Using internal in-plane k-shape steel bracing as a simple strengthening technique for RC box beams failed in torsion

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Abstract. The current paper aims to investigate, experimentally, the torsion behavior of reinforced concrete box beams made by self-compacting concrete and strengthened internally by in-plane steel bracing of K-Shape. Four identical large size beams had a nominal cross-section dimension of (0.3x0.3m) with a total length of (2.1m) were constructed and loaded to failure under the effect of pure torsion. The experimental result shows that the failure torsion moment of strengthened beam specimens with K-shape steel bracings increases with a percentage up to (82%) more than un-strengthened beam and the angle of twist decreases by a percentage up to (35.5%). While, the axial elongation decreases by a percentage up to (53%). The presence of the internal in-plane K-shape steel bracing is effective and simple method in enhancing the ultimate carrying torsion capacity.

Keywords: Bracing, Strengthening, Box-beam, Torsion, Self-compacting concrete

1. Introduction
Practically, there are several structural elements in which the torsional moment can be considered as a major source of stresses. Eccentrically loaded beams, curved box girders in bridges, spandrel beams in buildings, and spiral stair cases is a typical examples of the structural elements subjected to torsion. The closed thin-walled section of the box girders has a high torsional stiffness, which ensures good transverse distribution of eccentric loads. Therefore, the box girders are widely used in long spans bridge construction [1]. Generally, the structural elements are designed to satisfy both, strength and serviceability requirements. It is not logical or impossible replacing exist structural elements which, not satisfy strength or serviceability demands, by new elements. Therefore, the structural elements strengthening, during their service life period is arising. Many factors affect the requirement for strengthening of these elements including design or construction defects, increased working load, change of structure operation and new code requirements. For instance, to prevent torsion mode of failure, adequate reinforcement details, repairing and strengthening are required. To resist torsion stresses, concrete members strengthening may be done by adding additional reinforcement in the transverse direction, increasing the member cross-sectional area, applying an axial load to the member by external prestressing and by using externally bonded steel plates [2, 3]. The use of externally bonded carbon fiber reinforced polymer (EB-CFRP or FRP) for torsional strengthening of RC element causes a significant enhancements to strength, durability and economics [4, 5]. The effectiveness of internally strengthening by GFRP in increasing the torsional strength of RC beams is also investigated [6]. The influence of strengthening prestressed and non-prestressed box beams with transverse internal concrete diaphragms on strain, angle of twist, failure load and mode, ductility of beam, and torsional
strengthening were thoroughly studied [7, 8]. Occasionally, structural elements construction complexity, beam’s geometry and the environmental conditions imposes some constraints to perform external strengthening techniques. Hence, the needs to adopt internal and simple strengthening methods are arising. In the current study, K-Shape steel bracing is used as alternative strengthening method for the RC box beams under pure torsion.

2. Experimental program
Four beam specimen representative of a box beams were poured and tested under pure torsion. All the beams had a length of (2100 mm) and a cross section (300 mm) wide and (300 mm) deep. In addition, the experimental program consists of a series of tests performed on control specimens to estimate the mechanical properties of the used SCC. The main adopted parameter includes the number of internal K-shape bracing (0, 1, 3, and 5). The first beam was deemed as Reference Box beam and coded by (RB), while, the rest beams were strengthened by K-shape bracing and coded by (#K-B). It may be noted that, the symbol (#K) refers to the K-shape bracing Number; while, the symbol (B) refers to Box beam. The tested beam specimens were reinforced with (4ϕ12mm) longitudinal bars at the corners and (ϕ8@130mm) lateral bars (stirrups) at the mid-span and (ϕ8@65mm) lateral bars (stirrups) at the ends. It may be noted that, the longitudinal and lateral reinforcement were computed based on ACI-318 Committee [9] provisions for torsion; Table 1 show the beam specimen’s details, coding and description; while, the Figures 1 to 4, show the lateral and longitudinal, dimensions and reinforcement. The K-Shape bracings were fabricated and assembly by using (25x25x3mm) steel angles welded with a pair of (100x180x3mm) vertical plates. Two pairs of (10mm) diameter bolts were attached at the outer surfaces of each vertical steel plate to guarantee a complete connection between the inner surfaces of the box beam and the bracing system. It may be noted that, the dimension of the strengthening system (K-shaped bracing plus vertical plates) was selected conservatively, to be able to withstand more than the maximum expected torsional load capacity that may occur during specimens test. The strengthening system was not of a standard type, it was made by assembling of its parts using welding of (E60) type. To measure the bracing deformations (strains), strain gauges are fixed in an inclined arm of the steel bracings, Figure 5.

