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Torsional Behavior of Steel Fibers Reinforced Self-Compacting Concrete Beams

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Abstract

This research investigates experimentally torsional behavior of steel fibers reinforced self-compacting concrete beams with variables including steel fibers volume fraction(0.4% and 0.8%), reinforced with steel bars or non-reinforced self-compacting concrete beams and spacing of transverse steel bars reinforcement.

The experimental work includes investigation of nine beams tested under pure torsion and divided into three groups. Group (A) represents the non-fibrous normal strength SCC beams. Group (D) covers the fibrous normal strength SCC beams with steel fibers content (V_f) of 0.4%, and finally group (E) is fibrous normal strength SCC with steel fibers content (V_f) of 0.8%. Test results are discussed based on torque-twist behavior.

key words: *torsion, self-compacting concrete, steel fibers.*

سلوك اللي للعتبات الخرسانية المسلحة ذاتية الرص الحاوية على الالياف الحديدية

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الخلاصـــــة

تبحث هذه الدراسة عمليا سلوك اللي للعتبات الخرسانية الحاوية على الالياف الحديدية المسلحة ذاتية الرص بمتغيرات تشمل نسبة حجم الالياف الحديدية (0.4% و0.8%)، التسليح او عدم التسليح بالقضبان الحديدية للعتبات الخرسانية ذاتية الرص والمسافات الفاصلة بين حديد التسليح العرضي (الاطواق). يتضمن الجزء العملي دراسة سلوك تسعة عتبلت تم فحصها تحت تأثير اللي حيث تم تقسيم العتبات الى ثلاث مجموعات. المجموعة (أ) تشير الى العتبات الخرسانية اعتيادية المقاومة ذاتية الرص ، المجموعة (د) تشير الى العتبات الخرسانية اعتيادية المقاومة ذاتية الرص والحاوية على الياف الحديد بنسبة حجمية (0.4%) واخيرا المجموعة (ي) تشير الى العتبات الخرسانية اعتيادية المقاومة ذاتية الرص والحاوية على الياف الحديد بنسب ة حجمية (0.8%). تمت مناقشة النتائج اعتمادا على تصرف اللي - الدوران واستطالة العتبات.

1. Introduction

Self-compacting concrete (SCC) is an extremely fluid yet stable concrete that can flow consistently under its own weight and fill in formwork without the need for consolidation. The application of SCC effectively resolves the difficulties of concreting in situations with complicated formwork and intricate reinforcements. Because the mix design and material selections of SCC differ from that of conventional vibrated concrete, the torsional behavior of SCC may be different from that of conventional vibrated concrete or normal concrete. A proper estimate of torsional effect is important for the design and analysis of SCC beams. Limited information is available on the structural behavior of SCC under this type of effect, which is increasingly being used in casting congested members, as well as the placement of concrete in restricted areas where compaction may not be practical to achieve durable concrete. The research presented herein aims to determine the torsional behavior including cracking torque and ultimate torque capacities of fibrous reinforced self-compacting concrete beams.

1.2 Torsion in Reinforced Concrete Members

Structural members curved in plane, members of a space frame, eccentrically loaded beams, curved box girders in bridges, spiral stair-cases, and spandrel beams located at the perimeter of buildings carry loads from slabs, joists and beams from one side of the member only which generates torsional forces that are transferred from the spandrel beams to the columns. All of these are typical examples of the structural members subjected to torsional moments. The interest in gaining better understanding of the torsional behavior of reinforced concrete members has grown in recent decades. This may be due to the increasing use of structural members in which torsion is a central feature of the behavior such as curved bridge girders and helical slabs. The achievements, however, have not been as much as those made in the areas of shear and bending .

For many years, torsion was regarded as a secondary effect and was not considered explicitly in design, its influence being absorbed in the overall factor of safety of rather conservatively designed structures. Current methods of analysis and design, however, have resulted in less conservatism, leading to somewhat smaller members that, in many cases, must be reinforced to increase torsional strength[1].

2. Experimental Work

In the present research, a series of fibrous SCC beams were tested to investigate the torsional behavior of such beams. The variable parameters and material used in the test program will be explained.

