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Torsion Behavior of Steel Fibered High Strength Self Compacting Concrete Beams Reinforced by GFRB Bars

Khaled S. Ragab and Ahmed S. Eisa

***Abstract*—**This paper investigates experimentally and analytically the torsion behavior of steel fibered high strength self compacting concrete beams reinforced by GFRP bars. Steel fibered high strength self compacting concrete (SFHSSCC) and GFRP bars became in the recent decades a very important materials in the structural engineering field. The use of GFRP bars to replace steel bars has emerged as one of the many techniques put forward to enhance the corrosion resistance of reinforced concrete structures. High strength concrete and GFRP bars attract designers and architects as it allows improving the durability as well as the esthetics of a construction. One of the trends in SFHSSCC structures is to provide their ductile behavior and additional goal is to limit development and propagation of macro-cracks in the body of SFHSSCC elements. SFHSSCC and GFRP bars are tough, improve the workability, enhance the corrosion resistance of reinforced concrete structures, and demonstrate high residual strengths after appearance of the first crack. Experimental studies were carried out to select effective fiber contents. Three types of volume fraction from hooked shape steel fibers are used in this study, the hooked steel fibers were evaluated in volume fractions ranging between 0.0%, 0.75% and 1.5%. The beams shape is chosen to create the required forces (i.e. torsion and bending moments simultaneously) on the test zone. A total of seven beams were tested, classified into three groups. All beams, have 200cm length, cross section of 10×20cm, longitudinal bottom reinforcement of 3 10, longitudinal top reinforcement of 2Φ10, additional longitudinal steel 1Φ8 in the mid height of each side and closed stirrups equal to 10Φ8/m in the tested zone. Group one is considered as a reference group which is consisted of two beams were casted from ordinary concrete. A beam was reinforced by steel bars and the other was reinforced by GFRP bars. Group two is consisted from two beams were casted from self compacting concrete with steel fibers volume fraction equal to 0.0% and 0.75% and were reinforced by GFRP bars. Group three is consisted from three beams were casted from high strength self compacting concrete with steel fibers volume fraction equal to 0.0, 0.75% and 1.5% and were reinforced by GFRP bars. An analytical study is used formulas from previous studies to model the tested beams and numerical results are validated with the experimental results. It is found that the effect of steel fibered high strength self compacting concrete (SFHSSCC) on the beams reinforced by GFRP bars enhances the ultimate loads under torsion moments. The present work describes the experimental and the numerical research carried out, and presents the main obtained results.

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I. Introduction

FIBRE Reinforced Polymer (FRP) materials are becoming a new age material for concrete structures. The advantages of the FRP materials lie in their better structural performance especially in aggressive environmental conditions in terms of strength and durability (Machida 1993[4]; ACI 440R-96 1996 [6]; Nanni 1993 [5]). FRP materials are commercially available in the form of cables, sheets, plates etc. But in the recent times FRPs are available in the form of bars which are manufactured by pultrusion process whish are used as internal reinforcements as an alternate to the conventional steel reinforcements. These FRP bars are manufactured with different surface imperfections to develop good bond between the bar and the surrounding concrete. Fibre reinforcements are well recognised as a vital constituent of the modern concrete structures. FRP reinforcements are now being used in increasing numbers all over the world. FRP reinforcements are preferred by structural designers for the construction of seawalls, industrial roof decks, base pads for electrical and reactor equipment and concrete floor slabs in aggressive chemical environments owing to their durable properties.

Due to the advantages of FRP reinforcements in mind, many research works have been carried out throughout the worl d on the use of FRP reinforcing bars in the structural concrete flexural elements like slabs, beams, etc. (Nawy *et al.*, 1997 [7]; Faza and GangaRao, 1992 [3]; Sivagamasundari *et al*., 2008 [11]). Steel fibers can significantly enhance toughness of concrete and inhibit the initiation and growth of cracks. Addition of steel fibers into concrete improves mechanical behavior, ductility, and fatigue strength of concrete. Steel fibers change the properties of hardened concrete significantly. However, addition of fibers to fresh concrete results in a loss of workability and Self-compacting concrete (SCC) able to flow under its own weight, completely filling formwork and achieving full compaction without vibration. So, this paper studied composites of SCC and HSCC with steel fibers for further property enhancement. The SCC has been widely employed to produce beams of complex shapes and/or with high density of reinforcement structures.

Therefore the main objective of this study is to investigate experimentally behavior and capacity of steel fibers reinforced high strength self compacting concrete (SFRHSCC) of beams reinforced internally with Glass Fibre Reinforced Polymer (GFRP) under torsion, in which, a total of seven beams was tested. The paper performed an evaluation of accuracy of existing models and formulas in previous studies that used to predict torsion behavior of steel fibered high strength self compacting concrete beams reinforced by GFRP bars.