Table 1. Tested beams dimensions and coding.

| Beam Code | Dimensions (mm) | No. of Steel Bracing |
|-----------|-----------------|----------------------|
| RB a      | 2100 300 300 60 60 None |
| 1.0K-B    | 2100 300 300 60 60 One |
| 3.0K-B    | 2100 300 300 60 60 Three |
| 5.0K-B    | 2100 300 300 60 60 Five |

*aReference Beam.

Figure 1. Beam specimens details (RB).
**Figure 2.** Beam specimens details (1.0K-B).

| K-Shape Steel Bracing | 2\(\phi12\)mm | 2\(\phi12\)mm |
|-----------------------|----------------|----------------|
| \(\phi8@65\)mm       |                |                |
| \(\phi8@130\)mm      |                |                |

Section A-A

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**Figure 3.** Beam specimens details (3.0K-B).

| K-Shape Steel Bracing | 2\(\phi12\)mm | 2\(\phi12\)mm |
|-----------------------|----------------|----------------|
| \(\phi8@65\)mm       |                |                |
| \(\phi8@130\)mm      |                |                |

Section A-A

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**Figure 4.** Beam specimens details (5.0K-B).

| K-Shape Steel Bracing | 2\(\phi12\)mm | 2\(\phi12\)mm |
|-----------------------|----------------|----------------|
| \(\phi8@65\)mm       |                |                |
| \(\phi8@130\)mm      |                |                |

Section A-A

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**Figure 5.** Details of bracing system.

- (25x25x3mm) Steel Angles
- (100x180x3mm) Steel Plate
- (10mm) Diameter Steel Bolts
- Steel Plate
- Steel Angles
3. Materials

The mix composition of concrete consists of local materials; cement is the major constituent for most of the concrete; the ordinary Portland cement (type-I) was used in this investigation; crushed river gravel (Course Aggregates) with a maximum size of (12mm); natural sand (Fine Aggregates) from Al-Ukhaider region with maximum size of (4.75mm) and fineness modulus (3.18); fine limestone powder (L. S. P.) with fineness (3100 cm$^2$/gm), highly reactive silica fume (SF) (produced by Sika company), high water reducer (HWR) superplasticizer (Glenium 51 manufactured by BASF Construction Chemicals, Jordan); clean tap water was used for both, mixing and curing. Properties and description of the used steel bars and concrete mix proportions are presented in Tables 2 and 3 respectively.

Table 2. Properties of steel bars.

| $D_{\text{nominal}}$ (mm) | $D_{\text{measured}}$ (mm) | Bar Shape | $f_y$ (MPa) | $f_u$ (MPa) | Elongation % |
|--------------------------|----------------------------|-----------|-------------|-------------|--------------|
| 8                        | 7.9                        | Deformed  | 465         | 632         | 16           |
| 12                       | 11.8                       | Deformed  | 496         | 644         | 16           |

Table 3. Mix proportions per (m$^3$).

| Cement (kg/m$^3$) | F. Agg. (kg/m$^3$) | C. Agg. (kg/m$^3$) | L.S.P (kg/m$^3$) | S F (kg/m$^3$) | Water (liter/m$^3$) | HWR (Liter/m$^3$) |
|-------------------|-------------------|-------------------|-----------------|---------------|--------------------|------------------|
| 450               | 780               | 980               | 130             | 30            | 190                | 10               |

4. SCC properties

4.1. Fresh SCC

There are three distinct fresh concrete properties which essentially define SCC and which are fundamental to its performance both in the plastic and hardened state. The three essential fresh properties required by SCC (filling-ability, segregation resistance and passing-ability) were made according to EFNARC [10]. SCC test methods, results and the limitations of the adopted standard are shown in Table 4.

Table 4. SCC tests results at fresh state.

| SCC Properties        | SCC Test      | Tests Results | Limits $^a$ |
|-----------------------|---------------|---------------|-------------|
| Filling-ability       | Slump Flow (mm) | 800           | 650-800     |
| Filling-ability       | $T_{30}$ (sec) | 2.88          | 2.0-5.0     |
| Segregation Resistance | V-funnel (sec) | 8.43          | 6.0-12      |
| Passing-ability       | L-Box         | 1.0           | 0.8-1.0     |

$^a$ Reference [10].

