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BEHAVIOR OF RC BEAMS UNDER TWO POINTS LOAD WITH DIFFERENT OUT-OF-PLANE PARTS

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Abstract

This study focused on the out-of-plane beam behavior and the reduction caused by changes in the longitudinal axis and the out-of-plane span length in addition to the effect of adding torsion reinforcement. Five RC beams (150*200*2000) mm with constant cross section and reinforcement (except two with additional torsion reinforcement) were cast and tested under two points of monotonic load. The results showed that the existence of the out-of-plane part reduced the ultimate load by (80%), and the two out-of-plane span lengths (150mm and 300 mm) were different in behavior, that the out-of-plane span (300 mm) behaved as under pure torsion while the (150 mm) behaved like under flexural and torsion loads. The worst case was for the beam with an out-of-plane part (150 mm), and the effect of adding torsion reinforcement enhanced the ultimate load by (80%) for the beam with an out-of-plane part (300 mm) whilst by (5%) for the beam with out-of-plane part (150mm).

Keywords:

Two points loads;
RC Beams;
Out-of-plane parts;
SCC;
Different out-of-plane span;

1 Introduction

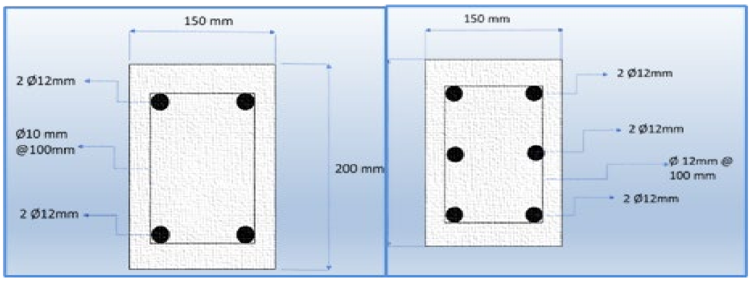
Sometimes we need to change the axis of the beam without support under this change due to architectural requirements or some rare structural requirements, such as zigzag beams or balcony beams [1]. Combined loads on RC beams developed by changing in longitudinal axis of the beam affected the beam behavior at different stages of loading. Many studies on the effect of combined loads on the straight beams were made, but very few studies refer to the out-of-plane beams. There are no constant methods to design the out-of-plane beams and not enough information about the behavior of this type of beam. Also, the indeterminate conditions affect the beam’s behavior studied by some researchers, but only for straight beams.

In 2021, Mohsin M, et al, studied the behavior of out-of-plane beams and compared them with straight beams, they studied the effect of out-of-plane parts number and the out-of-plane span length, and they found that the out-of-plane one part reduces the ultimate load capacity and ductility, high-strength concrete has improved the strength of beams and reduced the deflection, and twisting angle, the effect of the longitudinal torsion reinforcement was clear in increasing the ultimate load, but when compared with straight beam the effect still limited, the straight beam was failed in flexural while the beams with out of plane part failed in torsional and flexural cracks [1].

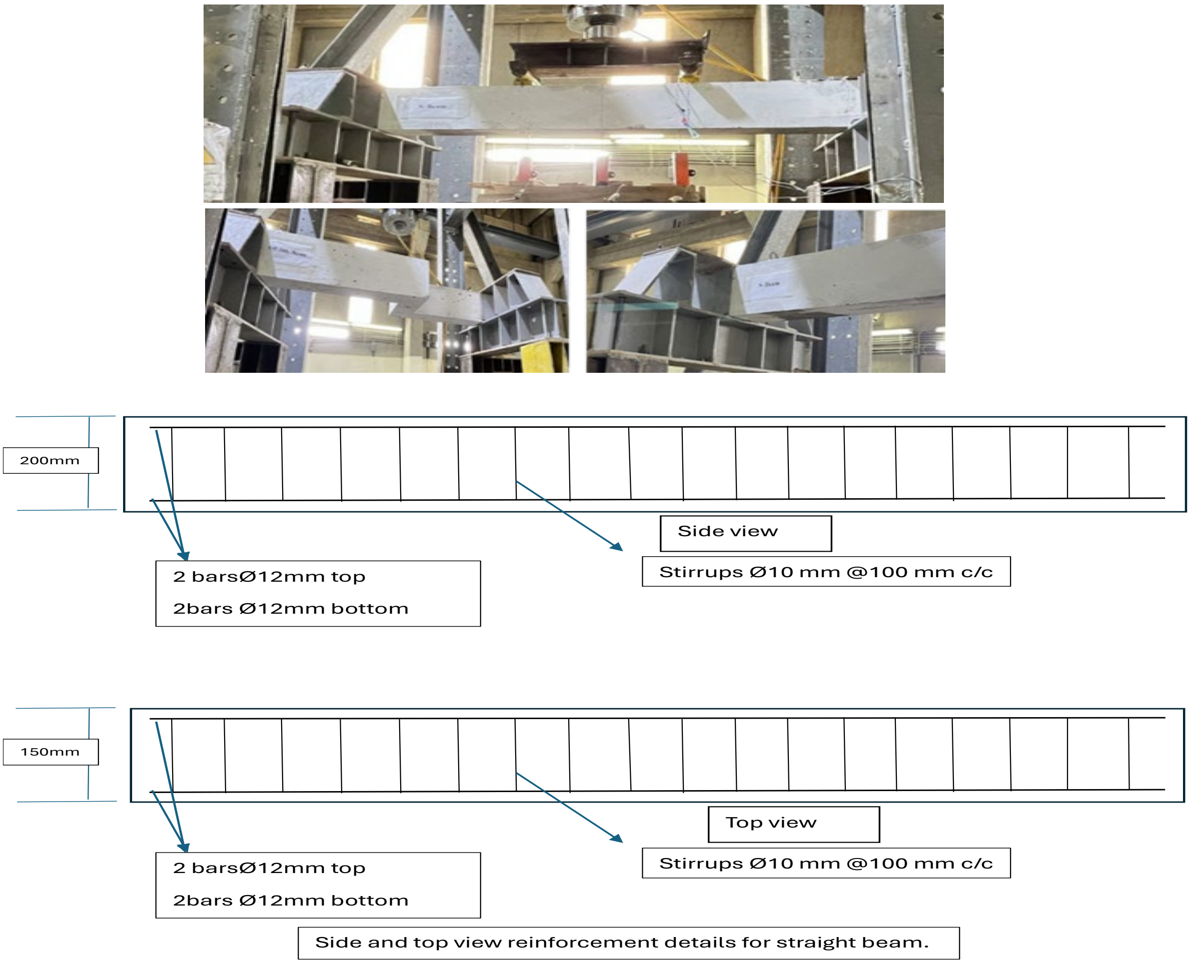
Mohsin M, et al, in 2022 studied the nonlinear FE structural analysis of RC beams with out-of-plane parts, they represent the out-of-plane beams by Abaqus, and they found that FE results were near the experimental results [2].

2 Beams Test

Five control beams were cast from the same mix of SCC, the major variations according to the geometry of beams, and the torsion reinforcement. All beams have the same cross-section and length (150*200*2000) mm and are tested monotonically one is a straight beam (S), and the other four beams were subdivided with variations in the span length of the out-of-plane part and added torsion reinforcement into the beam with out-of-plane part 150 mm (OP-150), beam with out-of-plane part 300 mm (OP-300), beam with out-of-plane part 150 mm with torsion reinforcement (OP-150 T), and beam with out-of-plane part 300 mm with torsion reinforcement (OP-300T). Fig. 1 shows the section reinforcement details for beams and the test setup. Fig. 2 shows the reinforcement details for a straight beam, and Fig.3 shows the reinforcement details for the out-of-plane beam with and without torsion reinforcement. Fig.4 shows the steel reinforcement.



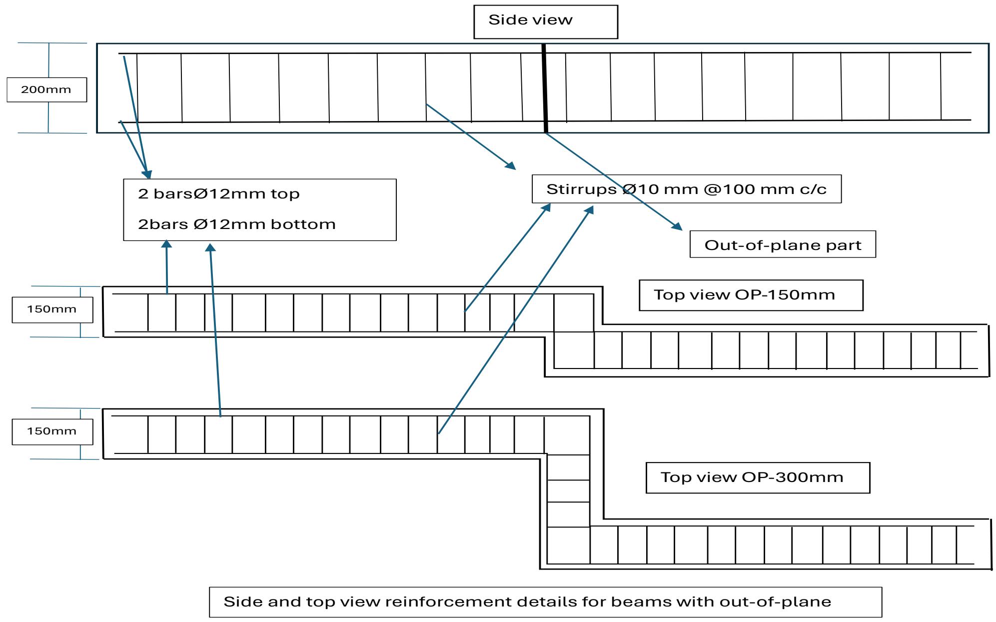
(a) (b)



