

TORSION ENHANCEMENT OF REINFORCED SELF-COMPACTING CONCRETE BOX BEAMS USING INTERNAL FRAMED STEEL STIFFENING RIBS

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Abstract: Researches concerning internal torsional strengthening of box beams are very little, since few researchers may study such method of strengthening. This research adopts employing of internal Framed Steel Stiffening Ribs (FSSRs) to strengthen reinforced Self-Compacting Concrete (SCC) box beams subjected to pure torsion. These FSSRs were fabricated to be fully bonded with SCC through using of bolts as shear connectors. Four specimens (the first was a reference one with no strengthening and the other three were strengthened with one, three and five FSSRs, respectively) of reinforced SCC were tested under effect of pure torsion up to failure. All specimens have the same dimensions and reinforcement. The effect of FSSRs presence and their number on torsional capacity was studied. Also, applied torque-angle of twist relation at end, quarter and mid span were studied. Test results show that the ultimate torsional capacity is increased by 45.7 %, 75.5 %, and 122.4 % for specimens strengthened with one, three and five FSSRs, respectively, as compared with reference specimen. Presence of FSSRs tends to reduce deformations where deformations decrease with increasing of FSSRs number. It is concluded that the torsional capacity of a reinforced SCC box beams can be enhanced using internal Transverse FSSRs. The number of used internal FSSRs have main effect on the amount of enhancement.

Keywords: *Steel Stiffening Ribs, FSSR, Torsion; Strengthening; Concrete; Box beam.*

1. Introduction

1.1. Torsion in structural members

Structural members made of reinforced concrete

are designed to resist flexural, shear, axial, and torsion forces according to loading conditions. Torsion forces are rarely act without bending, shear, or axial forces. Such torsion forces try to twist the member about its axis [1]. Torsional strength is of central feature in analysis and design of many structural members as curved bridges, eccentrically loaded box beams, edge beams in buildings, and helical stairway [1].

When a torque is applied to a member, shearing stresses on cross-sectional planes and on radial planes is developed extending from the axis of the member to its surface. In a circular member, the shearing stresses change, linearly, from zero value at the member axis to a maximum value at the outside of the member section. The maximum shear stress in circular section is constant along the circumference, while it changes from zero value at corners to a maximum value at the centers of the long sides of a rectangular member perimeter [2]. Torsional loading can be separated into two basic categories: *equilibrium torsion*, case of this research, where the torsional moment is required for the equilibrium of the structure, and *compatibility torsion*, where the torsional

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moment results from the compatibility of deformations of members meeting at a joint [2]. Recently, bridges with box girder have widespread use in flyovers of highway and modern light rail transport elevated structures since its torsional stiffness and strength are higher than those of open cross section. It is also accepted in bridge and freeway constructions because of its efficiency, better stability, serviceability, and economy. Furthermore it is easier to maintain the box girder due to simplicity of access to the interior space of the box girder. Rectangular and trapezoidal are commonly used sections in box girder construction [3].

1.2. Self-Compacting Concrete (SCC)

In this research, SCC is used because of small thickness of box section walls, presence of reinforcement as well as with FSSRs.

SCC is a mix with no need of vibration to expel air out of it and travels round obstacles, like reinforcement, to fill the formwork. Any mix has: *i.* passing ability, *ii.* Filling ability, and *iii.* Segregation resistance can be classified as SCC one. In addition, SCC overcomes poor accessibility near prestressing tendons and anchorages, and reduces noise level and health effects on operators using hand held vibrators. The only limitation is that the top surface must be horizontal [4]. Recognizing the lack of uniformity and complete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started in late 1980's to develop SCC. By the early 1990's, Japan had developed and used SCC that did not require vibration to achieve full compaction. By year 2000, the SCC had become popular in Japan for prefabricated products and ready mixed concrete [5].

1.3. Strengthening of Concrete members

Normally, concrete structures during their service life suffer in some way or another from

strength deficiency; therefore they require strengthening or repair. Need of them may be resulting from errors in construction or design, changes of function, updates of design code, maintenance lack, structural system changing, traffic volumes increasing, blasts and explosions, accumulated damage over time or caused by accidental overloading, fires, or earthquakes [6]. Civil engineering infrastructure renewal has, and still, considerable attention over the last two decades, although the option of deficient or deteriorated structure replacement is desirable. Economic reasons make strengthening or repair to be the choice [7].

Purposes and strengthening techniques of structures are vary. Most strengthening systems consist of a composite strengthening one. The composite strengthening can be achieved by enlargement of section, external post-tensioning, steel elements bonded externally, Textile Reinforced Concrete (TRC), Fiber-Reinforced Polymer (FRP) composites, and Near-Surface Mounted (NSM) system. Anyone of these techniques or a combination of them can be used provided that the structure functionality must be kept throughout its designed service life [8].

2. Previous studies

Imran (2012) [9] made a review on existing literature related to strengthening of reinforced beams for flexure, shear and torsion so behavior can be better understood. This review showed that strengthening of RC beams using Carbon Fiber Reinforced Polymers (CFRP) are the most widely and suitable strengthening technique. They concluded that torsion strengthening is difficult and different studies suggest full wrapping which it is practically impossible from application point of view. However, several experimental studies revealed that 45° CFRP wraps are useful to enhance torsional strength of beams.

