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Torsional Behavior of Solid and Hollow Core Self Compacting Concrete Beams Reinforced with Steel Fibers

Abstract- *Torsion of structural members and the behavior of steel fiber self-compacting reinforced concrete became the area of interest for many researchers nowadays. The experimental program of the present work consists of casting nine reinforced self-compacting concrete beams in three groups. Each group consists of three beams with the dimensions of 200×300×1500 mm. The first beam has a solid cross-section, the second beam has a hollow core with the dimensions of 60×120×1500mm and the last beam has a hollow core with the dimensions of 80×180×1500mm. The steel fiber contents were 0, 0.5 and 1.0 % by volume for first, second and third groups respectively. The torsional angle of twist versus torsional moment (torque) of each beam was found during the experiments, and the effect of variables, fibers volume fraction and section geometry, on this relationship was investigated. Moreover, the fresh and hardened properties of concrete were carried out using several tests, which included slump flow, L-Box, compressive strength, tensile strength, and finally the torsion test. The current results showed that the addition of steel fibers has improved the torsional strength for all beams and the fibers were more effective in hollow core sections than in the solid ones.*

Keywords- Self-compacting concrete, steel fibers, cracking torque, ultimate torque, twist angle, hollow section.

1. Introduction

Several structural elements in building and bridge construction are subjected to torsional moments that influence on the structural design. Spandrel beams, beams in eccentrically loaded frames of multi-deck bridges, and curved box girder bridges are examples of elements that subjected to torsion [1].Concrete is characterized as a brittle material; this characteristic could be enhanced by the addition of steel fibers, which will improve the mechanical properties of concrete such as tensile strength, flexural strength, impact and fatigue resistance, and ductility [2].

Structural trends show an increase in the interest of using hollow core sections, for both buildings and bridges. This is mainly due to their beneficial characteristics for structural as well as aesthetic design. Great progression was made [3-6], but still, there are areas which need some improvements. Hollow core sections are most widely used for providing economical solutions by reducing weight and cost. In other cases, their geometrical properties are required functionally.

Many researchers investigate the torsional behavior of hollow beams in their work [7]. The main conclusion reached is that the solid beam had higher torsion stiffness than hollow core beams but with an acceptable percentage of reduction and increase in twist angles and numbers of crack.

2. Experimental work

I. Material

1) Cement

Ordinary Portland cement (type I) manufactured by Mass Cement Company in Iraq was used in this work. This cement meets the Iraqi Standard Specification No.5/1984.[8]

2) Fine aggregate

Natural sand from Al-Ukhaidher region in Iraq was used. The fine aggregate grading and the sulfate content are conforming to the Iraqi standard specification No.5/1984 zone No. 2. [9]

3) Coarse Aggregate

Crushed gravel passing sieve 12 mm from Al-Niba'ee region was used. The coarse aggregate grading and physical properties conform to the Iraqi specification No.45/1984.[9]

4) Fly ash

Fly Ash or Pulverized Fuel Ash (PFA) is a by-product resulting from the burning of pulverized coal in coal-fired power stations. Fly ash used in this study produced by "DCP" company, and it

conforms to ASTM C 618 Class F [10] and BS EN 450[11].

5) Limestone Dust

"Al-Gubra" is a local name for Limestone dust, which is a white grading material excavated from limestone in varied regions in Iraq and generally used in the construction processes. The limestone powder used in this study was passing sieve No. 0.150 mm.

6) Fibers

The properties of steel fiber used in this work have been illustrated in Table 1.

7) Water

Tap water was used for both mixing and curing of concrete.

8) High-Range Water Reducer (Superplasticizer):

The high range water reducing admixture used in this work is commercially named Sika Viscocrete – 5930-L.

II. Experimental Work

The experimental program consists of casting nine reinforced concrete beams in three groups, having a rectangular shape with dimension (200×300×1500) mm, one of the solid and two others hollow with dimensions (60,120,1500),and (80,180,1500)mm.