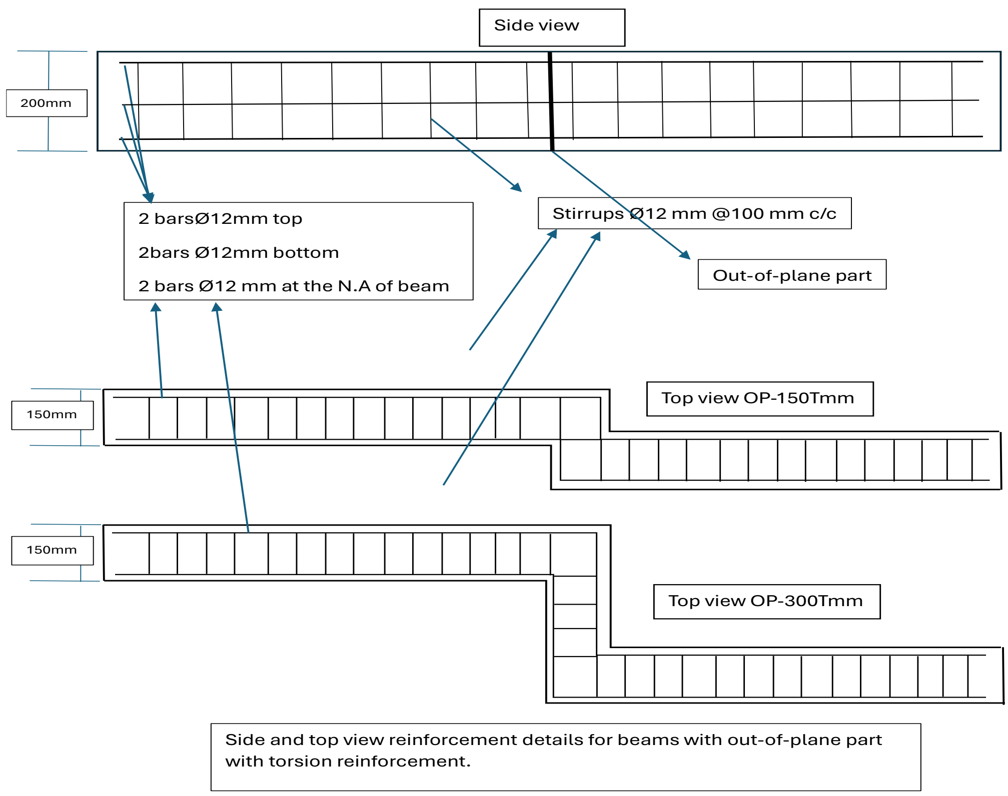
(c)

Fig.1: (a) The reinforcement details for OP-150, (b) The reinforcement details for OP-150T (with torsion reinforcement), and (c) setup details for beams.

Fig. 2 Straight beam reinforcement details.



(a) Out-of-plane beam reinforcement details without torsion reinforcement.



(b) Out-of-plane beams reinforcement details with torsion reinforcement.

Fig.3 The reinforcement details for out-of-plane beams (a) without torsion reinforcement, (b) with torsion reinforcement.

Fig.4 The steel reinforcement in the farmwork.

The load was applied on beams as two points load by using rigid spreader beams and two loading plates, for the out-of-plane beams the spreader beams were used in an inclined way to apply the load, Fig. 5 shows the applied load details.

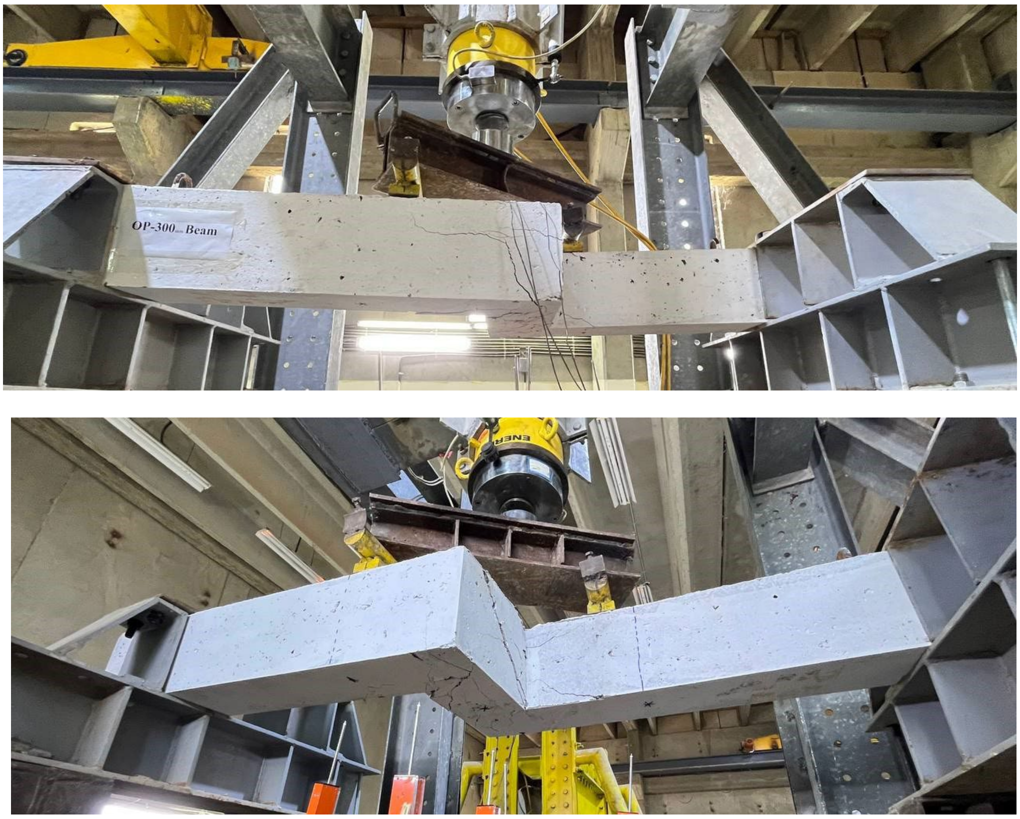


Fig. 5 The applied load details.

3 Load-Deflection Behavior

All control beams were tested monotonically in the same manner up to failure, the cracked, ultimate load, and deflection were recorded to recognize the behavior of beams, and LVDT was used to measure the deflection for straight beam (S) at three points at the beam soffit (mid-span, under each of two points load), and at five points for beams with out-of-plane part (mid-span, under each of out-of-plane part two ends, under each of two points load) as shown in Fig.6. Recorded ultimate load, cracking load, deflection, and rotation angles (front and out-of-plane part) are listed in Table 1. Figures 7 and 8 show the cracking load and the ultimate load for control beams. In this section load versus deflection results discussions are presented according to the existence of the out-of-plane part, the out-of-plane span length, and torsion reinforcement. Fig.9 shows the load-deflection relationships for control beams.

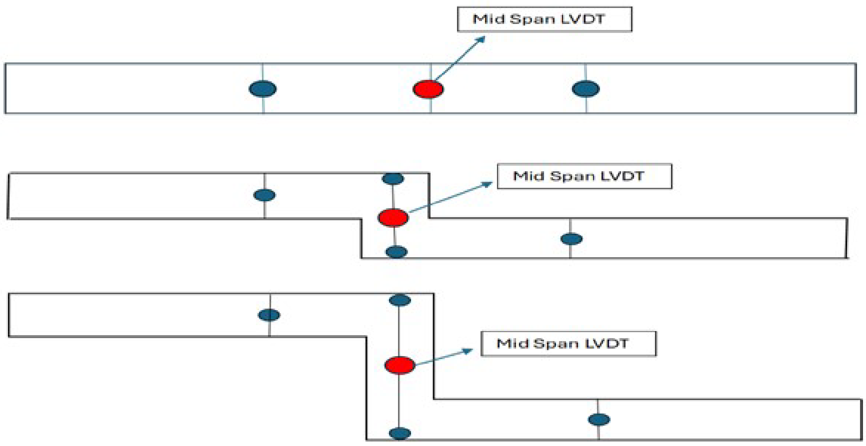


Fig.6: The LVDTs positions for beams soffit (mid-span was remarked).

