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Torsion strength enhancement of RC hollow beam web using steel diaphragms as in-plane technique

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Abstract. Sometimes the construction system complexity or beam's geometry imposes some difficulties in performing an external strengthening for RC hollow beam web. The main challenge is to select a proper strengthening method to overcome its low torsion strength to in-plane and out-of-plane stresses. Accordingly, the main goal of this research is to judge the possibility to adopt or (suggest) a certain internal in-plane technique to enhance the torsion strength. Six hollow beam web specimens of dimensions (1600x200x200mm) are tested experimentally under torsion effect. The major adopted variables including, the presence or absence of in-plane diaphragms, number of in-plane diaphragms (one, three and five), and strengthen the in-plane steel diaphragm with CFRP sheet on one or both faces. The experimental results show the ultimate torque increased by about (36%, 73% and 100%) for the tested specimens strengthened by one, three and five in-plane diaphragms respectively. On the other hand, the ultimate torque capacity was increased by about (53-55%) for beam specimens which contain one steel diaphragm strengthened by one and two CFRP sheets at their faces respectively, in comparison with the non-strengthened beam. It can be concluded that the torsional capacity has been enhanced due to the contribution of the adopted method.

1. Introduction

The torsion failure can be considered as one of the more dangerous failure types because of it's uncontrollable and does not give any precaution notice before taking place. Shear stresses due to torsion create diagonal tension stresses (in transverse and longitudinal directions) that produce diagonal cracking. If the member is not adequately reinforced for torsion, a sudden brittle failure can occur [1]. The torsion moment tends to twist the structural members, around its longitudinal axis, producing shear stresses. In most cases, the torsion act concurrently with the flexural moment and shear forces, therefore, the structural members are rarely subjected to pure torsion moment alone [2].

Appreciable torsion occurs in many structures, such as in the main girders of bridges which are twisted by transverse beams or slabs; in complex structures such as curved beams, helical stairways, eccentrically loaded box beams, balcony girders and whenever large loads are applied to any beam "off-center", the torsional effects control the structural behavior [3, 4].

In order to avoid torsion failure, several techniques can be provided such as the adequate design of transverse and longitudinal reinforcement, utilization of adequate repairing and strengthening techniques. The strengthening of concrete members to resist torsion stresses may be achievable by adding transverse reinforcement, increasing the member cross-sectional area, using externally bonded steel plates and applying an axial load to the member by external prestressing [5, 6]. Reinforced concrete sections under torsion stresses and externally strengthened by CFRP were interested in several research [7, 8, 9]. Moreover, the strengthened of the RC box beam by adding internal concrete diaphragms, in the transverse direction, for prestressed and non-prestressed SCC box beams were investigated [10, 11]. The investigation of the torsion behavior of reinforced SCC box beams strengthened by utilization of the in-plane steel bracing technique to enhance the torsion strength is also studied [12]. On the other hand, the torsional strengthening of RC beam with Glass Fiber Reinforced Polymers (GFRP) lamination and Aramid Fiber Strips (AFS) were studied experimentally and analytically [13, 14]. A literature review concerning the torsional behavior of RC beams strengthened with CFRP using both techniques, Externally-Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) were presented [15]. Many researches exhibit that self-compacting concrete (SCC) is an excellent material for precast and cast-in-place construction. Furthermore, the SCC is the best selection where the tightness of steel reinforcement is required and where the concrete sections are thin. To overcome the low torsion resistance of RC hollow beam web to in-plane concentrated stresses drawback, the technique of adding the in-plane steel diaphragms (placing inside the hollow beam web) in the transverse direction are investigated in this paper.

2. Study significance

In previous studies, several techniques have been implemented to enhance the torsion strength of RC solid or hollow web beams. The present study is aimed at proposing and evaluating the effect of adding internal in-plane (transverse direction) steel diaphragms, inside the hollow web beams, on torsion behavior RC hollow web beams under pure torsion. This technique seems to be a good concept, limited and not covered in previous literature.