The tests were conducted on nine self-compacting concrete simply supported beams with a square cross section of (15cm × 15cm) and having overall length of 118.5cm (Figure 1). The beams were loaded at the ends with eccentric loads using steel arm of length 56 cm. The clear span which was tested for torsion was 81cm. The main variables in these tests were steel fibers volume fraction(0.4% and 0.8%), reinforced with steel bars or non-reinforced self-compacting concrete beams and spacing of transverse steel bars reinforcement. The reinforcing bars were deformed 6mm diameter for longitudinal and 5mm diameter for stirrups. For all tested beams, 135-degree standard hook was formed at the ends of each stirrups bar. Additional stirrups were placed at the ends of specimen spaced at 3 cm to prevent shear failure at the steel arm region. In the experimental work, three mixes were used. The first mix was non-fibrous normal strength SCC while the second mix was fibrous normal strength SCC with steel fibers volume fraction (V_f =0.4%). The third mix was fibrous normal strength SCC with steel fibers volume fraction (V_f =0.8%). Details of the nine tested concrete beams are shown in Table (1).

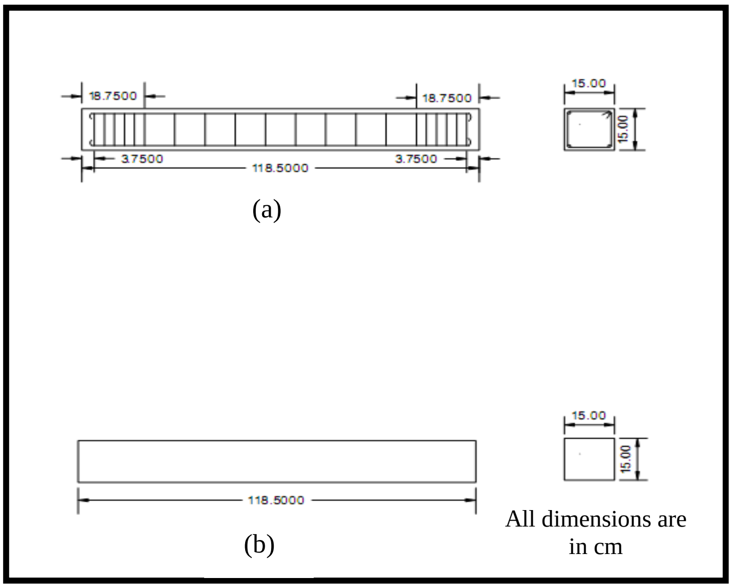


Figure (1) Beams Dimensions and Reinforcing Detailing.

a- Reinforced Concrete Beams with Variable Stirrups Spacing.

b- Concrete Beams without Longitudinal Bars or Stirrups.

Table (1) Details of the Tested Beams

Group	Beam designation	f′c (MPa)	Spacing of stirrups (mm)	%V_f
A	Ap	32.84	-	0
	A100	32.84	100	0
	A80	32.84	80	0
D	Dp	33.29	-	0.4
	D100	33.29	100	0.4
	D80	33.29	80	0.4
E	Ep	34.54	-	0.8
	E100	34.54	100	0.8
	E80	34.54	80	0.8

Group (A) denotes the non-fibrous normal strength SCC beams. Group (D) refers to the fibrous normal strength SCC beams with steel fibers content (V_f) of 0.4%. Group (E) consists of the normal strength SCC with steel fibers content (V_f) of 0.8%.

2.1 Materials

To produce self-compacting concrete, special mixes are required according to the mix design methods of EFNARC 2002[2] and other researchers. SCC materials are similar to materials used in conventional concrete but with some modification.

2.1.1 Cement

In the current research, ordinary Portland cement type I of (Al-jesser) mark made in Iraq was used. Test results of the chemical composition and physical properties are comply with the requirements of the Iraqi Standard Specification I.Q.S. No.5, 1984[3].

2.1.2 Fine Aggregate

The sand which was used in the present research is brought form Al-Ukhaider region in Karbala. It is a natural sand and has fineness modulus of 2.36. The sieve analysis and physical properties comply with the limits of the Iraqi Specification No.45/1984[4].

2.1.3 Coarse Aggregate

Al-Niba'ee region crushed gravel of maximum size 10 mm was used in the present work. The grading of the aggregate and its physical properties agree with the Iraqi specification No.45/1984[4] respectively.

