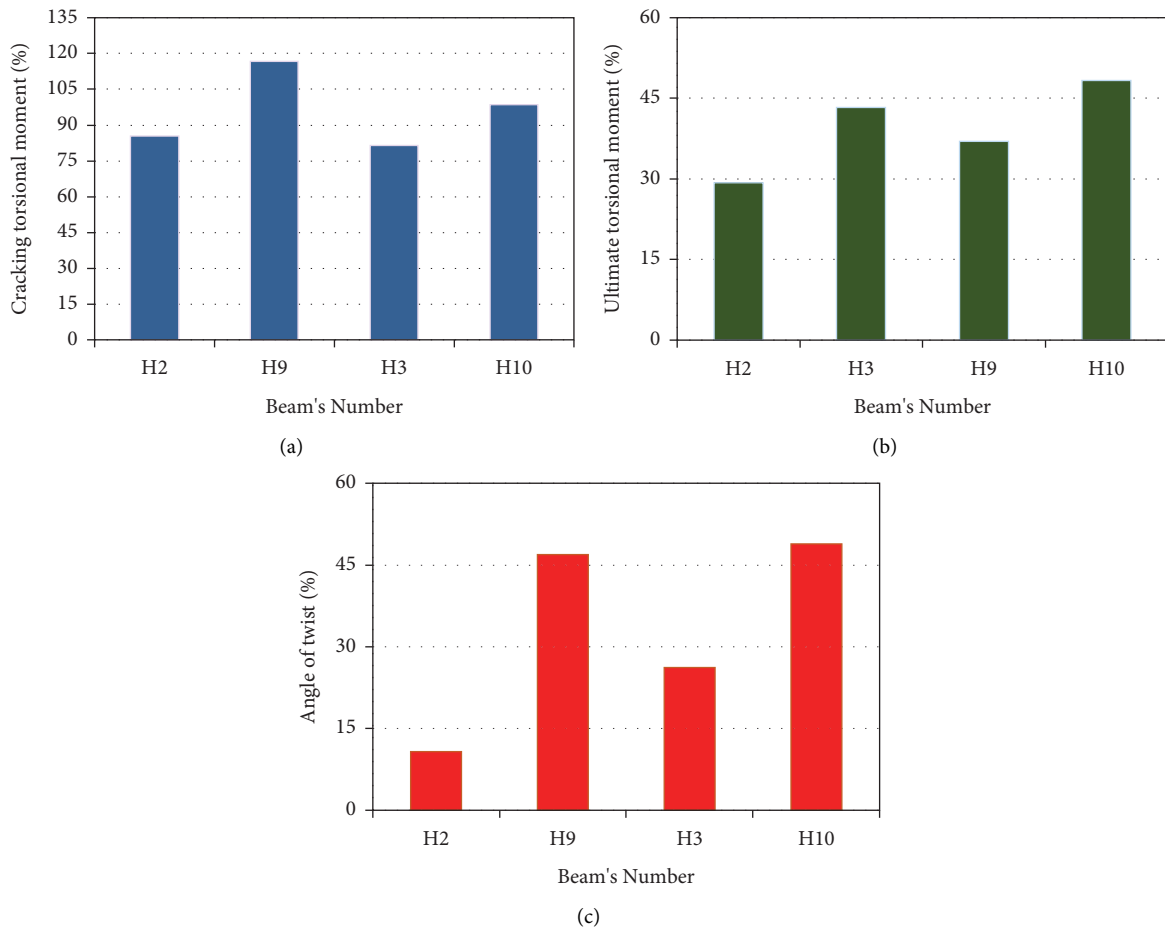| Beam no.	Spacing of stirrups (mm) (c/c)	Vf %	Maximum twist angle (Ø) (degree %)	Decrease in Ø according to H11 and H12 (%)
H11	150	0.5	9.8	—
H2	100	0.5	10.85	10.71
H9	60	0.5	14.04	46.94
H12	150	0.75	10.2	—
H3	100	0.75	12.87	26.18
H10	60	0.75	15.18	48.82

FIGURE 9: (a) Cracking torsional moment improvement. (b) Improvement of the ultimate torsional moment. (c) Twist angle improvement.