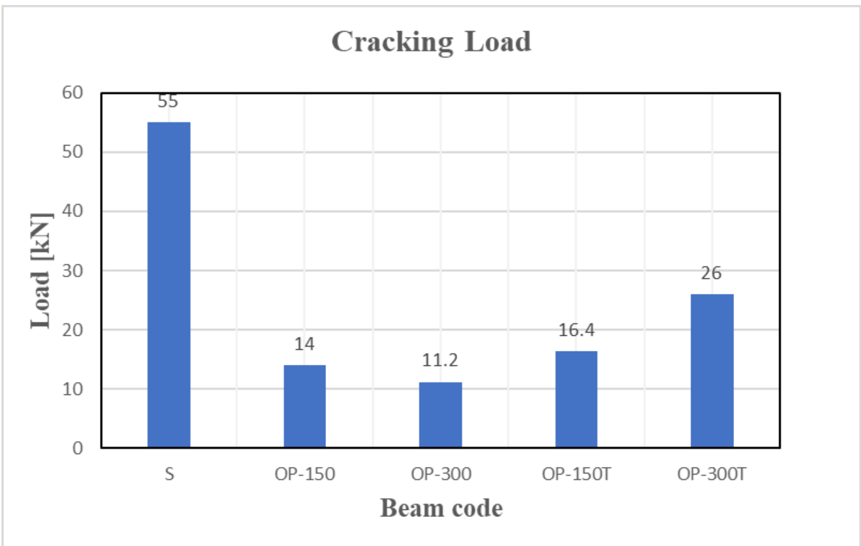


Fig. 7: Cracking load for control beams

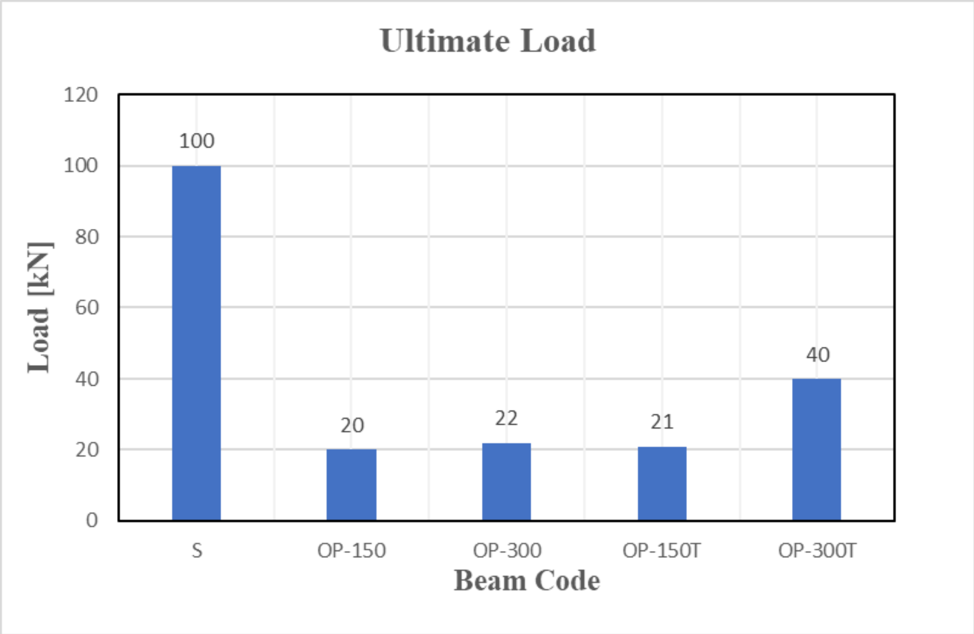


Fig.8: Ultimate loads for control beams.

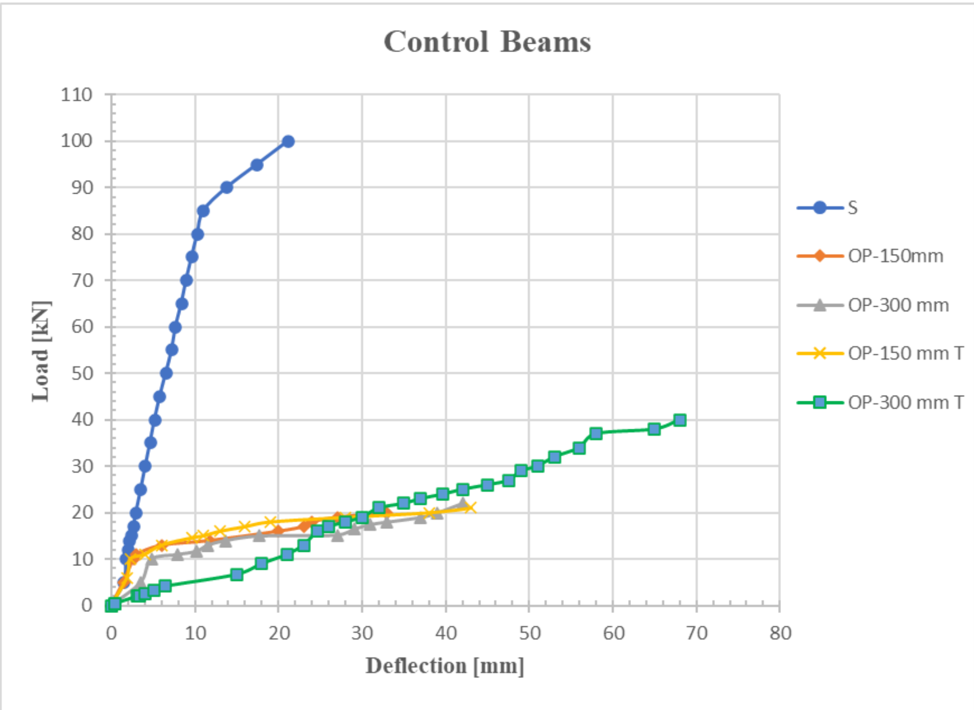


Fig. 9: Load-mid span deflection relationships for control beams.

Table 1: Loads, deflections, and rotation angles for control beams.

Code of beam	First crack load (Pcr) [kN]	Cracking load deflection (Δcr) [mm]	Ultimate load (Pu) [kN]	Ultimate load deflection (Δu) [mm]	Out-of-plane part twisting angle (degree) (side angle) at ultimate load		The front view angle of twisting [degree] at the ultimate load
					Right Side	Left Side	
S	55	7.22	100	21.12	-	-	0.632°
Op-150 mm	14	2.62	20	33	3.2°	2.3°	2.29°
OP-300 mm	11.2	4.8	22	42	3.5°	3.5°	1.4°
OP-150T mm	16.4	2.28	21	43	2.57°	5°	4.95°
OP-300T mm	26	0.44	40	68	4.15°	4.5°	6°

3.1 Effect of out-of-plane part

For the straight beam (S) the load-deflection curves shown in Fig. 10, the curve can be divided into three stages according to the change in slope. Linear behavior can be recognized at the first stages of loading then after the concrete cracks the second stage starts with a change in slope, the final stage the increase in load becomes slow with a rapid increase in deflection till the ultimate load. The straight beam behaved stiffly because of the fixed ends and the effect of compression steel reinforcement after yield in tension steel reinforcement occurs, for mid-span deflection it was softer than the deflection under two points loads.

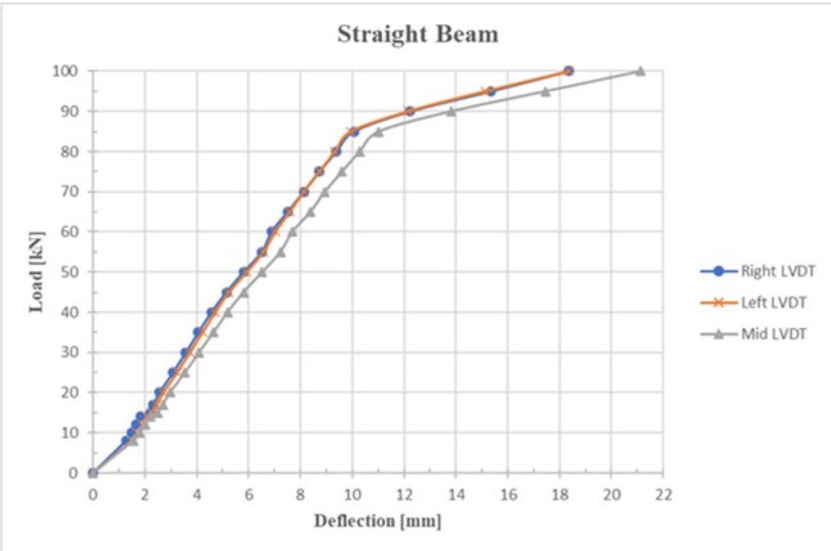


Fig. 10: Load-deflection relationship for beam (S).

The beam with an out-of-plane part (150 mm), the existing of out-of-plane part reduced the beam stiffness severely. The curve started stiff in the elastic linear stage till the first crack, after that the curve behaved more softly with a little hardened closer to the failure load. This behavior refers to the effect of the concrete strength on the beam's ultimate load which is subjected to combined loads due to changes in the beams' axis even after steel reinforcement yielding. The eccentricity applied load due to this change in the beam axis and generated a torsion load reduced the ultimate load of the beam [3]. Fig.11 represents the load-deflection relationship for the OP-150mm beam it is obviously clear that the out-of-plane part deflected in approximately the same values as shown from the LVDTs (2,3,4), also for the LVDTs (1,5) under two points loads have nearly the same deflection values.

For the beam with out-of-plane part 300mm the behavior takes the same stages for beam OP-150mm, but little difference at the second and last stage, the steel reinforcement yielding for beam OP-300 mm started at the stirrup's reinforcement not at the tension reinforcement (as in OP-150mm) because of the torsion effect on the out-of-plane part. The effect of transverse reinforcement yielding was clear at the second stage of the curve (elastic stage) causing a sudden increase in deflection at the middle zone (which represents the out-of-plane part) and making the load-deflection curve softer with differences between the middle part deflection and deflection under the two points load larger than in OP-150mm beam. The deflection at the out-of-plane part is still approximately equal for LVDTs (2,3,4), and the same for deflection under the two points loads LVDTs (1,5) as shown in Fig.12.

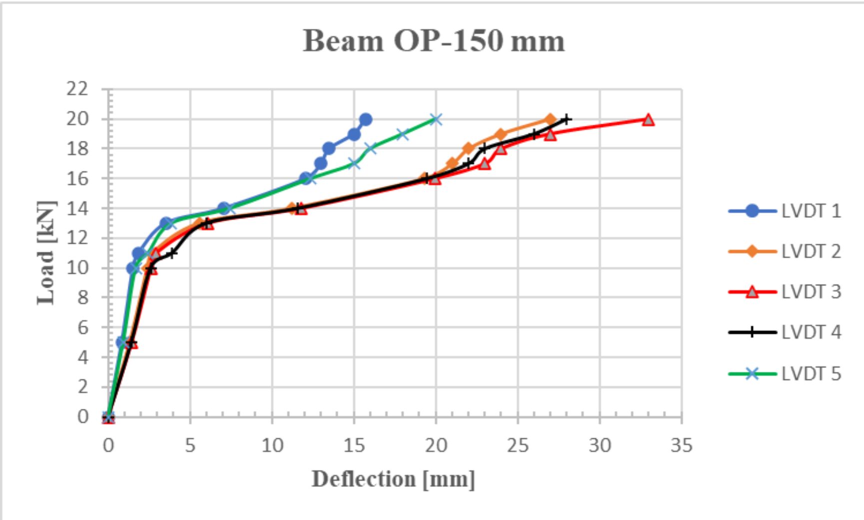


Fig. 11: Load-deflection relationships for beam (OP-150 mm).

