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Research paper



Torsional Strength Enhancement of Reinforced SCC Box Beams Using Internal Transverse Steel Bracing Technique

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Abstract

An experimental investigation was conducted, in this paper, to evaluate the torsional strength enhancement of reinforced self-compacting concrete box beams using internal transverse steel bracing technique. Seven beam specimens have dimensions of (2100x300x300mm) for length; width and depth respectively, were poured and tested under pure torsion. Three variables were adopted in the present study; presence or absence of steel bracings, type of steel bracing (X-Type and XW-Type) and a number of steel bracing (1,3 and 5). Accordingly, the tested beams are divided into three groups (based on steel bracing type), the first group consists of one non-strengthened beam specimen (reference), the second group consists of three beams strengthened by X-Type steel bracing; while, the third group consists of three beams strengthened by XW-Type steel bracing. It was found that the ultimate torque moment increased by about (14.4%, 34.3% and 59.2%) for beam specimens containing one, three and five X-Type steel bracing, respectively, in comparison with the reference beam. While, the ultimate torque moment increased by about (21.9%, 41.8% and 71.6%), for beam specimens containing one, three and five XW-Type steel bracing, respectively, in comparison with the reference beam. The paper concludes that the contribution was enhanced using the adopted technique.

Keywords: *Torsion; Strengthening; SCC; Box beam; Steel Bracing.*

1. Introduction

Reinforced concrete members in a structure may be subjected to axial forces, shear forces, bending moments, torque, or a combination of these effects. The torsional failure may be considered one of the more dangerous failure types than other types of failure because of its uncontrolled failure and does not give an attention before failure. Diagonal cracks occurred when the torsion stress exceeds the ultimate torsion strength of concrete; therefore, to improve the torsional capacity, there are several ways such as increasing the compressive strength of concrete, adding transverse and longitudinal reinforcement. Design codes are generally based on one of two major approaches, the space truss analogy and the skew bending theory. New revisions that were adopted in ACI Building Code 318 (1995; 1999; 2002; 2005, 2008, 2011) replaced the design method that was used before with one based on thin walled tube truss analogy [(1)]. The purpose of the modifications was to simplify the design procedures carried out to study the behavior of concrete members subjected to torsion or shear forces.

Box beams are referred to as thin-walled structures because of their cross-sectional dimensions. Box beams have been used widely in bridge construction, because of the structural advantages of closed box section [(2)]. However, prediction of the response of box beam bridges involves many difficulties caused by the complex interaction of the individual structural effects [(2)].

The structural elements are designed to meet requirements of service load. When the applied load increase, the elements must be meet new requirements. In certain situations, it may be not possible to replace the existing element that does not satisfy the structural requirements by a new one, or may be replacing a new element as alternate to old one is not economically feasible solution as well as substitutions of all structure. In this manner, with the end goal to turn away disappointment of these components at torsional stack, sufficient support (longitudinal and transverse), fixing and fortifying are required. Fortifying of solid individuals to oppose torsional stresses might be finished by one of the accompanying strategies: (I) expanding the part cross-sectional zone, (ii) including transverse fortification, (iii) utilizing remotely reinforced steel plates, (iv) applying a hub load to the part by outside prestressing (3, 4). Fortified solid segments under torsional stresses and remotely reinforced by CFRP are keen on a few research (5, 6). Shafts fortified inside with GFRP fortifications under unadulterated torsion are likewise intrigued (7). In addition, reinforcing by including inner solid stomachs, in transverse heading, for prestressed and non-prestressed self-compacting solid box bars was researched (8, 9).

Sometimes, it's difficult to perform an external strengthening for box beams (girders) due to beam's geometry or system complexity. Therefore, the needs for internal strengthening by using simple systems are arise. One of the best ways is placing (inserting) an internal steel bracing inside the hollow core of the box beams. Actually, the concept of transverse steel bracing is not new idea in steel structures. This idea is widely used in steel girders to resist torsional stresses. The new idea is utilization of this concept to torsional strengthening of the reinforced self-compacting concrete box beams by placing inside the hollow. In this research, two bracing systems were used with reinforced SCC box beams and compared their behavior under pure torsion.

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2. Research Significant

Despite the many investigations on the torsion behavior of RC box beams, in the present study, the concept of adding internal transverse steel bracing inside the RC box beam is a new idea and it is not studied in previous researches.

3. Experimental work

3.1. Experimental program

The experimental program consists of pouring and testing of seven beam specimens; one beam specimen was considered as a reference beam and denoted by (B-R), and three beam specimens were strengthened by X-type steel bracing and denoted by (B-#X), where (#) refer to number of internal steel bracing; and the last three beam specimens were strengthened by XW-type steel bracing (X-type welded at crossing point) and denoted by (B-#XW)), where (#) refer to number of internal steel bracing. All beam specimens have dimensions of (2100x300x300mm) for length, width and height respectively. Since, the reinforced concrete box beams can be design directly according to ACI-318M-14 code [(1)], the longitudinal and transverse reinforcement were calculated based on code requirement for torsion. Each beam specimen was reinforced by (2ϕ12mm) bars at the top and bottom, while, the transverse reinforcement consists of (ϕ8@65mm) stirrups at ends and (ϕ8@130mm) stirrups at the mid, as shown in Figure 1.