4.2. Hardened SCC

To estimate the SCC compressive strength, (150x150x150mm) concrete cubes were tested based on BS 1881-116 [11] standard. Also, (150x300mm) concrete cylinders were tested based on ASTM C39-96 [12] standard. Flexural tensile strength test for SCC was carried out according to ASTM C78-18 [13]. The dimension of the test specimen was (500x100x100 mm) concrete prisms loaded under two-point loading. Tensile strength based on the indirect splitting test on cylinders was carried out according to ASTM C496-96 [14]. This is also sometimes referred as, "Brazilian Test". The dimension of test specimen was (150x300mm) concrete cylinders. SCC modulus of elasticity was performed according to ASTM C469-02 [15]. Concrete cylinders of (150x300mm) dimensions were used for this test. To satisfy the international standards requirements, the SCC control samples as well as the beam specimens were tested at (28 days) after casting. Test results are reported and presented in Table 5.
Table 5. Mechanical properties test results.

| $f'_c$ (MPa) | $f_{oc}$ (MPa) | $f_r$ (MPa) | $f_t$ (MPa) | $E_c$ (MPa) |
|-------------|-------------|-------------|-------------|-------------|
| 41.3        | 47.8        | 3.78        | 3.2         | 29568       |

5. Test measurement and instrumentation

Universal testing machine (3000 kN capacity) was used to test the beam and control specimens. A simple method was used to estimate the angle of a twist by using dial gauge attached to the bottom fiber of the end of the beam at a point (30 mm) from the end of the longitudinal axis of the beam. A dial gauges, (1\times10^{-2}\text{mm}) accuracy, were provided to measure the vertical displacement to compute the angle of twist in degrees (or in radians) every stage of loading. Also, pair of dial gauges was attached at beam tips to measure the axial elongation, as shown in Figure 6. Structural elements deformation are measured by means of strain gauges attached at different locations; two shapes of strain gauges were used, the first shape for steel reinforcement and steel bracing (KFH-20-120-C1-11L1M2R 120 20) produced by Omega company and the second for concrete (PL-60-11) produced by TML company. The concrete strains were measured at the top surface near two positions, in the mid-span from distance (400mm) at the right and left sides. Data logger of (TML/ TC-32K) type is used to transform the electrical signal of the strain gauges to corresponding strains for steel reinforcements, steel bracing and concrete, as shown in Figure 7.

5. Beam specimens test procedure

As mentioned before, a hydraulic machine was used to test all the beam specimens. The normal load is applied directly by this machine at several points and the supports should be remaining fixed against rotating around the beam longitudinal axis (twisting). In order to obtain the torsional movement,
the applied loads outside the bed of the testing machine are needed. To transmit the load from the center of the testing machine to external points that represent load eccentricity (moment arms), steel I-section beam with (2.5m) length and (0.25 mm) deep was used. To generate the required pure torsion, special clamping loading frames attached at the ends of each tested beam specimens were used as shown in Figure 8. The clamping loading frames were manufactured by using (20 mm) thick steel plates connected by using (4x 24mm diameter) bolts. It may be noted that, the steel arms were made with (600 mm) length and the applied loading way to the beam center by a distance of (500 mm).

Figure 8. Calibration and setup of the tested beams.

7. Results and discussion

7.1. Comprehensive behavior

The experimental results are documented, summarized and provided Table 6. For all tested beam specimens, the first cracks were taken place at the mid-span and increased progressively. When the applied torsion increased, the cracks formed on each face and gradually took spiral shape. The final modes of failure, which appeared at the beams faces is shown in Figure 9. Clearly, the extensive diagonal concrete cracks caused all beam specimens to be failed. For the reference beam (RB), the cracks spread over a whole beam length due to the weakness of the box section, and with the number of cracks increasing, the failure occurred at the mid span.

For the rest beams (strengthened beams), the cracks were distributed over an entire beams with a little numbers and developed in more slowly manner in bracing zones. This may be due to the contribution of the transverse k-shaped bracing which carry a certain amount of stressed and distribute the rest to the concrete skin and transverse and longitudinal reinforcement. Moreover, the final failure location is occurred between steel bracing intervals.

| Beam Code | Pc (kN) | Pult. (kN) | P/Pult. (%) | Tc (kN.m) | Tc/(Tc)R | Tult. (kN.m) | Tult./(Tult.)R | Increase in Tc (%) | Increase in Tult. (%) |
|-----------|---------|------------|-------------|-----------|----------|-------------|---------------|-----------------|--------------------|
| RB        | 22.5    | 100.5      | 22.4        | 5.625     | -        | 25.125      | -             | -               | -                  |
| 1.0K-B    | 28.0    | 132.0      | 21.2        | 7.000     | 124.4    | 33.000      | 131.3         | 24.4            | 31.0               |
| 3.0K-B    | 33.5    | 153.0      | 21.9        | 8.375     | 148.9    | 38.250      | 152.2         | 49.0            | 52.0               |
| 5.0K-B    | 35.0    | 182.5      | 19.2        | 8.750     | 155.6    | 45.625      | 181.6         | 55.6            | 82.0               |

*Reference beam.