II. Experimental Work

A. Experimental Program

A total of seven beams were tested, classified into three groups. All beams, have 200cm length, cross section of 10×20cm, longitudinal bottom reinforcement of 3Φ10, longitudinal top reinforcement of 2Φ10, additional longitudinal steel 1Φ8 in the mid height of each side and closed stirrups equal to 10Φ8/m in the tested zone as shown in Fig. 1. Group one is considered as a reference group which is consisted of two beams were casted from ordinary concrete. A beam was reinforced by steel bars and the other was reinforced by GFRP bars. Group two is consisted from two beams were casted from self compacting concrete with steel fibers volume fraction equal to 0.0% and 0.75% and were reinforced by GFRP bars. Group three is consisted from three beams were casted from high strength self compacting concrete with steel fibers volume fraction equal to 0.0, 0.75% and 1.5% and were reinforced by GFRP bars. Strain gauges of 10mm length, 120ohms, and 2.04gauge factor were fixed with steel bars before casting, facing the out side of the beams using epoxy, then a wax film was layered at the top of the strain gauge to protect it. Each beam has four strain gauges; two were placed in the mid length of the longitudinal lower and upper corner bar and the other two at the same point in the transverse bar (stirrup) one on the vertical branch of the stirrups and other on the horizontal branch of the stirrups. The following Table I shows the standard cube compressive strength after 28 days for each beam and its description.

B. Materials

Ordinary Portland cement was CEM1 of grade 52.5 obtained from Suez – Factory in Egypt, and complies with ESS 4756-1-2006 [10]. Silica fume was a very fine by – product powder obtained as a fume from the foundry process in the Egyptian company for Iron Foundries. Fly Ash used in the concrete mix was imported from India through Goise Company in Egypt, and complies with ASTM C618 class F [8]. The Blaine fineness of the ash is 3200 cm2/gm and its specific gravity is 2.2. Steel fibers were obtained from Master Chemical Technology Company in Egypt. Type of steel fibers is double hooked edge, 0.6mm diameter, 30mm length, 50 aspect ratio, and 850 MPa tensile strength. Fig. 2 shows the shape of steel fibers and reinforcement of tested beams. Coarse aggregate used in self compacted beams was crushed dolomite with nominal maximum size of 10mm obtained from Attaka quarry , white fine aggregate was natural sand obtained from pyramids quarry in Egypt and complies with ESS 1109 , 2008 [12]. Polycorboxylate ether polymer glenium ASE 30 obtained from Basf Company in Egypt was used to produce self-compacted concrete mixes. Deformed high-grade steel bars of yield strength 400 MPa and 10 mm diameter was used.

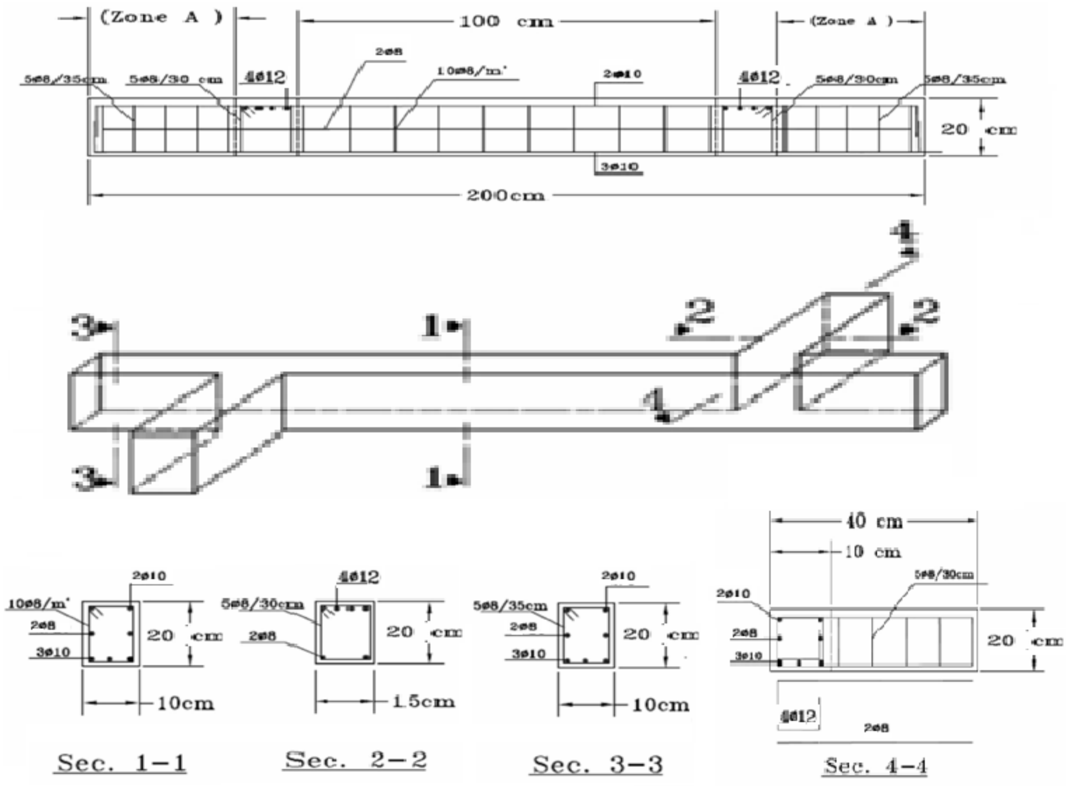

Fig. 1 Reinforcement details of tested beams

TABLE I
STANDARD CUBE COMPRESSIVE STRENGTH AND BEAM DESCRIPTION

Specimen	Symbol	Description	F_{cu} 28 day (MPa)
B11,B1	OC	Ordinary Concrete	30
B2	SCC	Self Compacted Concrete	45
B3	HSCC	High strength Self Compacted concrete	90
B4	SCC, V_f 0.75%	SCC with steel fiber 0.75%	45
B5	HSCC, V_f 0.75%	HSCC with steel fiber 0.75%	90
B6	HSCC, V_f 1.5%	HSCC with steel fiber 1.5%	90

Fig. 2 Shape of steel fibers and reinforcement of tested beams

C. GFRP bars

The GFRP strips used for stirrups were of 8 mm thickness and for main longitudinal (lower) GFRP bars were of 10 mm and upper 8 mm diameter as shown in Fig. 1 and 2. Table II shows the mechanical properties of the GFRP bars. The GFRP bars and strips were locally manufactured. The bars were covered by layer of raped fiber to improve its bond to concrete.