3. Experimental investigation

3.1. Laboratory program

The laboratory program involves the casting and testing of six full-scale SCC box beam specimens, as well as many tests that have been done on control specimens (cubic simples, cylindrical simples, and prisms) to evaluate the mechanical properties of wet (fresh) and hardened SCC. All beams were cast with a dimension of (200x200x1600mm) for width, depth, and length respectively. The longitudinal and transverse reinforcement (stirrups) were calculated (designed) directly according to ACI318-M14 code [16] provisions for torsion. The transverse reinforcement consists of (ϕ8@50mm) stirrups at the edges and (ϕ8@90mm) stirrups at the mid, while; the longitudinal reinforcement consists of (2ϕ10mm) bars at the top and the bottom. The major adopted variables including, the presence or absence of in-plane diaphragms, number of in-plane diaphragms (one, three and five), and strengthen the in-plane steel diaphragm with CFRP sheet on one or both faces. The dimensions of tested specimens, transverse and longitudinal reinforcement, concrete grade, and position of load were kept constant throughout this research. The first beam specimen was non-strengthened (reference beam), while the other beam specimens were strengthened by in-plane steel diaphragms. Designation of tested beams were selected in a way to refer to section type (B = Box beam), number of in-plane steel diaphragms (1, 3 and 5), the shape of opening of in-plane steel diaphragms (ROD= rectangular opening), and the strengthening of in-plane steel diaphragms with CFRP sheets (1CF= strengthening in one face, 2CF= strengthening in two faces). Tested beams designation, dimensions and details are provided in table 1 and figures 1 to 3.

Table 1. Details and Description of Tested Specimens.

Designation of Tested Beams	Dimensions (mm) L	W	D	Number Diaphragms	Diaphragm Strengthening by CFRP
B-R[a]	1600	200	200	None	None
B-1ROD	1600	200	200	One	None
B-3ROD	1600	200	200	Three	None
B-5ROD	1600	200	200	Five	None
B-1ROD&1CF	1600	200	200	One	One Face
B-1ROD&2CF	1600	200	200	One	Two Faces

[a]Reference beam.

The steel diaphragm was made by steel of dimension (120x120x2 mm) for width, length, and thickness, respectively. To keep the main function of the box beams, the steel diaphragms were made with a square opening of dimensions (46x46mm) in the center. The in-plane steel diaphragms were formed by welding of two vertical steel plates with two horizontal steel plates with dimensions of (120x25x2 mm) for width, length, and thickness respectively. To confine the steel diaphragms system within the inner faces of the hollow beam web, three steel bolts of (13mm) diameter were fixed at the outer faces of each horizontal and vertical steel plate by welded at the crossing point. To assembly the steel diaphragm's components; E6013 type of welding is used, figure 4.

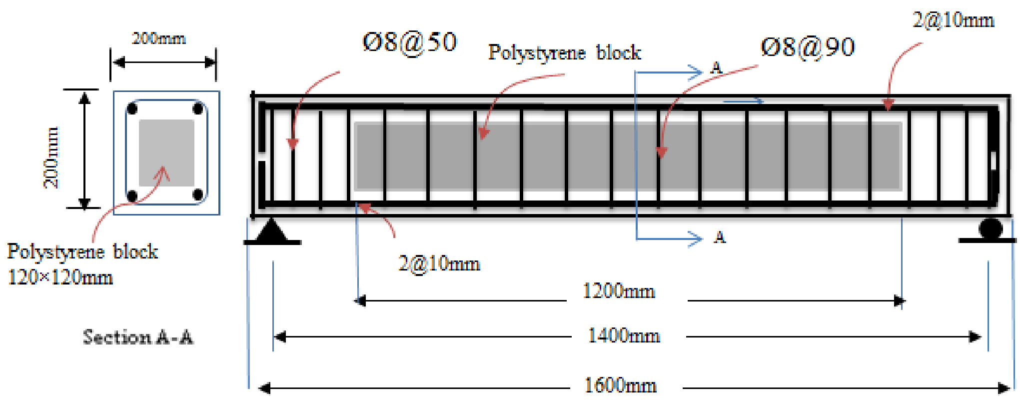

Figure 1. Reinforcement and details of tested Beam (B-R).

