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Structural behavior of RPC beams subjected to flexural and torsional effects

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ABSTRACT

This research is concerned with the behavior of reactive powder concrete beams (RPC) under the combined effects of bending and torsion moments, with three main parameters: torsional to bending moments ratio (T/M), longitudinal reinforcement ratio (ρ_L), and transverse reinforcement ratio (ρ_T). 12 rectangular reinforced RPC beams with dimensions of (1500 × 200 × 150) mm were tested. The outcome demonstrated that increasing the longitudinal reinforcement ratio from ρ_L=0.009 to ρ_L=0.016 improved the ultimate capacity significantly by 34.16%, and 35.54% in cases of (T/M) =0, and 0.5 respectively, also it significantly improved moment-deflection response in the case of (T/M) = 1, and well improved torque-rotation response in cases of (T/M)=0.5, and 1. Increasing the transverse reinforcement ratio from ρ_T= 0.0042 to ρ_T=0.0075 improved the ultimate capacity significantly by 49.22% in case of pure torsion and slightly improved it in other cases. Also it significantly improved moment- deflection response in case of (T/M) = 1 and improved torque -rotation response in cases of (T/M)=1and ∞.

1. Introduction

Several structural elements are affected by combined actions, such as spandrel beams, eccentrically loaded bridge girders, and beams that are curved in plan. The design of such members can be dominated by torsional and flexural moments

Moments of torsional (T) and flexural (M) combination can be critical in design. Aside from pure torsion, researchers have most commonly combined torsion with other stress-resultants based on two factors: first, they considered such studies prudent, the second reason is that beams subjected to combined T and M are much easier to test than beams subjected to other combinations. Using a four-point loading arrangement, it was easily modified to apply constant torsional moment along with bending moment in the central portion of a beam specimen in the absence of shearing forces. The most important factors influencing the behavior of a members subjected to a combination of torsion and bending are the presence of transverse reinforcement, the torque-to-bending ratio (T/M), the amount and distribution of longitudinal reinforcement, and other factors include the cross-sectional shape and the strength of the concrete [1].

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The T/M ratio affects the diagonal compression angle and the beam crack pattern. Tensile and compression strains are occurred in the bottom and top faces of beam sections due to the presence of flexural moments. It has been observed that compression on the top face delays torsional cracking and prevents its propagation in some cases until ultimate strength was reached [2].

Reactive powder concrete (RPC) can be considered a special type of concrete, because of its importance and structural applications, and one of the most significant and recent developments in concrete production. Few researchers investigated RPC beams subjected to pure torsion only and studied the torsional behavior of RPC I-beams or RPC T-beams (solid or hollow) and the impact of increasing fibers ratio, longitudinal or transverse reinforcement ratio and doubling the flange's width and thickness [3-6], or subjected to pure bending only and studied the flexural behavior of RPC I-beam or RPC T-beam and the impact of the increasing longitudinal steel reinforcement, fibers ratio, and silica fume ratio [7-10]. While another researchers conducted their papers to investigate RC beams behaviors under combined torsion and bending moments [11-15].

The present research studies the combined effect of torsional and bending moments on reactive powder concrete (RPC) beams with three main parameters: torque-to-bending moments (T/M) ratio, longitudinal reinforcement ratio (ρ_L), and transverse reinforcement ratio (ρ_T).

2. Significance of research

Design of the beams in ACI deals with the design process of bending moment and torsional moment separately due to the complex behavior of the beams subjected to these moments in combined form where it designs the beams for each type of moment separately, even though their effects are combined, therefore, it is essential to investigate the subject continuously to reach an accurate understanding for the behavior of beams under the influence of combined effects of both moments. Since RPC is a new important material, it was chosen to study the effect of the two moments on the behavior of beams made of RPC.

3. Experimental work

Experimental work included casting 12 beams with 1500mm length × 200 mm depth × 150 mm width and testing them and control samples (cylinders, and prisms) to determine RPC's mechanical properties.

3.1. Details of specimens

To study the effect of primary variables on beam behavior, 4 RPC beams in group (B) with (ρ_L=0.009, ρ_T=0.0042), 4 RPC beams in group (C) with increasing longitudinal reinforcement ratio to (ρ_L=0.0016), and 4 RPC beams in group (D) with increasing transverse reinforcement ratio to (ρ_T=0.0075). The beams reinforcement details and parameters of the study are listed in Table 1.

