Using Internal Framed Steel Stiffening Ribs as an Alternative Technique for Torsional Strengthening of RC Box Beams

Sabah H. Muhammed1* and Ali Hameed Aziz1

1College of Engineering, Mustansiriyah University, Baghdad, Iraq.
*Corresponding Author E-mail: sabah.hashim@uokerbala.edu.iq

Abstract. There is little research on internal torsional strengthening of box beams. This study uses internal framed steel stiffening ribs (FSSRs) as an alternative technique for torsional strengthening of reinforced self-compacting concrete (SCC) box beams. These FSSRs have been fabricated to a square shape of size equal to the internal dimensions of the box beam specimens, specified cross-section, and shear connectors on four sides. Four specimens of reinforced SCC were tested up to failure under the effect of pure torsion; one was a reference specimen without strengthening (designated as 1NR) and the other three (designated as 2N1OF, 3N3OF, and 4N5OF) were strengthened with one, three, and five FSSRs, respectively. Specimens had dimensions of 2100×300×300 mm for length (L), width (W), and height (H), respectively. The effect of FSSRs, and their number, on torsional capacity were studied, as was the application of torque-angle of twist relation at end, quarter and mid span. Results show that the ultimate torsional strength capacity is increased significantly by 32.7 %, 59.2 %, and 93.9 % for specimens 2N1OF, 3N3OF, and 4N5OF, respectively as compared with the reference specimen, 1NR. The presence of FSSRs tends to reduce deformation of specimens: deformation decreases with increase in the number of FSSRs. It is concluded that the torsional strength capacity of reinforced SCC box beams can be enhanced by use of internal FSSRs as in this study. The extent of enhancement depends mainly on the number of internal FSSRs deployed.

Keywords: Steel Stiffening Ribs; FSSR; Torsion; Strengthening; Concrete; Box Beam.

1. Introduction

Structural members made of reinforced concrete are designed to resist flexural, shear, axial, and torsion forces according to loading conditions. Torsion forces, which rarely act without bending, shear, and axial forces, try to twist the member about its axis [1]. Torsion strength represents a central feature in the analysis and design of many structures such as curved bridges, eccentrically loaded box beams, edge beams in buildings, and helical stairways. [1].

When a torque is applied, shearing stresses on cross-sectional planes and on radial planes develop and extend from the axis of the member to the 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 a circular section is constant along the circumference. In a member with rectangular perimeter it changes, from zero value at corners to a maximum value at the centers of the long sides [2]. Torsional loadings can be separated into two basic categories: equilibrium torsion, upon which we focus in this this study, and where the torsional moment is required for the equilibrium of the structure, and compatibility torsion, where the torsional moment results from the compatibility of deformations between members meeting at a joint [2].

Recently, bridges with box girders have enjoyed widespread use in road flyovers and elevated structures in modern light rail transport, since their torsional stiffness and strength are higher than those of open cross sections. Box girder designs also convey other benefits ideal for in bridge and freeway constructions; efficiency, enhanced stability, serviceability, and economy. Furthermore, it is easier to maintain structures with box girders thanks to the ease of access to the interior space of the box girder. Rectangular and trapezoidal sections are commonly used in box girder construction. [3].

Where box section flanges and webs are slender, longitudinal and transverse reinforcement may be used and with framed steel stiffening ribs (FSSRs), self-compacting concrete (SCC) is used. The air can...
be expelled from SCC without vibration, and it travels around obstacles, like reinforcements, to fill the formwork. Any SCC mix has: i. passing ability, ii. filling ability, and iii. segregation resistance. In addition, SCC overcomes poor accessibility near prestressing tendons and anchorages, and reduces noise levels and adverse health effects on operators using hand-held vibrators. The only limitation to SCC use is that the top surface must be horizontal [4].

Recognizing the lack of uniformity and incomplete compaction of concrete by vibration, researchers at the University of Tokyo, Japan, started to develop SCC in the late 1980s. By the early 1990s, SCC that did not require vibration to achieve full compaction had been used. By the year 2000, SCC had become popular in Japan for prefabricated products and ready mixed concrete [5].