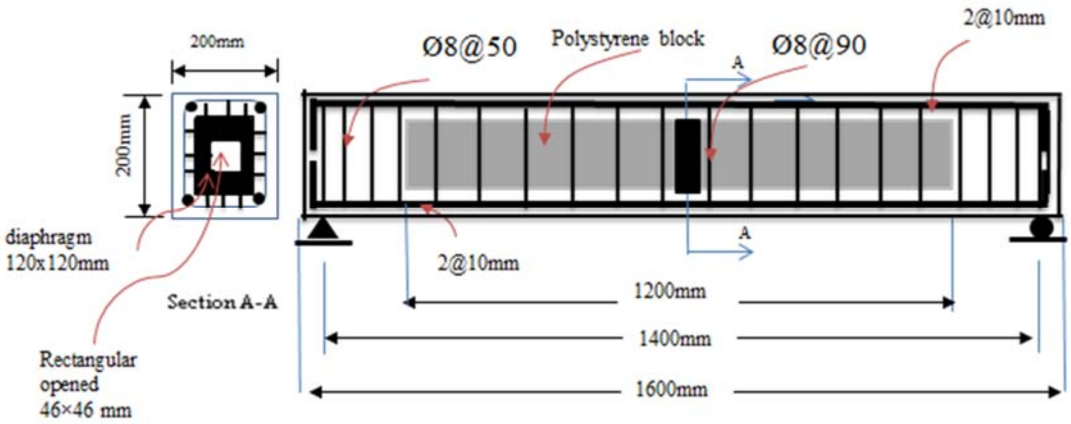

Figure 2. Reinforcement and details of tested beam (B-1ROD).

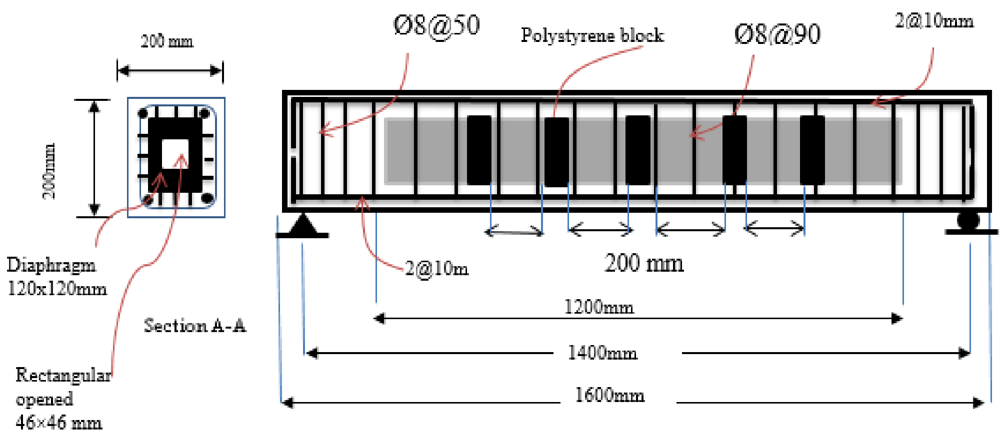

Figure 3. Reinforcement and details of tested beam (B-5ROD).

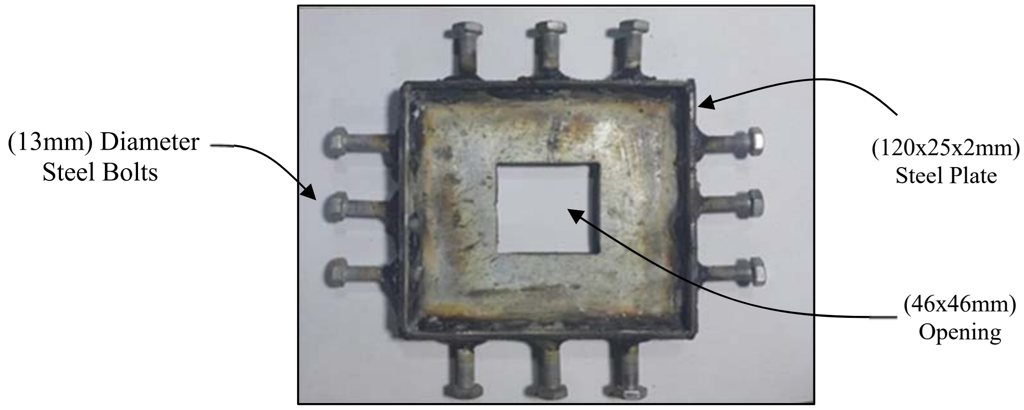

Figure 4. Steel diaphragm with rectangular opening**.**

3.2. Construction materials and additives

Special mixes are required, to produce SCC, according to the mix design method of EFNARC [17] and the procedures adopted by the other researchers. The used materials of SCC are similar to those used in conventional concrete but with some modification. SCC mix proportions (by weight) are reported and provided in table 2; and details, description, and properties of the used materials are reported and provided in table 3.

Table 2. Proportions of ($1m^3$) of SCC mixture.