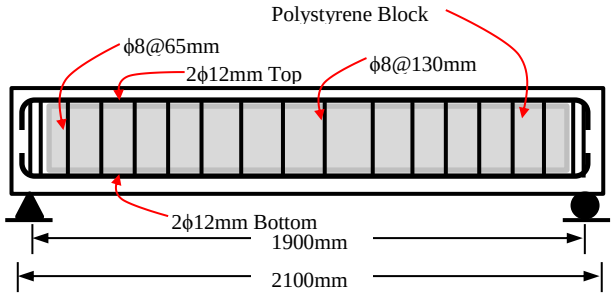


Fig. 1: Details of tested beam specimens

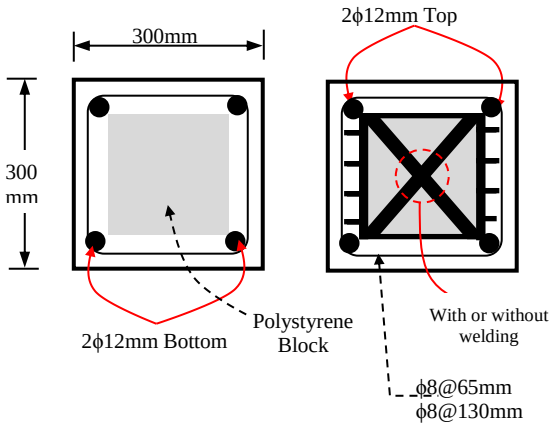


Fig. 2: Cross-section in strengthened and non-strengthened beam specimens

The longitudinal reinforcement, transverse reinforcement, dimensions of beams specimens, type and compressive strength of concrete, and the load location will be keeps constant throughout the study. Three variables were adopted herein, the presence or absence of steel bracing, type of steel bracing (X-type and XW-type) and number of steel bracing (1, 3 and 5). Description and details of tested beam specimens are shown in Table 1, and Figures 1 and 2. The steel bracing was made by steel angles with dimensions of (25x25x3mm) and fixed (weld) by two vertical steel plates with dimensions of (100x180x3mm). To ensure full bond between bracing system and inner faces of box beams, four steel bolts of diameter (10mm) were fixed at the outer faces of each vertical steel plate. Strain gages are fixed in steel bracing to measure strains, as shown in Figure 3.

Table 1: Details of beam specimens

Group	Beam Designation	Dimensions (mm)			No. of Bracing	Bracing Type
		L	W	D		
G-1	B-R*	2100	300	300	None	-
G-2	B-1.0X				One	X-Type
	B-3.0X				Three	
	B-5.0X				Five	
G-3	B-1.0XW				One	XW- Type
	B-3.0XW				Three	
	B-5.0XW				Five	

*Reference Beam.



Fig. 3: Details of bracing system (X and XW-Type)

3.2. Materials

In manufacturing the beam specimens, properties and description of the used materials as well as properties of steel bars are presented in Tables 2 and 3 respectively. To get, approximately, the same concrete strength for all samples, one concrete mix proportions are adopted, as shown in Table 4.

Table 2: Properties of construction materials

Material	Descriptions
Cement	Ordinary Portland Cement (Type I).
Sand	Natural sand from Al-Ukhaidher region with maximum size of (4.75mm).
Gravel	Crushed gravel of maximum size (12mm).
Limestone powder	Fine limestone powder (locally named as Al-Gubra) of Jordanian origin.
Silica Fume	Silica fume is a highly reactive material; this type of silica fume is produced by the Sika company.
Superplasticizer	Glenium 51 manufactured by BASF Construction Chemicals, Jordan.
Water	Clean tap water.

Table 3: Properties of steel bars

Property	Description (Value)	
$D_{Nominal}$ (mm)	8	12
$D_{Measured}$ (mm)	7.9	11.8
Bar Type	Deformed	Deformed
f_y (MPa)	465	496
f_u MPa)	632	644
E_s^* (GPa)	200	200
Elongation (%)	16	16

*ACI 318-M14

Table 4: Mix proportions details

Material	Quantity
Cement (kg/m^3)	450
Sand (kg/m^3)	780
Gravel (kg/m^3)	980
Limestone (kg/m^3)	130
Silica Fume (kg/m^3)	30
Water (liter/m^3)	190
Superplasticizer (Liter/m^3)	10

3.3. Properties of fresh and hardened concrete

3.3.1. Properties of fresh concrete

To check the self-compacting concrete, four tests to evaluate filling-ability, segregation resistance and passing-ability are made. Table 5 shows the test methods, test results and SCC requirements according to EFNARC [10].

Table 5: Tests results of fresh SCC

Test	Property	Test Result	EFNARC
Slump Flow (mm)	Filling ability	800	650-800
T_{50} (sec)		2.88	2.0-5.0
V-funnel (sec)	Segregation resistance	8.43	6.0-12
L-Box	Passing ability	1.0	0.8-1.0

3.3.2. Properties of hardened concrete

A series of tests were carried out to determine the compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity of the concrete. Average of three (150x150x150mm) cube specimens and three (150x300mm) cylinders are used in every mix to determine the uniaxial compressive strength according to (ASTM C39/C39M-01) [11] and (BS 1881-116 1983) [12] specifications. The determination of the flexural strength (modulus of rupture) of SCC is done by the use of a simple beam (prisms) with dimensions of (500x100x100 mm) under two-point loading. The prisms were loaded at (450mm) span. The indirect tensile strength was carried out according with ASTM C496-96 [13]. (150x300mm) cylindrical specimens were used to compute splitting tensile strength of concrete. The specimens were tested at the age of 28 days. Static modulus of elasticity was carried out according to ASTM C469-02[14]. (150x300mm) cylindrical specimens were used to compute modulus of elasticity of concrete. Tests results are collected and presented in Table 6.