Fig. 13 compares straight beams and beams with out-of-plane parts, the huge effect of existing the out-of-plane part was reduced the ultimate load (80%) for OP-150 and (78%) for OP-300. The out-of-plane part reduced the first cracking load by (70.36% and 79.63%) when compared with the straight beam for OP-150 and OP-300 respectively, and severely increased the deflection, the main cause of these effects was the combination of loads generated due to the out-of-plane part. Double torsion loads occurred on beams first about the main beam axis and the second about the main axis of the out-of-plane part in addition to the flexural load.

The reduction in ultimate load for beams with out-of-plane parts may reduce as the ratio of reinforcement increased as compared with a previous study made by Mohsin M., that the reduction was (35.96%) for beams with out-of-plane parts 150 mm and (35.96%) for beams with out-of-plane part 300mm when compared with straight beams, as referred to the higher reinforcement ratio used [1].

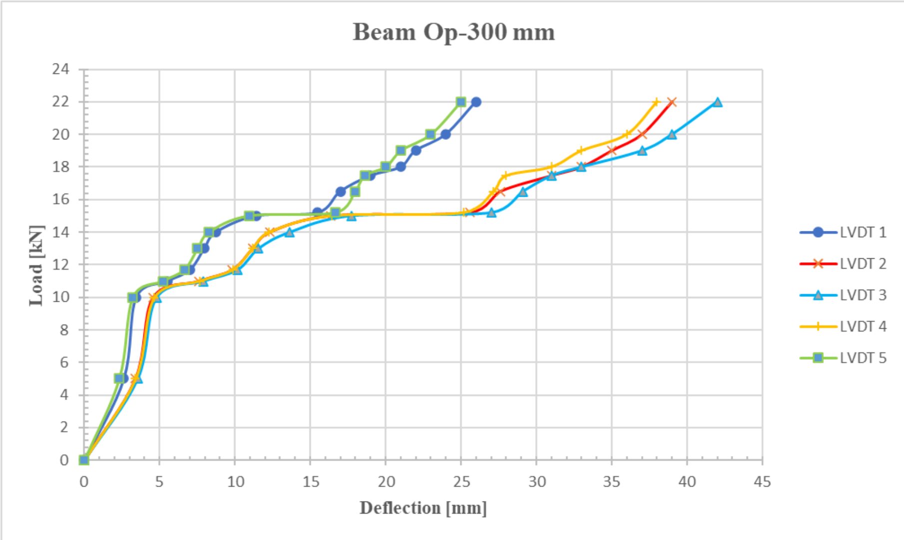


Fig. 12: Load-deflection relationships for beam (OP-300 mm).

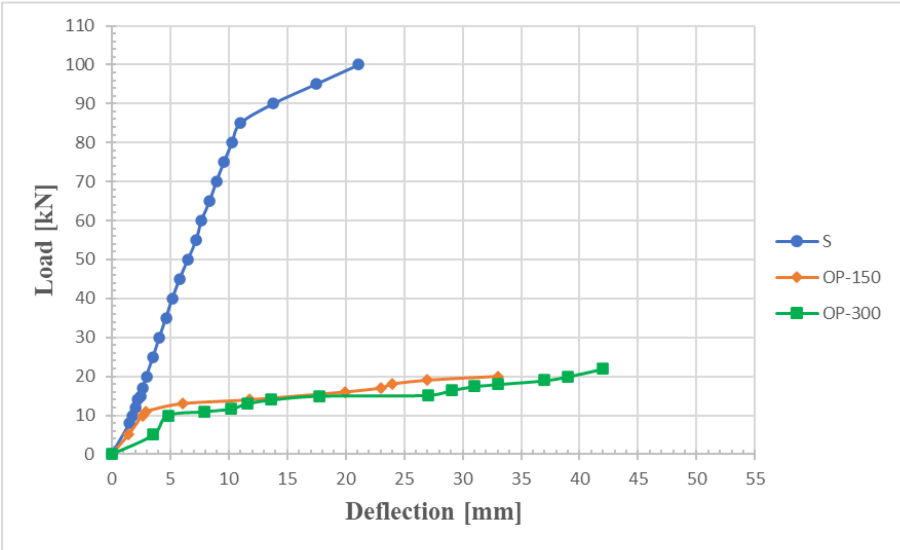


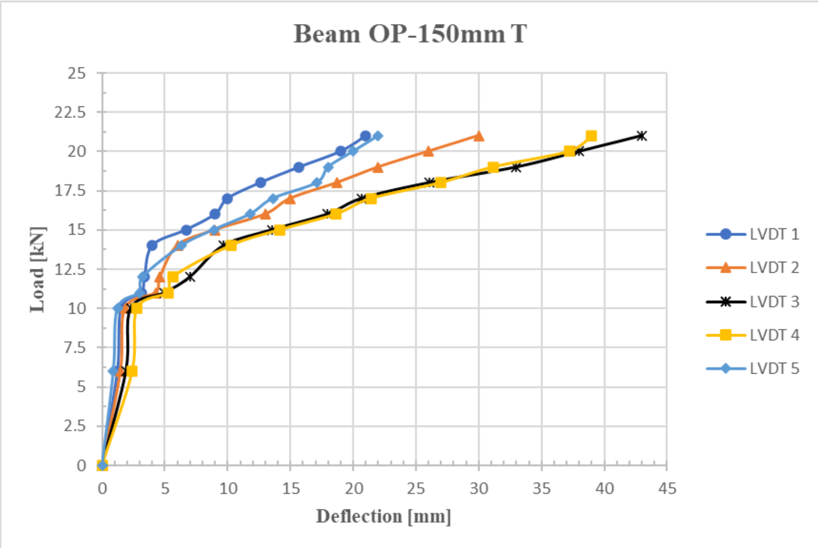
Fig.13: Load-deflection comparison between S, OP-150, and OP-300.

3.2 Effect of out of Plane Span Length

The span length of the out-of-plane part affected the generated torsion loads in addition to flexural load, so the increase in out-of-plane span length increased the torsion load, but the results showed that the beam with out-of-plane part 300 mm carried ultimate load more than beam with out-of-plane part 150 mm by (10%). This increase in ultimate load might occur due to the complex behavior of the out-of-plane beam. The beam with out-of-plane 150mm carrying a combination of flexural and torsion load more than the beam with an out-of-plane span of 300mm which behaved as a nearly pure torsion load more than the OP-150mm beam. This behavior appeared from the initiation of cracks that initiated at the flexural zone at the out-of-plane part for beam OP-150mm, while for beam OP-300mm the cracks were initiated at the out-of-plane part. The degradation of the load was the same way in the two beams that they behaved softer than the straight beam as shown in Fig.9. As compared with the previous study by Mohsin M. [1], he found that the OP-300mm reduced the ultimate load by (0.02%) more than the reduction for OP-150mm, this difference in behavior between the two studies belongs to the difference in reinforcement ratio and compression strength of concrete used, that the torsion capacity depended on them and effected on the formation of the plastic hinges.

3.3 Effect of Torsional Reinforcement.

Added torsion reinforcement to the beam section increased the ultimate load and changed the beam behavior to a little stiffer than the out-of-plane beams without torsion reinforcement, for beams OP-150mmT and OP-300mmT we added two bars (Ø12mm) at the mid of the beam height and increasing the transverse reinforcement by replace the bar with (Ø10 mm) to (Ø12 mm). The ultimate load increased by (5% and 81.81%) and increased the first cracking load by (17.14% and 132.14%) for beams OP-150 and OP-300 respectively, it is obviously clear that the effect of using torsion reinforcement is more effective in beams with out-of-plane 300 mm than beam with-out-of-plane 150mm, this caused by the torsion load due to changing in longitudinal beam axis was more in OP-300mm than OP-150mm as mentioned in previous paragraph. Also, the torsion reinforcement increased the both side and front twisting angles for beams as listed in Table 1. Fig. 14 and 15 show the load-deflection curves for beams. The comparison between beams with torsion reinforcement is shown in Fig.16 and 17 for OP-150Tmm and OP-300Tmm. Mohsin M. studied the effect of adding torsion reinforcement for HSC OP-150mm and he found that the torsion reinforcement increased the



ultimate load by (19.75%) as compared with the same beam without torsion reinforcement [4].

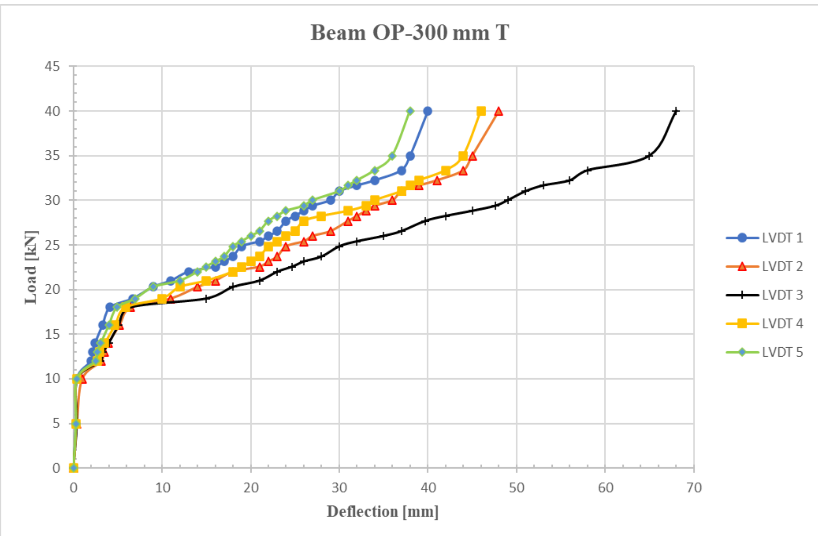


Fig. 14: Load-deflection relationship for beam (OP-150 mm T).