The first beams in each group were subjected to a pure bending moment in case of (T/M) =0, the second beam was subjected to a combination of bending and torsion moments in case of (T/M) =0.5, the third beam was subjected to a combination of bending and torsion moments in the case of (T/M) =1, and the fourth beam was subjected to a pure torsion moment in the case of (T/M)=∞.

Beams in group B are reinforced by 2Ø12 mm bottom longitudinal steel bars, 3Ø 6 mm top longitudinal steel bars with a top-to-bottom reinforcement ratio of 0.375, and a transverse reinforcement of Ø6mm@90mm of ties within the middle zone and Ø6mm@50mm within the shear zone was designed to prevent shear failure and to ensure the occurrence of flexural, torsional, or both failures. In group C, a larger longitudinal reinforcement with 2Ø16 mm bottom longitudinal steel bars and 3Ø8 mm top longitudinal steel bars were used where ρ_L=0.0016 with a top-to-bottom reinforcement ratio of 0.375, a transverse reinforcement of Ø6mm@30mm within the shear zone, and the rest reinforcement details are the same as these in group B. In group D a larger transverse reinforcement are used where ρ_T=0.0075 with Ø6mm@50mm within the middle zone, and the rest reinforcement details are the same as these in group B.

Table 1. Details of specimens.

	Beam name	Bottom longitudinal reinforcement	ρ_L	Top longitudinal reinforcement	Transverse. reinforcement for shear zone	Transverse reinforcement For middle zone	ρ_T	T/M
Group B	B0	2Φ12	0.009	3Φ6	6@50mm	6@90mm	0.0042	0
	B0.5	2Φ12	0.009	3Φ6	6@50mm	6@90mm	0.0042	0.5
	B1	2Φ12	0.009	3Φ6	6@50mm	6@90mm	0.0042	1
	B ꝏ	2Φ12	0.009	3Φ6	6@50mm	6@90mm	0.0042	ꝏ
Group C	C0	2Φ16	0.016	3Φ8	6@30mm	6@90mm	0.0042	0
	C0.5	2Φ16	0.016	3Φ8	6@30mm	6@90mm	0.0042	0.5
	C1	2Φ16	0.016	3Φ8	6@30mm	6@90mm	0.0042	1
	C ꝏ	2Φ16	0.016	3Φ8	6@30mm	6@90mm	0.0042	ꝏ
Group D	D0	2Φ12	0.009	3Φ6	6@50mm	6@50mm	0.0075	0
	D0.5	2Φ12	0.009	3Φ6	6@50mm	6@50mm	0.0075	0.5
	D1	2Φ12	0.009	3Φ6	6@50mm	6@50mm	0.0075	1
	D ꝏ	2Φ12	0.009	3Φ6	6@50mm	6@50mm	0.0075	ꝏ

3.2.Materials of RPC and mix properties

The materials of the RPC mixture: Iraqi ordinary Portland cement which conforms to Iraqi specifications requirements No. 5/2019 [16], a grade of fine aggregate with a maximum size of 600 µm which conforms to Iraqi Specifications Requirements No. 45/1984 [17], Silica fume has a fineness of 8820 $\boldsymbol{cm^2}$/gm which conforms with ASTM C1240/2005 requirements [18]. Also, low-carbon, copper-coated microsteel fibers with lengths of 12 -14, diameters of 0.2 -0.25 mm, and tensile strengths greater than 2850 MPa. A liquid high-performance polycarboxylic ether based superplasticizer used to reduce workability loss, this plasticizer is types A and F according to the classification given in ASTM C494 [19]. The mix proportions of RPC are shown in Table 2. These quantities have been adopted from previous study [20].

Table 2. RPC mix proportions

W/C Ratio	Cement (Kg/ $\mathbf{m^3}$)	Sand (Kg/ $\mathbf{m^3}$)	Silica Fume%	Microsteel fibers%	Water (L/ $\mathbf{m^3}$)	Super-plasticizer%
0.2	1000	1000	25	2	200	7

3.3. Test setup and measurements

On the transverse and longitudinal reinforcements of all beams, 6mm Japanese steel strain gauge type (FLAB-6-113LJC-F) was used as shown in Fig. 1.