The first group was cast without fiber, the second group was cast with steel fibers with volume fraction equal to 0.5%, while the third group was cast with steel fibers volume fraction equal to 1.0%.For all beams, two sizes of steel reinforcing deformed bars are used. Six bars Ø 12 mm are used for longitudinal reinforcement and Ø 10 mm bars for transverse reinforcement stirrups with spacing 50 mm at ends and 100 mm in the middle of beams. Three galvanized molds were used in this work to avoid the difficulty of exit mold from the concrete specimen. Cork was used instead of galvanizing to make hollow beams. Molds were oiled and the reinforcement mesh was placed in its location, and then cast without any vibration. Figure1 shows the steel reinforcement details. In addition, Figure 2 shows the mold with reinforcement and cork.

Table 1: Specifications of steel

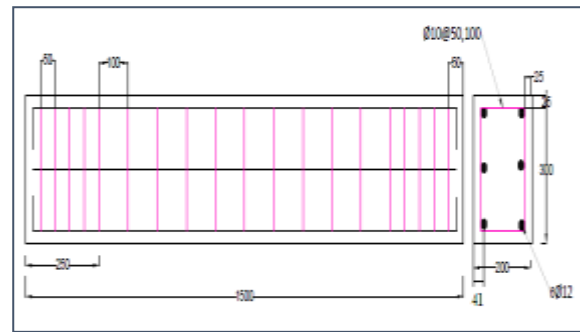| Length mm	15
Diameter, mm	0.2
Aspect ratio	75
Geometry	Straight
E modulus, GPa	212
Tensile strength, MPa	2850
Density, Kg/m³	7850
Cross Section area	circular

Figure 1: Steel reinforcement details

Figure 2: Mold with steel reinforcement and cork

III. Mix Proportions

After several trial mixes were made to satisfy the criteria of filling ability, passing ability, and segregation resistance. Self-compacting concrete mixes were designed to have a 28-day characteristic compressive strength of 30 MPa. The mix design used in this work was according to **EFNARC** [12]. Table 2 indicates the mix proportions of SCC.

Table 2: Mix design

Mix	M_0	$M_{0.5}$	M_1
Cement, kg/m³	420	420	420
Coarse aggregate, kg/m³	800	750	750
Fine aggregate, kg/m³	790	840	840
Fly ash, kg/m³	65	65	65
Limestone dust, kg/m³	65	65	65
Superplasticizer, L/m³	7	9	11
Water, L/m³	170	170	170
Steel fiber, V_f%	0	0.5	1

Table 3: Requirement of EFNARC

Slump flow ,mm	650-800
T_{500}, sec	2-5
L-Box	0.8-1

Figure 3: Practical side of work
(Mixing, casting and curing)

IV. Compressive Strength and Splitting Tensile Strength:

Six cylinders with dimension (100×200) were tested for each test. After water-cured for 28 days, three of them were tested. The other three were let on air with beams in the same conditions until test day (age of 90 days).

V. Test Procedure and Instrumentation

In the laboratory, the available testing machine was designed to apply vertical loads. Thus, frames were made to enable the existing 2000kN machine to apply the torsional moment on the beams. This designed frame consists of two large steel clamps which work as arms for the applied torque with separated faces to connect them over the beam by six bolts. The final form is similar to bracket. Figure 5 shows the frame during the test.

The beams were placed in the machine on free supported rollers at each end with a clear span of 1200 mm. To get pure torsion, the center of supports should be coinciding with the center of the moment frame.

Steel girder with depth 300mm and 3m length is used to transmit vertical loads from the center of the universal machine to the two frames to applied pure torsion on the beam. Two linear variable displacement transducers (LVDTs) were used to measure the vertical deflection in one side of the beam to calculate the angle of twist. During testing, the load was applied gradually, every stage of loading recorded with (LVDTs) reading. First crack torque and the ultimate torque were recorded. The torque was increased gradually until failure of the beam. Failure is defined as dropping in load capacity with an increase in the rotation of the beam.

3. Results and Discussion

I. Results of Fresh SCC

Flowability of fresh concrete is evaluated through the measurement of slump flow time a diameter, to assess the passing ability and stability of the SCC, the L-box ratio measured.