Normally, concrete structures exhibit, in some way or another, deficiency during their life span. Therefore, they require strengthening or repair. Such requirements may arise from errors in construction or design, changes of function, updates to design codes, lack of maintenance, changes to the structural system, increased traffic volumes, blasts and explosions, damage incurred over time or caused by accidental overloading, fires, or earthquakes [6].

The renewal of civil engineering infrastructure has experienced considerable attention over the last two decades, and continues to attract substantial interest. In particular, many wish to determine when/whether deficient or deteriorated structures should be replaced. Frequently, economic reasons make strengthening or repair more desirable [7].

The purposes and techniques in the strengthening of structures are various. Most strengthening systems include composite strengthening. The composite strengthening can be achieved by section enlargement, external post-tensioning, steel elements bonded externally, textile-reinforced concrete (TRC), fiber-reinforced polymer (FRP) composites, and the near-surface mounted (NSM) system. Any one of these techniques or a combination of them can be used, provided that the structure functionality can be kept throughout its intended service life [8].

M. Imran, N. Shafiq, I. Akbar, T. Ayub (2012) [9] reviewed the existing literature related to the strengthening of reinforced beams for flexure, shear and torsion so that these behaviors may be better understood. This review showed strengthening of RC beams using carbon fiber reinforced polymers (CFRP) to be most widely-applicable and suitable strengthening technique. They concluded that torsion strengthening is difficult; some studies have suggested full wrapping, which is practically impossible from a practical point of view. However, several experiments have revealed that 45° CFRP wraps are useful to enhance the torsional strength of beams.

In 2013, Ghaidaik Al-Bayati and Riadh Al-Mahaidi [10] presented a literature review concerning the torsional behavior of reinforced concrete beams strengthened with CFRP since two techniques, externally-bonded reinforcement (EBR) and near-surface mounted (NSM) were still in widespread use. Of the different strengthening layouts, full-wrap along the beam span seemed to be the most effective layout for resistance and ductility improvement. Using such a strengthening technique also restricted the propagation of cracks. The spacing and number of layers of CFRP considerably affected the beam torsional capacity. The use of anchors produced a longer response and delays in failure, but was liable to the cracking of concrete at unstrengthened areas. Use of inclined 45° spiral strips seemed to be the most effective layout but had practical limitations. This literature review found no available data concerning torsional behavior using NSM techniques to strengthen reinforced concrete beams.

Abd El-Hakim Khalil, Emad Etman, Ahmed Atta, and Sabry Fayed (2015) [11] investigated the behavior of ten reinforced concrete box beams, with and without web opening, under pure torsion. Beams were strengthened using an external prestressing technique (EPT) horizontally and vertically. The EPT strengthening enhanced the torsional capacity by 58%, vertical EPT was more effective, and there was an increased torsional capacity in beams with opening of about 13%.

Shengqiang Ma, N. Muhamad Bunnori and K. K. Choong (2016) [12] fabricated four RC beams of box section and tested under pure torsion until failure. Their first beam was a control beam while the second, third and fourth were externally bonded with CFRP. The second beam was strengthened using U-wrap of one layer, the third was strengthened using one-layer of both U-wrap and longitudinal strip and the fourth one strengthened using two layers of U-wrap and one layer of longitudinal strips. Ultimate torque was increased moderately by 16.6%, 15.9%, and 20.5% for the second, third and fourth
strengthened beams, respectively. Torsional stiffness of strengthened box beams with longitudinal strips increased slightly, the cracking torque also increased.

Sandeep Aghara and Prof. Tarak Vora (2017) [13] studied torsional strengthening of RC beam with glass fiber reinforced polymers (GFRP) lamination experimentally and analytically. Six rectangular beams, having rectangular sections, were cast; one was the control beam and the others were wrapped with GFRP of different configurations. Non-linear finite element (NLFE) was used in the numerical work. The work contained a good review of previous studies of torsional strengthening for beams. The authors concluded that wrapping patterns at a 45° angle give more torsional strength than wrapping at 90 degrees.

S. B. Kandekar and R. S. Talikoti (2018) [14] studied the torsional behavior of reinforced concrete beams, using aramid fiber strips to wrap the beams with different patterns. Twenty-one reinforced concrete beams of rectangular section were cast and tested until they failed in torsion. The various effects of aramid fiber configurations on torsional capacity, twist angle and mode of failure of the beams were studied. The authors noted that torsional moment carrying capacity increased when the beams were wrapped using aramid fiber strips. As strips spacing were increased, the torsional moment capacity decreased and the twist angle showed small variations. In strengthened beams, initial cracks occurred at higher torsional moments.