Table 6: Mechanical properties of hardened SCC

Mix Type	Compressive Strength (MPa)		f_r (MPa)	f_t (MPa)	E_c (MPa)
	f'_c	f_{cu}			
SCC	41.3	47.8	3.78	3.20	29568

3.4. Molds and polystyrene blocks

Wooden molds with (18mm) thickness plywood were used to cast beam specimens. Each mold consists of a bed and two movable sides, these sides have been fixed together by screws to form the required shape. Polystyrene blocks are used to form the hollows inside the beams because of it is lightweight and its facility to configure with the required dimensions. For all tested beams, beyond the cells (at the ends), whole beam section was solid concrete.

3.5. Test measurement and instrumentation

Pressure driven widespread testing machine of (3000 kN) limit was utilized to test the shaft and control examples. A straightforward technique was utilized to assess the edge of wind by utilizing dial check appended to the base fiber of the finish of the pillar at a point (30 mm) from the finish of the longitudinal pivot of the shaft. The dial check (0.01mm/div. precision) recorded the vertical avoidance to discover the wind edge in radians at each heap organize. Likewise, two dial checks were connected at the edges of each bar to gauge the longitudinal lengthening, as appeared in Figure 4. The strains were estimated by methods for strain checks connected in various areas, as appeared in Figure 5 and Table 7.



Fig. 4: Dial gauges locations



Fig. 5: Strain gauges in steel bars, concrete and steel bracing

Table 7: Strain gauges locations

Gauge No.	Location
1	At stirrup (280mm) away from the edge.
2	At longitudinal steel bars (200mm distance from the edge).
3	At stirrup (mid-span).
4	At longitudinal steel bars (mid-span).
5	At intermediate steel bracings (mid-span).
6	At steel bracings (at edge).
7	At the side face of beam (concrete), (mid-span and 40mm distance from right side).
8	At the top face of beam (concrete), (mid-span and 40mm distance from left side).

3.6. Beam specimens test procedure

Before testing, positions of supports, applied load, strain gauges and dial gauges were marked. The beam specimens were placed on the testing machine and adjusted so that the centerline, supports, point loads, strain gauges and dial gauges were fixed in their correct or proper locations. The surfaces (faces) of beam specimens were painted with slightly white color for monitoring the concrete cracks pattern and to "capture" first crack easily. While placing the specimens in the testing machine, care should be taken to ensure that loading is at the end of the steel arm. The loads are applied symmetrically, as shown in Figure 6.



Fig. 6: Beam specimen setup and loading arrangement

The steel girder of (250 mm) deep and (2500 mm) long was used to transmit the loads from the center of the universal machine to the two arms to produce pure torsion to the tested beams. During application of load to the beam, single point load is applied to the top of steel arm and is transferred as pure torque to the top of the beam, loading is continued until severe cracking of the beam occurs. The frame used in testing consists of two large steel clamps which work as arms for applied torque with separated faces to connect them over the sample by large bolts, where four bolts are used for each arm. High carbon steel plate is used to manufacture the frame with 20 mm in thickness and bolted by four 24 mm diameter bolts to prevent torque. Arm length is maximum 600 mm were applied loading of 500 mm and these points measured a way to the beam center. In order to get pure torsion, the center of sup-

port should coincide with the center of the moment arm, as shown in Figure 6.

4. Results and discussion

During the experimental work, general behavior, mode of failure, cracking load, ultimate load, torque versus angle of twist, torque versus longitudinal elongation and torque versus strains were recorded for each beam specimen. Photographs for the tested beams were taken to show the crack pattern and some other details.

4.1. General behaviour

The test results are recorded, summarized and given in Tables 8 and 9. First crack of all specimens occurred at mid span and increased gradually. When the torque moment increased, cracks appeared on each side and finally took the spiral shape. Figure 7 shows the failure modes for the tested beams; all beam specimens were failed by extensive diagonal concrete crack (torsional spiral cracks). For reference beam specimen (B-R), due to the weakness of box section, the cracks spread in an entire beam length (non-strengthened zone) and with increasing in cracks number, the failure occurred at the mid span. For other tested beams (beam specimens strengthened with steel bracing), the cracks spread with smaller number and develop more slowly in strengthening zone (bracing zones) because the transverse bracing carry a certain amount of stressed and distribute the rest to concrete and steel bars. Also the failure position of beam specimens took place between steel bracings.

Table 8: Test results of tested beam specimens

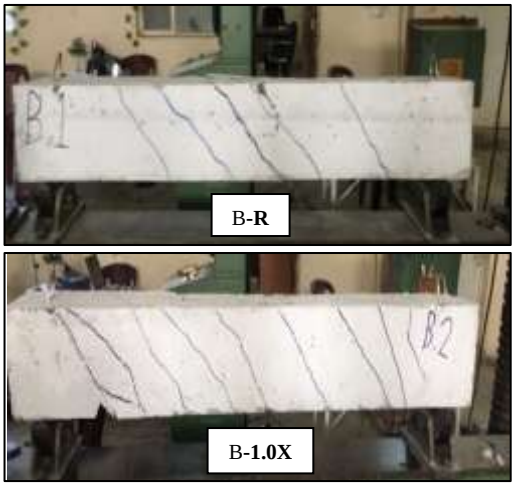
Group	Beam Designation	Pcr (kN)	Pu (kN)	Pcr/Pu %
1	B-R*	22.5	100.5	22.4
2	B-1.0X	25.0	115.0	21.7
	B-3.0X	27.0	135.0	20.0
	B-5.0X	30.0	160.0	18.8
3	B-1.0XW	26.5	122.5	21.6
	B-3.0XW	29.0	142.5	20.4
	B-5.0XW	31.5	172.5	18.3