TABLE 9: Effect of steel fiber ratio on cracking and ultimate torsional moment.

Beam no.	Vf %	Cracking torque (Tcr) (kN.m)	Increase in Tcr according to H1 (%)	Ultimate torque (Tu) (kN.m)	Increase in Tu according to H1 (%)
H1	0	8.3	—	21.1	0
H2	0.5	15.77	90	26.24	24.4
H3	0.75	17.59	112	29.51	45.6
H4	1	19.25	132	32.09	62.7
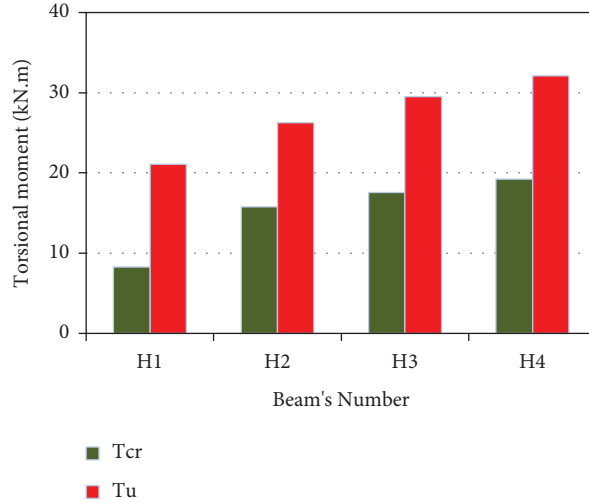
FIGURE 10: Torsional moment of the tested beams.
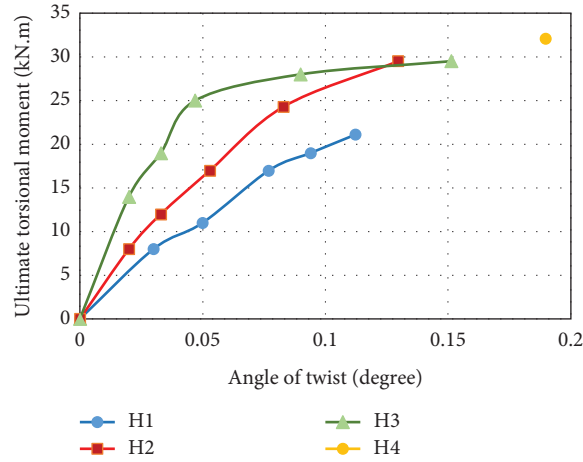

FIGURE 11: The twist angle and torque relationship.

TABLE 10: The effect of fiber ratio on the twist angle.

Beam no.	Vf %	Maximum twist angle (Ø) (degree %)	Decrease in Ø according to H1 (%)
H1	0	9.40	—
H2	0.5	10.85	15.42
H3	0.75	12.87	36.91
H4	1	15.89	69.10