The strengthening of SCC box beams using internal transverse concrete diaphragms or steel bracing can be used to improve torsional capacity. Ali Aziz and Oday Hashim (2018) [15] studied, experimentally, the torsional behavior of six SCC box beams strengthened with transverse concrete diaphragms which could be opened or closed. The first beam was the reference beam, of hollow section. The second and third beams were strengthened by two closed and opened diaphragms, respectively, the fourth and fifth were strengthened by four closed and opened diaphragms, respectively, and the sixth was of solid section. Results showed that the ultimate torque increased by 43%, 61%, 89%, and 94% for the strengthened second, third, fourth, and fifth beam specimens, respectively. The beam specimen of solid section had ultimate torque increments of 28% and 33% compared with the fourth and fifth beam specimens. The cracking torque increased by 57%, 29%, 100%, 86% for the strengthened second, third, fourth, and fifth beam specimens, respectively. Toughness was higher in strengthened beam specimens.

Muhammad Hussein Abdallah1, Ali Hameed 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). The 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 the 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.

As we have seen, there are many methods and categories of method for structural strengthening techniques. A review of literature on torsional strengthening indicates that very little research has been performed on the internal torsional strengthening of box beams. In this paper the technique used for torsional strengthening of reinforced SCC box beams employed internal FSSRs. This is a relatively new technique.

2. Research Significance
Since the torsional strengthening of reinforced concrete box beams is usually made externally, the idea of an internal torsional strengthening method using different techniques is somewhat novel. Thus, the authors of the present paper have studied this method knowing that very little related research has been carried out, especially concerning the use of SCC. The objectives of this study can be summarized as: i. to investigate, experimentally, the effectiveness of using internal FSSRs to strengthen reinforced SCC box beams, and ii. To study the effect of the number FSSRs on the extent of increase in torsional strength.
3. Experimental work

3.1 Experimental program

The experimental program was directed to prepare, cast and test of four reinforced SCC box beam specimens under pure torsion. The first of the four specimens was a reference beam specimen without strengthening. The other three beam specimens were strengthened with one, three, and five FSSRs having opened section, respectively. A series of tests were performed on control samples (cylinders and prisms) to find the mechanical properties of hardened concrete (concrete compressive and tensile strength, modulus of elasticity) as well as many tests to control self-compacting concrete (slump flow, L-box, V-funnel, U-box and G-ring tests). Also, the reinforcing steel and steel plate from which the FSSRs were made were tested for yield and ultimate strength. During all specimen tests, the clear span, concrete grade, and loading condition remained constants. All specimens were simply supported on rotatable supports.

Cracking and ultimate loads, mode of failure, and torque-angle of twist behavior are presented and discussed in this study. Fresh SCC test methods adopted in this paper is based on EFNARC, Specification and Guidelines for Self-Compacting Concrete, [17].

3.2 Description of beam specimens

All specimens had the same dimensions, of 2100×300×300 mm for length, width and height respectively. The longitudinal and transverse reinforcements were directly calculated based on ACI-318-14 code [18] torsion requirements. Each beam was reinforced longitudinally by 2φ12mm bars at top and bottom and transversely by φ8@50 mm stirrups at both ends of beam specimen to a length of 200 mm and φ8@130mm stirrups otherwise. Table 1 shows the beam specimens’ designation, dimensions, reinforcement, and strengthening details. Figure 1 shows the details of the reference beam specimen, 1NR, which are typical for all tested beam specimens except presence of FSSRs.

As mentioned previously, the new technique of strengthening of box sections using internal transverse FSSRs (to enhance resistance against torsional stresses) was adopted in this study. Therefore, lateral FSSRs of different number were used and put in position before SCC pouring, as Figure 3 shows. These FSSRs were fabricated to have square shape of size equal to internal dimensions of the box beam specimens, specified cross-section, and shear connectors on four sides. The cross section of FSSRs was not of a standard type. It was made by assembling its parts (steel plates) prepared previously, utilizing welding of type E6013. Details of FSSR are illustrated in Figure 2.