Al-Bayati and Al-Mahaidi (2013) [10] aimed to present a literature review concerning the torsional behavior of reinforced concrete beams strengthened with CFRP since both techniques, Externally-Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) were and still of widespread using. Among different strengthening layouts, full-wrap along the beam span seems to be the most effective layout for resistance and ductility improvement. Using such strengthening technique restricted propagation of cracks. Spacing and number of layers of CFRP affect considerably the beam torsional capacity. Anchors using produces a longer response and delays failure but crushing of concrete at unstrengthened areas may occur. Use of inclined 45° spiral strips seems to be the most effective layout but it has practical limitations. Reviewing of literature shows that no available data on torsional behavior using NSM technique to strengthen reinforced concrete beams.

Khalil et al (2015) [11] investigated the behavior of ten reinforced concrete box beams, with and without web opening, under pure torsion. Beams were strengthened using External Prestressing Technique (EPT) horizontally and vertically. The strengthening using EPT enhance the torsional capacity by 58%, vertical EPT was more effective, and increased torsional capacity of beams with opening by about 13% were some of conclusions of the investigation related to present work.

Shengqiang Ma et al (2016) [12] fabricated four RC beams of box section and tested under pure torsion till failure. First beam was a control beam while second, third and fourth one were externally bonded with CFRP. Second one was strengthened using U-wrap of one-layer, third one was strengthened using one-layer of both U-wrap and longitudinal strip and fourth one was strengthened using two-layers of U-wrap and one-layer of longitudinal strips. Ultimate torque

is increased moderately by 16.6%, 15.9%, and 20.5% for second, third and fourth strengthened beam respectively. Torsional stiffness of strengthened box beams with longitudinal strips increased slightly, the cracking torque also increased.

Aghara and Vora (2017) [13] studied torsional strengthening of RC beam with Glass Fiber Reinforced Polymers (GFRP) lamination experimentally and analytically. Six rectangular beams having rectangular section were casted; one of them was control beam and the others were wrapped with GFRP of different configuration. Non-Linear Finite Element (NLFE) was used to perform the task of numerical work. The work contained good review on previous studies of torsional strengthening for beams. They concluded that wrapping pattern at 45° angel give more torsional strength than wrapping at 90° degree.

Kandekar and Talikoti (2018) [14] studied the torsional behavior of reinforced concrete beams strengthened using aramid fiber strips to wrap the beams with different patterns. Twenty one reinforced concrete beams of rectangular section were cast and tested until failed in torsion. Different aramid fiber configuration effect on torsional capacity, twist angle and mode of failure of the beams is studied. It is seen that torsional moment carrying capacity increases when the beams was wrapped using aramid fiber strips. As strips spacing were increased, the torsional moment capacity decreases and the twist angle has small variations. In strengthened beams, Initial cracks occurred at higher torsional moments.

Aziz and Hashim (2018) [15] studied, experimentally, the torsional behavior of six SCC box beams strengthened with transverse concrete diaphragms which may be opened or closed. First beam was the reference beam of hollow section, second and third were strengthened by two closed and opened

diaphragms, respectively, fourth and fifth were strengthened by four closed and opened diaphragms, respectively, and sixth was of solid section. Results showed that the ultimate torque increases by 43%, 61%, 89%, and 94% for strengthened second, third, fourth, and fifth beam specimens, respectively. Beam specimen of solid section has ultimate torque increment of 28% and 33% compared with fourth and fifth beam specimens. The cracking torque increased by 57%, 29%, 100%, 86% for strengthened second, third, fourth, and fifth beam specimens, respectively. Toughness was higher in strengthened beam specimens.

Abdallah and Aziz (2017) [16] evaluated the enhancement of torsional strength of reinforced SCC box beams internally strengthened with transverse steel bracing. Seven beam specimens were poured and tested under pure torsion. Two types of internal bracing were employed, cross (X-type) and welded cross (XW-type). First beam was the reference box beam. The ultimate torque moment increased by 14.4%, 34.3% and 59.2%, twist angle decreased by 8.2%, 18.8% and 30.365%, elongation decreased by 8.2%, 21.7% and 33.3% for second, third, and fourth specimens which were strengthened by one, three, and five X-type bracing, respectively. The ultimate torque moment increased by 21.9%, 41.8% and 71.6%, twist angle decreased by 12.3%, 26.2% and 32.42%, elongation decreased by 17.3%, 26.6% and 40% for fifth, sixth, and seventh specimens which were strengthened by one, three, and five XW-type bracing, respectively

3. Research Significance

As shown in section 2 above, literature survey, there are many categorized methods for structural strengthening techniques. Review of literature on torsional strengthening indicated that very few researches were performed on

internal torsional strengthening of box beams. So, the technique of this research for torsional strengthening of reinforced SCC box beams depended on employing of internal transverse FSSRs.

Usually external strengthening is made to improve torsional strength of reinforced concrete box beams. Also sometimes, it is very difficult, if not impossible, to apply strengthening for all sides of the box girder bridges. So, the idea of internal torsional strengthening using different techniques comes to the light. So the attention is given to make a research on such method knowing that very little previous researches were carried out especially using SCC. This relatively new technique may be economic and safer especially when it is used in high elevated box girders. Main objectives of this research can be briefly stated as: *i.* Examining, experimentally, the significance of using the internal transverse FSSRs in strengthening of reinforced SCC box beams. *ii.* Studying the influence of number of the FSSRs on the amount of torsional strength enhancement. The new adopted method may be used to strengthen existent or prefabricated box girders according to cost study.