*****Reference of group

Table 9: Ultimate and cracking torque of tested beam specimens

Group	Beam Designation	Tcr (kN.m)	Tcr/(Tcr)R %	Tu (kN.m)	Tu/(Tu)R %
1	B-R*	5.625	-	25.125	-
2	B-1.0X	6.250	111.1	28.750	114.4
	B-3.0X	6.750	120.0	33.750	134.3
	B-5.0X	7.500	133.3	40.000	159.2
3	B-1.0XW	6.625	117.8	30.628	121.9
	B-3.0XW	7.250	128.9	35.625	141.8
	B-5.0XW	7.875	140.0	43.125	171.6

*****Reference of group ** T=(P/2)*Arm Arm=0.5m



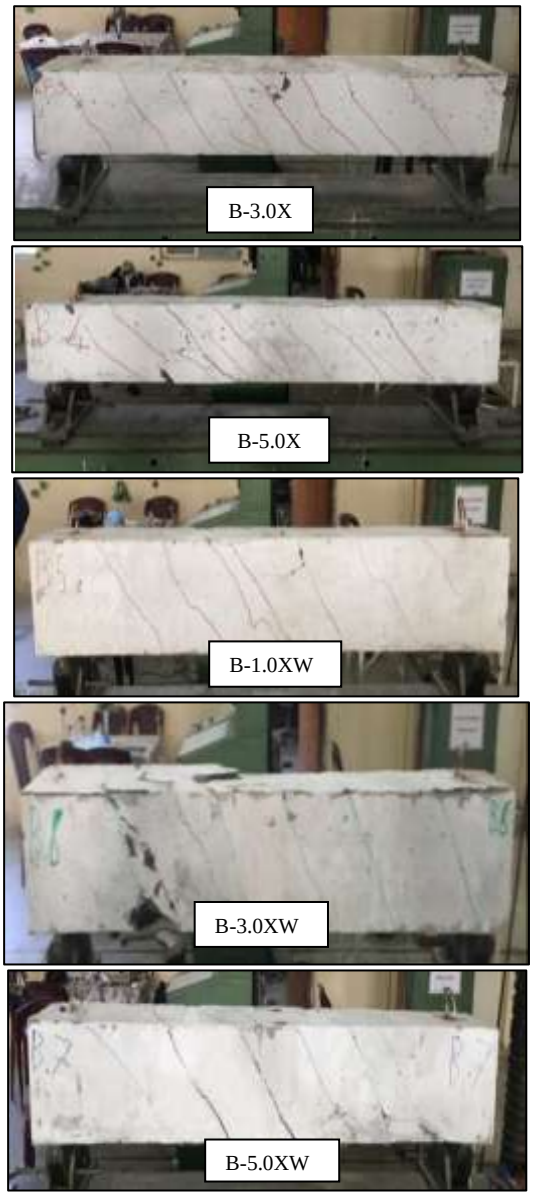


Fig. 7: Mode of failure of tested beams Specimens

4.2. Cracking and ultimate torque

The recorded cracking and ultimate torque of the tested beams have been recorded and presented in Table 9, and the crack patterns for tested specimens are shown in Figure 7 for all tested beams.

4.2.1. Cracking torque

The first visible diagonal crack loads of the tested beams varied from (18.3%) to (22.4%) of the experimental ultimate loads, and all the first diagonal crack were initiated at a position, approximately, near to mid-span of the tested beams. For group two, in comparison with the reference beam, (B-R), It can be seen that the first cracking torque moment increases about (11.1%-20%-33.3%) for beam specimens (B-1.0X, B-3.0X and B-5.0X) which strengthened internally by one, three and five steel bracing respectively. For group three, in comparison with the reference beam, (B-R), it can be seen that the first cracking torque moment increases about (17.8%-28.9%-40.0%) for beam specimens (B-1.0Xw, B-3.0XW and B-5.0XW) who strengthened internally by one, three and five steel bracing respectively. This means the presence of internal bracing improves the torsional resistance and allowing higher forces to be carried through internal bracing.

4.2.2. Ultimate torque

For group two, in comparison with the reference beam, (B-R), It can be seen that the ultimate torque moment increases (14.4%, 34.3% and 59.2%) for beam specimens (B-1.0X, B-3.0X and B-5.0X) which strengthened internally by one, three and five steel bracing respectively. For group three, in comparison with the reference beam, (B-R), it can be seen that the ultimate torque moment increases (21.9%, 41.8% and 71.6%) for beam specimens (B-1.0XW, B-3.0XW and B-5.0XW) who strengthened internally by one, three and five steel bracing respectively. This means the presence of internal steel bracing improves the torsional resistance and allowing higher forces to be carried through internal bracing.
Test results, indicated that the change of internal bracing from (X-type) to (XW-type), lead to increase of the ultimate capacity for about (7.5%), (7.5%) and (12.4%) for beam specimens containing one, three and five steel bracing respectively. This means that the (XW-type) of steel bracing is more efficient technique, to increase torsional capacity (strengthening), in comparison with the other types.

4.3. Torque-angle of twist relationship

Figures 8 and 9 shows the relationship between the torque and angle of twist, where it was drawn through the calculated results obtained in the test run for each tested beam.