Table 1. Beam specimens’ details.

| Specimen Designation | Dimensions (mm) | Reinforcement | FSSRs qt. (No.) | FSSRs Type |
|----------------------|-----------------|---------------|-----------------|------------|
|                      | L   B   H   t_b  t_w | Long. | Trans. |                |            |
| 1NR                  |      | 2φ12mm       | -φ8@50mm      | -----      | -----      |
| 2N1OF                | 2100 300 300 60 60 | Top and    | at ends       | 1          | opened     |
| 3N3OF                |       | bottom       | -φ8@130mm     | 3          | section    |
| 4N5OF                |       |              | otherwise     | 5          |            |

*a* First number refers to specimen number, *N* means non-prestressed, *R* means reference, second number refers to quantity of FSSRs, *O* means opened section FSSR, and *F* means FSSR.

*b* Called wall thickness of beam section.

*c* Reference beam specimen.
**Figure 1.** Reference beam specimen (1NR) details (dimensions are in centimeters).

**Figure 2.** Framed steel stiffening rib (FSSR) details (dimensions are in centimeters).

**Figure 3.** Strengthening details of the beam specimens, (a) Beam specimen 2N1OF, one FSSR (b) Beam specimen 3N3OF, three FSSRs, and (c) Beam specimen 4N5OF, five FSSRs.
3.3 Preparation and casting
3.3.1 Materials
To make the required test beam specimens, ordinary Portland cement, fine aggregate, coarse aggregate, limestone powder, silica fume, superplasticizer, and water were required to produce the SCC. The properties and description of materials used are explained in Table 2. Figure 4 shows details of the works of longitudinal and transverse reinforcement, the fixing of FSSRs into their final position, and Styropor fixing. All materials used in this study conformed to applicable Iraqi standards.

Table 2. Properties and description of materials.

| 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.      |                    |

Figure 4. Beam specimens reinforcement, steel stiffening ribs, and styropor details, (a) 1NR (b) 2N1OF (c) 3N3OF (d) 4N5OF.
3.3.2 Mix and pour of SCC
A rotary mixer, shown in Figure 5, was used to mix the raw materials and produce SCC for all specimens. Two steel formworks made of 2 mm thickness steel plate, stiffened with steel angle section members, had been fabricated and were used to cast the beam specimens. The molds had internal dimensions of 2100x300x300 mm. The formworks were set on firm ground in horizontal level and were well lubricated before casting, as Figure 6 shows. The proportions of SCC mix are reported in Table 3.

Table 3. SCC mix design proportions.

| Material                      | Quantity | Calculated Ratio (%) | Limits, EFNARC [17] |
|-------------------------------|----------|-----------------------|----------------------|
| Cement (kg/m³)                | 470      |                       | 350 - 600            |
| Sand (kg/m³)                  | 750      | 33 %<sup>a</sup>      | < 40%                |
| Gravel (kg/m³)                | 900      | 40 %<sup>b</sup>      | < 50%                |
| Silica Fume (kg/m³)           | 23.5     | 5 %<sup>c</sup>       | -----                |
| Limestone powder (kg/m³)      | 130      |                       | -----                |
| Super Plasticizer (l/m³)      | 11.5     | 1.844 %<sup>d</sup>   | < 2%                 |
| Water (l/m³)                  | 188      |                       | -----                |
| W/P (%)                       |          | 30.2 %<sup>e</sup>    | 28% - 38%            |

<sup>a</sup> Sand ratio=sand / (cement+ sand+ gravel+ silica fume+ limestone).
<sup>b</sup> Gravel ratio=gravel / (cement+ sand+ gravel+ silica fume+ limestone).
<sup>c</sup> As percentage replacement of cement.
<sup>d</sup> Superplasticizer ratio = superplasticizer / (cement content +silica fume+ limestone).
<sup>e</sup> W/P=water/( cement content+ silica fume+ limestone).

---

Figure 5. Rotary mixer.

Figure 6. Formwork.
4. Instrumentation, measurements and test procedure.