4. Experimental work

4.1. Experimental program

The experimental program comprised of pouring and test four reinforced SCC box beam specimens until failure by torsion only. The four specimens included one reference beam which has no strengthening and three beams strengthened with one, three, and five FSSRs of closed sections, respectively. The experimental program, also, contains a series of tests performed on control samples (cylinders and prisms) so mechanical properties of hardened SCC (compressive and tensile strength, modulus of elasticity) can be determined as well as many

test to control SCC (slump flow, L-box, V-funnel, U-box and G-ring tests). Also, the reinforcing steel and steel plate from which the FSSRs are made were tested for yield and ultimate strength. During all specimens tests, clear span, concrete grade, and loading condition remain unchanged. Also, all specimens were simply supported attached on rotatable supports. Cracking and ultimate loads, mode of failure, and torque-angle of twist behavior are presented, and discussed in this research. Fresh SCC test methods adopted in this paper is based on EFNARC, Specification and Guidelines for Self-Compacting Concrete, [17].

4.2. Beam specimens description

All specimens have the same dimensions of (2100 x 300 x 300) mm for span length, width and height, respectively, and wall thickness of (60) mm. The longitudinal and transverse reinforcement were directly calculated based on ACI-318-14 code torsion requirements [18]. All beam specimens were of same reinforcement consisting of longitudinal bars (2 ϕ 12mm top and bottom) and transverse stirrups (ϕ 8@50 mm at both ends of beam specimen to a length of 200 mm and ϕ 8@130mm stirrups otherwise). Details of tested beam specimens are shown in Table (1). Details of the reference beam specimen, 1NR, which are, except presence of FSSRs, typical for all tested beam specimens as explained in Figure (1).

As mentioned previously, the new technique of strengthening of box sections using internal transverse FSSRs (to enhance resistance against torsional stresses) is adopted in this paper. Therefore, transverse FSSRs of different number were used and located in their position before SCC pouring, see Figure (3). These FSSRs were fabricated to have square shape of dimensions, (180x180) mm as that of internal dimensions of the box beam specimens' cross

section, closed cross-section, and shear connectors on all sides. The cross section of FSSRs was not of a standard type. It was made by assembling of its parts made of steel plates prepared previously, utilizing welding of (E6013) type. Details of FSSR are illustrated in Figure (2).

Table 1. Beam specimens' details.

Specimen Designation*	1NR**	5N1CF	6N3CF	7N5CF
Dimensions (mm)	<i>L</i>	2100		
	<i>B</i>	300		
	<i>H</i>	300		
	<i>t_f</i> ***	60		
	<i>t_w</i> ***	60		
Reinforcement	Long.	2 ϕ 12 mm, Top and bottom		
	Trans.	- ϕ 8 @ 50 mm, at ends - ϕ 8 @ 130 mm, otherwise		
FSSRs qt. (No.)	----	1	3	5
FSSRs Type	----	Closed section		

*First number refers to specimen number, *N* means nonprestressed, *R* means reference, second number refers to quantity of FSSRs, *C* means closed section, and *F* means FSSR.

**Reference beam specimen.

***Called wall thickness of beam section.

4.3 Beam specimens' preparation and casting

4.3.1 Materials

To make the required test beam specimens, the materials shown in Table (2) were used to produce the SCC as well as with longitudinal, transverse reinforcement and FSSRs in addition to styropore needed to form section hollowness.

Figure (6) shows details of works of longitudinal and transverse reinforcement, FSSRs fixing in their final locations, and styropor fixing in proper position. All materials used in this research were conforming to applicable standards in Iraq.

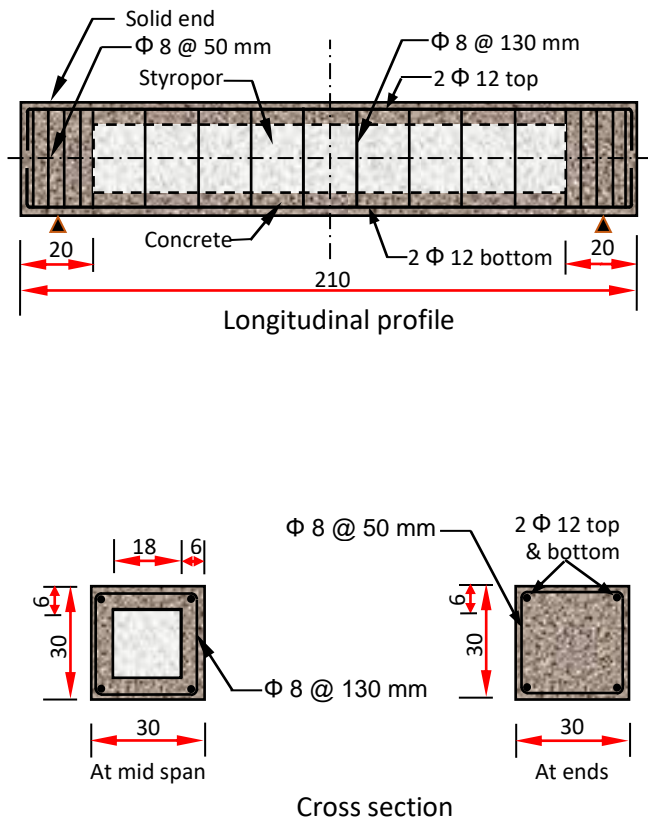


Figure 1. Reference beam specimen (1NR) details (Dimensions are in centimeters, not to scale).