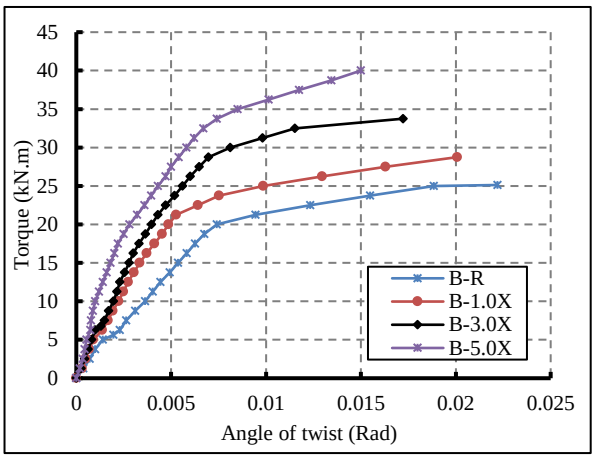


Fig. 8: Torque-angle of twist behavior for groups one and two

All tested beams show linear relationship until the first crack and then gradually increase the angle of twist until failure. For beam specimens of group two, in compared to the control beam specimen (B-R), the ultimate twist angle of beam specimens (B-1.0X), (B-3.0X) and (B-5.0X) are decreased by about (8.2%), (18.8%) and (30.365%) respectively. This is due to contribution of the transverse steel bracings to carry torsional moment at a certain level. For beam specimens of group three, in compared with the control beam (B-R), the ultimate twist angle of beam specimens (B-1.0XW), (B-3.0XW) and (B-5.0XW) are decreased by (12.25%), (26.235%) and (32.42%) respectively. The presence of internal steel bracings (inside the beams) seems to be more effective in increase the section torsional rigidity, as a result the angles of twisting decreased.

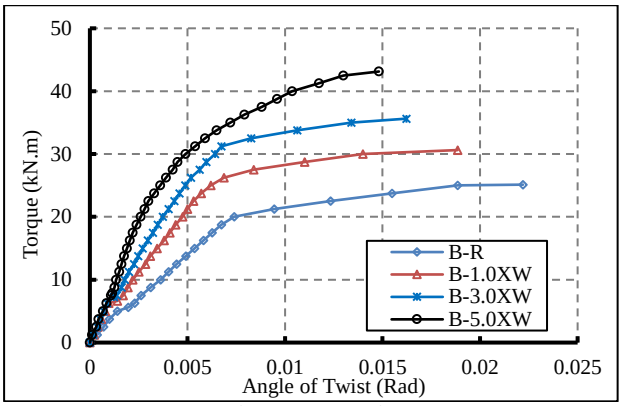


Fig. 9: Torque-angle of twist behavior for groups one and three

4.4. Torque-longitudinal elongation relationship

Warping displacement practically occurs at the ends of the beams out of plane distortion of the cross-section in the direction of the longitudinal axis; this is because of the shear strain which varies around the circumference of the section, causing the section deformation in such a manner that plane sections through the beams do not remain plane. In this case, the shear stresses at the top and bottom become zero and, at the middle section become maximum [15]. Figures 10 and 11 shows the relationships between torque and warping, for each specimen in right and left side, the general relationship between torque and warping is such that, initially does not happen longitudinal elongation in beams even cracking loads and the warping gradually increased up to failure. The longitudinal elongation of beam specimens (B-1.0X), (B-3.0X) and (B-5.0X) were decreases for about (8.235%, 21.56% and 33.33%) respectively. While, for beam specimens (B-1.0XW), (B-3.0XW) and (B-5.0XW), the longitudinal elongation decreases for about (17.25%, 26.62% and 40%) respectively.

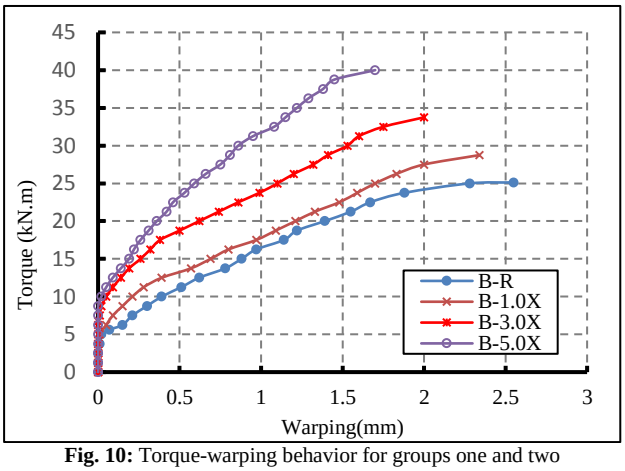


Fig. 10: Torque-warping behavior for groups one and two

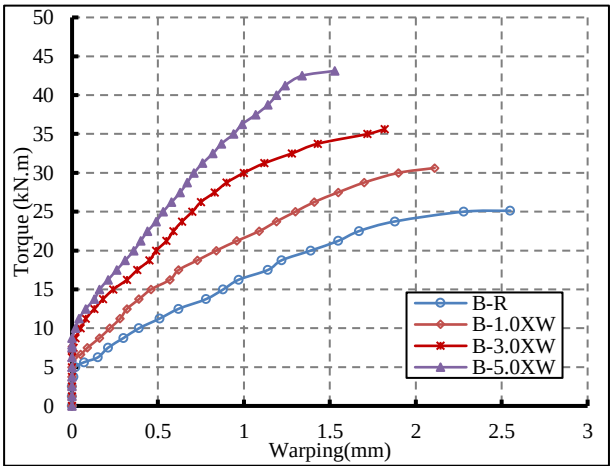


Fig. 11: Torque-warping behavior for groups one and three

4.5. Reinforcement, steel bracing and concrete strains

The experimental strains for concrete surfaces (faces), steel reinforcement (longitudinal bars and stirrups) and steel bracing (mid and end steel bracing) were measured using a sets of gauges positioned as indicated in Table 7. Test results of concrete, steel reinforcement and steel bracing strains for each beam specimen were recorded and discussed as follows: -