O.P. Cement	Sand	Gravel	Limestone	Silica Fume	Water	Superplasticizer
500kg	750kg	900kg	100 kg	30kg	150Liter	10Liter

Table 3. Construction material properties.

Construction Material	Features Description
O.P. Cement	Type-I general purposes Portland cement.
Sand	Size (4.75mm) natural sand.
Gravel	Size (12mm) natural crushed gravel.
L.S.P	Fine limestone powder Jordanian origin (Al-Gubra).
Superplasticizer	Silica fume is a highly reactive material; this type of silica fume is produced by the Sika company.
Reinforcing Bars	(ϕ10mm) deformed steel bar with yield strength of (f_y =518.66MPa); and (ϕ8mm) deformed steel bar with yield strength of (f_y =477 MPa).
Water	Clean tap water
CFRP	Fiber type: High strength carbon fiber; Fiber orientation: 0° (unidirectional) Areal weight: 225 g/m^2; Fabric design thickness: 0.13 mm (based on total area of carbon fibers); Tensile E-Modulus of fiber: 3500 MPa; Elongation at break: 1.5%; Fabric length/roll: ≥ 45.7 m; Fabric width: 305/610 mm

3.3. Fresh and hardened SCC properties

To check the SCC, three main tests have been carried out to evaluate three characteristics (passing-ability, filling-ability and resistance to segregation) of SCC according to EFNARC [17] and (ACI 237R-07) [18]. The test results are provided in table 4.

Table 4. Results of tests conducted on the fresh SCC.

Name of Test	Properties	Unit	Test Result	Range [a]
Slump (Flow)	Fill-ability	mm	800	650-800
T50	Fill-ability	Sec.	2.93	2-5
V-funnel	Segregation Resistance	Sec.	8.7	6-12
L-Box	Pass-ability	H_2/H_1%	1.0	0.8-1.0

[a]EFNARC [13].

Several tests were carried out to measure the mechanical properties of hardened SCC; Compressive strength tests were conducted on the standard cylindrical and cubic specimens based on (ASTM C39M-01) [19] and (BS 1881-116 1983) [20] standard specifications respectively. The concrete splitting strength test (indirect tensile strength) has been carried out on the standard cylindrical specimens according to (ASTM C496-96) [21]. To evaluate the rupture modulus of the SCC, prisms (simple beams) of (500x100x100 mm) dimensions were tested under the effect of 2-point concentrated loading. Finally, the concrete elasticity modulus test has been conducted according to (ASTM C469-02) [22] using the standard cylindrical specimens. It may be noted that all control specimen tests were conducted at the age of (28days). The test results of the hardened SCC are provided in table 5.

Table 5. Results of tests conducted on the hardened adopted SCC.

Mix Type	Compressive Strength (MPa) f'_c	f_{cu}	f'_c / f_{cu}	f_r (MPa)	f_t (MPa)	E_c (MPa)
SCC	46.4	51	0.91	4.36	3.5	25755

3.4. Beam specimens mold and polystyrene blocks

The molds were manufactured by using plywood with a constant thickness of (18mm). The mold parts consist of four movable sides and flat pad (at the bottom); these parts were connected by using screws. To form (create) the hollows inside the beams, polystyrene blocks were inserted inside the beams. It may be noted that, for all tested beam specimens, at the edges (beyond the hollows or cells), and to prevent the local failure at the edges, the whole beam section has been closed (becomes a solid section).

3.5. Test instrumentation, measurement and set-up

The load control procedure is adopted throughout the experimental work of the present study. The load is applied using a hydraulic machine with a maximum loading capacity of (300 Ton). The method used to estimate the twist angle was performed by using two dial gauges with the accuracy of (0.01mm/div. accuracy) attached to the bottom fiber of each end of the tested beam at a point away (30 mm) from the end of the longitudinal axis of the beam. The dial gauge recorded the vertical deflection to find the twist angle in radians at every load stage. Two dial gauges were attached at the edges of each beam to measure the axial displacement of the beam, figure 5. The strains were measured by using strain gauges attached in two locations, at the beam mid-span (for strains in the stirrup) and close to (200mm) from the beam edge (for strains in longitudinal bars), figure 6. The tested beams were put on the test machine and then calibrated so that the support centerlines, applied loads, dial and strain gauges were fixed in their proper and correct positions. A steel frame consisting of two clamps is used as applied torsion arms, and, to produce pure torsion (torsion at the edges), a steel girder of (2500 mm) long, and (250 mm) deep is used to transmit the applied loads from the center of the testing machine to the arms. It may be noted that, both, the support center and the center of the moment arm should coincide to generate pure torsion.