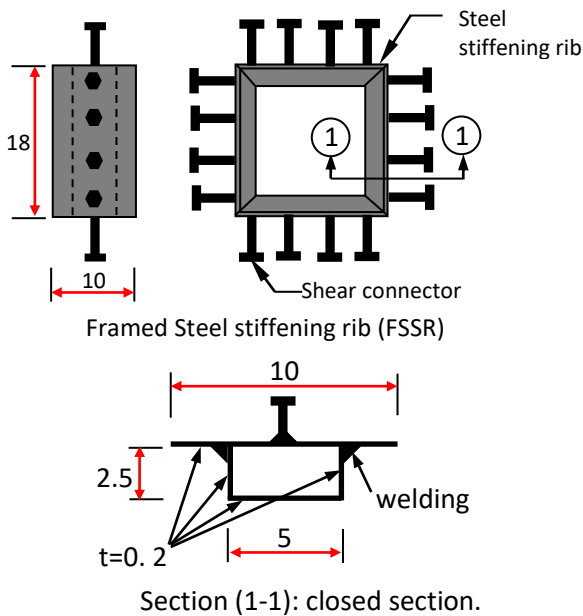


Figure 2. Framed steel stiffening rib (FSSR) details (Dimensions are in centimeters, not to scale).

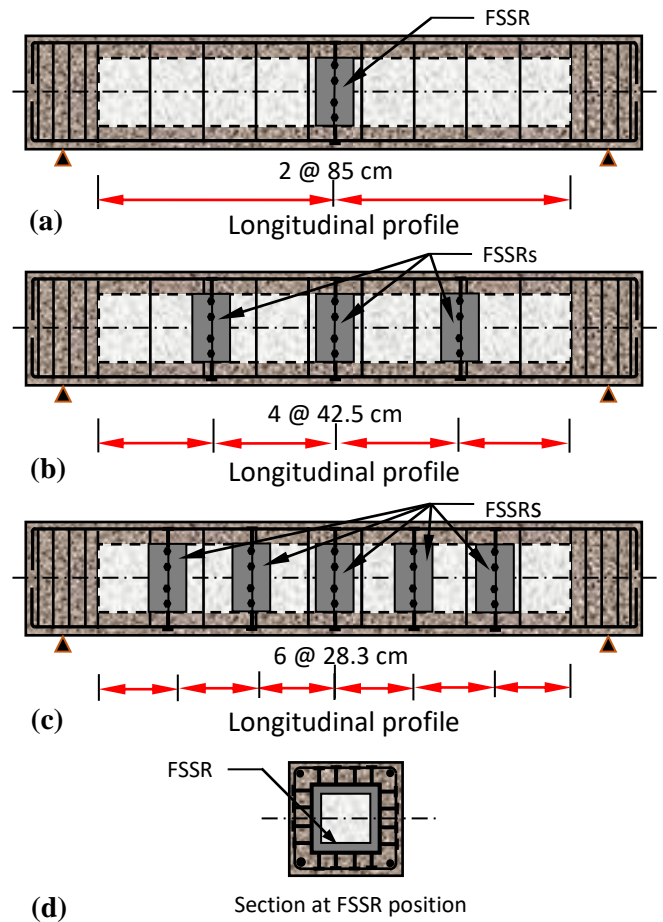


Figure 3. Strengthening details of the beam specimens, (a) Beam specimen 5N1CF, one FSSR (b) Beam specimen 6N3CF, three FSSRs, (c) Beam specimen 7N5CF, five FSSRs, and (d) Cross section.

4.3.2 Mix and pour of SCC

Rotary mixer, Figure (4), was used to mix the raw materials and produce the SCC for all specimens. Two steel formworks made of (2 mm) thickness steel plate stiffened with steel angle section members had been fabricated and used to cast the beam specimens. The molds had an internal dimensions of (2100x300x300) mm. Formworks was set on firm ground in horizontal level and well lubricated before casting, see Figure (5). The proportions of SCC mix are reported in Table (3).

Table 2. Materials properties and description.

Material*	Descriptions	Granular materials
Cement	Ordinary Portland Cement (Type I).	
Fine aggregate (Sand)	Natural sand of (4.75mm) maximum size.	
Coarse aggregate (Gravel)	Crushed gravel of (14 mm) maximum size.	
Limestone powder	Fine limestone powder of Iraqi origin.	
Silica fume	Silica fume marked MegaAdd MS(D) made by CONMIX.	
Superplasticizer	Viscocrete - 5930 - L produced by Sika.	
Water	Conforming to tap water specification.	

*All local materials were conforming to applicable Iraqi standards and specifications.

Table 3. SCC mix design proportions.

Material	Quantity	Calculated Ratio (%)	Limits, EFNARC [17]
Cement (kg/m ³)	470	-----	350 - 600
Sand (kg/m ³)	750	33 %	< 40%
Gravel (kg/m ³)	900	40 %	< 50%
Silica Fume (kg/m ³)	23.5	5 %	-----
Limestone powder (kg/m ³)	130	-----	-----
Super-plasticizer (l/m ³)	11.5	1.844 %	< 2%
Water (l/m ³)	188	-----	-----
W/P (%)	-----	30.2 %	28 % - 38 %

Notes:

- Sand ratio = sand / (cement + sand + gravel + silica fume + limestone).
- Gravel ratio = gravel / (cement + sand + gravel + silica fume + limestone).
- As percentage replacement of cement.
- Superplasticizer ratio = superplasticizer / (cement content + silica fume + limestone).
- W/P = water / (cement content + silica fume + limestone).

5. Instrumentation, measurements and test procedure.

5.1. Instrumentation and measurements.

Specimens of this research were tested for cracking and ultimate torques using hydraulic universal testing machine (produced by

Maschinen Fabrik Liezen, MFL) with load capacity of (3000 kN), Figure (8). Angle of twist was measured at four locations; at both ends of specimen using two dial gauges for each end, at mid-span and at quarter span. All dial gauges which have accuracy of (0.01 mm/division), were attached to the bottom face of the specimen and located transversely at distance of (100 mm) from longitudinal axis. Twist angles were calculated, in degrees, depending on vertical deflection recorded for each step (5 kN) of loading at the locations illustrated above. Loading was applied gradually at constant rate.