TABLE II
MECHANICAL PROPERTIES OF GFRP BARS

Fiber Volume Fraction %	34 - 38
Ultimate Tensile Strength (MPa)	344.9 - 373.4
Modulus Of Elasticity (MPa)	42300 - 46100
Bond Strength (MPa)	2.069 - 2.207

D. Test Measurements and Instrumentation

The tested beams were load gradually with load increment of 1 ton up to failure. The recorded data were Cracking, ultimate load capacity, concrete strains, and reinforcement strains. The vertical strains in concrete beams were measured using three linear variable displacement transducers (LVDTs). Two at two arms of torsion and the third at mid length of beam span as shown in Fig. 3. The data from (LVDTs) were connected to data acquisition system (DAS), while steel strain gauges were connected to strain indicator device to get steel strains directly.

E. Test Results of Specimens

Concrete mixes were prepared and summarized in six mixes as shown in Table II. The cement content was 350 Kg/m^3 for normal strength beams , while increased to 500 Kg/m^3 for high strength ones. Silica fume was 15% of cement content in all mixes, fly ash was 10% of cement content in all self compacted mixes, water – binder ratio was 0.35 for all self compacted mixes, the super plasticizer ratio was 2.5% to achieve self compacted beams with steel fibers. Steel fiber of double hooked edge was added to mix no. 4, 5 with ratio 0.75% and to mix no. 6 with ratio 1.5%. Filling ability and viscosity of self compacted concrete were evaluated using slump flow test according to ESS 1109, 2008 [12], their results are recorded at the end of Table II.

F. Test Procedure

All beams were tested in torsion simply supported under load applied. The set up of each test consisted of installing the tested beam in a horizontal position between machine heads, the machine heads insured that the load eccentricity was maintained at all stages of the loading and also head bearing plates were adjusted to prevent any eccentricity from wrong position. All beams were tested using capacity hydraulic Jacks machine in reinforced concrete laboratory in H.B.R.C. Fig. 3 (a) shows test setup and Fig. 3 (b) shows the details of tested beams and positions of LVDTs.

TABLE II
CONCRETE MIX DESIGN

Beam No.	**Type of Mix**	**Mix Proportions (Kg)**									**Fresh test**	
		Cement	**Sand**	**Coarse aggregate**		**Steel fibers**	**FA**	**SF**	**Add.**	**Water (Liter)**	**Slum (cm)**	**Slump flow (cm)**
				C.agg1	**C.agg2**							
B11,B1	OC	350	750	550	550	-	-	-	-	225	6	-
B2	SCC	350	950	950	-	-	35	52.5	10	172	26	65
B3	HSCC	500	850	850	-	-	50	75	14	180	26	66
B4	SCC V_f 0.75%	350	950	950	-	58.5	35	52.5	11	183	10	60
B5	HSCC V_f 0.75%	500	850	850	-	58.5	50	75	14	198	28	80
B6	HSCC V_f 1.5%	500	850	850	-	117	50	75	16	187	27	70

OC: Ordinary concrete, SCC: Self compacted concrete, HSCC: High strength self compacted concrete, V_f: percentage of fiber volume fraction, FA: fly ash, SF: silica fume, and Add.: admixture.

III. TEST RESULTS AND DISCUSSION

A.Failure Modes and Crack Patterns of Test Specimens

Failure mode of all tested specimens was torsional moment (Mt) as shown in Fig. 3 (b), Table III shows the test results of all tested specimens including; specimens' description, ultimate load, ultimate torsional moment, and angle of twist. The initial cracks were observed in the top surface of the test zone then diagonal cracks were developed and increased with the load.

Typical torsional spiral cracks developed around the specimens. The cracks inclination torque was approaching the cracks widened, then concrete concrete at the top surface abruptly crushed. Beams without steel fibers failed in very brittle manner, where, concrete cover fell apart. The beams with steel fibers failed in more ductile mode. In these beams, typical cracking patterns around the surface of these beams were observed, cracks formed uniformly with smaller width due bridging effect of steel fibers. By observing the test results, it can be concluded that the steel fibers improve significantly concrete torsional moment. Fig. 3 (b) shows the failure modes and crack patterns of the tested specimens.