Figure 5. Locations of dial gauge and test setup of all considered beam specimens.

Figure 6. Fixing of strain gauges in steel reinforcement.

4. Analyse, evaluation and discussion of the test results

4.1. Overall behavior

Experimental results are summarized and provided in tables 6. The first visible cracks of all tested beams have appeared approximately at a position between the supports and mid-span; with increasing of the applied loads, cracks formed on each side, and finally took the spiral form, which means all tested beams were failed by extensive diagonal cracks. For the reference beam specimen (B-R), the cracks spread through an entire beam length (in the non-strengthened zone), as a result of the increase in the number of cracks, the failure happened at the mid-span. For the strengthened tested beams, the cracks spread with a smaller number and develop more slowly in the strengthened zone (diaphragm zones) because the concrete (skin) and steel bars carry a certain amount of stresses and distribute the rest to the in-plane steel diaphragms. Therefore, the failure locations took place between the in-plane (transverse) steel diaphragms; figure 7 provided the modes of failure for all the tested beams.

Table 6. Cracking and associated ultimate torque of all considered beam specimens**.**

Designation of Tested Beams	P_{cr} (kN)	P_u (kN)	P_{cr}/P_u %	T_{cr} (kN.m)	$T_{cr}/(T_{cr})_R$ %	T_u[b] (kN.m)	$T_u/(T_u)_R$ %
B-R[a]	18.5	51.5	36.0	4.625	-	12.875	-
B-1ROD	27.5	70.0	39.3	6.875	148.6	17.500	135.92
B-3ROD	35.0	89.0	39.3	8.750	189.2	22.250	172.82
B-5ROD	40.0	103	38.8	10.00	216.2	25.750	200.00
B-1 ROD&1CF	32.5	79.0	41.0	8.125	175.7	19.750	153.39
B-1 ROD&2CF	35.0	80.0	43.8	8.750	189.2	20.000	155.34

[a]Reference Beam.
[b]T=(P/2)*Arm, and Arm=0.5m

4.2. Torque at cracking and peak (ultimate) state

The values of cracking and the peak moment of all tested beams were measured and provided in table 6, and the patterns of cracks for the tested beams are shown in figure 7. The first cracks of all tested specimens have appeared approximately at a position between the support and mid-span. In compared with the control beam (B-R), it can be observed that cracking torque moment increases by about (48.6%, 89.2%, and 116.2%) for beam specimens (B-1ROD, B-3ROD and B-5ROD) respectively; While, the cracking torque moment increases by about (75.7% and 89.2%) for beam specimens (B-1ROD&1CF) and (B-1ROD&2CF) respectively. It is concluded that the existence of in-plane diaphragms progresses the torsional resistance and this allowing higher forces to be carried through in-plane steel diaphragms.