**Figure 4.** Rotary mixer.**Figure 5.** Formwork.

Total longitudinal deformation was measured at both specimens' ends using one dial gauge for each end with (0.01 mm/division) accuracy fixed at the center of end cross section. Then horizontal deflection was calculated to find longitudinal elongation, in millimeters, for each loading stage. Figure (9) shows a photo of locations of used dial gauges.



(a)



(b)



(c)



(d)

Figure 6. Beam specimens reinforcement, steel stiffening ribs, and styropor details, (a) 1NR (b) 5N1CF (c) 6N3CF (d) 7N5CF.

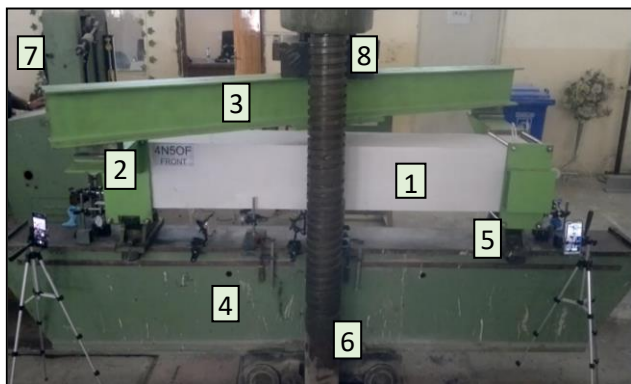


Figure 7. Setup of beam specimen test,
1.Beam specimen. 2.Loading Arm.
3.Steel beam,WF-sec., 4. Main bed.
5.Rotatable support. 6.Hydraulic jack.
7.Load dial. 8.Moving head.

5.2 Test procedure

Test setup of beam specimens is as shown in Figure (7). Beam specimen which to be tested is attached to machine supports which can set to be rotatable, so the specimen can rotate freely at ends about its longitudinal axis. The load is applied on the center of wide flange steel beam which transfers it equally to the loading arms as two concentrated loads out of the longitudinal axis of beam specimens under test by a distance of (500 mm). This eccentric distance, at the ends of specimen, is necessary to obtain torsional behavior through transfer of loading on the arms as concentrated torque at the ends of specimen and concentrated vertical force which transferred directly to the support. Applied loads of first visible crack (P_{cr}) and of final failure (P_u) were recorded. It is clear that this set up is symmetric about specimen's mid-span except (T) which has opposite sense at the ends.



Figure 8. Hydraulic universal testing machine.

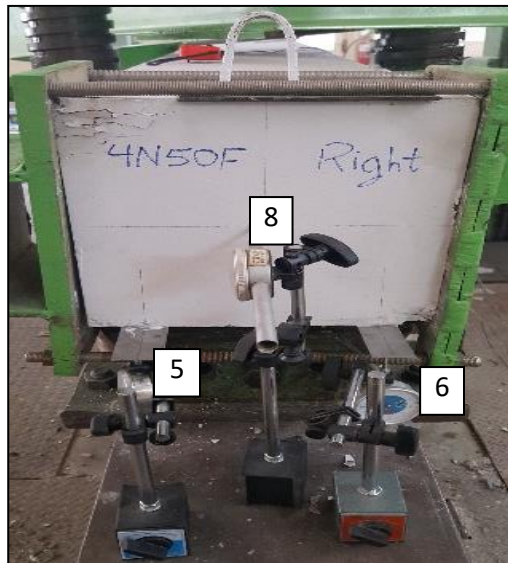
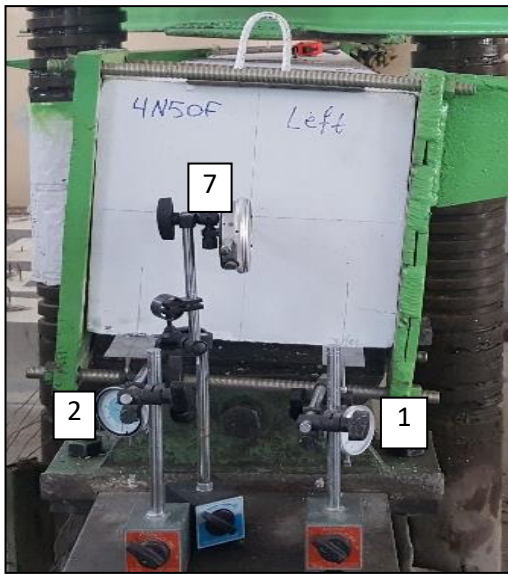


Figure 9. Locations of dial gauges, Twist angle (1,2 left end - 5,6 right end - 3 quarter span - 4 mid span), longitudinal elongation (7, 8).

6. Properties of SCC

6.1 Fresh SCC Control Tests

According to EFNARC [17] standards, there are ten different tests to ensure that the produced concrete is of a SCC type. It is not necessary to make all of these ten tests on fresh SCC; so five tests were adopted in the present research as a control tests on fresh SCC, namely slump flow, J-ring, L-box, V-funnel, and U-box tests, see Figure (10-14). These five tests gave an indication for fresh SCC properties specially the important three characteristics of the SCC, filling ability, passing ability, and segregation resistance. Tests results indicated that used SCC conforms to the requirements of EFNARC [17].



Figure 10. Slump flow



Figure 11. J-ring



Figure 12. L-box test.



Figure 13. V-funnel Test.



Figure 14. U-box Test.