Figure 4: Frame with beam during the test

Table 4: The fresh state results of the tested SCC mixes

Mix	Vf%	Slump,mm	T_{500},sec	L-Box, H_2/H_1
M_0	0	730	2.7	1
$M_{0.5}$	0.5	680	4.1	0.95
M_1	1	650	4.25	0.9

Table 5: Compressive and splitting tensile strength results

mix	Compressive strength, MPa		Splitting Tensile Strength, MPa	
	28-day	90-day	28-day	90-day
M_0	36	40	3.6	4.2
$M_{0.5}$	42	45	4.6	5.2
M_1	45	49	6.0	6.9

From results, SCC mixes have an acceptable fluidity and filling ability according to **EFNARC** [12].

II. Results of Strength Tests

The average of three cylinders presented in Table 5.

The results indicate that all specimens exhibited a continuous increase in strength with age. This increase in compressive and flexural strength with age is due to the continuity of the hydration process and the addition of fibers [13].

The strength increase due to the inclusion of steel fibers is attributed to the mechanism of steel fibers in arresting crack progression. Where the presence of fibers in concrete restrains the development of internal micro-cracks and thus led to increasing in tensile strength. This conclusion was in agreement with Haddadou et al. [14] and Al-Ameeri [15].

Figure 5: Slump flow test

Figure 6: L-Box test

**Figure 7: Compressive and tensile tests**

III. Results of Torsion Test for Beams

The results of the torsion test for nine beams are illustrated in Table 6, including cracking and ultimate torque, twist angle at cracking and at ultimate torque, and the percentage of redaction due to section variation. Torque to twist angle curves for all beam groups are illustrated in Figures 8-10.

Table 6: Cracking and ultimate torque with the angle of twist and redaction due to section variation

Beam	Cracking torque T_{cr}, kN.m	Reduction in cracking The torque due to section variation, %	Angle of twist per length at crack θcr, rad/m	Ultimate torque, T_u, kN.m	Reduction in ultimate torque due to section variation, %	Angle of twist per length at failure θu, rad/m
M_{0S}	20.4	-	0.001547	25.9	-	0.003067
M_{0H1}	14.5	28.9	0.000747	23.5	9.0	0.0036
M_{0H2}	12.2	40.2	0.000693	22.7	12.1	0.00344
$M_{0.5S}$	26.3	-	0.002053	43.1	-	0.0136
$M_{0.5H1}$	23.5	10.4	0.001733	38.2	11.4	0.013999
$M_{0.5H2}$	20.0	23.9	0.00192	30.4	29.5	0.013813
M_{1S}	29.4	-	0.00216	46.7	-	0.020052
M_{1H1}	27.0	8.0	0.002321	42.7	8.4	0.022131
M_{1H2}	23.5	20.0	0.002747	38.7	17.0	0.021358

[*]: S: solid beam, H1: Hollow beam with a small opening (60*120*1500 mm), H2: Hollow beam with a large opening (80*180*1500 mm)
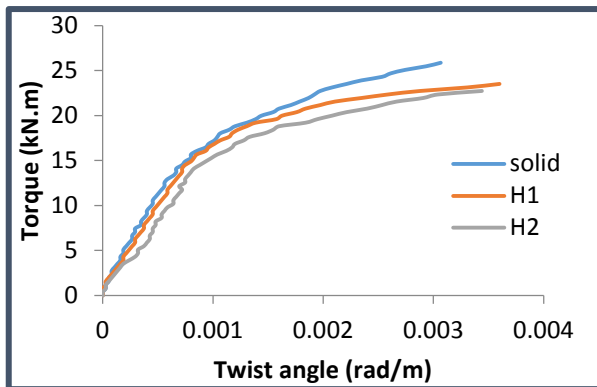
Figure 8: Torque – twist angle for M_0
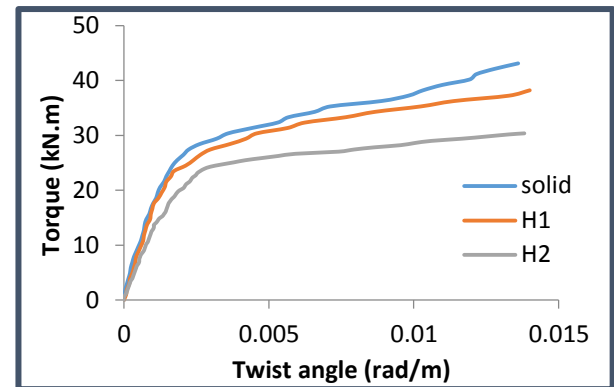
Figure 9: Torque – twist angle for $M_{0.5}$
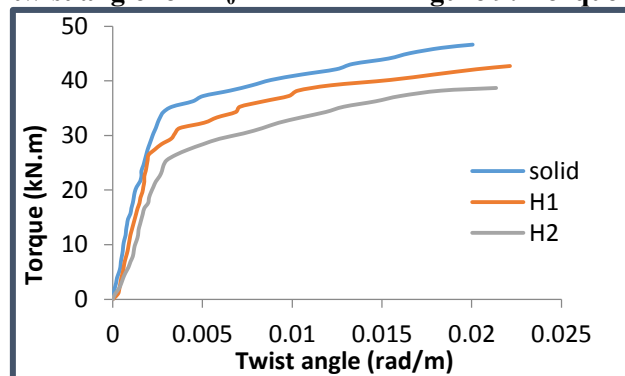
Figure 10: Torque – twist angle for M_1