highest steel fiber ratio (0.75%), has 8.98% growth in carrying capacity and 68.72% development in cracking resistance according to H3. As a result, the beam torsional strength increased by increasing the longitudinal reinforcements. Also, it can be observed that the effect of changing the fiber ratio and main reinforcement on the
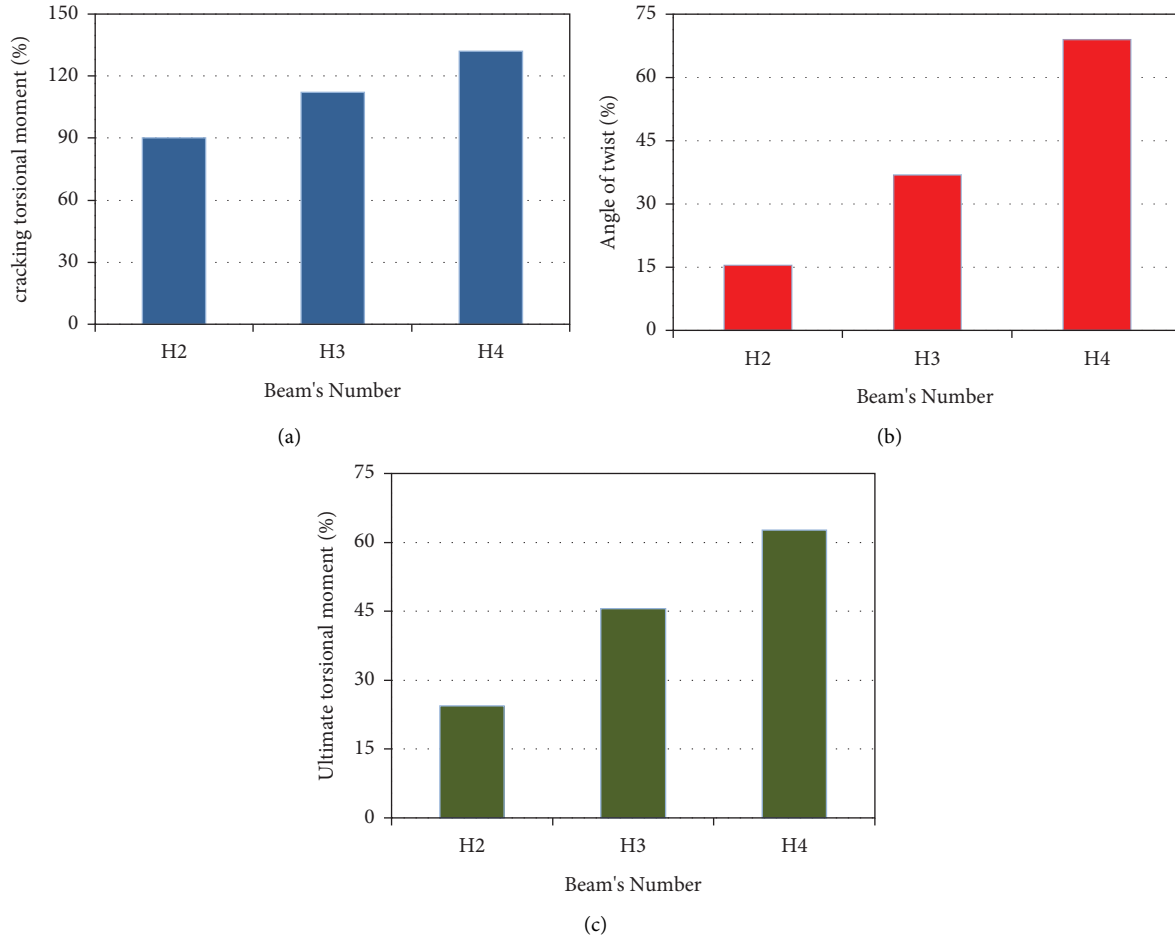
(a)

(b)

(c)

FIGURE 12: (a) Improvement of the Tcr. (b): Improvement of the twist angle. (c) Improvement of the Tu.

TABLE 11: Effect of the main reinforcement number on cracking and ultimate torsional moment.

Beam no.	Vf %	No. of longitudinal steel reinforcement	Cracking torque (Tcr) (kN.m)	Increase in Tcr according to H2 and H3 (%)	Ultimate torque (Tu) (kN.m)	Increase in Tu according to H2 and H3 (%)
H2	0.5	4	15.77	—	26.24	—
H5	0.5	6	16.35	3.68	44.37	69.09
H7	0.5	8	17.18	8.94	44.94	71.27
H3	0.75	4	17.59	—	29.51	—
H6	0.75	6	18.50	5.17	47.94	62.45
H8	0.75	8	19.17	8.98	49.79	68.72

ultimate torsional moment will decrease by increasing the number of main reinforcements from 6 to 8 bars.