6.2 Hardened SCC Control Tests

Hardened SCC properties comprise compressive strength (f'_c), splitting tensile strength (f_t), modulus of rupture (f_r), hardened density (γ_c), modulus of elasticity (E_c), shear modulus (G_c) and Poisson's ratio (ν_c). These properties were determined using three sets of samples, each one consists of five standard cylinders having (150) mm diameter and (300) mm height (three for f'_c test, one for f_t test, and one for E_c and ν_c test), and three prisms of (500x100x100) mm dimensions for f_r test. Table (4) reported the properties mentioned above.

Table 4. Hardened SCC characteristics.

Mix Type	SCC
f'_c (MPa)	56
γ_c (kg/m ³)	2424
f_r (MPa)	6.6
f_t (MPa)	2.9
E_c (MPa)	41555
G_c (MPa)	28192
ν_c	0.26

7. Test results and discussion

7.1 Cracking and ultimate load

Beam specimens were tested under application of only torsion loading gradually. Loading process was continued until final failure mechanism occurs. Both cracking and ultimate loads (P_{cr} and P_u) were recorded, and then torsional moments (torques) were calculated, see Table (5) and Figure (15).

As compared with reference specimen 1NR, the cracking torque (T_{cr}) increases by (25.0 %), (28.6 %), and (32.1 %) and the ultimate torque (T_u) by (45.7 %), (75.5 %), and (122.4 %) for specimens 5N1CF, 6N3CF, and 7N5CF, respectively. It can be noticed, the percentages of increasing are of appreciable values. This means that the presence of FSSR(s) improves the ability of box section to resist further torsional loading. Also, it can be noticed, the

percentages of (T_{cr}) increasing have little differences while they have considerable differences for (T_u). This may be resulted from the fact that at starting of loading, the applied load is resisted mainly by concrete and first crack initiates at midpoint of the external fiber of box section side. After that reinforcing steel begin to have its role in resisting the applied load. At final stages of loading, the applied load will mainly be resisted by FSSRs. On other point of view, it can be said that the (T_{cr}) value depends mainly on concrete contribution in resisting of applied load, while the (T_u) value depends on contributions of concrete, reinforcing steel, and FSSRs. As results, it can be concluded that the adopted strengthening technique gives a good enhancement in torsional ultimate capacity.

Table 5. Cracking and ultimate load capacity (T_{cr} and T_u).

Specimen Designation	1NR	5N1CF	6N3CF	7N5CF
P_{cr} (kN)	70.0	87.5	90.0	92.5
P_u (kN)	122.5	178.5	215.0	272.5
Arm (m)	0.5			
T_{cr} (kN.m)	17.50	21.88	22.50	23.13
T_u (kN.m)	30.63	44.63	53.75	68.13
Increasing* (%) , T_{cr}	0.0	25.0	28.6	32.1
Increasing* (%) , T_u	0.0	45.7	75.5	122.4

*Increasing % is relative to 1NR.

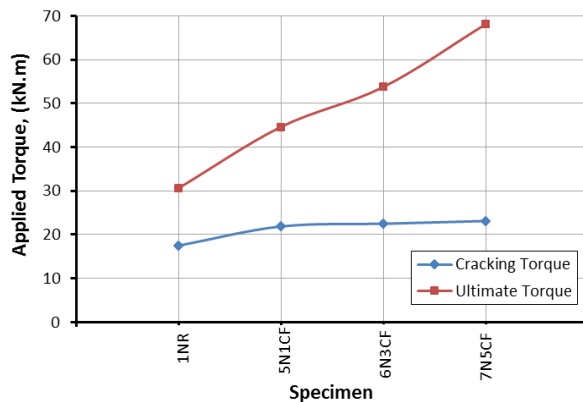


Figure 15. Applied torque capacity, cracking and ultimate torques.

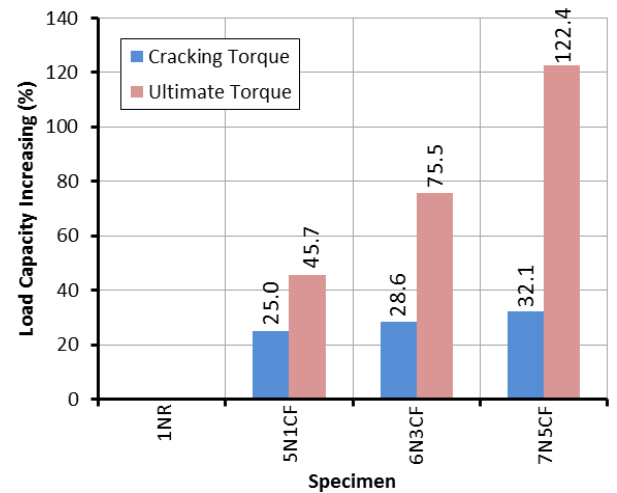


Figure 16. Percentage of increasing of torque capacity.

7.2 Angle of twist and longitudinal elongation

Two types of deformation were considered in present research, angle of twist θ and longitudinal elongation δ_L . The angle of twist was recorded at four locations; left end and right end which averaged to obtain end span angle of twist θ_{ES} , quarter span θ_{QS} , and mid span θ_{MS} of the tested specimens. Longitudinal elongation δ_L is found by summing of two values recorded at left and right ends of the tested specimens. These deformation were recorded for both T_{cr} and T_u , Table (6). Figure (17-19) shows the applied torque-angle of twist curves and Figure (20) shows the applied torque relation with longitudinal elongation. Note that θ is the total angle of twist in degrees and δ_L is the longitudinal elongation in millimeters. Subscripts ES, QS and MS means end, quarter and mid span, respectively.