IV. Effect of Steel Fiber Addition on Torsional Behavior

The addition of steel fiber with volume fraction 0.5% improves the ultimate torque by 66.67, 62.63 and 33.65% for beams M_S, M_{H1}, and M_{H2} respectively. Meanwhile, the cracking torque increased by 26.3, 23.5 and 20 % respectively. Table 5 indicates the percentages of improvement in cracking and ultimate torque due to the inclusion of fibers.

Changing the volume fraction of steel fibers from 0.5 to 1.0% has caused a little change in the value of ultimate torque moment. These conclusions are in agreement with the results of Sable et al. [2]. The beams showed more ductile behavior with the addition of fibers and the increase in twisting angle could be considered as an indication.

In beam M_{1H2}, the improvement of ultimate torque reached 70.30% and that was close to that of the beam M_{1H1}. On the other hand, the improvement in the ultimate load of beam $M_{0.5H2}$ was 33.65 %. This means that the increase in fiber content enhanced the cracking and ultimate torque in small opening beams (H2) and decreased the redaction in ultimate torque that happened due to section variation. The addition of steel fibers helps to bridge cracks in the whole volume of concrete, transfers tensile stress through two opposite faces of cracks until the fibers are totally pulled-out or broken, and delays cracking torque with the increase in the number of cracks and decrease the

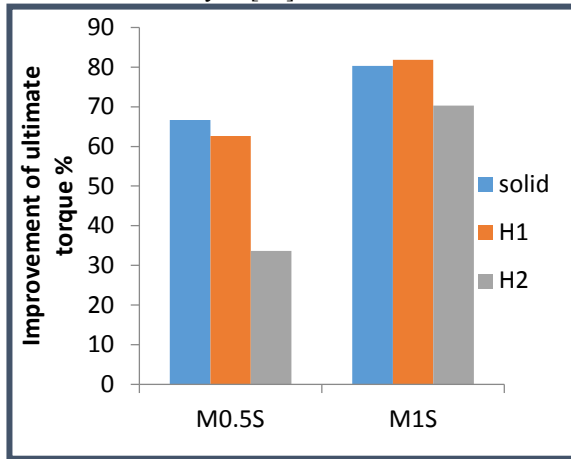width of cracks. These findings are compatible with Premachand and Jayant[16].