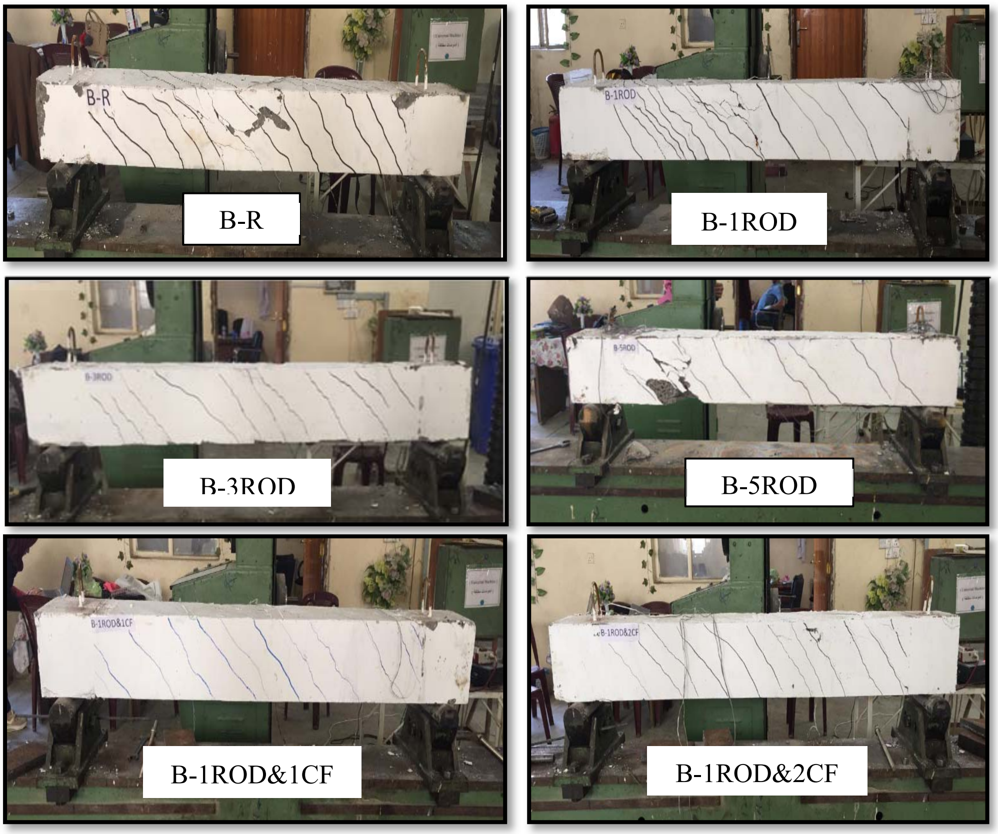

Figure 7. Torsion mode of failure for tested beams.

The test results show the ultimate torque moment were increased by about (35.9%, 72.8% and 100%) for tested beam specimens (B-1ROD, B-3ROD, and B-5ROD) respectively, in compared with the control beam (B-R). On the other hand, the ultimate torque moment increases about (53.4% and

55.3%) for beam specimens (B-1ROD&1CF and B-1ROD&2CF) respectively. It is concluded that beam specimens with five in-plane steel diaphragms have the highest torsion capacity and no separation has occurred between concrete and steel diaphragms. The presence of internal steel diaphragm in-plane within the plane of torque stresses allows carrying higher forces in the transverse direction, due to the contribution of the steel diaphragms, and this leads to increase the beam section efficiency and improves the torsional resistant capacity.

Regarding the specimens with CFRP sheet (B-1ROD&1CF and B-1ROD&2CF), no separation occur along the plane of CFRP with the steel diaphragms faces; and the increase in ultimate torque was about (53% and 55%) for beam specimens containing CFRP in one face and two faces respectively, in compression with the control beam. It can be noted that the addition of CFRP in two faces didn't change the torsion capacity significantly compared to the same in-plane steel diaphragm with CFRP in one face only. The efficiency of the steel diaphragms containing CFRP in one face is similar to steel diaphragms containing CFRP in two faces. Therefore, it can be stated that the using of CRFP for strengthening of steel diaphragms is sufficient as strengthening material and it is recommended to be used for structural purposes.

4.3. Torsion-angle of twist response

The response of the tested beam specimens to the applied torque can be represented by the torque-angle of twist diagram (T-θ Diagram). As shown in figure 8, it can be observed that the ultimate twist angle was increased by about (34.6%, 53.9%, and 49.4%) for beam specimens (B-1ROD, B-3ROD and B-5ROD) respectively, in compared with the reference beam (B-R). While, the increase in ultimate twist angle is slight and approached to about (1.3% and 13.8%) for beam specimens (B-1ROD&1CF and B-1ROD&2CF) respectively, in compared with the reference beam (B-R).

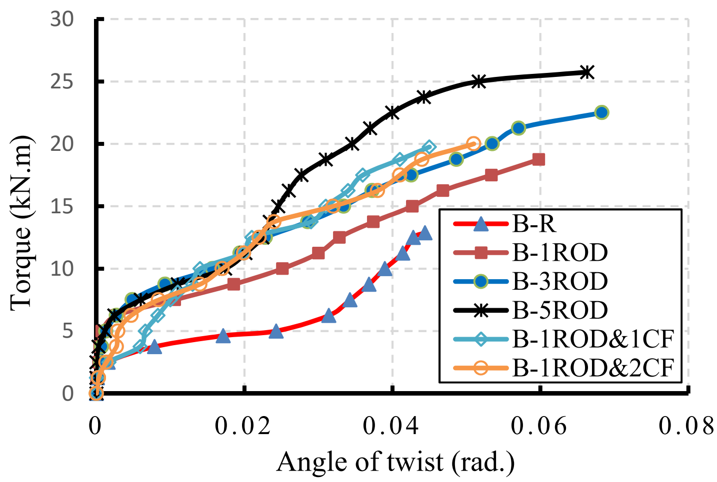

Figure 8. Torque-angle of twist response for tested beam specimens.