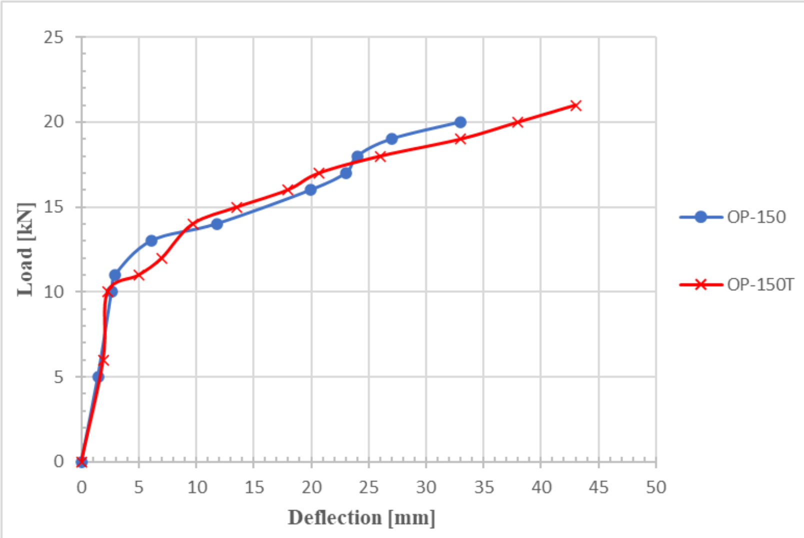


Fig.15: Load-deflection relationship for beam (OP-300 mm T).

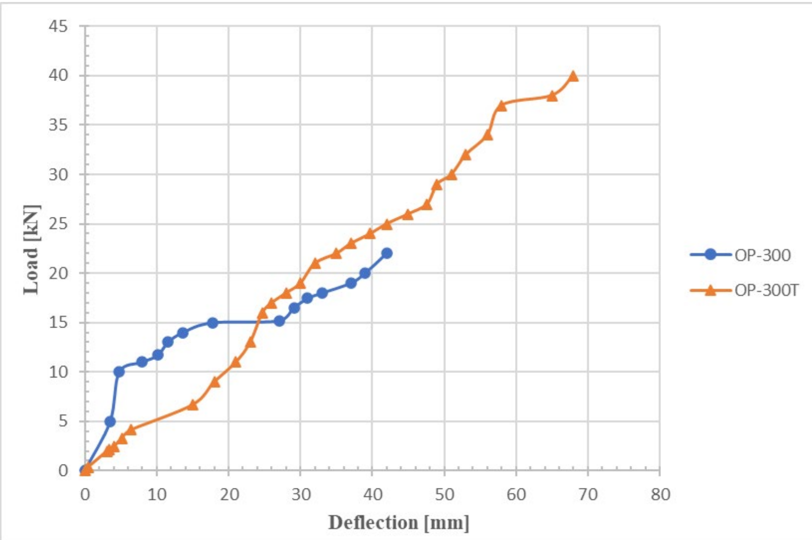


Fig. 16: The effect of torsion reinforcement for beam OP-150.

Fig.17: The effect of torsion reinforcement for beam OP-300.

4 Ductility of Beams

The ductility of reinforced concrete beams depends mainly on the steel reinforcement which is used to resist flexure, shear, and torsion. The steel reinforcement ratio is constant for all specimens, the ductility index as referred to flexural load can be determined by equation (1) which represents the displacement ductility index [5]. For out-of-plane beams, the ductility index depended not only on the flexural ductility but also on the torsional ductility which can written as in equation (2) which represents the twisting ductility index, the combined behavior of out-of-plane beams affected on calculating the ductility index because the yield occurred in a various reinforcement type (stirrups, lower bars, top bars, and mid-high bars) according to the load capacity of the beam and the complex behavior (especially after elastoplastic point) might cause by forming a plastic hinge at each corner of out-of-plane part. According to that the ductility of out-of-plane beams is calculated depending on the flexural reinforcement from equation (eq.1) and because of the torsion generated the ductility can be calculated by using by using equation (eq.2) [6], for the front twisting angle and side twisting angle as listed in Table 2. Fig. 18 shows the displacement ductility index for control beams, and the twisting ductility indexes are shown in Fig. 19, 20, and 21.

$$\mu = \frac{\Delta u}{\Delta y} \quad (1)$$

$$\mu = \frac{\theta u}{\theta y} \quad (2)$$

Where:
μ - The ductility index,
Δu - Mid-span deflection at ultimate load,
Δy - Mid-span deflection at yield load,
ɵu - The angle of twisting at ultimate load,
ɵy - The angle of twisting at yield load.

Table 2: Ductility indexes for control beams.

Code of beam	Ductility index from eq. 1	Ductility index from eq. 2 (front twisting)	Ductility index from eq. 2 (Right side twisting)	Ductility index from eq. 2 (Left side twisting)
S	2.2	3.13	-	-
OP-150	1.43	3	1.405	1.127
OP-300	1.135	1.27	1.14	1.06
OP-150T	1.3	1.18	1.42	1.32
OP-300T	1.94	1.7	1.4	1.6

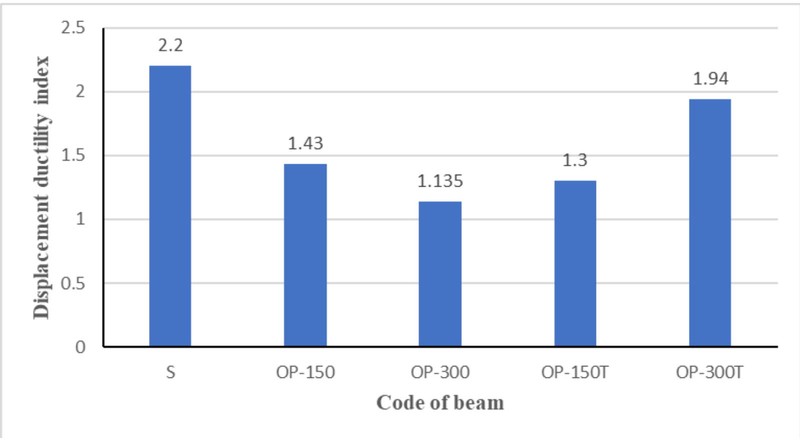


Fig.18: Displacement ductility index.

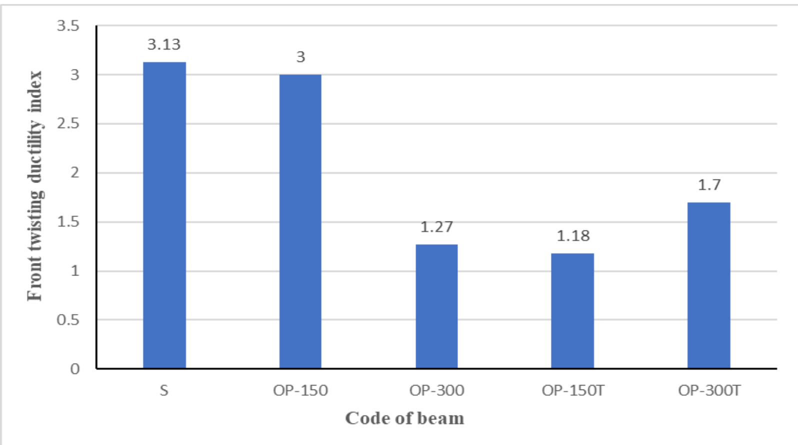


Fig. 19: Front twisting ductility index.

For the displacement ductility index, the out-of-plane part reduced the index by (35%, 48.4%, 41%, and 11.8%) for OP-150, OP-300, OP-150T, and OP-300T beams respectively. The reduction caused by the out-of-plane part referred to as the flexural failure occurred followed by the torsion failure which was caused by the non-straight beam axis which caused weakness in behavior. The front twisting ductility index from the front twisting angle decreased by (4.15%, 59.42%, 62.5%, and 45.68%) for beams OP-150, OP-300, OP-150T, and OP-300T.

The side twisting ductility index changed variously for the right side and the left side, but it’s obviously clear that the torsion reinforcement increases the twisting ductility indexes, for the right side twisting the ductility index increased by (1.05%) for OP-150T as compared with OP-150, and by (22.8%) for OP-300T as compared with OP-300. Also, for the left side twisting the ductility index increased by (17.125% and 51%) for OP-150T and OP-300T as compared with OP-150 and OP-300 respectively, the effect of torsion reinforcement appeared in OP-300 more than for OP-150 because of the out-of-plane span length which increased the torsion load effect and augmented the torsion failure to occur.