4.1. Instrumentation and measurements.

All specimens were tested for cracking and ultimate twisting moments (torques) using a hydraulic universal testing machine (produced by Maschinen Fabrik Liezen, MFL) with a load capacity of 3000 kN, which is shown in Figure 7. The angle of twist was measured at four locations. The first and second locations were at the left end and right end of the specimen; here, the angle of twist was measured using two dial gauges for each end. The third location was at mid-span. The fourth, and last, location was at quarter span. All dial gauges, having 0.01 mm/division accuracy, were attached to the bottom face of the specimen and located transversely at distance of 100 mm from longitudinal axis. Vertical deflection was recorded for each stage of loading and then twist angles were calculated, in degrees, at the locations illustrated above.

Total longitudinal deformation was calculated at both specimens' ends using dial gauges with an accuracy of 0.01 mm/division for each end. Each dial gauge was fixed at the center of the end of the cross section. Horizontal deflection in millimetres was recorded to calculate longitudinal displacement for each loading stage. Figure 8 shows a photograph of these locations, taken during the test.

4.2 Test procedure

The test setup of beam specimens is shown in Figure 9. The beam specimen to be tested is attached to machine supports which can set to be rotatable, so the specimen can rotate about its longitudinal axis freely. The load is applied on the center of a wide flange steel beam which transfers it equally to the loading arms, as two concentrated loads out of the longitudinal axis of the beam specimen under test, by a distance of 50 cm. 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. Applied loads of first crack ($P_{cr}$) and of final failure ($P_u$) were recorded. It is clear that this set up is symmetric about the specimen's mid-span, except ($T$) which has opposite signs at the ends.

Figure 7. Hydraulic universal testing machine.

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

5.1 Fresh SCC Control Tests

According to EFNARC\cite{17} standards, ten different tests may be undertaken to ensure that the produced concrete is of SCC type. It is not necessary to conduct all ten of these tests on fresh SCC; therefore five tests were used in the present study as control tests on fresh SCC. These were slump flow, J-ring, L-box, V-funnel, and U-box tests, which are illustrated in Figure 10. These five tests gave an indication of fresh SCC properties, especially the three primary characteristics of the SCC, i.e. filling ability, passing ability, and segregation resistance. Tests results indicated that the SCC mix used conforms to the requirements of EFNARC\cite{17}.

![Figure 9. Setup of beam specimen test.](image)

![Figure 10. Control Tests for Fresh SCC. (a) Slump flow (b) L-box (c) J-ring (d) V-funnel (e) U-box.](image)
5.2 Hardened SCC Control Tests
Hardened SCC properties comprise compressive strength ($f'_c$), splitting tensile strength ($f_t$), modulus of rupture ($f_r$), hardened density ($\gamma_c$), and modulus of elasticity ($E_c$). 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 $E_c$ test), and three prisms of 500x100x100 mm dimensions for $f_r$ test. Properties mentioned above are reported in Table 4.

Table 4. Hardened SCC characteristics.

| Mix Type | Compressive Strength, $f'_c$ (MPa) | $\gamma_c$ (kg/m$^3$) | $f_t$ (MPa) | $f_r$ (MPa) | $E_c$ (MPa) |
|----------|---------------------------------|-----------------------|-------------|-------------|-------------|
| SCC      | 56.02                           | 2424                  | 6.6         | 2.9         | 41555       |

6. Test results and discussion

6.1 Cracking and ultimate load
Beam specimens were tested under pure torsion by application of the load gradually. Loading process was continued until final failure mechanism occurred. Both cracking and ultimate loads ($P_{cr}$ and $P_u$) were recorded, and then torsional moments (torques) were calculated, as shown in Table 5 and Figure 11.

Compared with reference specimen 1NR, the cracking torque ($T_{cr}$) increased by (32.1 %), (28.6 %), and (28.6 %) and the ultimate torque ($T_u$) by (32.7 %), (59.2 %), and (93.9 %) for specimens 2N1OF, 3N3OF, and 4N5OF, respectively. It can be noticed that the percentages of increase are of appreciable values. This means that the presence of FSSR(s) improved the ability of box sections to resist further torsional loading. Also, it can be noticed that the percentages of ($T_{cr}$) increase had little difference, but there were considerable differences for ($T_u$). This may have resulted from the fact that at the initial point of loading, the applied load is resisted mainly by concrete, and first cracking initiates at midpoint of the external fiber of the box section’s side. After that, the reinforcing steel begins to resist the applied load. Finally, the applied load will be resisted by FSSRs. Alternatively, it can be said that the ($T_{cr}$) value depends mainly on the concrete’s contribution in resisting the applied load, while the ($T_u$) value depends on the contributions of concrete, reinforcing steel, and FSSRs. From our results, it can be concluded that the adopted strengthening technique gave a good enhancement in torsional resistance.