Table 6. Deformations at cracking loading (T_{cr}).

Specimen	Deformation at cracking T_{cr}			
	θ_{ES}	θ_{QS}	θ_{MS}	δ_L
1NR	0.328	0.183	0.057	0.376
5N1CF	0.271	0.183	0.069	0.155
6N3CF	0.275	0.258	0.103	0.271
7N5CF	0.208	0.126	0.069	0.168

Table 7. Deformations at ultimate loading (T_u).

Specimen	Deformation at ultimate T_u			
	θ_{ES}	θ_{QS}	θ_{MS}	δ_L
1NR	3.528	2.667	1.975	3.829
5N1CF	3.653	3.740	3.484	3.786
6N3CF	4.061	4.657	4.845	3.508
7N5CF	3.767	3.250	3.900	3.261

As a result, for all tested box beam specimens, the internal strengthening using FSSRs changes clearly the deformation capacity. The angle of twist, θ , as longitudinal elongation, δ_L , has small values before initiating of first visible crack. After that it begins to have larger values till failure happens where it has the ultimate value. This is coinciding in all locations where the angles of twist were recorded.

Ultimate θ_{ES} of strengthened specimens increases by (3.5 %), (15.1 %) and (6.8 %) for 5N1CF, 6N3CF and 7N5CF, respectively, as compared with 1NR specimen. Although 7N5CF had more FSSRs than that of 6N3CF, but it had smaller percentage of θ_{ES} increasing. The reason may be that θ is directly proportional to T but inversely with torsional stiffness represented by torsional constant, J . Stiffness increasing due to presence of five FSSRs in 7N5CF may have greater effect in reducing θ_{ES} than the effect of T increasing which it tends to increase θ_{ES} .

Although (θ_{MS}) must be of zero value due to test set up, it has some very small values at range of loading up to T_{cr} . Non homogenous nature of concrete can be the reason; also one or more condition of test set up symmetry may be violated even if violation is very small. Beyond T_{cr} , the behavior is different because cracks growing more and more, so θ_{MS} has large values at T_u level.

Longitudinal elongation, δ_L , decreases slightly with increasing of number of FSSRs. This may be because of stiffness increasing caused by number of FSSRs increasing which it tends to reduce δ_L has more effect than T increasing which it tends to increase δ_L .

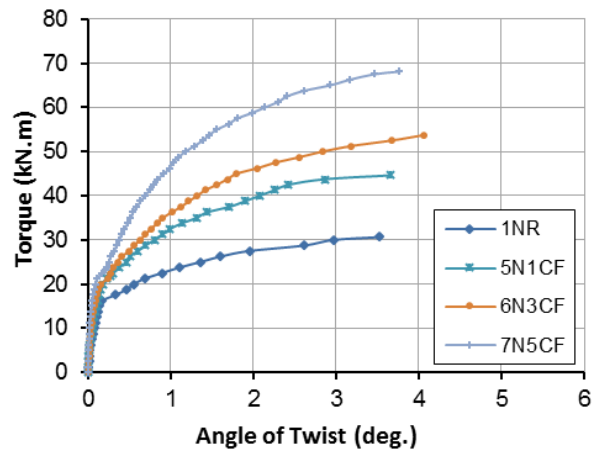


Figure 17. Applied torque-angle of twist relation. Up to ultimate torque, (End span)

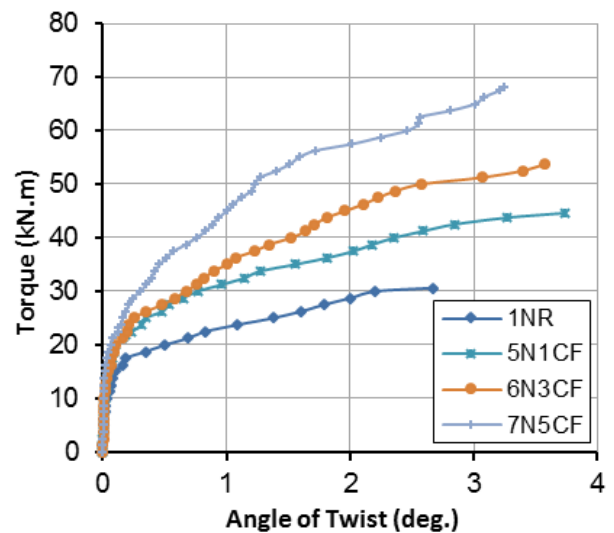


Figure 18. Applied torque-angle of twist relation. Up to ultimate torque, (Quarter span)

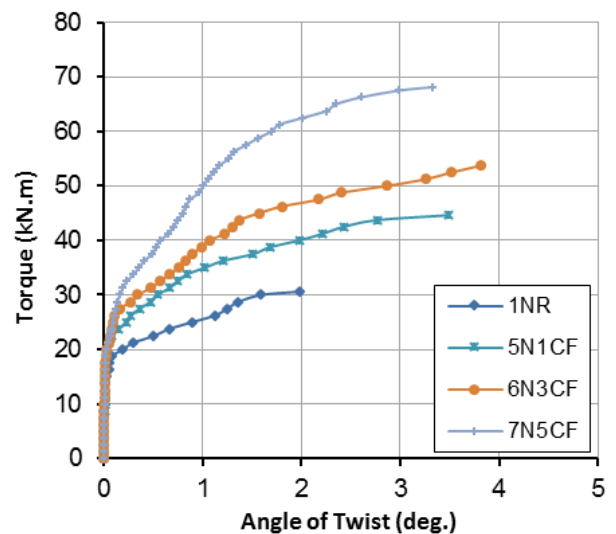


Figure 19. Applied torque-angle of twist relation. Up to ultimate torque, (Mid span)