2.1.4 Water

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

2.1.5 Limestone Powder

Limestone powder (locally named Gubra) has been used as filler for SCC production in the present work. It has been found that to increase workability and early strength, as well as to reduce the required compaction energy, the particle size of the limestone powder according to EFNARC 2002[2] must be less than 0.125 mm to be most beneficial.

2.1.6 Superplasticizer

To produce SCC, a superplasticizer known as (High Water Reducing Agent HWRA) was used. It has the trade mark known as Glenium 51. It is compatible with all Portland cements that meet recognized international standards. Glenium 51 is a new generation of modified polycarboxylic ether. Also, it is free from chlorides and complies with ASTM C494-05 [5] types A and F. The concrete which contains superplasticizer exhibits a large increase in slump without segregation(i.e. it has a greater workability).

2.1.7 Steel Reinforcement

In the current research, deformed steel bars of 6mm diameter were used as longitudinal reinforcement with concrete cover of 15mm and deformed steel bars of 5mm diameter were used as stirrups with variable spacing, Figure (2) shows the steel reinforcement and the mold used in casting the beam samples.

2.1.8 Steel Fibers

In the present research work, hooked end mild carbon steel fibers were used. This type of fibers was manufactured in Belgium by N.V. Bekaert Corporation for steel wire fibers

Figure(2) Steel Reinforcement and Wooden Mold

2.2 Mix Design

To meet the self compactability requirements and the designed compressive strength, many trial mixes were carried out in the Laboratory of Constructional Materials at the College of Engineering / AL-Mustansiriyah University. The final mixes which have been used for casting the tested samples were performed in the Structural Laboratory of the College. The SCC mix was designed according to EFNARC 2002[2] to satisfy SCC fresh properties. In the present work, three mix design were made to produce non-fibrous normal strength SCC beams with f'_c=32.84 MPa, fibrous normal strength SCC with volume fraction (V_f=0.4%) and f'c=33.29MPa and finally fibrous normal strength SCC with volume fraction (V_f=0.8%) and f'c=34.54MPa respectively. In each SCC mix, cement content was 400 kg/m^3, fine aggregate content was 797 kg/m^3, coarse aggregate content was 767 kg/m^3, limestone powder content was 170 kg/m^3, water content was 190 l/m^3 and the superplasticizer content was 7.5 l/m^3. The proportion of these components by weight is 1:1.4:1.35 and the w/p(water to powder) ratio is 0.33.

2.3 Mixing Procedure for SCC

In the present research, the laboratory mixing procedure used was outlined by Emborg [6] and modified by Al-Jabri [7]. The procedure is stated as follows:

1. The fine aggregates are added to the mixer with 1/3 quantity of water and mixed for 1minute.

2. The cement and mineral admixtures are added with another 1/3 quantity of water. Then, the mixture is mixed for 1 minute.

3. The coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of superplasticizer, and the mixing time lasts for 1½ minutes then the mixer is left for 1/2 minute to rest.

4. Then, the 2/3 of the leftover of the dosage of superplasticizer is added and mixed for 1½ minutes. Steel fibers are added gradually in this stage if it is present in the mix design.

5. The concrete is then discharged, tested for fresh properties and cast.

2.4 Fresh Properties of SCC

The fresh properties of SCC are listed in Table (2).

Table (2) Results of SCC Fresh Properties

Mix type	Slump flow mm	T_{50} sec	L –box (H1/H2)
N-SCC	770	2.5	1.0
N-SCC-0.4	740	3	0.97
N-SCC-0.8	700	4	0.90
Limits	650-800	2-5	0.8-1.0

2.5 Mechanical Properties of Hardened Concrete

The mechanical properties of SCC including the concrete compressive strength at (28) days of age, flexural strength (modulus of rupture), the splitting tensile strength and the static modulus of elasticity are listed in Table (3).