Tc=(Pc/2)*Arm, Tult.=(Pult./2)*Arm, and Arm length= 500mm.
7.2. Beam specimens capacity

The cracks pattern photos for the tested beams, after testing, are presented in Figures 9; and the measured cracking and ultimate loads are reported in Table 6. The first visible diagonal tension crack were observed, approximately, near to the location of the mid-span and the cracking loads ($P_c$) varied by about (19.2-22.4%) of ultimate load ($P_{ult}$). In comparison with the reference beam, (RB), the first cracking torsional moments ($T_c$) were increased by about (24.4%, 49%, and 55.6%) for the tested beams (1.0K-B, 3.0K-B and 5.0K-B). While, the ultimate torsional moment ($T_{ult}$) were increased by about (31%, 52%, and 82%) for the tested specimens (1.0K-B, 3.0K-B, and 5.0K-B) respectively.

The utilization of the K-shape steel bracing leads to creates an additional internal rigid structural component which works in-plan of the torsion stress; this leads to permits a higher forces to be carried through the concrete skin, lateral reinforcement, longitudinal reinforcement and internal K-shape steel bracing, as a result, the torsional capacities are improved.

7.3. Torsion - Twisting angle relationship

Figure 10 shows the curves of the applied torsion- versus- the corresponding twisting angles. At the initial stage of loading, linear responses were recorded up to the first crack; then the twisting angles were gradually continued to increase up to the failure stage. In comparison with the reference beam, (RB), the twisting angles corresponding to the ultimate torsion moment of the tested beams (1.0K-B), (3.0K-B) and (5.0K-B) were decreased by about (20%, 29.5% and 35.5%) respectively. This may be due to the major contribution of the K-shape bracings to carry torsion at a different loading levels, as a result, the torsional rigidity were increased and leads to improve the torsional capacities and decreasing to the corresponding twisting angles.

The utilization of the K-Shape bracings, inside the box beams, is more effective and more efficient to enhance the section torsional rigidity and improves the beam capacity.
7.4. Torsion–Axial elongation relationship
Figure 11 shows the torsion- versus- axial elongation at the left and right sides for all tested beam specimen. As shown in Figure 11, at the initial stage of loading, the axial elongation does not happen in the tested beams even the section reached the cracking loads (P_c) and the elongation gradually increased up to the failure stage. For strengthened beam specimens, in comparison with the control beam specimen (RB), the measured axial elongation were decreased by about s (21%, 32%, and 53%) for the tested beam specimens (1.0K-B), (3.0K-B) and (5.0K-B) respectively.

7.5. Reinforcing steel bars strains
Longitudinal bars strains were assessing at the bottom bars in two locations, mid-span and at 200mm distance from the edge. The relationship between strains, at mid-span, and the applied torsion were depicted and presented in Figure 12. All tested beams show linear (elastic) behavior before the first visible crack; behind the elastic stage, clear disturbance in strain values were observed in all tested beams. At the ultimate stage, the recorded strains for all beam specimens indicated to tension stress (positive values). The maximum tensile strain is recorded for longitudinal reinforcement of beam specimen (5.0K-B) which equals to (2262*10^-6), this value is approach to recorded tensile strains for longitudinal reinforcement of beam specimens (1.0K-B), (3.0K-B) and (RB) which equals to (1835*10^-6).
6), (1788*10^-6) and (1514*10^-6) respectively. Test results indicated that the strains in longitudinal steel bars of the tested beam (5.0K-B) reached the point of yield strain; this means that the longitudinal bars carry the significant longitudinal stress, which induced due to torsion stress, at the mid-span.

Figure 12. Torsion- versus-Longitudinal reinforcing bars strain (a) at mid-span (b) at edge.

For strains in longitudinal reinforcement near the edges, the relationship between strains and the applied torsion were plotted and presented in Figure 12. All steel bars behave linearly before the first crack occurred, beyond this stage; clear disturbance in strain values for all beam specimens was recorded. At the ultimate stage, the recorded strains for all beam specimens indicated to tension stress (positive values). The greater tensile strain for longitudinal reinforcement is recorded for tested beam specimen (3.0K-B) and equals to (1325*10^-6). This value is approach to recorded tensile strains for longitudinal reinforcement of beam specimens (5.0K-B), (1.0K-B) and (RB) which equals to (1230*10^-6), (1258*10^-6) and (1210*10^-6) respectively. The test results showed that the longitudinal reinforced bars did not reach its yield state and the stresses at the mid-span are greater in comparison with the stresses at the edges.