Figure 11: Improvement of torsional strength by addition of steel fiber

Table 7: Increase in the crack and ultimate torque due to the inclusion of fibers

Beams	T_{cr}, kN.m	Increase in T_{cr},%	T_u, kN.m	Increase in T_u, %
M_{0S}	20.4	-	25.9	-
M_{0H1}	14.5	-	23.5	-
M_{0H2}	12.2	-	22.7	-
$M_{0.5S}$	26.3	28.7	43.1	66.7
$M_{0.5H1}$	23.5	62.2	38.2	62.6
$M_{0.5H2}$	20.0	63.9	30.4	33.7
M_{1S}	29.4	44.1	46.7	80.3
M_{1H1}	27.0	86.5	42.7	81.8
M_{1H2}	23.5	92.8	38.7	70.3

V. Effect of Section Variation on Torsional Behavior

In this present work three types of the sections were used, solid and two hollow core sections with a reduction in cross-sectional area of 12 % for H1 and 24 % for H2. All results show a reduction in cracking and ultimate torque in hollow core sectioned beams due to the decrease in the rigidity.

The percentages of redaction in ultimate torque for H1 beams were 9%, 11.4% and 8.4% for M_{0H1}, $M_{0.5H1}$, and M1H1 respectively. These low percentages are acceptable and could be considered economically useful in addition to architectural purposes. While the percentages of reduction in ultimate torque for H2 beams were 12.1, 29.5 and 17 % for M_{0H2}, $M_{0.5H2}$ and M_{1H2} respectively. These percentages are higher than those of small opening beams but still acceptable with more economy due to decreasing in self-weight of beams.

The comparison between two of the hollow core sections with solid sections, for small opening it is clear that the percentage of increase in ultimate torsion about doubled that in a large opening. From the results of cracking torque (first visible crack), there is a large reduction in beams with the large opening when it compares with their solid section. However, it decreases with increase in fiber volume fraction.The angle of twist increased due to decreasing in the rigidity of beams. The increasing in twist angle in small opening beams is more than that in the large opening beams due to decreasing in ultimate torque that corresponds with the conclusions of Makhlouf [17].

VI .Cracks Pattern of Tested beams

All the tested beams failed under pure torsion. The load applied gradually with increasing the load. The cracks increased on each side and finally took the spiral shape until the specimen reaches to failure. For all solid section beams, the cracks occurred at mid-span and increased gradually in number and width until failure. This is roughly similar to small hollow section beams. Reference group failed with sudden brittle manner. Cracks made angle about 40-50 degree on the side faces of beam group with steel fiber 0.5% sustains much more ultimate torque than reference due to inclusion of steel fibers. The number of cracks increases, but the crack width decreases and makes an angle about 45-55 degree on the side faces of beam. The third group with steel fiber volume fraction 1% shows an increase in ultimate torque with a decrease in crack width but increase in its number. The cracks make angle about 50- 60 degree on the side faces of the beam. That has a good agreement with Ragab and Eisa [18].
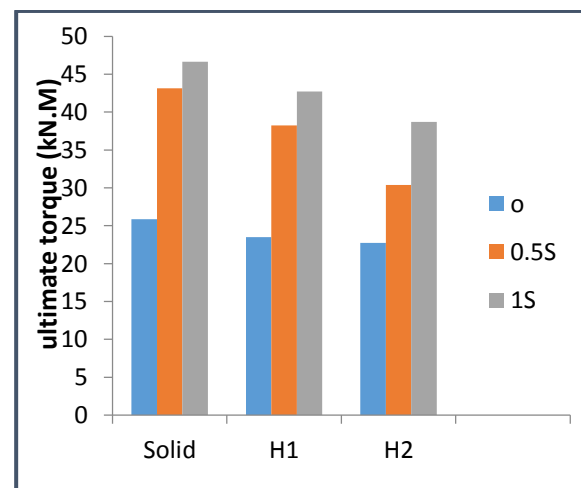

Figure 12: Ultimate torque with section

Figure 13: Crack pattern and failure mode for M$_{0.5H}$, M$_{0.5S}$ beams

4. Conclusions

Based on the results obtained from the study, the following conclusions can be observed:

1- Addition of steel fibers to self-compacting concrete improves the cracking and ultimate torque for reinforced concrete beams imparts significantly to the post-cracking ductility and toughness of beams. The addition of steel fiber causes a reduction in fresh properties of self-compacting concrete, but increasing in compressive and tensile strength.

2- The enhancement of ultimate torque in M$_{1H2}$ is more than that improvement of M$_{0.5H2}$. This means that the increase in the volume fraction of steel fibers improves the ultimate torque for the large opening beam.