Table (3) Properties of Hardened SCC

Mix Type	Compressive Strength(f'c) MPa	Modulus of Rupture(fr) MPa	Splitting Tensile Strength(ft) MPa	Modulus of Elasticity(Ec) MPa
Normal Strength SCC	32.84	4.41	3.12	24897
Normal Strength SCC- V_f = 0.4%	33.29	6.32	3.78	25365
Normal Strength SCC-V_f = 0.8%	34.54	7.02	4.15	26184

3. Testing Procedure

Torsion application was conducted by placing the tested beams on freely supported rollers at both ends with clear span of 1160mm; lever arm with maximum eccentricity of 560mm with respect to the longitudinal axis of the beam was made from steel sections and attached to the tested beams by four large bolts in each arm. In order to obtain pure torsion, the center of the arms should be within the centerline of supports. A steel channel section of (1.75 m) length was laid diagonally on the lever arms to distribute the load from the center of the universal machine to the arms; Figure (3) shows the test setup. The load was applied at increments of (2 kN), readings were recorded manually using four dial gages (two of them for the angle of twist and the others for elongation). The strain readings of demec points which were attached diagonally at two faces of the tested beams was recorded each (6 kN), Figure(4) shows the dial gages and demec points arrangement. In addition, at each load stage, crack propagation was recorded according to cracks occurrence. The torque is gradually increased up to failure of the tested beam.

3.1 Angle of Twist Measurements

The method used to calculate the angle of twist is performed by using a dial gages attached to the bottom fiber of each end of beam at a point laid at (65 mm) from the center of the longitudinal axis of the beam as shown in Figure (4c). The dial gages recorded the down values to find the twist angle in radians.

3.2 Elongation Measurements

Two dial gages were fixed at the center of the beam ends to measure the elongation of the beam as shown in Figure (4d).

Figure (3), Test setup

(a)

(b)

(c)

(d)

Figure (4), Demec Points and Dial Gauges Arrangement

(a) and (b)-demec points arrangement

(c) and (d)-dial gages arrangement

4. Experimental Results and Discussion

4.1 Test Results of Normal Strength SCC Beams (Group A)

For normal strength self-compacting concrete (SCC), three beams were tested to investigate the influence of the selected experimental variables on the torsional behavior. Two of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter deformed stirrup bar at (100mm and 80mm) spacing. The third beam was casted from plain concrete. Figures (5) and (6) respectively show the torque-twist and torque-elongation behavior of normal strength SCC. The values of cracking and ultimate torques and corresponding angle of twists and elongations are shown in Table (4) .In the present research, the tested beams having stirrup spacing of 80mm were designed to have minimum transverse and longitudinal steel reinforcement according to volumetric ratio of steel of about 1% to avoid the failure of beam at cracking torque [8]. Beam (A80) was chosen to be the reference beam.

For beam (Ap) which was plain SCC beam, the cracking torque was equal to ultimate torque and equal to 1.12 kN.m. The plain concrete beams practically had no torsional ductility because of the absence of steel reinforcement in longitudinal and transverse direction which resisted the applied torque beyond the cracking stage. The formation of a first inclined crack occurred when the ultimate torque was applied. The beam failed suddenly and separated into two parts, Figure (7). The torque-twist behavior of beam (Ap) is shown in Figure (5) and it is approximately constant up to 50% of the ultimate torque.

For the reference beam (A80), diagonal crack was observed at 3.36 kN.m applied torque. At larger values of the applied torque, the diagonal cracks at different regions of the tested beam were formed; these cracks joined together and formed a single major spiral crack. As the applied torque increased, spiral cracks developed at about 45 degrees to the longitudinal axis of the beam and spread over the test region. Because the beam was reinforced with equal amounts of reinforcement in both longitudinal and transverse directions, all cracks were inclined at 45 degrees throughout the loading history as shown in Figure (8). The ultimate torque capacity of beam (A80) is 8.96 kN.m. The tested beam (A80) shows ductile behavior which is due to the presence of reinforcing steel bars in both longitudinal and transverse directions. Beam (A100) in which the stirrups spacing is larger than the spacing of the reference beam (A80) by 25%, the first diagonal crack initiated at a value of torque equal to 2.8 kN.m. The formation of diagonal and spiral cracks continued until the maximum torque capacity was reached at 6.4 kN.m ,Figure (9).