4.5.1. Reinforcement strains

4.5.1.1. Longitudinal bars strains

The variations of the torque with strain in longitudinal bars are measured in mid-span and edge and presented in Figure 12. For mid-span, all beams behave linearly before first crack, beyond this point, there are clearly disturbance for strain values for all tested specimens. At ultimate stage, all values of strain for beam specimens are positive. Maximum positive strain is recorded for beam specimen (B-5.0XW) and equal to ($2275*10^{-6}$), this value is approach to recorded strain for beam specimen (B-5.0X) which equals to ($2207*10^{-6}$). The maximum longitudinal bars strains for beam specimens (B-3.0X), (B-3.0XW), (B-1.0X) and (B-1.0XW) equal to ($1788*10^{-6}$), ($1369*10^{-6}$), ($1330*10^{-6}$) and ($1259*10^{-6}$) respectively. While, the maximum strain, for control beam specimen (B-R) equals to ($1514*10^{-6}$). The results indicated that the strains in longitudinal bars of beam specimens (B-5.0X) and (B-5.0XW) reached the yield strain; this means that the longitudinal bars carry the major longitudinal stress which produced due to torsion stress at the mid span.

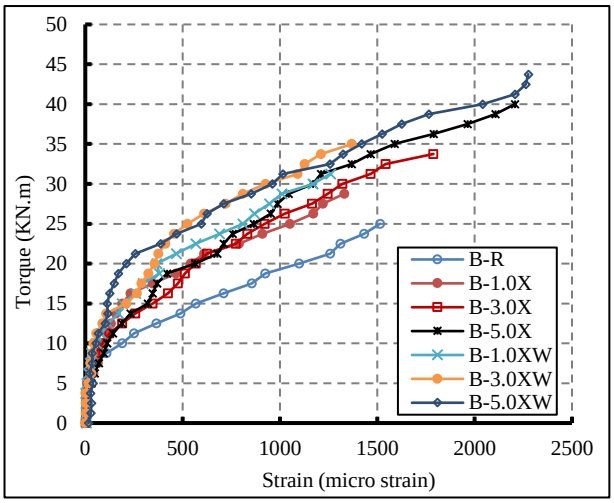


Fig. 12: Torque-longitudinal bars strains at mid-span

For strains at the edge, Figure 13, all beams behave linearly before first crack, beyond this point, there are clearly disturbance for values of strain for all specimens. At ultimate stage, all values of strain for tested specimens were positive. The greater maximum positive strain is recorded for beam specimen (B-5.0X) and equals to ($1398*10^{-6}$). This value is approach to recorded strain for beam specimen (B-5.0XW) which equals to ($1230*10^{-6}$). The maximum longitudinal bars strains for beam specimens (B-R), (B-3.0XW) and (B-1.0X) equal to ($1210*10^{-6}$), ($1225*10^{-6}$) and ($1258*10^{-6}$) respectively. From the other hand, the beam specimens (B-3.0X) and (B-1.0XW) records maximum positive strain which equal to ($1198*10^{-6}$) and ($1185*10^{-6}$) respectively. It may be noted that, the longitudinal bars at the edges dose not reach it yield state. This means that the stresses at the edges are small in comparison with the stresses at the mid span.

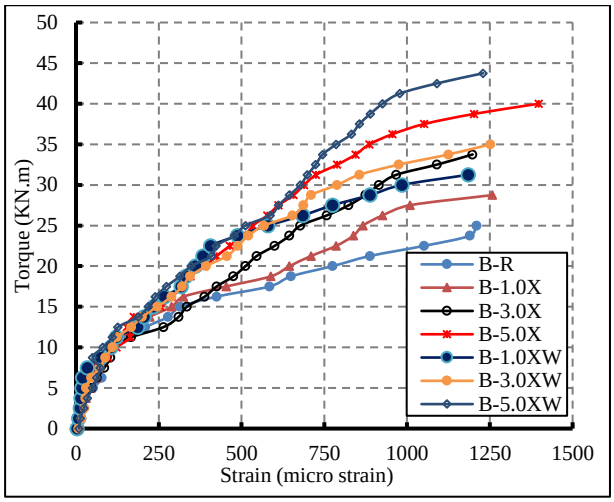


Fig. 13: Torque-longitudinal bars strains at edge

4.5.1.2. Stirrup strains

The variations of the torque with strain in stirrups were measured in mid span and edge. For mid span, Figure 14, the maximum stirrups strain was recorded for reference beam specimen (without internal steel bracing), (B-R) which represents the higher value in comparison with the other specimens. This may be due to the uniform distribution of the normal forces due to the absence of internal steel bracing throughout the beam length. The strain in stirrups of all beam specimens is positive (tension). The maximum recorded stirrups strains for beam specimens (B-R), (B-1.0X), (B-3.0X), (B-5.0X), (B-1.0XW), (B-3.0XW) and (B-5.0XW) are equal to ($2231*10^{-6}$), ($1879*10^{-6}$), ($1773*10^{-6}$), ($1955*10^{-6}$), ($1725*10^{-6}$), ($1700*10^{-6}$) and ($1625*10^{-6}$) respectively.