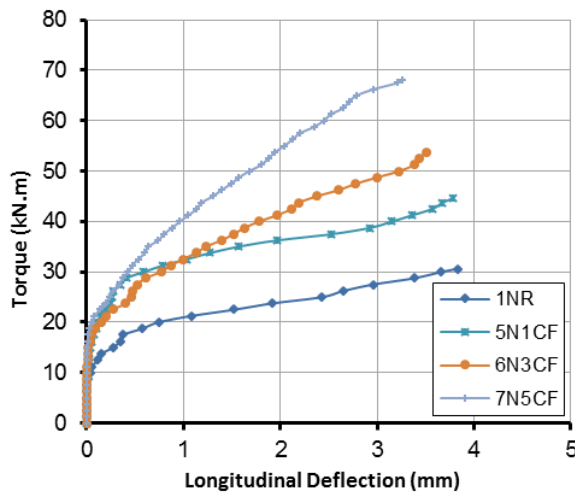


Figure 20. Applied torque-longitudinal elongation relation, Up to T_u .

7.3 Modes of failure

Many failure modes may be expected in the present research. The final failure may be due to failure of concrete in diagonal tension, failure of transvers reinforcement (stirrups) by yielding, failure of longitudinal reinforcement by yielding, or failure of FSSR(s) due to failure of shear connectors, or failure of FSSR cross section in tensile stress because of warping. All tested beam specimens were failed by diagonal tension of SCC where it reached its ultimate strength, Figure (21).

7.4 Mechanisms of failure

The propagation of cracks throughout length of beam specimen during the test gave good information regarding the failure mechanism. First visible crack of all specimens occurred near mid span at some point on mid height of front face of beam specimen which represents the weaker point and subsequently it increased gradually. As applied torque moment was increased, cracks extended to all sides gradually and finally took the spiral shape. Generally, major cracks, including first visible crack, were initiated and developed within the middle third of the span; then as cracks became closer to the ends of beam specimen, they had smaller

width. This is may be due to that both ends of the specimen were solid and had transverse reinforcement more than that at entire span; also ends of the specimen were confined vertically by concentrated force at supports and laterally by forces due to loading steel arms fixation, and even that both ends were free to rotate. Accordingly, the final failure position of most beam specimens occur near mid span. Figure (21) shows the failure mechanisms of tested specimens. It can be noted that all tested specimens failure was caused by diagonal cracks in concrete which had a spiral shape.

7.5 Cracks pattern

For reference beam specimen 1NR, which had no strengthening FSSRs, the cracks spread in an entire beam length. The cracks of middle third of the span was of width slightly more than that of the end thirds while near the supports the cracks had much smaller width. Generally, with increasing of loading the number of cracks increased and failure take place somewhere near the mid span. At failure, excessive parallel cracks at all sides along the span of the beam were observed.

For strengthened beam specimens 5N1CF, 6N3CF, 7N5CF, the cracks spread with nearly the same number and grow slower at the strengthened zones where the strengthening FSSRs were provided since they reduce the rate of cracks growth. The angle of specimen's 1NR cracks, with respect to longitudinal axis, were ranged from 46° to 51° , from 46° to 52° for 5N1CF, from 42° to 49° for 6N3CF, from 45° to 49° for 7N5CF. All cracks are between 30° and 60° as expected. Distance of first visible crack from mid span was (6 cm) for 1NR, (18 cm) for 5N1CF, (9 cm) for 6N3CF, (13 cm) for 7N5CF. First visible crack of specimen 5N1CF developed at distance more than that of specimens 6N3CF and 7N5CF relative to 1NR

due to presence of one FSSR only that means section at mid span has stiffness more than that at ends. When more than one FSSRs were used, specimens 6N3CF and 7N5CF, the first visible crack tends again to be nearer to the mid span but still having distance more than that for specimen 1NR. This is may be due to that stiffness was increased at ends as at mid span. Finally, in all tested specimens, the cracks had the spiral shape around all faces of each specimen. The number of complete cracks of each tested beam specimen was approximately the same. This means that the strengthening process has no large effect on the number of cracks like its effect on values of cracking and ultimate torques as explained in section 6.1.



(a)



(b)



(c)



(d)

Figure 21. Tested beam specimens.

- (a) Reference specimens, 1NR.
- (b) Specimen 5N1CF.
- (c) Specimen 6N3CF.
- (d) Specimen 7N5CF.

8. Conclusions

The following can be concluded depending on output results of the experimental work of this research and according to the discussion presented in section (7) above.

1- Ultimate torsional strength capacity increased significantly by 45.7 %, 75.5 %, and 122.4 % for specimens 5N1CF, 6N3CF, and 7N5CF, respectively as compared with reference specimen, 1NR.

2-The torsional capacity is increasing with increasing of FSSRs number.

3-Presence of FSSRs restrained deformation growth due to increasing of specimen stiffness; this restriction increases as number of FSSRs is increased.

4- Ultimate angle of twist, θ_{ES} , of strengthened specimens increases by (3.5 %), (15.1 %) and (6.8 %) for 5N1CF, 6N3CF and 7N5CF, respectively, as compared with reference specimen, 1NR.

5-The suggested technique for internal strengthening by using framed steel stiffening ribs (FSSRs) of closed section is effectively enhances the torsional capacity of reinforced SCC box beams with reasonable simplicity.

6-Position of the first crack, which is expected to be at or very close to mid span due to test setup, depends on number and distribution of FSSRs.

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