Table (4) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of Normal Strength SCC Beams (Group A)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr}
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	
Ap	1.12	0.2292	0.04	1.12	0.2292	0.04	1.00
A80	3.36	0.2820	0.00	8.96	2.3522	1.04	2.66
A100	2.80	0.0793	0.75	6.44	0.3614	4.24	2.30

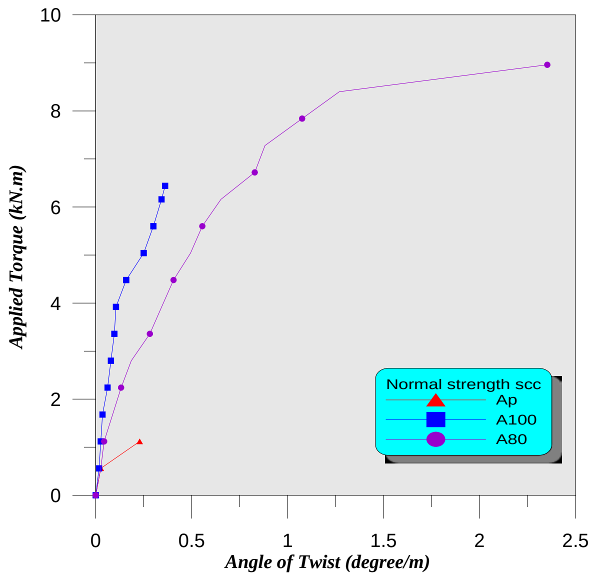


Figure (5), Torque -Twist Behavior of Normal Strength SCC Beams (Group A)

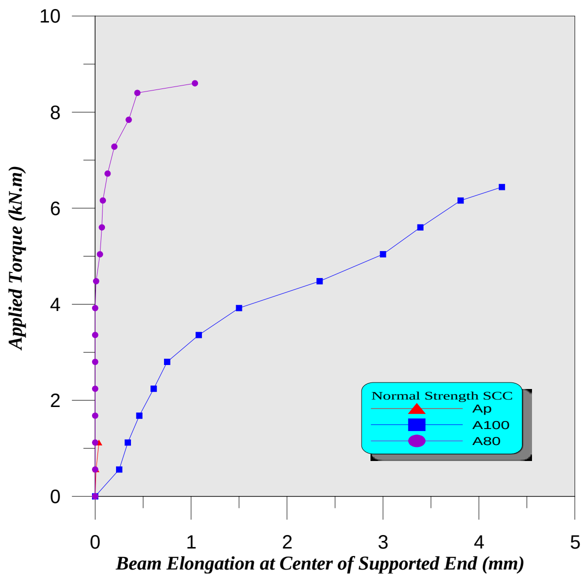


Figure (6), Beam Longitudinal Elongation of Normal Strength SCC Beams (Group A)

Figure (7), Failure Mode of Normal Strength SCC Beam (Ap)

Figure (8), Crack Pattern and Failure Mode of Normal Strength SCC Beam (A80)

Figure (9), Crack Pattern and Failure Mode of Normal Strength SCC Beam (A100)

4.2 Test Results of Fibrous SCC Beams (Group D,Vf =0.4%)

In group D, three SCC beams with steel fibers content of (V_f = 0.4%) were tested to investigate the torsional response of these beams with the considered variables. Two of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter stirrup deformed bars at (100mm and 80mm) spacing. The third was without reinforcing steel (with steel fibers only). The torque-twist and torque- longitudinal elongation behavior of (group D) are shown in Figures (10) and (11) respectively. Values of cracking and ultimate torques and corresponding angles of twist and elongations are shown in Table (5).

For beam (Dp), which had no longitudinal or transverse reinforcement, the presence of steel fibers in the SCC mix provides more closely spaced cracks which means narrower crack width. The cracking torque of this beam is equal to the ultimate torque and both are equal to 2.38 kN.m. The ultimate torque of beam (Dp) is greater than the ultimate torque of beam (Ap) by 112% . Failure mode of this beam differs from the mode occurring in previous plain SCC beams because the beam remained one part and has a spiral single crack around its longitudinal axis .Finally, Figure (12) shows failure mode of beam (Dp).