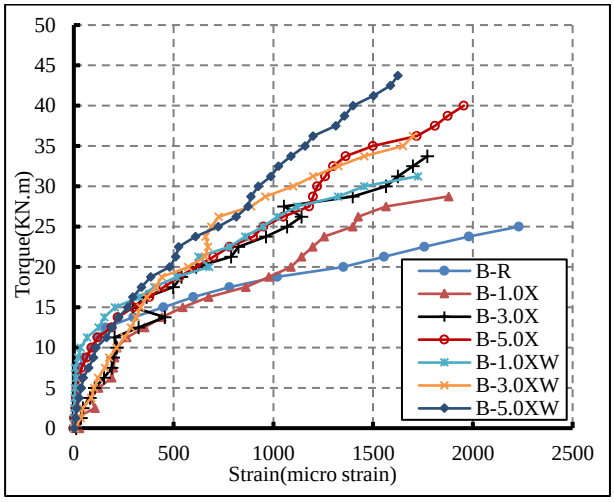


Figure 14: Torque-stirrups strains at mid-span

At the edge, Figure 15, all recorded strain values of were positive (tension). The maximum positive value of strain is recorded for reference beam (B-R) which equals to ($1423*10^{-6}$). While, the maximum positive strain values for beam specimens (B-1.0X), (B-3.0X), (B-5.0X), (B-1.0XW) (B-3.0XW) and (B-5.0XW) were equal to ($1355*10^{-6}$), ($1455*10^{-6}$), ($1269*10^{-6}$), ($1088*10^{-6}$), ($1190*10^{-6}$) and ($1289*10^{-6}$) respectively.

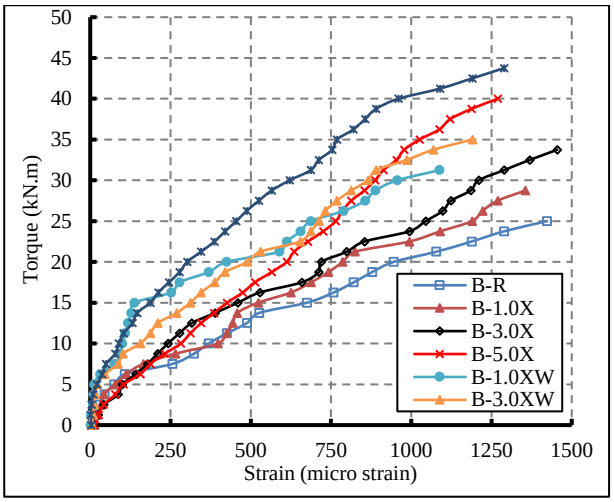


Figure 15: Torque-stirrups strains at edge

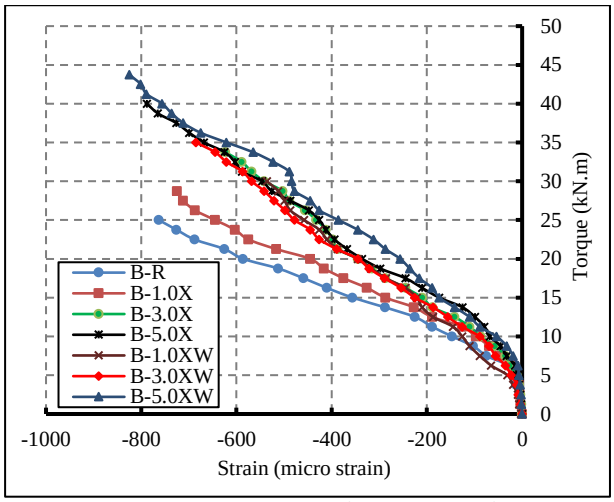


Fig. 17: Torque-concrete strain for location-1 (left side)

4.5.2. Concrete strains

Variation of the torque with strain in concrete was measured in top surface of tested beams for two locations in mid span from distance (40cm) right and left side. According to ACI-318-14, the ultimate compressive strain of concrete at crushing was (0.003) to higher than (0.008) under special conditions. In the present study, the value of strain was recorded every (5kN). All beam specimens were failed with a diagonal concrete crack (torsional spiral cracks) failure, which means the ultimate load (ultimate stress) exceeds the ultimate strength and the concrete approaches to its peak response. All recorded strain values were negative (compression), for location one (Right side), as shown in Figure 16. The maximum measured strain for reference beam specimen (B-R) is equal to ($-717*10^{-6}$), which represents the largest values. The maximum measured strain for beam specimens (B-1.0X), (B-3.0X), (B-5.0X), (B-1.0XW), (B-3.0XW) and (B-5.0XW) are equal to ($-425*10^{-6}$), ($-752*10^{-6}$), ($-654*10^{-6}$), ($-535*10^{-6}$), ($-410*10^{-6}$) and ($-712*10^{-6}$) respectively.

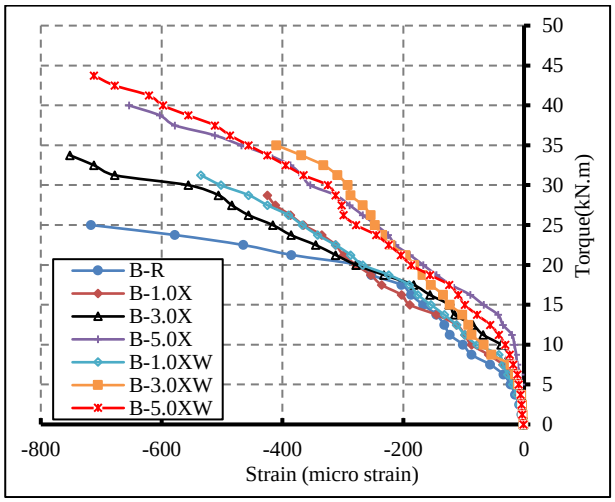


Fig. 16: Torque-concrete strain for location-1 (right side)

For location two (Left side), Figure 17, the maximum measured strains were recorded for beam specimen (B-5.0XW) and (B-5.0X) which equal to ($-825*10^{-6}$) and ($-788*10^{-6}$) respectively which represents the largest values. The maximum measured strain for beam specimens (B-R), (B-1.0X), (B-3.0X), (B-1.0XW) and (B-3.0XW) are equal to ($-763*10^{-6}$), ($-752*10^{-6}$), ($-623*10^{-6}$), ($-536*10^{-6}$) and ($-685*10^{-6}$) respectively.