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

| Specimen Designation | $P_{cr}$ (kN) | $P_u$ (kN) | Arm (m) | $T_{cr}$ (kN.m) | $T_u$ (kN.m) | $T_{cr}$ Increasing* (%) | $T_u$ Increasing* (%) |
|----------------------|---------------|------------|---------|-----------------|--------------|--------------------------|------------------------|
| 1NR                  | 70.0          | 122.5      |         | 17.50           | 30.63        | 0.0                      | 0.0                    |
| 2N1OF                | 92.5          | 162.5      | 0.5     | 23.13           | 40.63        | 32.1                     | 32.7                   |
| 3N3OF                | 90.0          | 195.0      |         | 22.50           | 48.75        | 28.6                     | 59.2                   |
| 4N5OF                | 90.0          | 237.5      |         | 22.50           | 59.38        | 28.6                     | 93.9                   |

*Increasing % is relative to 1NR.
This may be because smaller than different test setup loading up to reducing stiffness reason may be that 4N5OF, and 4N5OF, respectively, as compared with value. This is initiati def

Table 6. Deformations at cracking and ultimate loading (Tc and Tu).

| Specimen | Deformation at cracking Tc |  | Deformation at ultimate Tu |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | θES | θQS | θMS | δL | | θES | θQS | θMS | δL | | |
| 1NR | 0.328 | 0.183 | 0.057 | 0.376 | | 3.528 | 2.667 | 1.975 | 3.829 | | |
| 2N1OF | 0.441 | 0.200 | 0.063 | 0.346 | | 4.357 | 3.501 | 2.964 | 3.558 | | |
| 3N3OF | 0.319 | 0.160 | 0.063 | 0.241 | | 4.107 | 3.438 | 2.833 | 3.308 | | |
| 4N5OF | 0.218 | 0.103 | 0.052 | 0.256 | | 3.913 | 2.913 | 2.581 | 3.129 | | |

Note: 1- θ is the total angle of twist, (deg.) and δL is the longitudinal elongation, (mm). 2- ES, QS and MS means end span, quarter span and mid span, respectively.

Figure 11. Applied torque capacity, (a) Cracking and ultimate torques, (b) Percentage of increasing.

6.2 Angle of twist and longitudinal elongation

Two types of deformation were considered in the present study, which were the angle of twist θ and longitudinal elongation δL. The angle of twist was recorded at four locations: left end, right end, quarter span θQS, and mid span θMS of the tested specimens. Angles of twist at the left and right ends were averaged to represent the end span angle of twist θES. Longitudinal elongation δL was found by summing of two values recorded at left and right ends of the tested specimens. These deformations were recorded for both Tc and Tu, as shown in Table 6. Figure 12 shows the applied torque angle of twist curves and Figure 13 shows the applied torque relation with longitudinal elongation.

For all tested box beam specimens, the internal strengthening using FSSRs clearly changed the deformation capacity. The angle of twist, θ, as longitudinal elongation, δL, had small values before initiation of the first crack. Thereafter, it showed larger values until failure, where it had the ultimate value. This is the case in all locations where the angles of twist were recorded.

Ultimate θES of strengthened specimens increased by 23.5 %, 16.4 % and 10.9 % for 2N1OF, 3N3OF and 4N5OF, respectively, as compared with the 1NR specimen. The percentage of increase shown by 4N5OF was smaller than that of 2N1OF and 3N3OF though its number of FSSRs was greater. The reason may be that θ is directly proportional with T and L but inversely with (G) and (J), (θ=TL/GJ). Stiffness resulting from the use of five FSSRs was greater in 4N5OF, and the influence of this on reducing θ may be greater than T increasing effect in increasing of θ.