Figure 1. Strains placement.

Two steel inspection arms were attached to the beam, allowing a combination of bending, torsion moments, and pure torsion moment to be applied. The arms were designed using the Staad Pro program with sufficient cross-section to withstand the expected stresses of the applied loads. Fig. 2. shows a cross-sectional view for beams and the arm with all dimensions in mm.

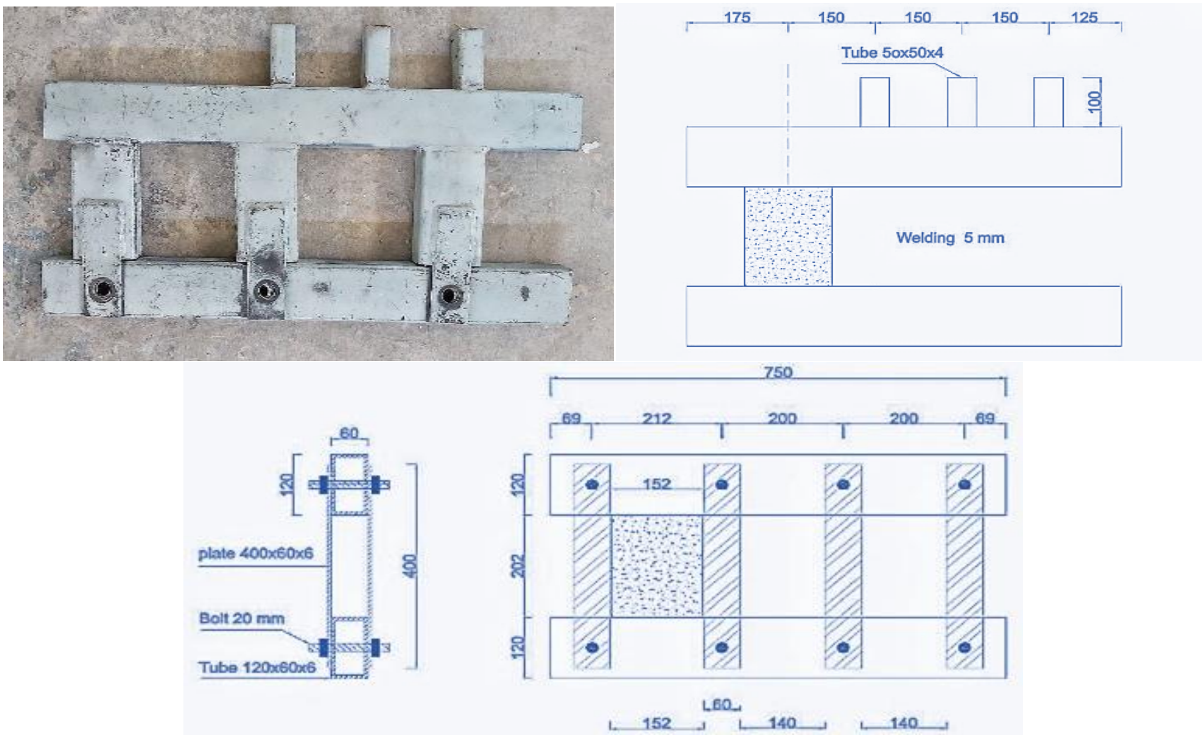

Figure 2. The frame section with dimensions.

As shown in Fig. 3, an LVDT was used to measure the vertical deflection at the center of the beam, and another LVDT was placed on both side of the beam ends to measure the beam rotation. Rotation is determined using the following formula:

$$\Theta = \frac{\Delta}{L} * \frac{180}{\pi} \qquad \ldots\ldots(1)$$

where:

Δ - average of deflection value, for both sides of beam.

L - distance between the LVDT's tip and the canter of the beam.

Θ - angle of twist in degree.