4.4. Torsion-longitudinal elongation response

Figure 9 shows the relationship between the applied torque and warping. At the first stage of loading, no longitudinal elongation was recorded in beam specimens, even cracking loads, and the warping gradually increased up to the failure. For strengthened beam specimens, in compared to the same level of the control beam specimen (B-R), the longitudinal elongation of beam specimens (B-1ROD), (B-3ROD) and (B-5ROD) were generally decreased by about (30%, 63%, and 96%) respectively. While, the longitudinal elongation of beam specimens (B-1ROD&1CF) and (B-1ROD&2CF), were generally increased by about (35%, and 44%) respectively, in compared to the same level of the control beam specimen (B-R). Even though there is a disturbing decrease in longitudinal elongation (warping) of beam specimens, the specimens were able to perform structurally well with horizontal control of crack separation between the zones of the diaphragms.

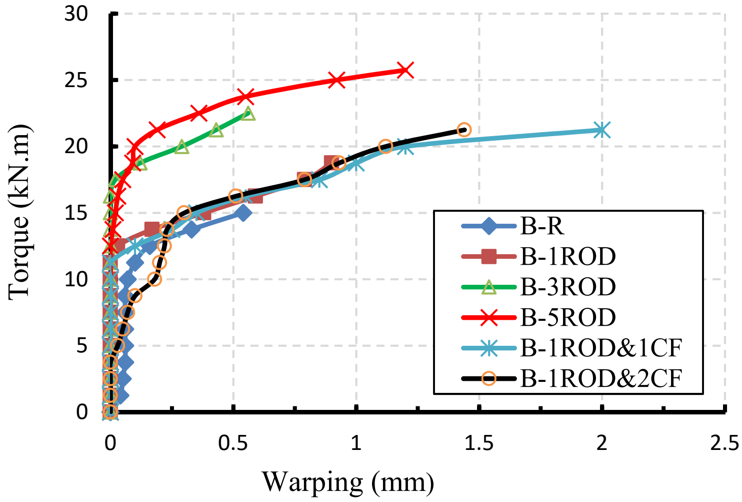

Figure 9. Torque-warping behavior for tested beam specimens.

4.5. Longitudinal steel bars and stirrups strains

4.5.1. Longitudinal reinforcement strains

As mentioned before, the strains in longitudinal steel bars were measured at the beam edge. The relationship between the applied torque and the corresponding longitudinal reinforcement strains are plotted and provided in figure 10.

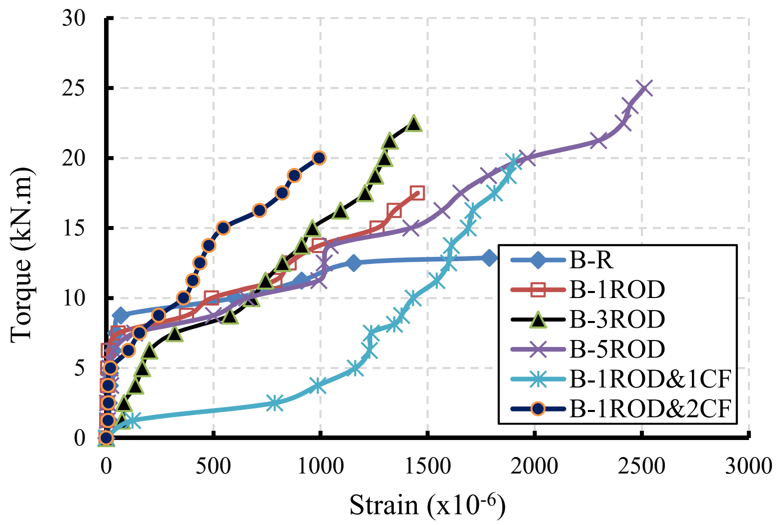

Figure 10. Torque-strain in longitudinal bars.

Before the first crack, all tested beams were behaved linearly, after (beyond) this stage; there was a clear disturbance for strain values of all tested beam. At the ultimate stage, all strain values were positive (tension-strain); the maximum recorded strain for the control beam specimen (B-R) is equal to (69%), while, the maximum strains for beam specimens (B-1ROD), (B-3ROD), (B-5ROD) and (1ROD&2CF)

are equal to (56%, 55%, 102%, 73% and 38%) respectively. It may be concluded that strain in longitudinal bars of beam specimen (B-5ROD) represents the largest value and exceeds the yielding value, these means it is reached to yield strain before the other specimens, in compared to theoretically calculated yield strain value of (ε_y=2590x10^{-6}). While the other beam specimens do not reach it yield strain; these mean the longitudinal bars of these beam specimens can carry additional torsional moment beyond the recorded maximum strain.