Although (θMS) must be of zero value due to the test setup, had some very small values at range of loading up to Tc. This may be due to the non-homogenous nature of concrete; also, one or more of the test setup conditions may have been non-symmetrical, even if only slightly. Beyond Tc, the behavior is different due to increasing levels of cracking, so θMS has large values at Tu level. Generally, θMS was still smaller than θQS which in turn was smaller than θES as expected.

Longitudinal elongation, δL, decreased slightly with increasing of number of strengthening FSSRs. This may be because the effect of increasing load capacity may be smaller than the effect of increased stiffness where δL is directly proportional.
6.3 Modes of failure

Many failure modes may have been expected in the present study. Final failure can be due to failure of concrete in diagonal tension, failure of transvers reinforcement (stirrups) in tensile stress, failure of longitudinal reinforcement in tensile stress, or failure of FSSR(s) due to the failure of shear connectors, or failure of FSSR cross section in tensile stress due to warping. All tested beam specimens were failed by diagonal tension of SCC where it reached its ultimate strength. This is shown in Figure 14.

Figure 12. Applied torque angle of twist relation. (a) Up to cracking torque. (b) Up to ultimate torque.
6.4 Mechanisms of failure
The propagation of cracks throughout lengths of beam specimen during the test gave good information regarding the failure mechanism. For all specimens, the first visible crack occurred near mid span, at some point on mid height of the beam’s front face – which represents the weaker point – and subsequently increased gradually. As the applied torque moment was increased, cracks extended to all sides gradually and finally took a spiral shape. Generally, major cracks, including the first visible crack, were initiated and developed within the middle third of the span; then, as cracks became closer to the ends of each beam specimen, they showed smaller width. This may be due to that both ends of the specimen were solid and had transverse smaller width. This is may be because both ends of the specimen were solid and had
transverse reinforcement more than that at entire span; also the ends of the specimen were confined vertically by concentrated force at the supports, and laterally by forces due to loading the fixation of the steel arms, and/or because both ends were free to rotate. Accordingly, the final failure position of most beam specimens occurred near mid span. Figure 14 shows the failure mechanisms of tested specimens. It can be noted that for all tested specimens, failure was caused by diagonal cracks in the concrete which had a spiral shape.

6.5 Cracks pattern
For reference beam specimen 1NR, which had no strengthening FSSRs, the cracks spread across the entire beam length. The cracks at the middle third of the span were slightly wider than at the end thirds, while near the supports the cracks were markedly narrower. Generally, with increase in loading the number of cracks increased and failure took 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 2N1OF, 3N3OF and 4N5OF, the cracks were smaller in number grew more slowly at the strengthened zones where the strengthening FSSRs were provided, since these reduced the rate of the cracks’ growth. The angle of specimen 1NR’s cracks, with respect to longitudinal axis, ranged from 46° to 51°, the corresponding range was from 47° to 51° for 2N1OF, from 44° to 49° for 3N3OF, and from 52° to 55° for 4N5OF. All cracks were between 30° and 60° as expected. The distance of the first visible crack from mid span was 6 cm for 1NR, 22 cm for 2N1OF, 12 cm for 3N3OF, and 10 cm for 4N5OF. The first visible crack of specimen 2N1OF developed at a distance more than that of specimens 3N3OF and 4N5OF, relative to 1NR, due to presence of just one FSSR, which meant the section at mid span had stiffness more than was present at the ends. Where the number of FSSRs used was greater than one, for specimens 3N3OF and 4N5OF, the first visible crack tended again to be nearer to the mid span, but still had a greater distance than that for specimen 1NR. This may have occurred because stiffness was increased at ends as well as mid span.

Finally, in all tested specimens, the cracks followed a spiral shape around all faces of each specimen. The number of complete cracks in each tested beam specimen was approximately the same. This means that the strengthening process had no substantial effect on the number of cracks, which is similar to its effect on the values of cracking and ultimate torque, as explained in Section 6.1.