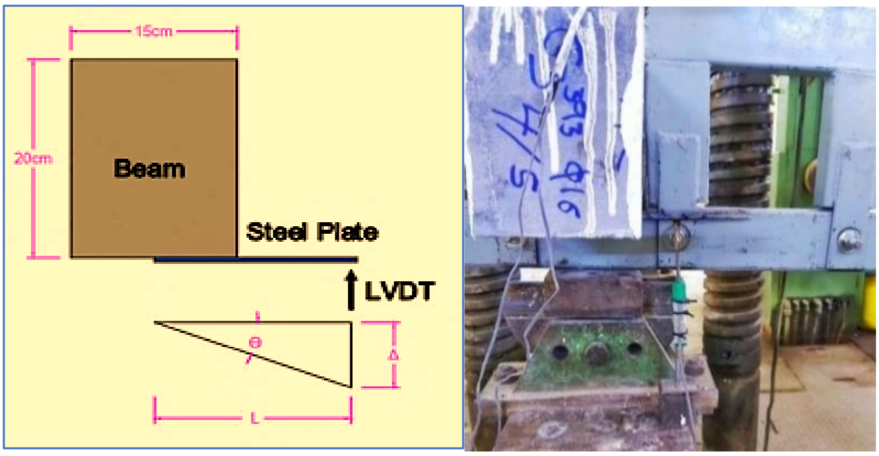

Figure 3. Deflection and rotation measurement.

Fig. 4 and Fig. 5 shows the data logger arm microcontroller and the beam test setup. Test measurements were recorded using the LabVIEW language. It received electrical signals from a load cell installed on the top of the hydraulic system in contact with the base. The data logger also received electrical signals from the strain gauges and LVDT that measured deflections. It takes 80 readings per second, and the readings were recorded through LabVIEW program.

Figure 4. Data logger.

Figure 5. Test setup of the beam.

In cases of pure bending moment and combined torsional, 1400 mm distance between the supports is adopted. The load is applied through an I-section steel beam placed 300 mm from the support so that the distance between the two-point loads is 800 mm and the two-point loads are applied on both sides of the beam to provide a constant torque as well as a constant bending in the middle zone (torsion-bending zone). The torque/bending moment ratio T/M can be changed by adjusting the lever arm while the bending arm is kept as constant distance 300mm from the support. The I-section steel beam was resting on the arms with distance of 150mm from the center of the beam to obtain (T/M)=0.5, and to achieve (T/M) = 1 the steel I-section beam rests on the arms with distance of 300 mm from the center of the beam. For case of pure torsion, the support will be under the steel frame arms at a position away from the center of the beam so that the spacing between the supports and between two-point loads is 800mm.

Since the angle of twist is constant across the distance between the support and the steel arm frame (T=0), the angle of twist is measured at a distance of 15 cm from the support (middle of shear zone). Fig. 6 illustrates the load application in four cases.