4.5.2 Transverse Reinforcement (Stirrups) Strains
As mentioned before, the strains in transverse reinforcement (stirrups) were measured in stirrups closed to (near) the mid-span. This location (mid-span) is select to record (measure) maximum response due to coincidence of the stirrup location with the position of maximum torsion stresses. The relationship between the applied torque and the corresponding strains are plotted and provided in figure 11. For all tested specimens, the recorded strains were positive (tension); The maximum strain for the control beam specimens (B-R) is equal to (66%); and for internally strengthened beam specimens (B-1ROD), (B-3ROD), (B-5ROD), (B-1ROD&1CF) and (B-1ROD&2CF), are equal to (59%, 57%, 93%, 62% and 44%) respectively, in comparison with theoretically calculated yield strain of steel bars of (ε_y=2885x10^{-6}).

Based on the previous results, two things can be concluded, first, the stirrup strains of the beam specimens (B-5ROD) represents the largest value and didn't reach the yielding value; which means the ability of stirrups to undergo (carry) addition torsional moment, second, the using of CFRP layers, for beam specimen (B-1ROD&1CF) and (B-1ROD&2CF), lead to reduce stirrup strains by about (4%-22%), clearly, this means the CFRP sheets works simultaneously with the in-plane steel diaphragm and as a result, the stirrup strains were reduced.

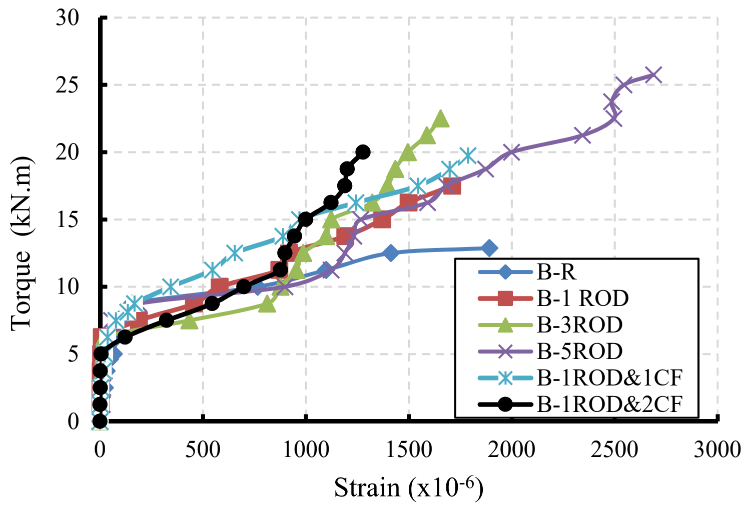

Figure 11. Torque-strain relationship for stirrups**.**

5. Conclusions
1- The maximum torque moments capacity were increased by about (35.9, 72.8 and 100%) for tested beams which strengthened by one, three and five in-plane diaphragms, respectively; while, the ultimate torque moment increased by about (53.4%, and 55.3%) for tested beams which strengthened internally by one steel diaphragm containing one and two CFRP sheet faces respectively. It is concluded that enhancing torsion capacity is attainable by using the adopted technique and it was proportion with the number of in-plane steel diaphragms.
2- No separation occurred between concrete steel diaphragms and the presence of internal steel diaphragm in-plane within the plane of torque stresses, allows to carrying higher forces in the transverse

direction, due to increase in torsional stiffness, and this leads to increase the efficiency of beam section and improves the torsion capacity.
3- For the beam specimens which containing one in-plane steel diaphragm strengthened by one and two CFRP sheet faces, the torsional capacity were increased due to two reasons, presence of in-plane steel diaphragms and presence of CFRP sheets. The efficiency of the steel diaphragms containing CFRP in one face is similar to steel diaphragms containing CFRP in two faces. Therefore, it can be stated that the using of CRFP for strengthening of steel diaphragms is sufficient as strengthening material and it is recommended to be used for this purpose.

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[22] ASTM C469-02, 2002 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression *American Society for Testing and Material, USA.*