TABLE III
TEST RESULTS

Specimen	Concrete properties	Compressive strength, F_{cu} (MPa)	Fiber volume fraction, V_f (%)	Ultimate load, P_u (kN)	Torsional moment T_u (kN-m)	Angle of twist per length θ_u(rad/m)
B11 B1	OC	30	0.0	30.1 15.5	4.5 2.3	0.03244 0.02681
B2	SCC	45	0.0	22.4	3.36	0.00634
B3	HSCC	90	0.0	30.0	4.5	0.04616
B4	SCC	50	0.75	25.0	3.75	0.03293
B5	HSCC	90	0.75	33.6	5.04	0.01785
B6	HSCC	90	1.5	33.8	5.07	0.03031

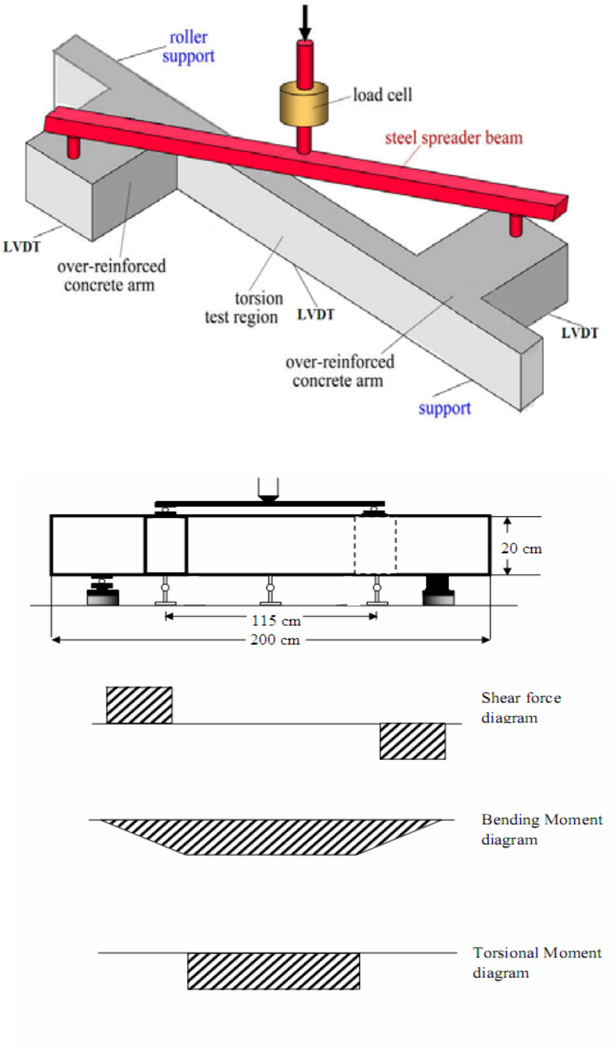

Fig. 3 (a) Test set up

Fig. 3 (b) Details of tested beams and positions of LVDTs

Fig. 4 (a) Failure modes and crack patterns of the tested beam B11

Fig. 4 (b) Failure modes and crack patterns of the tested beam B1

Fig. 4 (c) Failure modes and crack patterns of the tested beam B2

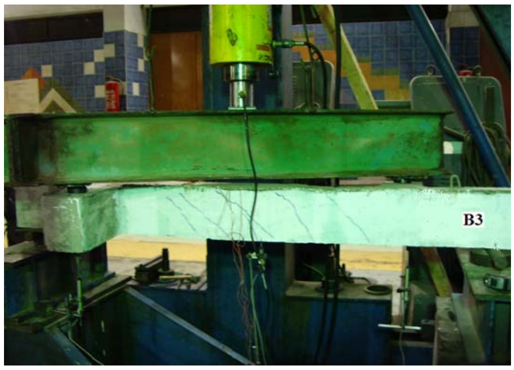

Fig. 4 (d) Failure modes and crack patterns of the tested beam B3

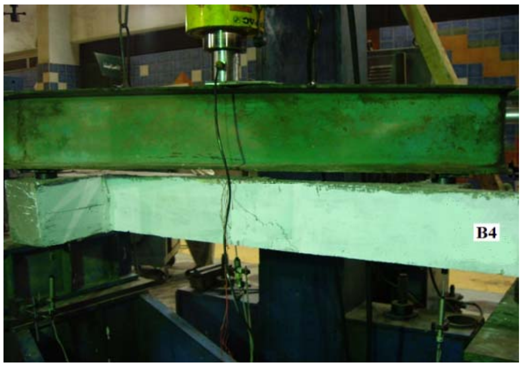

Fig. 4 (e) Failure modes and crack patterns of the tested beam B4

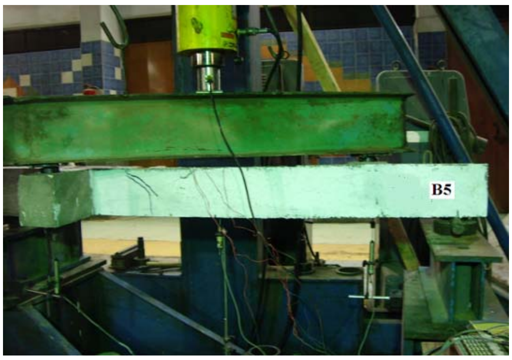

Fig. 4 (f) Failure modes and crack patterns of the tested beam B5

Fig. 4 (g) Failure modes and crack patterns of the tested beam B6

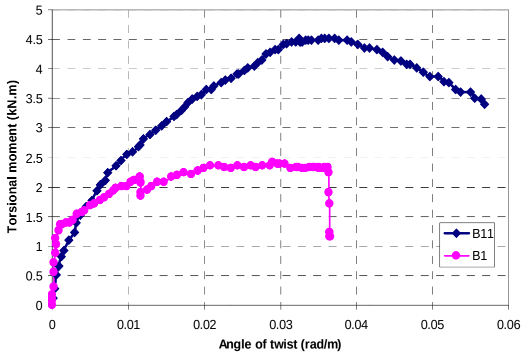

Fig. 5 Comparison between steel and GFRP

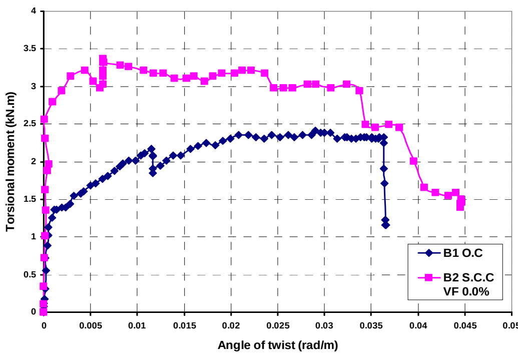