Figure 14 depicts the relationship between the torsional moment and the average twist angles for the examined beams. The stiffness and twist angle of the beams could well be improved by increasing the main reinforcements while maintaining the same stirrup and fiber spacing ratio. Figure 14 shows the relationship between the average of two twist angles and the torsional moment for the tested beams. Increasing the number of main reinforcements with the same spacing of stirrups and fiber ratio leads to an improvement in the beam stiffness and angle of twist (see Table 12).

According to current observations of tested beams, increasing the longitudinal reinforcement number improves Tcr, Tu, and Ø. As evident in Tables 11 and 12, the increment rate in the torsional properties to the related number of longitudinal reinforcement was not the same for all tested beams. Figures 15(a)–15(c) show that the cracking torsional moment increased by 81.71%, the twist angle improved by 31.98%, and the ultimate torsional moment improved by 8.98%.

4.4. Crack Patterns of Tested Beams. Figure 15 shows the failure modes of the tested beams. The control beam (H1) demonstrates typical torsion failure behavior, with spiral
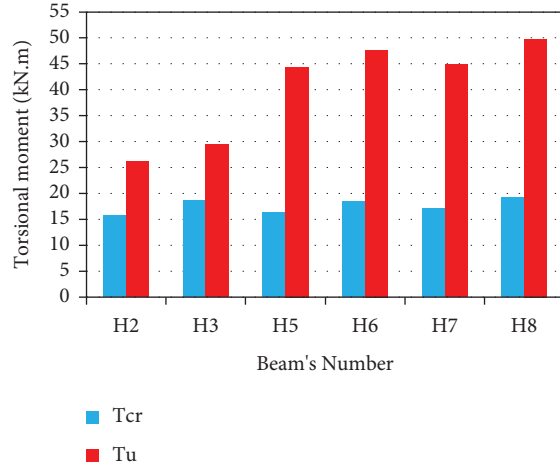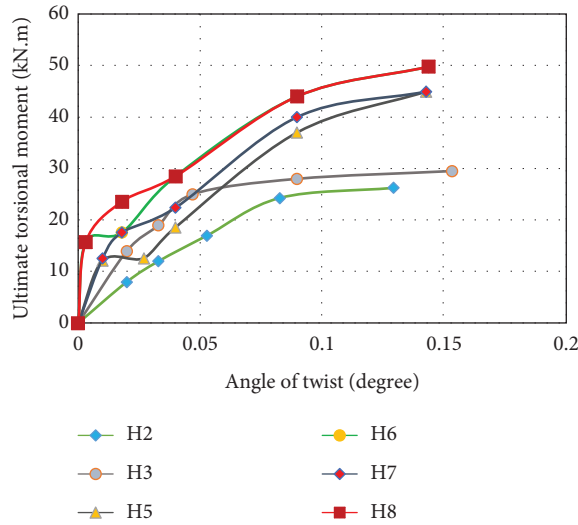
Figure 13: Load-carrying capacity of the tested beams.

Figure 14: Torque-twist relationship.

Table 12: Effect of increasing the longitudinal steel number on the twist angle.

Beam no.	Vf %	Longitudinal reinforcement number	Maximum twist angle (Ø) (degree)	Decrease in Ø according to H2 and H3 (%)
H2	0.5	4	10.85	—
H5	0.5	6	12.06	11.15
H7	0.5	8	14.30	31.80
H3	0.75	4	12.87	—
H6	0.75	6	13.24	2.87
H8	0.75	8	14.42	12.04