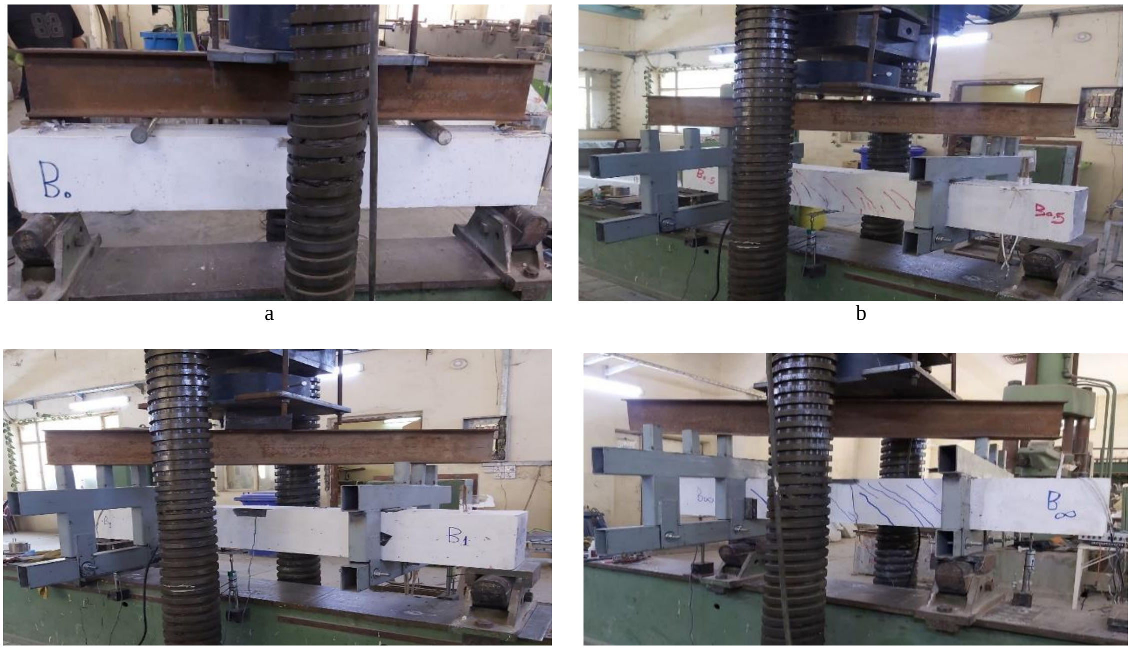

Figure 6. Application of load: (a) T/M=0, (b) T/M=0.5, (c) T/M=1, (d) T/M=∞.

4. Results and discussion

4.1. Test result of control samples and beams

Standard cylinder and prism samples were cast and tested for determination of compressive strength, tensile strength, modulus of rupture, and modulus elasticity at 28 days. Table 4. summarizes result of tests performed on RPC control samples. Results represent the average value of three samples.

Table 4. Test results of mechanical properties of concrete.

Compressive strength $f_{c'}$ (MPa)	Splitting tensile strength f_{sp} (MPa)	Modulus of rupture f_r (MPa)	Modulus of elasticity Ec (GPa)
110.42	13.7	13.82	46.1

Table 3. Presents the experimental results on 12 beams, including the first cracking load, the ultimate load, the first cracking moment, the ultimate moment, and as well the basic parameters adopted in the study.

Table 3. Experimental results of tested beams.

Beam name	T/M	ρ_L	ρ_T	P_{cr}(KN)	P_u(KN)	M_{cr} (KN.m)	T_{cr} (KN.m)	M_u (KN.m)	T_u (KN.m)
B0	0	0.009	0.0042	78	230.15	11.70	-	34.52	0.00
B0.5	0.5	0.009	0.0042	65	169.93	9.75	4.88	25.49	12.74
B1	1	0.009	0.0042	49	125.47	7.35	7.35	18.82	18.82
B ∞	∞	0.009	0.0042	106	218.11	-	7.95	-	16.36
C0	0	0.016	0.0042	87	308.77	13.05	-	46.32	-
C0.5	0.5	0.016	0.0042	68	230.32	10.20	5.10	34.55	17.27
C1	1	0.016	0.0042	50	152.40	7.50	7.50	22.86	22.86
C ∞	∞	0.016	0.0042	112	248.13	-	8.40	-	18.61
D0	0	0.009	0.0075	80	236.84	12.00	-	35.53	-
D0.5	0.5	0.009	0.0075	70	178.24	10.50	5.25	26.74	13.37
D1	1	0.009	0.0075	55	130.19	8.25	8.25	19.53	19.53
D ∞	∞	0.009	0.0075	117	325.45	-	8.78	-	24.41

The M, and T are calculated by: At T/M=0 (pure bending moment), M= $\frac{P}{2} * 0.3m$
At T/M=0.5 (combined moments), M= $\frac{P}{2} * 0.3m$, T= $\frac{P}{2} 0.15m$
At T/M=1 (combined moments), M= T = $\frac{P}{2} * 0.3m$
At T/M= ∞ (pure torsional moment), T= $\frac{P}{2} * 0.15m$

4.2. Effect of T/M ratio on beam behavior

4.2.1. Effect of T/M ratio on cracking and ultimate capacities

Table 7 shows that when (T/M) ratio increased from 0 to 1 it caused a decrease in cracking bending moment. This means the presence of torsional moment with a bending moment reduces cracking bending capacity. Also, this reduction is larger with increasing ρ_L and smaller with increasing ρ_T for all values of (T/M) ratios. The maximum effect of (T/M) ratio was decreasing the cracking capacity by 42.5% in case of (T/M)=1 by using a large value of longitudinal reinforcement ratio (ρ_L= 0.016), and the minimum effect was decreasing it by 12.5% in case of (T/M)=0.5 by using a large value of transverse reinforcement ratio (ρ_T=0.0075).

Table 7. Effect of T/M ratio on cracking bending moment capacity.