Figure 13. Torsion- versus- Lateral reinforcement strains (a) at mid-span (b) at edge.

The stirrups strains were measured at two locations, at mid-span and at (280mm) distance from the edge. For mid-span stirrup, the variation of strains with applied torsion was plotted and presented in Figure 13. The maximum recorded strain is for the sample (RB); this may due to the uniform distribution of the normal stresses and absence of internal K-shape bracings through an entire the beam’s length, which permits to stirrups to carry large stresses. For all beam specimens, the strains in stirrups are tension strain (positive) and the larger recorded stirrups strains are for beam specimens (RB), (1.0K-B), (3.0K-B) and
(5.0K-B) which equals to (2231x10^6), (1899x10^6), (1685x10^6) and (1825x10^6) respectively. For stirrups strains at the edges, the relationship between strains and the applied torsion were plotted and presented in Figure 13. The recorded values were tension strain (positive strain values). The maximum recorded strain is for the sample (RB) which equals to (1423x10^6); while, the maximum strain values were recorded for beam specimens (1.0K-B), (3.0K-B) and (5.0K-B) which equals to (1390x10^6), (1258x10^6) and (1536x10^6) respectively. The above experimental results means, the measured strains, in transverse reinforcement (stirrups), do not reach its yield capacity.

7.6. Strains in concrete skin
As mentioned before, the tested samples were failed by a torsional diagonal cracks failure. This can be explained easily, the ultimate stresses exceed the ultimate tensile strength of the skin concrete, which means the concrete reached to its peak response. In all tests, the measured values were negative, which means a compression strain; Figure 14 shows the torsion- versus- concrete strain at the right and left sides. At the right side, for un-strengthened beam specimen (RB), reference beam, the recorded concrete strain was (-717x10^6), which represents the greatest values. While, for the strengthened tested beams, the ultimate recorded strain were (-646*10^6), (-550*10^6) and (-773*10^6) for the tested beams (1.0K-B), (3.0K-B) and (5.0K-B) respectively. From the other hand, at the left side, for un-strengthened beam specimen (RB), the recorded concrete strain was (-825*10^6), which represents a greatest amount. While, for the strengthened tested beams, the ultimate recorded strain were equal to (-880x10^6), (-823x10^6) and (-722x10^6), for the tested beams (1.0K-B), (3.0K-B) and (5.0K-B) respectively. It may be noted that, the measured values exceed the concrete ultimate crushing strain of (3x10^3) adopted by ACI-318M14 Code.

Figure 14. Torsion- versus- Concrete strain (a) at the left side (b) at the right side.

7.7. Strains in bracing members
Figure 15 show the strain verses corresponding torsion, for the samples (1.0K-B); (3.0K-B) and (5.0K-B) at the mid-span and ends bracings. For the K-shape bracing at the mid-span, the measured amounts are positive which means the bracing member subjected tension stresses due to torsion field. The K-shape bracing strain of the samples (3.0K-B) and (5.0K-B) were smaller than (1.0K-B) at the failure moment by (16%) and (15%) respectively, because the longitudinal strengthening was distributed equally in closed intervals (distance between steel bracing) along beam sections this leads to decrease the corresponding strain. Again, for the end steel bracing of beam specimens (3.0K-B) and (5.0K-B), all measured values are positive which means the bracing member subjected tension stresses due to torsion field. The strain in steel bracings of the beam specimens (5.0K-B) was smaller than (3.0K-B) at the
failure moment by (7%). The strain in mid-span was larger than the strain in ends this might be due to the direct relation between the torsional stresses distribution and the beam span (the maximum torsion stress was take place at the mid-span and decreased towards the supports as a result, the ultimate strain increased near the mid-span).

Figure 15. Torsion- versus- Bracing strain (a) at mid-span (b) at edge.

8. Conclusions
1- Presence of the internal K-shape steel bracing inside the reinforced SCC box beams are effective and simple method to enhance the cracking as well as the ultimate torsion capacities.
2- The failure torsion moment of strengthened beam specimens with K-shape steel bracings increases with a percentage up to (82%) more than un-strengthened beam and the angle of twist decreases by a percentage up to (35.5%). While, the longitudinal elongation decreases by a percentage up to (53%).
3- Increasing the K-shape steel bracings lead to increase the ultimate torsion moment and decrease the corresponding angle of twist at the edges (ends).

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Acknowledgement
This paper forms part of a MSc. thesis recently prepared, by the second author, at the Civil Engineering Department, Engineering College, Mustansiriyah University. The authors present would like to thank everybody who contributed in any way to the completion of this study.