For beam (D80), the cracking torque was 3.36 kN.m which is the same value as that obtained for beam (A80). While the ultimate torque was 14.28 kN.m which is greater than ultimate torque of beam(A80) by about 37% . From the behavior of self-compacting concrete beams of (group D) with(V_f =0.4%) steel fibers, it can be concluded that for the same torque value, the longitudinal elongation occurring in this group is less than that of non-fibrous beams of group (A) because the steel fibers prevent the formation of wider cracks which leads to smaller elongation. For beam (D100), the first crack was observed at a torque value of 2.92 kN.m which is slightly greater than cracking torque of beam (A100) which is 2.8 kN.m. The ultimate torque of beam (D100) was 11.84 kN.m which is greater than ultimate torque of beam (A100) by about 78%.

Crack propagation and width are similar to the crack pattern occurring in beam (D80). Obviously, the cracks occurring in these two beams are narrower than cracks occurring in the non-fibrous beams of group (A). Finally, both beams (D80 and D100) have ductile behavior as shown in Figure(10). Figures (13) and(14) respectively show the crack pattern and failure mode of beams(D80) and (D100).

Table (5) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of Fibrous SCC Beams (Group D,Vf =0.4%)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr} (%)
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm	
Dp	2.38	0.3614	0.79	2.38	0.3614	0.79	1.00
D80	3.36	0.0763	0.00	14.28	4.4070	0.73	4.25
D100	2.92	0.2644	0.00	11.48	3.8200	0.98	3.93

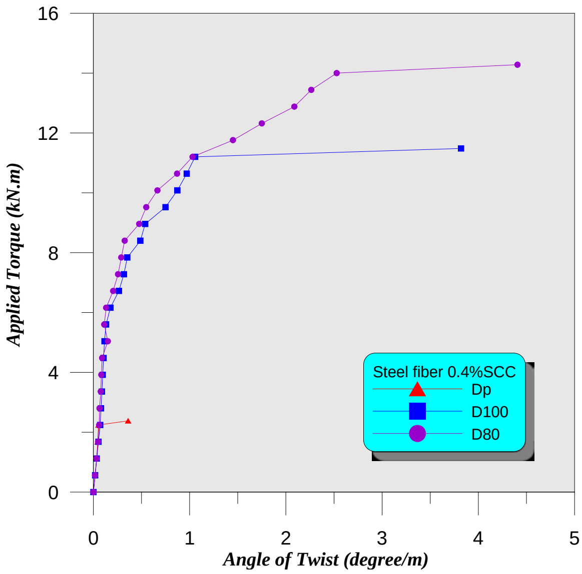
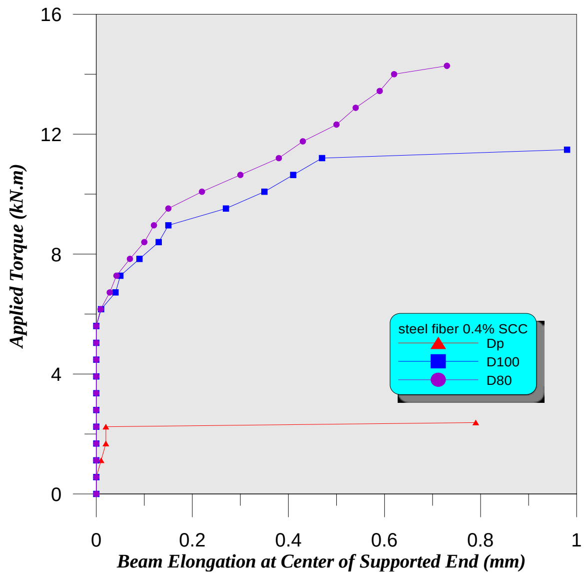


Figure (10), Torque –Twist Behavior of Fibrous SCC Beams (Group D,Vf =0.4%)



Figure(11), Beam Longitudinal Elongation of Fibrous SCC Beams (Group D,Vf =0.4%)

Figure (12), ***Crack Pattern and Failure Mode of Fibrous (V_f =0.4%) SCC Beam (Dp)***

Figure (13), ***Crack Pattern and Failure Mode of Fibrous (V_f =0.4%) SCC Beam (D80)***