3- All hollow core beams with the fiber volume fraction of 0.5 and 1% have torsional strength more than that in no fibrous solid beam.

4- Using hollow core beams reduces the cracking and ultimate torque, but this reduction decreased with the increase of fiber volume fraction.

5- The improvement in ultimate torque for small opening beams is about double that for large opening beams.

6- The angle of twist increased with the increase in steel fiber volume fraction. This was due to increasing ductility of beams and tension stress of fibers.

7- The angle of twist for small opening beams is more than that in solid beams due to the decreasing in the rigidity of beams. Twist angle of large opening beam is less than that in a small opening due to the decreasing in rigidity and ultimate load.

References

[1] K.N. Rahal, "Torsional strength of reinforced concrete beams," Canadian Journal of Civil Engineering, 27, 3, pp.445-453, 2000.

[2] K. Sable, M. Rathi and A. Mehetre, "Performance of self-compacting concrete under shear and torsion with fly ash and steel fibers," Elixir International Journal, 41, pp. 10775-10778, 2012.

[3] J. Meng, R. Werasak and L. Zhongxian "Torsional strengthening of Reinforced Concrete Box Beams Using Carbon Fiber Reinforced Polymer," Composite Structures Journal, 78, pp. 264–270, 2007.

[4] T.T. Hsu, "Torsion of Reinforced Concrete," Van Nostrand Reinhold Company, New York, 494 pp, 1984.

[5] ACI Committee 318M, "Building Code Requirements for Reinforced Concrete (ACI 318-11)," American Concrete Institute, Detroit, 2011.

[6] M.P. Collins, "Stress-Strain Characteristics of Reinforced Concrete in Pure Shear," Inelasticity and Non-Linearity in Structural Concrete, Study No. 8, University of Waterloo Press, pp. 211-225, 1973.

[7] E.M. Munaa, L.D. Al-Maliki, and A.P. Waryosh, "Torsional Behavior of Reinforced Concrete Hollow Core Beams," Journal of Engineering and Sustainable Development, 19, 2, pp.72-88, 2015.

[8] Iraqi Standard Specification No.5/1984, "Portland Cement," Central agency for standardization and quality control, planning council, Baghdad, Iraq.

[9] Iraqi Standard specification No. 45/1984, "Aggregate from Natural Sources for Concrete and Construction," Central agency for standardization and quality control, planning council, Baghdad, Iraq.

[10] American Society for Testing Materials. "Standard Specification for coal fly ash and raw or calcined natural pozzolan for use in concrete- ASTM C-618," 04.02, 2013.

[11] British Standards Institution, "Specification for pulverized-fuel ash for use with Portland cement," BS 3892: Part 1, 1993.

[12] C. Bibmand E. Ermco, "EFNARC," The European Guidelines for Self-Compacting Concrete. Specification, Production, and Use" 2005.

[13] T.K. Mon, "Flexural behaviour of steel fiber reinforced concrete slab," B.Sc., College of Civil Engineering, University of Technology, 2010, Malaysia.

[14] N. Haddadou, R. Chaid, Y. Ghernouti, and N. Adjou, "The effect of hybrid steel fiber on the properties of fresh and hardened self-compacting concrete," Journal of Building Materials and Structures, 1, 2, pp.65-76, 2014.

[15] A.A. Abbas, "The effect of steel fiber on some mechanical properties of self-compacting concrete," American Journal of civil engineering, 1, 3, pp.102-110, 2010.

[16] P. Premachand, and S. Kanase "Enhancement of Torsional Strength of Reinforced Concrete by

Application of Steel Fibers," International Journal, 2, pp.590-595, 2016.

[17] M.H. Makhlouf, "Torsional Behavior of RC Beams with Opening Using (CFRP-GFRP-Steel) Stirrups," Advances in Research, 8, 3, pp 1-10, 2016

[18] K. S. Ragab, and A.S. Eisa, "Torsion behaviour of steel fibered high strength self-compacting concrete beams reinforced by GFRP bars," International Journal of Civil Science and Engineering, 7, 9, pp.218-228, 2016.