7. Conclusions
Depending on results of this work and according to the discussion explained in Section 6 above, the following most important conclusions can be drawn:
1- Ultimate torsional strength capacity increased significantly, by 32.7 %, 59.2 %, and 93.9 % for specimens 2N1OF, 3N3OF, and 4N5OF, respectively as compared with reference specimen, 1NR.
2- The torsional capacity increased as the number of FSSRs increased.
3- The presence of FSSRs restrained deformation growth, both angle of twist and longitudinal deflection, due to increasing of specimen stiffness; this restriction increased as the number of FSSRs went up.
4- Ultimate angle of twist, θes, of strengthened specimens increased by 23.5 %, 16.4 % and 10.9 % for 2N1OF, 3N3OF and 4N5OF, respectively, as compared with reference specimen, 1NR.
5- The suggested technique for internal strengthening by using framed steel stiffening ribs (FSSRs) effectively increases the torsional capacity of reinforced SCC box beams with reasonable simplicity.
6- The position of the first crack, which is expected to be at or very close to mid span due to test setup, depends on the number and distribution of FSSRs.

Acknowledgement
This paper forms part of a Ph.D. thesis recently prepared at the Civil Engineering Department, College of Engineering, Mustansiriyah University. The authors present would like to thank everybody who contributed in any way to the completion of this study.
References
[1] Arthur H Nilson, David Darwin and Charles W Dolan 2010 Design of Concrete Structures, 14th ed., McGraw-Hill, pp 421.
[2] James K Wight, and James G MacGregor 2012 Reinforced Concrete: Mechanics and Design 6th ed. Pearson pp. 312, 336.
[3] Payoshni Mali, Shilpa Kewati and Savita Lok 2015 Comparison of rectangular and trapezoidal sections of post tensioned box girder International Journal of Scientific and Engineering Research vol. 6 issue 12.
[4] A M Nevile and J J Brooks 2010 Concrete Technology 2nd ed. Pearson p 409.
[5] M S Shitty 2014 Concrete Technology: Theory and Practice S Chand and Company Ltd. p 373.
[6] Kalid Heiza, Ahmed Nabil, Nageh Meleka and Magdy Tayel 2014 State-of-the-art review: strengthening of reinforced concrete structures – different strengthening techniques Sixth Int. Conf. on Nano-Technology in Construction, Egypt.
[7] Bishy J H ND Se P 2002 An introduction to FRP strengthening of concrete structures ISIS Educational Module 4 p 1–39.
[8] Alkhredaji A and Thomas J 2002 Techniques and design considerations for upgrade of parking structures National Parking Association.
[9] M Imran, N Shafiq, I. Akbar, T. Ayub 2012 A review of RC beams strengthened for flexure, shear and torsion loading. Conference paper June 2012 https://www.researchgate.net/publication.
[10] Ghaidak Al-Bayati and Riadh Al-Mahaidi 2013 Torsional strengthening of concrete members using CFRP composites: a state-of-the-art review Fourth Asia-Pacific Conference on FRP in Structures (APFIS 2013) 11-13 December 2013, Melbourne, Australia.
[11] Abd El-Hakim Khalil, Emad Etman, Ahmed Atta, Sabry Fayed 2015 Torsional strengthening of RC box beams using external prestressing technique. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume 12, Issue 2
[12] Shengqiang Ma, N. Muhammad Bunnori and K. K. Choong 2016 Behavior of Reinforced Concrete Box Beam Strengthened with CFRP U-Wrap Strips Under Torsion MATEC Web of Conferences 2016.
[13] Sandeep Aghara and Tarak Vora 2017 Experimental and analytical study on torsion behavior of RC beam strengthened with GFRP laminations International Journal of Advance Engineering and Research Development Volume 4, Issue 4, p 870–872.
[14] S B Kandekar and R S Talikoti 2018 Study of torsional behavior of reinforced concrete beams strengthened with aramid fiber strips International Journal of Advanced Structural Engineering 10: p 465 – 474.
[15] Ali H A and Oday H H 2017 Torsional strength evaluation of reinforced SCC box beams strengthened internally by opened and closed transverse concrete diaphragms, Proceeding of 3rd international conference on buildings, construction and environmental engineering Egypt.
[16] Muhammad Hussein Abdallah and Ali Hameed Aziz 2017 Torsional strength enhancement of reinforced SCC box beams using internal transverse steel bracing technique, International Journal of Engineering and Technology.
[17] EFNARC, Specification and Guidelines for Self-Compacting Concrete 2002 European federation to specialist construction chemicals and concrete systems. Available at (www.efnarc.org).
[18] ACI Committee 318 2014 Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14) American Concrete Institute Farmington Hills MI USA p 519.