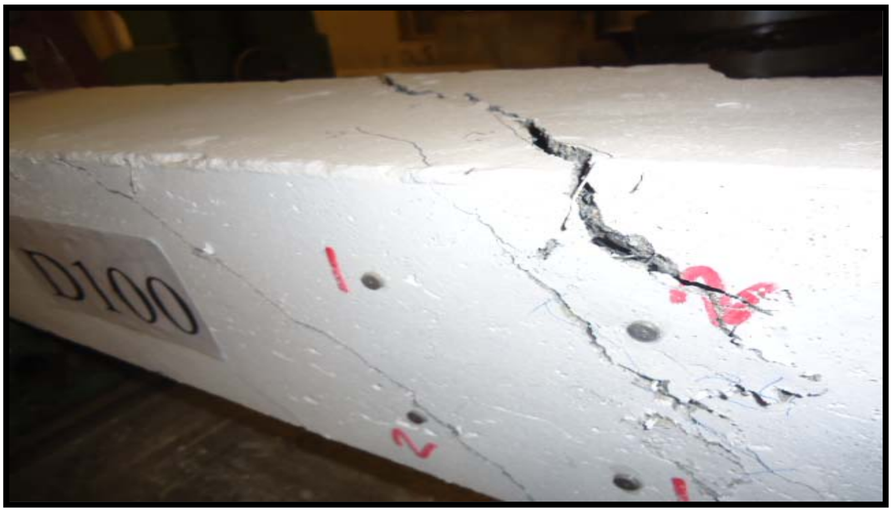


Figure (14), Crack Pattern and Failure Mode of Fibrous (Vf =0.4%) SCC Beam (D100)

4.3 Test Results of Steel Fibers SCC Beams (Group E,Vf =0.8%)

For (group E) ,three SCC beams having steel fibers content of (V_f = 0.8%) were tested to investigate the torsional response of these beams and role of the considered variables. Two of these beams were reinforced longitudinally with 6mm diameter deformed bars and 5mm diameter stirrup deformed bars at (100mm and 80mm) spacing . The third was without reinforcing steel (with steel fibers only). The torque-twist and torque- longitudinal elongation behavior of SCC beams of (group E) are shown in Figures (15) and (16) respectively. Values of cracking and ultimate torques and corresponding angles of twist and elongations are shown in Table (6).

For fibrous SCC beam (Ep), the cracking torque was recorded at a value of 2.8 kN.m. While the torque capacity was 3.08 kN.m. In this SCC beam, the higher percentage of steel fibers increases the ductility and the torsional resistance exceeds the cracking value by about 10%. The cracking torque of beam (Ep) was greater than the cracking torque of beams (Ap) and (Dp) by about 150% and 17.64% respectively. The angle of twist and longitudinal elongation at cracking stage of beam (Ep) were (0.2027 deg./m) and (0.0 mm) which are the smallest values of the other beams (Ap and Dp). The ultimate torque of beam (Ep) was greater than the ultimate torque of beams (Ap) and (Dp) by about 175% and 29.41% respectively. Failure mode of this beam differs from that of plain non-fibrous SCC beams because the beam remains one part and has a spiral single crack around its longitudinal axis. Figure (17) shows the failure mode of beam (Ep).

Beam (E80) had a ductile behavior, the cracking torque of this beam was 4.48 kN.m which is greater than the cracking torques of beams (A80 and D80) by about 33.33%. On the other hand the ultimate torque was 18.48kN.m which is greater than ultimate torques of beams (A80 and D80) by about 106.25% and 29.4% respectively. The last beam of this group was beam (E100) which also had a ductile behavior and a cracking torque of 4.48kN.m, this torque is greater than cracking torques of beams (A100 and D100) by about 60%and 53.4% respectively. Conversely the ultimate torque was 17.36kN.m which is greater than ultimate torques of beams (A80 and D80) by about 169.56% and 51.22% respectively. Figures (18) and(19) show the cracks pattern and failure mode of beam(E80) and (E100) respectively.