Fig. 6 Comparison between ordinary concrete and self compacted concrete

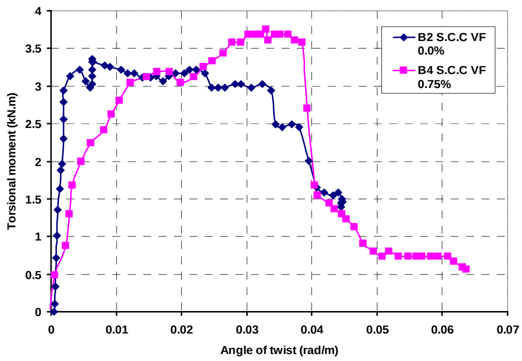

Fig. 7 Effect of change percentage of steel fibers volume fraction Vf% in S.C.C

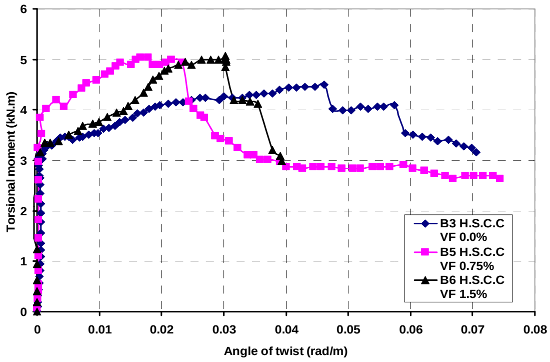

Fig. 8 Effect of change percentage of steel fibers volume fraction Vf% in H.S.C.C

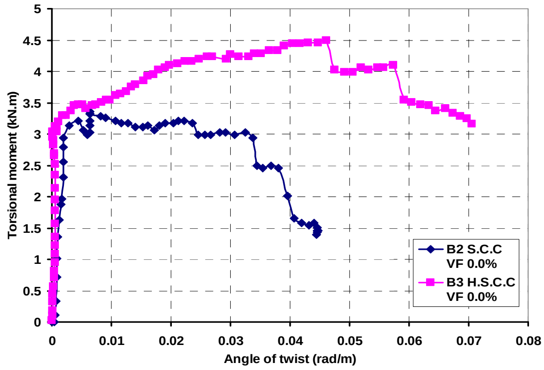

Fig. 9 Effect of strength of S.C.C

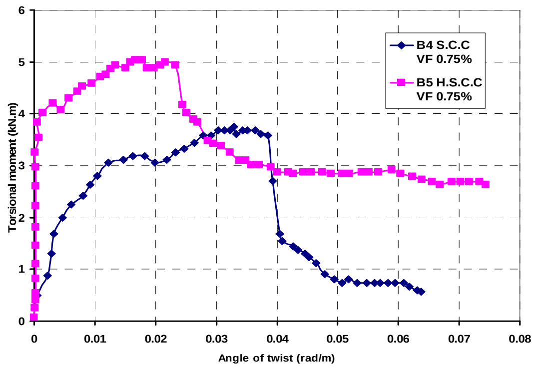

Fig. 10 Effect of change of Fcu in S.C.C with steel fibers Vf=0.75%

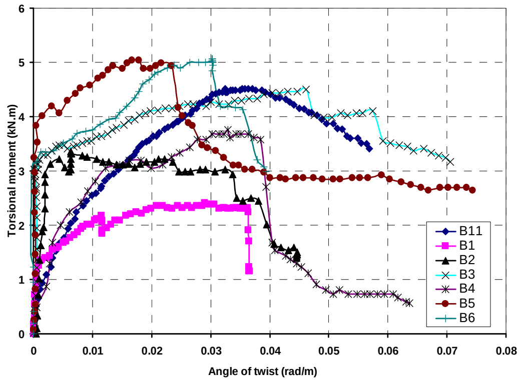

Fig. 11 Relation between torsional moment and angle of twist for all specimens

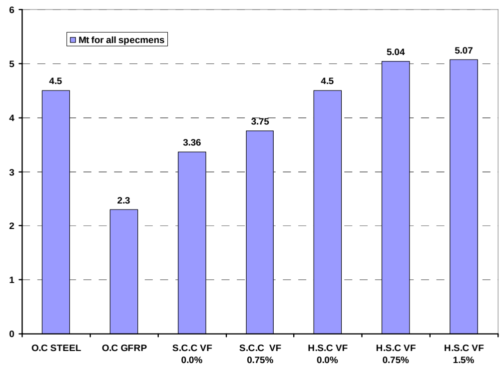

Fig. 12 Comparison for torsional moment for all specimens

B. Torsional Moment and Angle of Twist Analysis

Based on the experimental results, the behavior of the tested beams is discussed in terms of observed behavior, concrete types, ultimate load, torsional moment, and angle of twist as shown in Table III and Figs from 5 to 12 which indicate that the relationship between torsional moment and angle of twist at the torsional zone of the beam was typical for all the tested beams, an approximate linear increase behavior followed by a nonlinear behavior until failure.