Group	(T/M)=0	(T/M)=0.5		(T/M)=1	
	M_{cr}	M_{cr}	Difference %	M_{cr}	Difference %
B, (ρ_L=0.009 & ρ_T=0.0042)	11.70	9.75	-16.7	7.35	-37.2
C ,(ρ_L=0.016)	13.05	10.20	-21.8	7.50	-42.5
D,(ρ_T=0.0075)	12.00	10.50	-12.5	8.25	-31.3

Table 8 shows that when (T/M) ratio increased from 0 to 1 it caused a decrease in ultimate bending moment. This means the presence of torsional moment with bending moment reduces ultimate bending capacity. Also, this reduction is slightly larger with increasing ρ_L for case of increasing (T/M) to 1 while the effect of (T/M) ratio on ultimate capacity is close for all values of ρ_t. The maximum effect of (T/M) ratio was decreasing the ultimate capacity by 50.6% in case of (T/M) =1 using a large value of longitudinal reinforcement ratio (ρ_L= 0.016), and the minimum effect was decreasing it by 24.7% in case of (T/M) =0.5 by using a large value of transverse reinforcement ratio (ρ_T=0.0075).

Table 8. Effect of T/M ratio on ultimate bending moment capacity.

Group	(T/M)=0	(T/M)=0.5		(T/M)=1	
	M_u	M_u	Difference %	M_u	Difference %
RPC(B), ρ_L=0.009 & ρ_T=0.0042	34.52	25.49	-26.2	18.82	-45.5
RPC(C), ρ_L=0.016	46.32	34.55	-25.4	22.86	-50.6
RPC(D), ρ_T=0.0075	35.53	26.74	-24.7	19.53	-45.0

Table 9 shows that when (T/M) ratio decreased from ∞ to 0.5 it caused a decrease in cracking torsional moment. This means presence of bending moment with torsional moment reduces cracking torsional capacity. This effect is larger with increasing ρ_L and smaller with increasing ρ_T in case of (T/M)=1 while the effect is convergent for all values of ρ_L and ρ_T in case of (T/M)=0.5.

Table 9. Effect of T/M ratio on cracking torsional moment capacity.

Group	(T/M)=∞	(T/M)=1		(T/M)=0.5	
	T_{cr}	T_{cr}	Difference %	T_{cr}	Difference %
B, (ρ_L=0.009 & ρ_T=0.0042)	7.95	7.35	-7.5	4.88	-38.7
C ,(ρ_L=0.016)	8.40	7.50	-10.7	5.10	-39.3
D,(ρ_T=0.0075)	8.78	8.25	-6.0	5.25	-40.2

From Table 10 it is concluded that the presence of small bending moment can improve the ultimate torsional capacity in case of (T/M)=1 where it increased by 15.1% and 22.8% when ρ_T=0.0042, while it decreased when ρ_T is high (ρ_T=0.0075). But when the value of the bending moment is high, it will weaken the torsional capacity, and this effect is larger with increasing ρ_T and smaller with increasing ρ_L as shown in case of (T/M)=0.5.

Table 10. Effect of T/M ratio on ultimate torsional moment capacity.

Group	(T/M)=∞	(T/M)=1		(T/M)=0.5	
	T_u	T_u	Difference %	T_u	Difference %
B, (ρ_L=0.009 & ρ_T=0.0042)	16.36	18.82	15.1	12.74	-22.1
C ,(ρ_L=0.016)	18.61	22.86	22.8	17.27	-7.2
D,(ρ_T=0.0075)	24.41	19.53	-20.0	13.37	-45.2

The effect of bending moment on improving ultimate torsional capacity is due to generation of bending stress which prevented torsional crack propagation into compression zone (top part of the beam) due to compression stresses in it that improved the concrete's resistance to torsional effects. Also, due to presence of steel fiber in RPC composition that improves cracking capacity, and hence the small values of bending moments do not have effects on torsional capacity for this type of concrete beams.