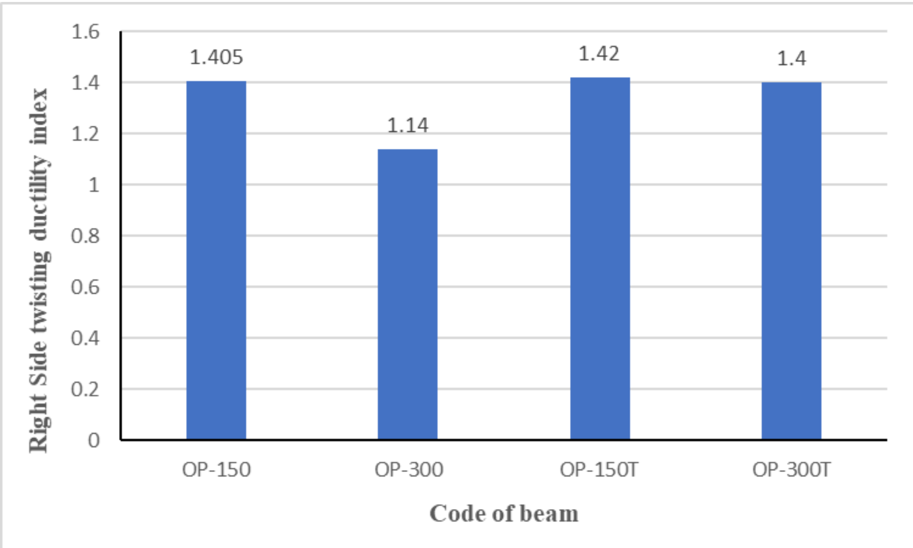


Fig. 20: Right Side twisting ductility index.

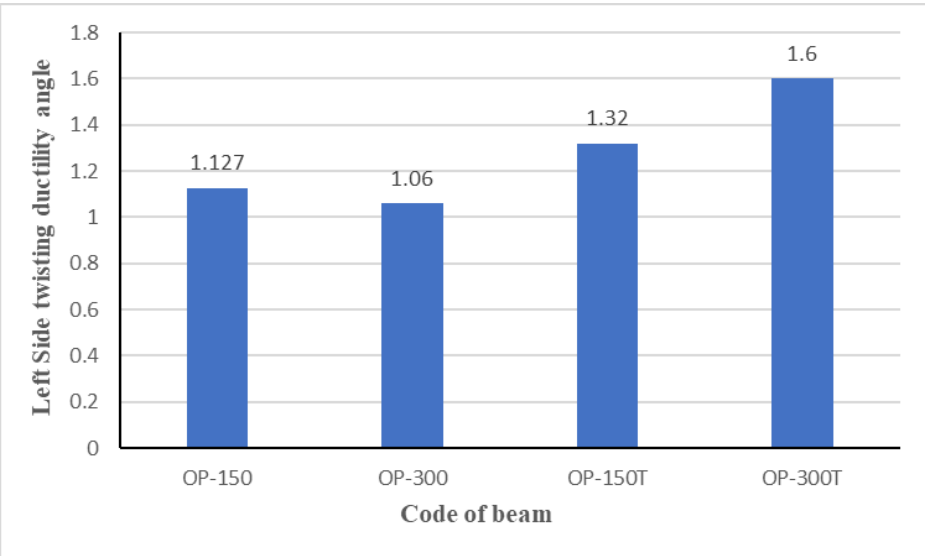


Fig.21: Left Side twisting ductility index.

5 Beam's torsional capacity.

For out-of-plane beams torsion load was generated due to the non-straight beam axis, the torsional capacity varied according to the out-of-plane span length and the torsion reinforcement added. To simplify the complex behavior of an out-of-plane beam two torsion forces might generated on beams first affected on the longitudinal parts of the beam (named as side torque) and the second affected on the mid part (the out-of-plane part) (named as front torque). The side torque gained from multiplying the load by the span length of the out-of-plane part, and the front torque gained from multiplying the load by the distance between two points load, Fig.22 and 23 show the torsional capacity front and side torque respectively, the maximum front torque was for OP-300T beam as compared with OP-300 beam the torsion reinforcement increased the front torque by (81.81%). The torsion reinforcement increased the front torque by (5%) for the OP-150 beam, the advantage of using the torsion reinforcement was very clear for the OP-300 beam because the failure of this beam was nearly the pure torsion as compared with the OP-150 beam which failed between flexural and pure torsion.

For the side torque, the effect of torsion reinforcement increased the torque by (5% and 80%) for OP-150 and OP-300 beams respectively. As for front torque, the high advantage was for OP-300 for the same cause mentioned above.

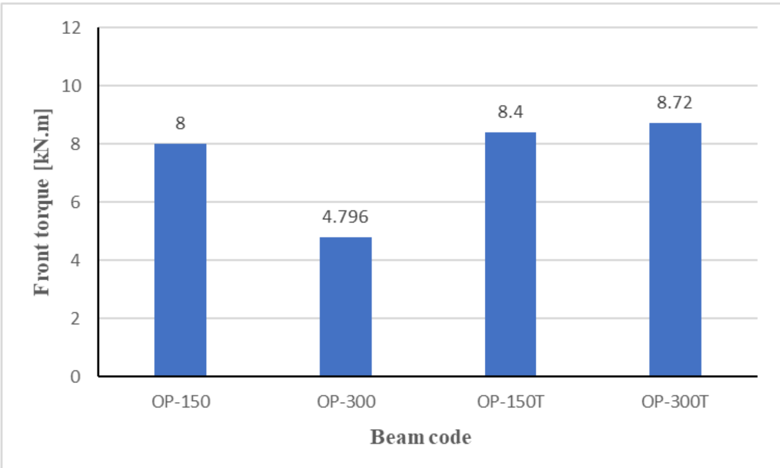


Fig.22: Front torsional capacity for out-of-plane control beams.

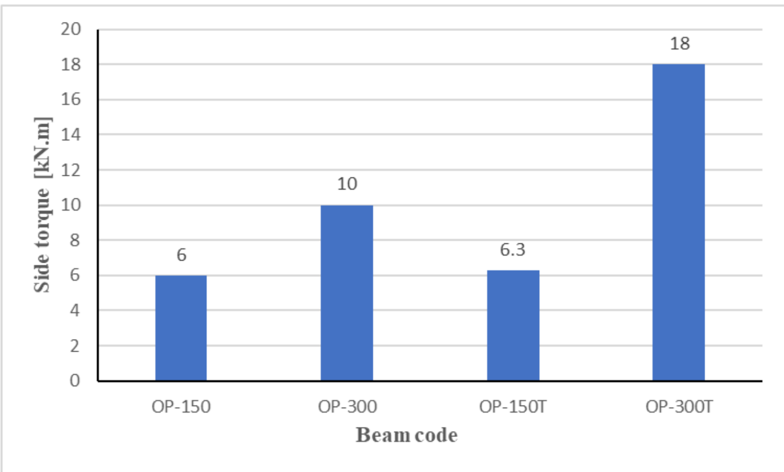


Fig. 23 Side torsional capacity for out-of-plane control beams.

The effect of out-of-plane span length is different in effect on front and side torque. For OP-300 the reduction in front torque was more than the reduction in side torque this belongs to a weakness in stiffness that occurred at the out-of-plane part (300mm), but for side torque, the behavior of the OP-300 was better than OP-150 this caused by the reduction in stiffness for beam long span due to the combination of loads (flexural and torsion) more than OP-300 which behaved nearly pure torsion. Fig.24, 25, 26, and 27 show the torque-twisting angle for control out-of-plane beams.

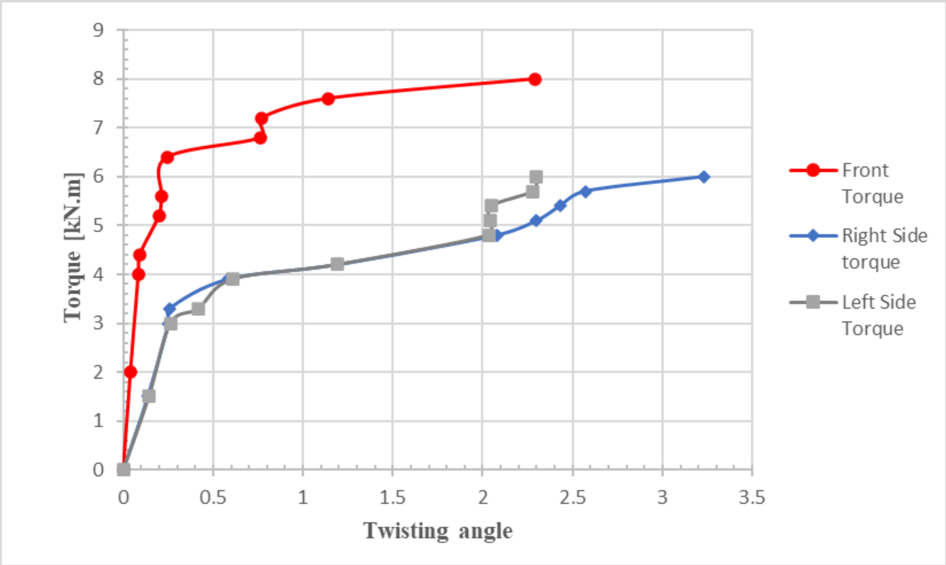


Fig.24: The torque angle of twisting relationships for OP-150mm.

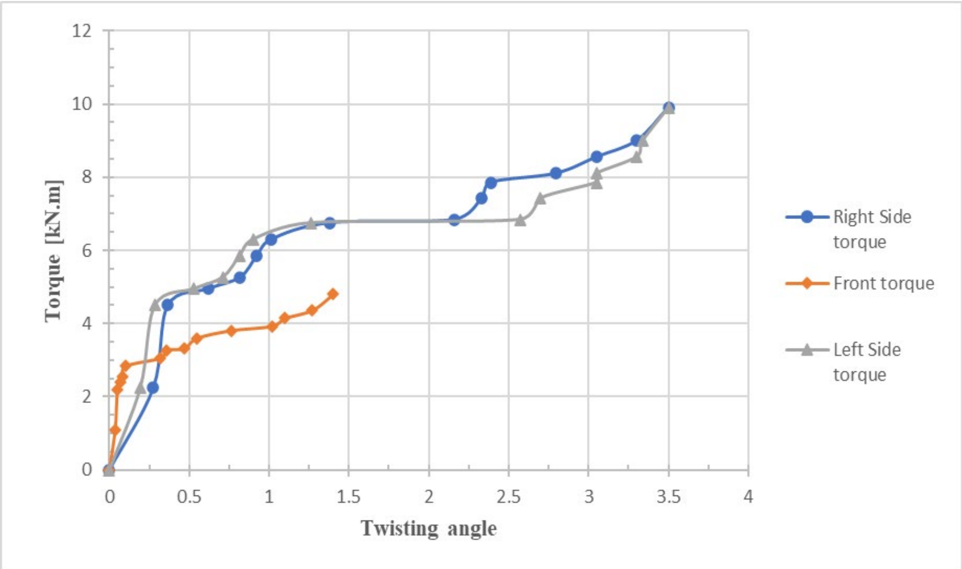


Fig. 25: The torque angle of twisting relationships for OP-300mm.