1. Comparison between Beams Reinforcement by Steel and Other by GFRP (B11, B1)

Beam-11 was reinforced by steel and beam-1 was reinforced by GFRP. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 5 was plotted. As shown in Table III the beam-11 failed commpletely in torsion at a load 30.1 kN and torsional moment 4.5 kNm and the beam-1 failed commpletely in torsion at a load 15.5 kN and torsional moment 2.3 kNm. This meaning that the beams which using GFRP as reinforcement causes that the ultimate load and the ultimate torsion moment decreases to half value comparison to beams reinforcement by steel. This phenomena may be occurs because worst indusdrial of the correr GFRP stirrups. Also, the angle of twist for (B1) is bigger than the angle of twist for (B11) because GFRP having lower of youngs of modulus than youngs of modules for steel. It was found that the crack were appeared making an angle 40-50 degree with the main beam on the side faces and top surface as shown in Fig. 4 (a) and (b). The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

2. Comparison between Beams Excuted by Ordinary Concrete and Other by Self Compacted Concrete (B1, B2)

Beam-1 was excuted by ordinary concrete and beam-2 was excuted by self compacted concrete. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 6 was plotted. As shown in Table III the beam-1 failed commpletely in torsion at a load 15.5 kN and torsional moment 2.3 kNm and the beam-2 failed commpletely in torsion at a load 22.4 kN and torsional moment 3.36 kNm. This meaning that the beams which used self compacted concrete causes that the ultimate load and the ultimate torsion moment increases by 45% comparison to beams used ordinary concrete. Also, using self compacted concrete causes decreases in the angle of twist comparison to beams used ordinary concrete. This phenomena occurs because the compressive strength for self compacted concrete equal to 45 Mpa whish is hgier than ordinary concrete by 50% although the percentage of cement in the two beams is the same. It was found that the crack were appeared making an angle 40-50 degree with the main beam on the side faces and top surface as shown in Fig. 4 (a), (c). The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

3. Effect of Change Percentage of Steel Fibers Volume Fraction Vf% in S.C.C (B2, B4)

Beam-2 was excuated by self compacted concrete with steel fibers volume fraction Vf% equal to zero and beam-4 was excuated by self compacted concrete with steel fibers volume fraction Vf% equal to 0.75%. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 7 was plotted. As shown in Table III the beam-2 failed commpletely in torsion at a load 22.4 kN and torsional moment 3.36 kNm and the beam-4 failed commpletely in torsion at a load 25.0 kN and torsional moment 3.75 kNm. This meaning that the beams which using steel fibers volume fraction Vf% equal to 0.75% causes that the ultimate load and the ultimate torsion moment increases with percentage 10% comparison to beams without steel fibers volume fraction. This phenomena may be occurs because steel fibers making bridges acrose the cracks and delay progressive of cracks and this delay makes increse in the ultimate loads with 10% and decrease in the number and width of cracks. It was found that the crack were appeared making an angle 45-60 degree with the main beam on the side faces and top surface as shown in Fig. 4 (c), (e). The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

4. Effect of Change Percentage of Steel Fibers Volume Fraction Vf% in H.S.C.C. (B3, B5, B6)

Beam-3 was excuated by high self compacted concrete with steel fibers volume fraction Vf% equal to zero and beam-5 and beam-6 were excuated by high self compacted concrete with steel fibers volume fraction Vf% equal to 0.75% and 1.5% respectively. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 8 was plotted. As shown in Table III the beam-3,5,6 failed commpletely in torsion at a load 30.0, 33.6, 33.8 kN respectively and torsional moment 4.5, 5.04, 5.07 kNm respectively. This meaning that the beam-5 which using steel fibers volume fraction Vf% equal to 0.75% causes that the ultimate load and the ultimate torsion moment increases with percentage 10% comparison to beams without steel fibers volume fraction. This phenomena may be occurs because steel fibers help to bridge cracks in the whole concrete volume and transfer tensile stress through two opposite faces of cracks until the fibers are totally pulled-out or broken. For this reason, in stage of initiation and propagation of cracks, tensile zone of steel fibers self compacting concrete beams (SFRSCC) still sustains load. This increases concrete tensile strength and indirectly leads to increase the torsion moment of the beams. Change percentage of steel fibers volum fraction Vf% from 0.75% (B5) to 1.5% (B6) was given little change in the value of ultimate load or torsion moment. The reason of this little change because the higher value of concrete tension ruptur for high strength self compacted concrete and it may be needed to increase percentage of steel fibers volum fraction Vf% than 1.5%. It was found that the crack were appeared making an angle 45-60 degree with the main beam on the side faces and top surface as shown in Fig. 4 (d), (f), (m). The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