4.5.3. Steel bracing strains

The variations of torque with strain in steel bracings were measured in mid-span and the end bracings. For mid span bracing, Figure 18, all values of strain for bracings are positive except (X-Bracing) one leg is positive and second leg is negative because the transverse steel bracing were placed inside the beam subject to two opposite force due to torque moment. The maximum measured strains for beams specimens (B-1.0X (T)), (B-1.0X(C)) and (B-1.0XW) were equal to ($1514*10^{-6}$), ($-1150*10^{-6}$) and ($1625*10^{-6}$) which represents the largest value. The maximum measured strains for beam specimens (B-3.0X(T)), (B-3.0X(C)), (B-5.0X(T)), (B-5.0X(C)), (B-3.0XW) and (B-5.0XW) were equal to ($1478*10^{-6}$), ($-988*10^{-6}$), ($1387*10^{-6}$), ($-1085*10^{-6}$), ($1478*10^{-6}$) and ($1534*10^{-6}$) respectively.

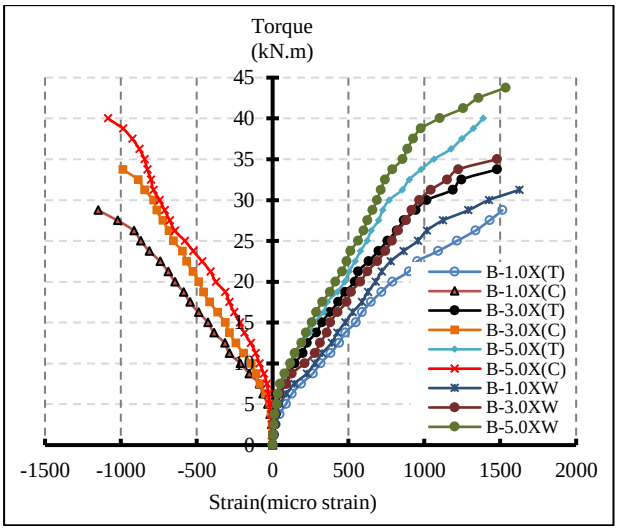


Fig. 18: Torque-strain for steel bracing (mid-span bracing)

For end bracing, Figure 19, all values of strain for bracings are positive except (X-Bracing) one leg is positive and second leg is negative because the transverse steel bracing were placed inside the beam and subject to two opposite force due to torque moment. The maximum measured strain for beam specimens (B-3.0XW) and (B-5.0XW) is equal to ($1325*10^{-6}$) and ($1422*10^{-6}$) which represents the largest values. The maximum measured strains for beam specimens (B-3.0X (T)), (B-3.0X(C)), (B-5.0X (T)) and (B-5.0X(C)) were equal to ($1220*10^{-6}$), ($-955*10^{-6}$), ($1236*10^{-6}$) and ($-1050*10^{-6}$) respectively.

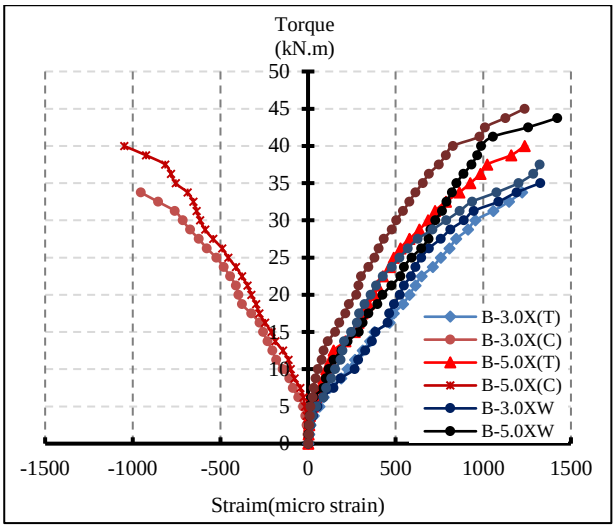


Fig. 19: Torque-strain for steel bracing (end bracing)

5. Conclusion

The following conclusions can be drawn:-

1-The adopted technique (strengthening by internal steel bracings) seems to be simple and more effective to increase section torsional capacity.

2- For beam specimens who strengthened internally by one, three and five X-type steel bracing, the ultimate torque moment increases for about (14.4%, 34.3% and 59.2%) respectively, also, the angle of twist decreases for about (8.2%, 18.8% and 30.365%) respectively. From the other side, the longitudinal elongation decreases for about (8.235%, 21.56% and 33.33%) respectively.

3- For beam specimens who strengthened internally by one, three and five XW-type steel bracing, the ultimate torque moment increases for about (21.9%, 41.8% and 71.6%) respectively, also, the angle of twist decreases for about (12.25%, 26.235% and 32.42%) respectively. From the other side, the longitudinal elongation decreases for about (17.25%, 26.62% and 40%) respectively.

4- The XW-type steel bracing is more efficient than the X-type steel bracing.

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