Table (6) Values of Torque and Corresponding Angle of Twist and Elongation at Cracking and Ultimate Stages of Fibrous SCC Beams (Group E, Vf =0.8%)

Beam Designation	Cracking stage			Ultimate stage			T_u/T_{cr}
	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	Torque (kN.m)	Angle of twist (deg./m)	Elong-ation (mm)	
Ep	2.80	0.2027	0	3.08	0.7492	0.98	1.10
E80	4.48	0.1146	0	18.48	3.7140	1.32	4.13
E100	4.48	0.2027	0	17.36	3.0246	1.80	3.88

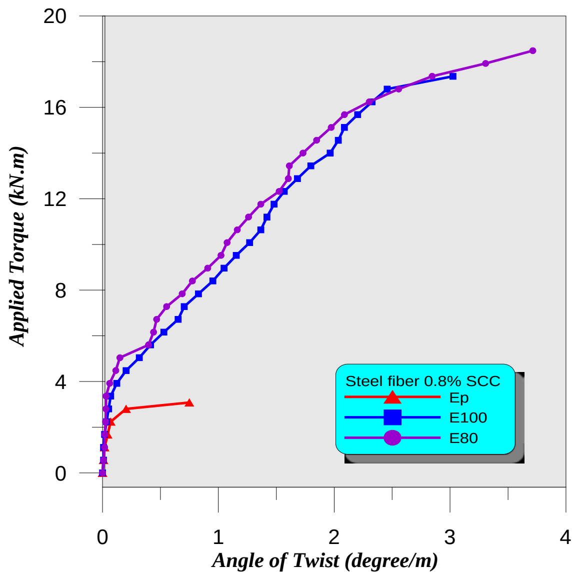


Figure (15), Torque –Twist Behavior of Fibrous SCC Beams (Group E,Vf =0.8%)

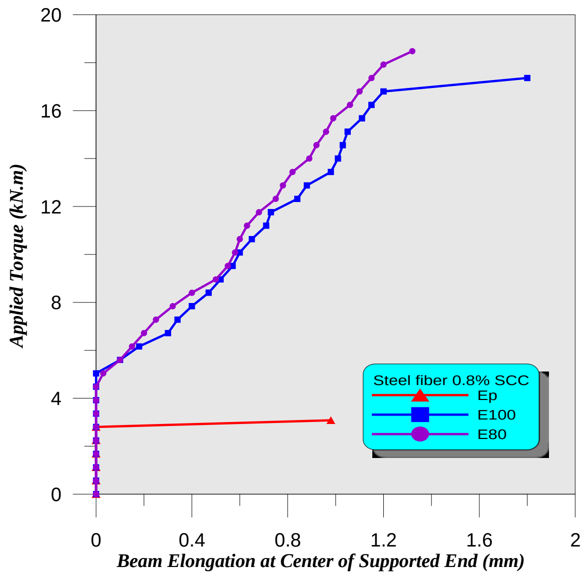


Figure (16), Beam Longitudinal Elongation of Fibrous SCC Beams (Group E,Vf =0.8%)

Figure (17), ***Crack Pattern and Failure Mode of Fibrous (V_f =0.8%)SCC Beam (Ep)***

Figure (18), ***Crack Pattern and Failure Mode of Fibrous (V_f =0.8%)SCC Beam (E80)***

Figure (19), Crack Pattern and Failure Mode of Fibrous (V_f =0.8%)SCC Beam (E100)

5. Conclusions

Based on the results of this study, the following can be concluded:

1- For non-fibrous and fibrous(V_f=0.4%)self-compacting concrete beams without longitudinal reinforcement or stirrups, cracking torque is equal to ultimate torque. The ultimate torque is slightly higher than cracking torque in corresponding fibrous beam (V_f=0.8%).

2- The using of fibrous normal strength self-compacting reinforced concrete beams(V_f=0.4%) yields a 60% to 80% of increase in ultimate torque in comparison with non-fibrous normal strength self-compacting concrete beams depending on the stirrups spacing .

3- The using of fibrous normal strength self-compacting concrete beams(V_f=0.8%) yields a 100% to 160% of increase in ultimate torque in comparison with non-fibrous normal strength self-compacting concrete beams depending on the stirrups spacing .

4- Depending on the stirrups spacing, the using of fibrous (V_f=0.8%) normal strength self-compacting concrete beams yields a 30% to 50% of increase in ultimate torque in comparison with fibrous (V_f=0.4%) normal strength self-compacting concrete beams.

6. References

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