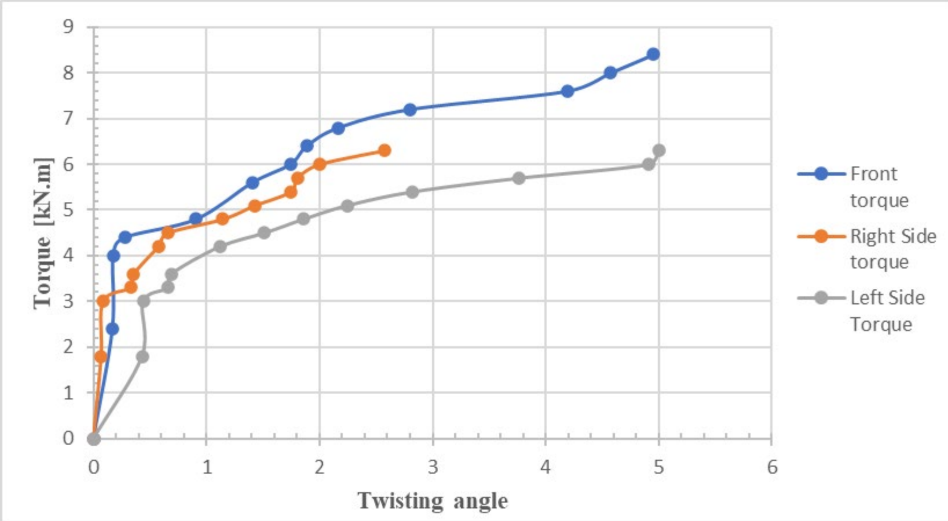


Fig.26: The torque angle of twisting relationships for OP-150Tmm.

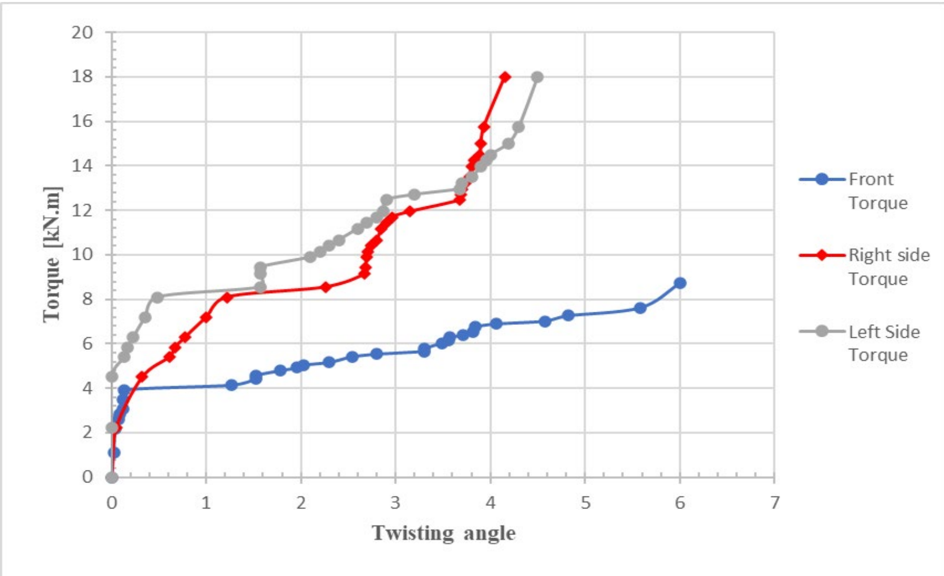


Fig. 27: The torque angle of twisting relationships for OP-300Tmm.

The highest rotation occurred at OP-300T (18 kN.m) for side torque and the lowest front rotation occurred at OP-300 (4.796 kN.m), also the highest front rotation occurred at Op-300T (6◦), but the lowest front rotation occurred at OP-150 (2.29◦) this refer to that the torsion reinforcement benefit gained for the out-of-plane part of OP-300 because it carried almost pure torsion load with little or no flexural load, but for OP-150 it carried a combination of both flexural and torsion load, so the torsion reinforcement not effective alone for this case.

According to the building standards around the world, there are many different equations to predict the beam's torsion strength, ACI code [7-10], in Table 3 the torsion results and calculated torsion strength from codes equations listed to show the ratio of the variation between experimental torsion strengths for out-of-plane beams and the codes values. The out-of-plane beam's torsion strength varied with all code equations because the codes depend on the straight beam subjected to pure torsion, but for out-of-plane beams, there are combined loads effected on beams caused by the own geometry and the indeterminate which caused redistribution of loads. So, the code equations couldn’t predict the out-of-plane beam's torsion strengths.

Table 3: Torsion strengths for control beams.

Beam	Exp. Torque [kN.m]		ACI Code Torsion Strength [kN.m]	BS. Code Torsion Strength [kN.m]	EN. Code Torsion Strength [kN.m]	AS. Code Torsion Strength [kN.m]
	Front	Side				
OP-150	8	6	11.9	8.3	5.56	11.9
OP-300	4.796	10	11.9	8.3	5.56	11.9
OP-150T	8.4	6.3	20.75	14.44	5.56	20.75
OP-300T	8.72	18	20.75	14.44	5.56	20.75

6 Beams Failure Modes and Crack Patterns

The straight beam failed in flexural as shown in Fig. 28 the cracks started from the beam soffit at the mid-span and then progressed toward the side faces gradually till failure. Cracks width increased as load increased and formed the flexural failure cracks at the flexural zone. The steel yielding was followed by vertically and diagonally cracks, and then concrete crushing occurred [11]. For OP-150 the crack started at the out-of-plane zone as a torsion crack in 45◦ then progressed to the sides of the flexural zone to form wide cracks in different angles until flexural-torsion failure occurred as shown in Fig. 29. (OP-300 beam failed in torsion failure cracks were started at the out-of-plane part at 45◦ angle and became wider as the load increased the cracks then took different angles and finally at the failure little cracks occurred at the side face of the beam as progress for torsion cracks, Fig. 30 shows the OP-300 failure.

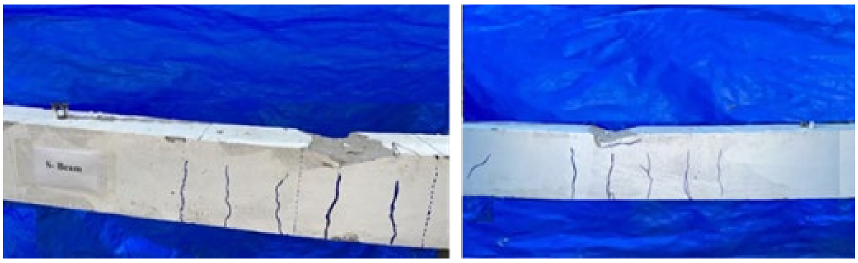


Fig. 28: Cracks pattern at failure for S beam.

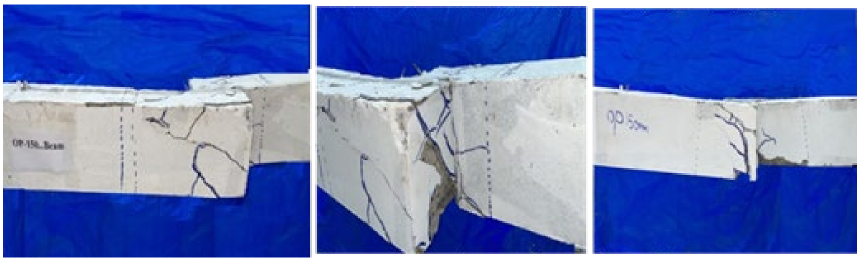


Fig. 29: Cracks pattern at failure for OP-150 beam.

Fig. 30: Cracks pattern at failure for OP-300 beam.

The using of torsion reinforcement for OP-150T led to an increase in the cracks and the width of cracks at the flexural zone that ensured the behavior of OP-150 beam between flexural and torsion behavior when added the torsion reinforcement attempt to fail in flexural failure but the failure still between flexural and torsion just nearly flexural, Fig 31 shows the failure crack for OP-150T beam.

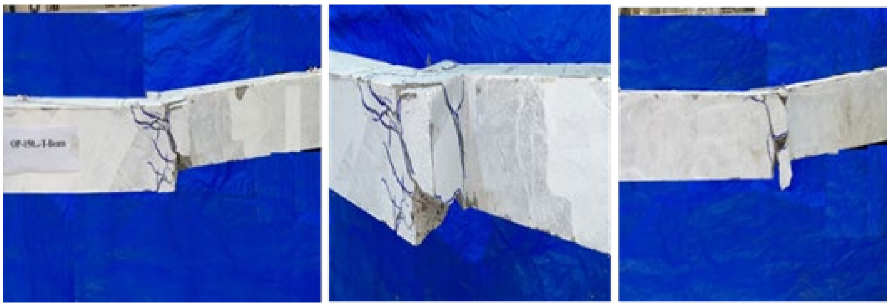


Fig.31: Cracks pattern at failure for OP-150T beam.