5. Effect of Strength of S.C.C. (B2, B3)

Beam-2 was excuated by self compacted concrete with steel fibers volume fraction Vf% equal to zero and beam-3 was excuated by high self compacted concrete with steel fibers volume fraction Vf% equal to zero. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 9 was plotted. As shown in Table III the beam-2 failed commpletely in torsion at a load 15.5 kN and torsional moment 2.3 kNm and the beam-3 failed commpletely in torsion at a load 30.0 kN and torsional moment 4.5 kNm. This meaning that the beam B3 which using high self compacted concrete with steel fibers volume fraction Vf% equal to zero causes that the ultimate load and the ultimate torsion moment increases with percentage equal to the same percentage increasesing in the compressive strength. This phenomena may be occurs because the big defference in the compersive strength in the beam-2 and beam-3. It was found that the crack were appeared making an angle 40-50 degree with the main beam on the side faces and top surface as shown in Fig. 4. The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

6. Effect of change of Fcu in S.C.C with steel fibers Vf=0.75% (B4, B5)

Beam-4 was excuated by self compacted concrete with steel fibers volume fraction Vf% equal to 0.75% and beam-5 was excuated by high self compacted concrete with steel fibers volume fraction Vf% equal to 0.75%. Using the load and deflection data from experment, the corresponding torsion moment and twisting angle were calculated and the graph as shown in Fig. 10 was plotted. As shown in Table III the beam-4 failed commpletely in torsion at a load 25.0 kN and torsional moment 3.75 kNm and the beam-5 failed commpletely in torsion at a load 33.6 kN and torsional moment 5.04 kNm. This meaning that the beam B5 which using high self compacted concrete with steel fibers volume fraction Vf% equal to 0.75% causes that the ultimate load and the ultimate torsion moment increases with percentage equal to 30% comparison to B4. The This phenomena may be occurs because the big defference in the compersive strength in the beam-4 and beam-5 but the percentage increasing not the same in the beams without steel fibers (B2, B3). It was found that the crack were appeared making an angle 45-55 degree with the main beam on the side faces and top surface as shown in Fig. 4 (e), (f). The cracks were developed in a spiral pattern all over the main beam which later leads to the collapse of the beam in torsional shear.

7. Relation between Torsional Moment and Angle of Twist for All Specimens

The relation between torsional moment and angle of twist for all specimens shows in Fig. 11. Fig. 12 shows the amount of increase in torsion moment for each beam with respect to control beam.

IV. Evaluation of Torsion Shear Resistance

A. Comparison of Results to Other Models

In this section a series of models and equations will be presented from the work of other researchers and compared to the results obtained during testing. The equations are first presented in this section and then compared to the results obtained during testing in section IV-B.

1. Mansur and Mansur Paramasivam

Mansur [1] and Mansur Parmasivam [2] carried out the tests on steel fiber reinforced concrete beams without reinforcement, in pure bending, pure torsion, torsion-bending, torsion-shear and torsion-bending-shear. Based on the experimental data, they have proposed two modes of failure viz. mode I and mode II.

Mode I: Fibrous concrete beams which are subjected to combined loading under torsion- bending- shear fail by bending about a skewed axis. The compression zone is getting formed at the top face in skewed bending for smaller values of torsion to moment ratio (T/M). Based on the observed failure modes a theoretical model has been proposed by Mansur for the estimate of the ultimate torsional strength of SFRC beams for the combined loading. The model is reflecting the torsional strength as independent of transverse shear as seen from (1).

$$T_{u1} = (1/3) * (bh^2\ \phi\ f_r * (((1/\psi^2)+(1))^{0.5} - (1/\psi))) \quad (1)$$

Mode II: Mode II failure occurs when the torsional moment predominates the bending moment. The compression zone is getting formed at the side face in skewed bending for larger values of torsion to moment ratio. Based on the observed failure modes a theoretical model has been proposed by Mansur and Parramasivam to the estimate of ultimate torsional strength of SFRC beams for the combined loading under consideration. The equation (2) is reflecting the torsional strength as independent of bending moment.

$$T_{u2} = (0.71b^2hf_r) / (3(1+(b/6\alpha)) \quad (2)$$

where T_{u1}= Torsional strength by mode I N mm.,T_{u2} = Torsional strength by mode II N mm.,b = width of the beam section in mm.,h = depth of the beam section in mm.,fr= modulus of rupture of concrete in N/mm2, ψ = T/M ratio, ϕ = 1+ (0.29(1-R)/(1+R), R = (1+(ψ/3K)2)0.5, K = 0.179 for (h/b = 1.5), α= T/V, M = bending moment at failure in N mm,V = shear force at failure in N, $f_r = 0.8\ (f_{cuf})^{0.5}$, f_{cuf} = fiber cube strength in N/mm2, $f_{cu} = f_{cuf}/(1+0.1F)$, fcu= cube strength in N/mm2, F = (L/d) ρ d_f, L/d = aspect ratio of steel fibers, ρ = volume fraction of steel fibers, d_f =bond factor (0.75 for crimped steel fibers).

2. Egyptian Code of Concrete

The equation for calculating the ultimate strength of reinforced concrete beam, recommended by Egyptian code of concrete (code No. 203 Ver. 2004 second edition) [9] for ultimate torsion strength limit state, the maximum shear stresses results from torsion could be calculated at the beam section (closed section) with the maximum torsional moment from the following formula.

$$q_{tu} = T_u / 2A_o * t_e \quad (3)$$

where, A_o is the area inside the shear pass per unit length could be calculated as follow.

$A_o = 0.85\ A_{oh}$ where A_{oh} the area inside the transverse steel using for torsion resistance.