diagonal fractures seen throughout the beam's cross section, with an angle of around 45 degrees. By increasing the applied load, larger cracks will appear until the concrete fails by crushing in the center of the beam. This mode of failure is the typical mode of beams without steel fiber. On the other hand, beams with steel fibers fail differently, especially those with a high steel fiber fraction, where the presence of fiber makes the crack control system resist pseudo-ductility in postcracking action. To be more precise, the primary cracks started to show up on the beam's surface before the postpeak falling branch of the torque vs. twist response started to develop (Figures 8, 11, and 14). As the torque deducted after the peak, the damage gradually summarized in a single crack, whose width was larger than the other and it increased until the test ending. From Figure 16, it can be seen that the hollow beam H10, with the largest fiber volume fraction and less spacing of stirrups, is best at resisting cracks.
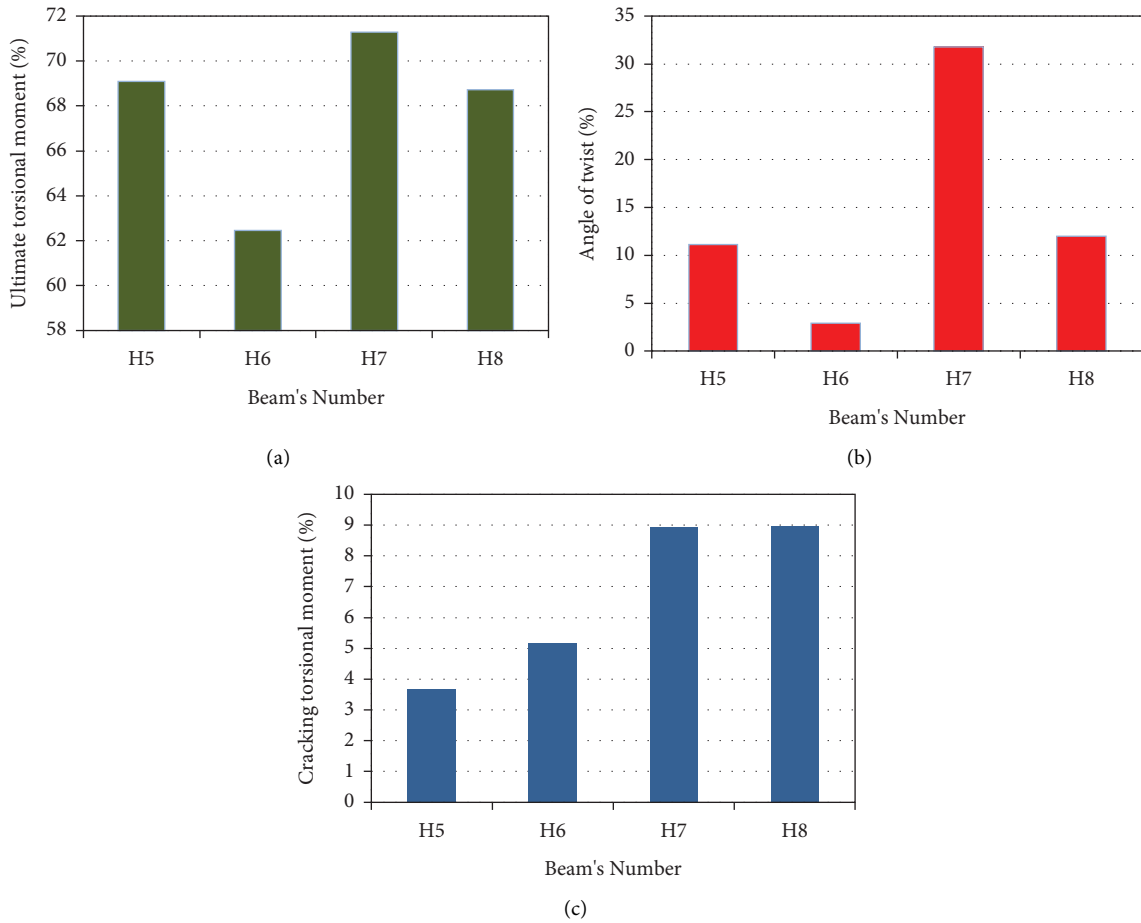
(a)

(b)

(c)