For the OP-300T beam, the torsion reinforcement increased the cracks and the width of cracks at the out-of-plane zone only and prevented the progress of cracks to the flexural zone, the first crack delay appeared when using torsion reinforcement, the beam failed in a torsion manner. Fig. 32 shows that.

Fig.32: Cracks pattern at failure for OP-300T beam.

7 Energy Absorption

Energy absorption can be considered as a method to predict the capability of the structure to carry loads. For the control beams the energy absorption is calculated as the area under the load-deflection curve depending on the mid-span deflection, and calculated as the area under the torque-twist curves because beams subjected to combined loads (the cross-section area is constant for all beams) [12]. Generally, the energy absorption can indicate the capacity of beams to deform (as deflection, twisting angle, and strain) under known values of load, or represent the work needed to deform the beam. Fig. 33 shows the energy absorption values according to the load-mid deflection curve for control beams.

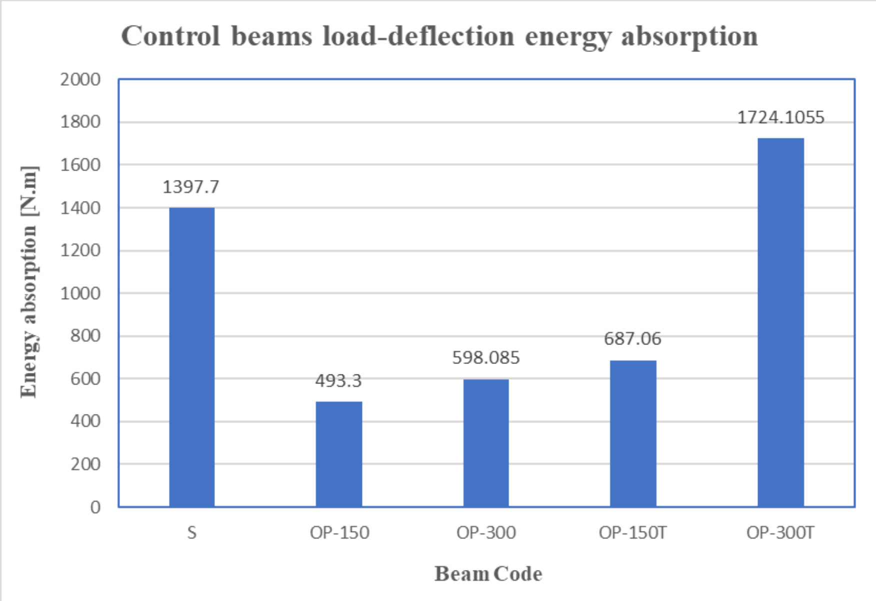


Fig. 33: Energy absorption values according to load-mid deflection curve for control beams.

From Fig.33 we can recognize the reduction in energy absorption for beams with out-of-plane parts as compared with straight beams, they dropped with different ratios (47.04%, 46.642%, and 23.184%) for (OP-150, OP-300, and OP-150T) respectively, that's referred to the effect of out-of-plane part on the capacity of beams to absorb loading and stay in serviceability for a known time. We indicated from this behavior that the beams with out-of-plane parts represent urgent cases when subjected to additional load or seismic load, so in this case, the strengthening is important to increase energy absorption. For one case of out-of-plane beams the energy absorption increased, the beam with out-of-plane part 300 mm and with torsion reinforcement (OP-300T), the increase was (59.2%) and (198.38%) as compared with straight beam and OP-300 beam respectively. This unexpected increase in energy absorption might be caused by the additional torsion reinforcement that in spite of the reduction in ultimate load capacity of OP-300T, the area under the load-deflection curve increased more than the straight beam because OP-300T subjected to nearly pure torsion due to his geometry, so the effect of torsion reinforcement was so clear.

According to the torque-twisting angle curve, the energy absorption gate from this curve represents the ability to twist under torsion load, so the values here are different than the values gate from the load-mid deflection curve because the concrete behaves in different behavior in twisting deform. Two manners of energy absorption calculation depend on the combination of load caused by the beams' geometry, the energy absorption is divided between flexural and torsion according to the load and the reinforced concrete response towards it. Fig.34 shows the energy absorption values for control beams according to the torque-twisting angle curve for both front and side torque generated due to the beam geometry.

From Fig. 34 the energy absorption for OP-150 and OP-150T from the front torque was higher than this found by the side torque, but for the OP-300 and OP-300T it is oppositely, which might refer to the out-of-plane span length increase the applied torque of beam and then reduced the energy absorption for front torque than for side torque.

Using the torsion reinforcement increased the energy absorption by (95.8% and 63.75%) for front and side torque respectively for OP-150, and (590%and 66.47%) for front and side torque respectively for Op-300, the effect of torsion reinforcement appeared clearly in OP-300 as referred in previous sections. This behavior of indeterminate out-of-plane beams complexed the choice of strengthening methods. Many studies referred to the relation between lower deflection and high energy absorption [13], but for beams with out-of-plane parts, this rule wasn't applicable.

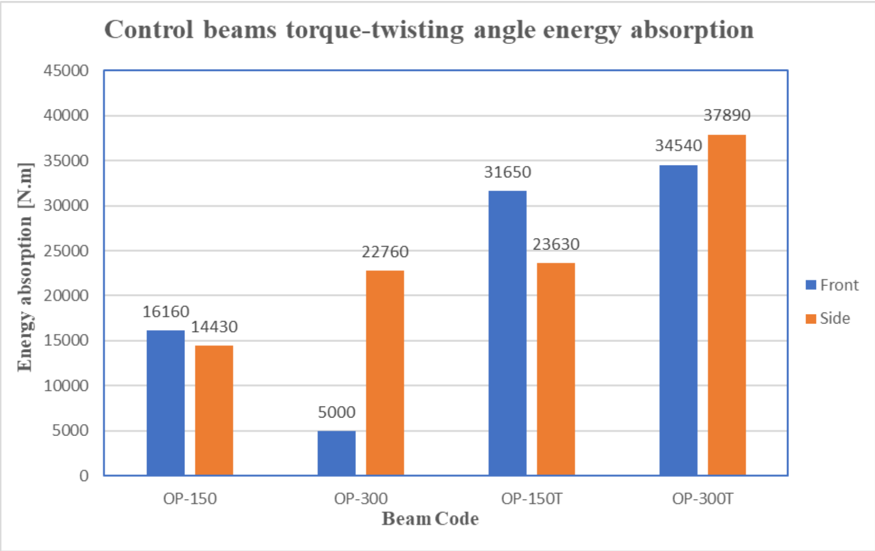


Fig.34 Energy absorption values according to torque-twisting angle curve for control beams.

8 Torsional Stiffness

The rigidity of the material can be explained as the stiffness [11], when the beam is subjected to torsion we can find the stiffness from the torque-twisting angle curve by equations represented by the tangent of the curve, the stiffness gated from the curve can be divided to two parts: first stiffness before cracking found by equation (eq.3), and second after cracking found by equation (eq.4) [14-17]. Table 4 shows the torsional stiffness for control beams.

$$K(pre-crack) = \frac{(Tcr)}{(\text{ɵ}cr)} \quad (3)$$

$$K(post-crack) = \frac{(Tmax-Tcr)}{(\text{ɵ}max-\text{ɵ}cr)} \quad (4)$$

Table 4: Torsional stiffness for control beams.

Twisting angle	Beam	Tcr	ɵcr	ɵmax	Tmax	Kpre	Kpost
Front	OP-150	6.8	0.23	2.3	8	8.91	0.78
	OP-300	4.142	1.1	1.4	4.8	3.76	2.19
	OP-150T	7.6	4.19	4.95	8.4	1.81	1.05
	OP-300T	5.66	3.3	6	8.72	1.71	1.133
Side	OP-150	4.2	1.19	3.23	6	3.53	0.88
	OP-300	8.55	3.3	3.5	10	2.6	7.25
	OP-150T	5.7	1.804	2.57	6.3	3.16	0.78
	OP-300T	11.7	2.96	4.15	18	3.95	5.29

9 Serviceability

The serviceability determined by the ACI-318-19 [7] as a maximum limit for mid-span deflection at the service load (0.6 Pu) does not exceed L/180, L represents the clear span of the beam. The service loads and deflection for control beams and the ACI-318-19 limit are listed in Table 5.

Table 5: The service loads and deflection for control beams and the ACI-318-19 limit.

Beam	P_u [kN]	Service P [kN]	Service deflection [mm]	ACI-318-19 deflection =L/180 [mm]	Experimental/ ACI
S	100	60	7.68	7.77	0.98
OP-150	20	12	6		0.77
OP-300	22	13.2	11.6		1.5
OP-150T	21	12.6	7.5		0.965
OP-300T	40	24	29		3.73

From Table 5 it is obviously clear that the out-of-plane span length affected the service deflection that exceeded the ACI limit, all beams were with the ACI limit except the beams with out-of-plane part 300 mm. This refers to the effect of semi-pure torsion behavior for these out-of-plane beams.

10 Conclusions

From the beams tested, we concluded that:

1. The out-of-plane part caused an aggressive effect on the beam's ultimate load due to the change in the beam’s geometry that generated the combination loads.
2. The effect of torsion reinforcement for beams with long out-of-plane spans is better than for short ones.
3. The out-of-plane span length affects the maximum deflection and the beam behavior.
4. The ductility equations are not applicable to find the ductile index for out-of-plane beams.
5. The torsional capacity was less than predicted by code equations.
6. The torsion twisting varied randomly.
7. The stiffness of out-of-plane beams cannot be predicted by the code’s equations.
8. Energy absorption increased for beams with long out-of-plane beams and increased when adding torsion reinforcement.

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