Te is the thickness of the wall equivalent closed section = A_{oh}/P_h where Ph is the perimeter of the transverse steel using for torsion resistance = 2(x+y), where x is the width without cover and y is the depth without cover.

$$q_{tu} = T_u * (x+y)/0.85(xy)(xy) \quad (4)$$

The additional steel to resist the additional stresses resulting from torsional moments could be calculated for the beam section from the following formula.

$$A_{str.} = T_u * S / 1.7\ (xy) * (F_{yst}/\gamma_s) \quad (5)$$

This equation colud be modified as follow for GFRP stirrups.

$$\Phi\ A_{str.} = T_u * S / 1.7\ (xy) * (F_{dg}/\gamma_s) \quad (6)$$

where S is the distance between the stirrups, Φ is the bond reduction factor resulting from low bond between the fiber glass stirrups and the concrete also due to the stresses losses especially at the stirrups corners, and F_{dg} is the design stress of the fiber glass bars (equal to 0.85 of the ultimate strength of the bars).

From the experimental study Φ for the used materials equal to 0.33

B. Compared to the Results Obtained during Testing

Table IV shows the results obtained during testing and the results obtained from equations are presented from the work of other researchers. As shown in Fig. 13 the present study gives good agreement results with the Modified Egyptian Code equation. Egyptian code [9] equation gives results bigger than the present study. Mansur [1] and Mansur Parmasivam [2] Mode II, gives results lower than the present study. The results of the analysis indicate that the best equation for predicting the nominal ultimate torsional strength of beams with steel fibers and reinforced by GFRP is the Modified Egyptian Code equation.

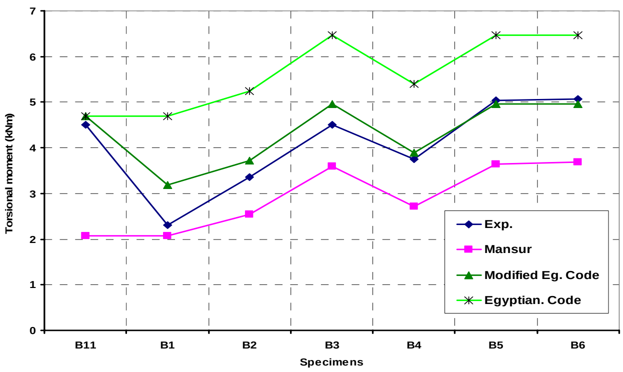

Fig. 13 Comparison of results to other models

TABLE IV
COMPARISON OF RESULTS TO OTHER MODELS

Spec.	Conc.	Exp. T_u (kNm)	Mansur[1,2] T_{u1} (kNm)	Eg. Code [9] T_{u2} (kNm)	Modified Eg. Code T_{u3} (kNm)	$\frac{T_{u1}}{T_{uExp.}}$	$\frac{T_{u2}}{T_{uExp.}}$	$\frac{T_{u3}}{T_{uExp.}}$
B11	OC	4.5	2.074	4.699	4.699	0.461	1.044	1.044
B1	OC	2.3	2.074	4.699	3.182	0.902	2.043	1.384
B2	SCC	3.36	2.540	5.244	3.723	0.756	1.561	1.109
B3	HSCC	4.5	3.592	6.473	4.957	0.798	1.439	1.102
B4	SCC	3.75	2.715	5.404	3.887	0.724	1.441	1.037
B5	HSCC	5.04	3.643	6.473	4.956	0.723	1.285	0.984
B6	HSCC	5.07	3.692	6.473	4.956	0.728	1.277	0.978

V. CONCLUSIONS

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

1. The torsional behavior for concrete beams reinforced by GFRP bars was very close to the same behavior for concrete beams reinforced by normal steel.
2. The use of GFRP bars as a reinforcement in the beams gives half value of ultimate torsion moment compared with beams reinforcement by normal steel.
3. The stirrups manufactured from GFRP bars were not effective as an additional torsional resisting reinforcement; this was due to weak bond between the fiber glass stirrups and the concrete in addition to overstressed stirrups corners.
4. GFRP reinforced concrete beams showed higher angle of twist than the conventional reinforcements. This fact is primarily due to lower elastic modulus and higher tensile strain values for GFRP reinforcements than the steel reinforcements.
5. Torsional strength and angle of twist increases with the in crease in increase grade of concrete.
6. The use of self compacting concrete (SCC) or high strength self compacted concrete (HSCC) improves the ultimate torsion moment compared with ordinary concrete.
7. Steel fibers improve the ultimate torsion moment of the beams considerably. Using steel fibers with volume fraction equal to 0.75% with high self compacted concrete or self compacted concrete is the ideal percentage to increase the ultimate torsion moment with percentage 10% and decrease the number and width of cracks.
8. The study showed that the increase of the punching shear capacity of (SFRHSCC) beams became insensible from the fiber volume fraction over 0.75% to 1.5%. It may be needed to increase the fiber volume fraction than 1.5%.
9. The study showed that the increase of the ultimate torsion moment of (SFRHSCC) beams became insensible compared with (SFRSCC).
10. The beams without fibers failed suddenly in brittle manner, while, the fiber reinforced ones collapsed in more ductile type.
11. The results of the analysis indicate that the best equation for predicting the nominal ultimate torsional strength of beams with steel fibers and reinforced by GFRP is the Modified Egyptian Code equation.

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