FIGURE 15: (a) Improvement of the Tu. (b) Improvement of the angle of twist. (c) Improvement of the Tcr.
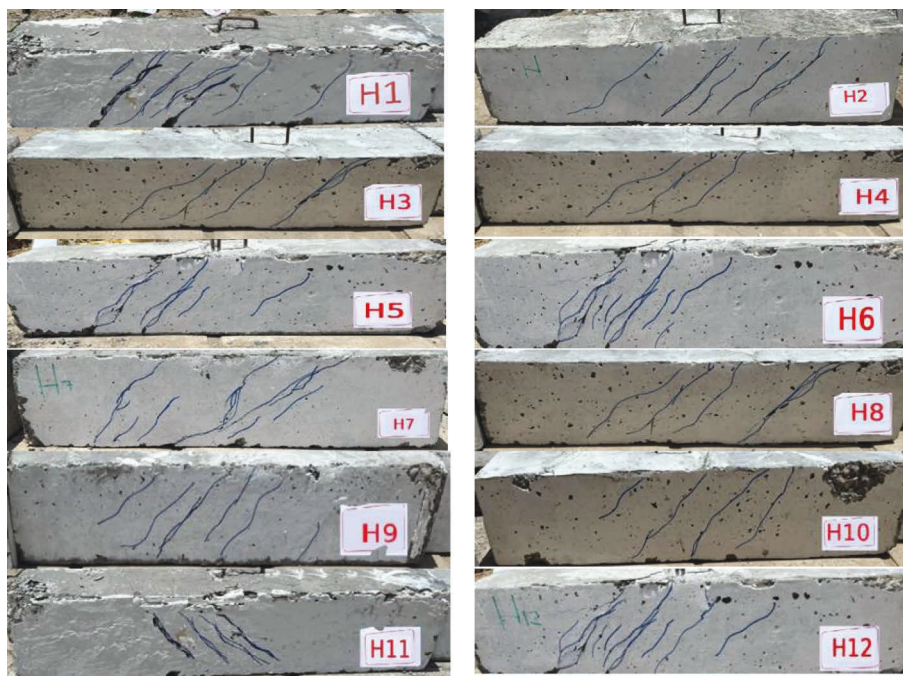

FIGURE 16: Failure mode of the tested beams.

5. Summery and Conclusion

The experimental results concerning the torsion behavior of full-scale hollow reinforced concrete beams under pure torsional loading are presented and discussed. The main variables were longitudinal reinforcement, stirrups, and steel fiber ratio. The angle of twist, cracking torsional moment, and ultimate torsional moment for HCS beams were measured. It is possible to draw the following conclusions based on the test results:

(1) The deformations and torsional stresses of hollow RC beams were improved by increasing the number of stirrups.

(2) The deformations and torsional stresses for hollow RC beams were improved using a larger number of longitudinal reinforcements.

(3) The insertion of steel fibers to hollow RC beams subjected to a pure torsion load enhanced the principal tensile stress resistance following crack formation until total fiber pullout occurred at the critical fracture.

(4) The percentage of improvement for Tcr, Tu, and Ø for beams H1 to H12 is as follows:

　(i) Tcr has a range of 3.68%–132%
　(ii) Tu ranges from 29.26% to 71.27%
　(iii) Ø ranges from 2.87% to 69.1%

(5) It is preferable to increase the torsional strength (Tcr and Tu) of the hollow beam rather than its stiffness. Before the failure, the significant increase in Ø makes adding the main reinforcement and stirrups better to save lives and draw attention to the situation.

(6) For beams H1 through H12, the relationship between the twist angles and torsional moments is the same. The amount of stress energy in the beam could be increased by including additional stirrups and main reinforcement.

(7) With increasing main reinforcements, the rise in Tu is more than the increase in Tcr in hollow RC beams, whereas the rise in Tcr is greater than the increase in Tu with increasing VF and the number of stirrups.

(8) The effect of steel fiber decreases with increasing main reinforcement and decreases in the spacing of stirrups for Tcr and Tu.

6. Disclosure

The experimental work was carried out at the University of Basrah Laboratory.

Data Availability

The data results of this study are based on our experimental work.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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