4.2.2 Effect of T/M ratio on moment-deflection and torsion-angle response

Fig.7 shows the effect of (T/M) ratio on moment – deflection response, for groups B, C, and D. Increasing (T/M) ratio makes the response softer, and this effect is larger in advanced loading stages. Increasing (T/M) ratio from 0 to 0.5 has small effect on the response and this effect is larger in advanced loading stages, while increasing (T/M) ratio from 0 to 1 has a significant effect on the response and leads to a clear difference in deflection values especially in advanced loading stages. Generally, the difference is clear after the first cracking. The effect of increasing (T/M) on softening the response is smaller with increasing ρ_T and ρ_L due to the efficiency of longitudinal reinforcement in carrying the tensile stresses and reducing the cracked zone area and due to the efficiency of transverse reinforcement ratio ρ_T in improving the resistance to the torsional cracks and hence improves the flexural stiffness.

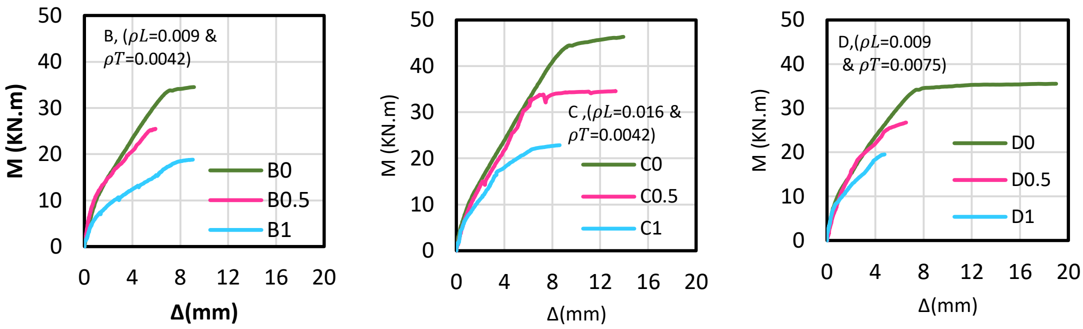

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Figure 7. Moment –deflection response for groups (1) B; (2) C; (3) D.

Fig.8 shows effect of (T/M) ratio on torque–rotation response, for group B, C, and D. Decreasing (T/M) ratio makes the response softer, and this effect is larger in advanced loading stages. Decreasing (T/M) ratio from ꝏ to 1 and from ꝏ to 0.5 has a significant effect on the response and leads to a clear difference in rotation values especially in advanced loading stages. The minimum effect of (T/M) on softening the response is with larger longitudinal reinforcement ratio ρ_L= 0.016 due to the efficiency of longitudinal reinforcement on improving the resistance to the flexural cracks that leads to improving the torsional stiffness.

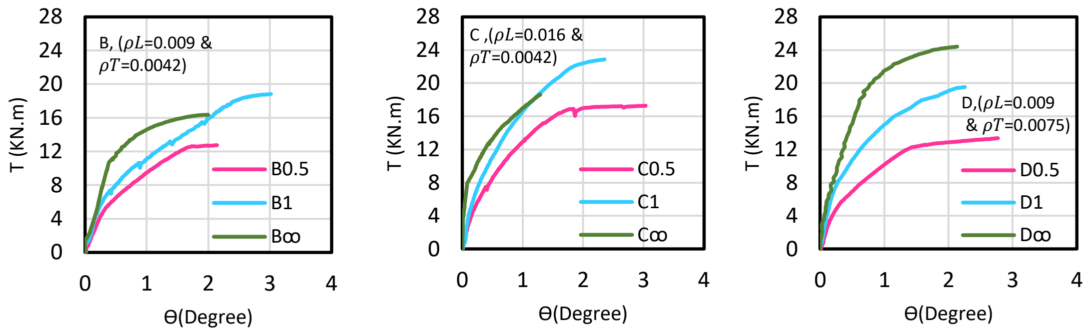

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Figure 8. Torque -angle response for groups (1) B; (2) C; (3) D.

4.2.3 Effect of T/M ratio on strain value in longitudinal and transverse bars

The effect of (T/M) ratio on the relation between moment- longitudinal reinforcement strain for groups B, C, and D is shown in Fig.9. Increasing (T/M) ratio has significant effect on the response and makes it softer especially in advanced loading stages. Generally, the difference is more pronounced after the first cracking. Increasing longitudinal reinforcement leads to smaller effect of increasing (T/M) on softening this response while increasing transverse reinforcement does not significantly change this effect.

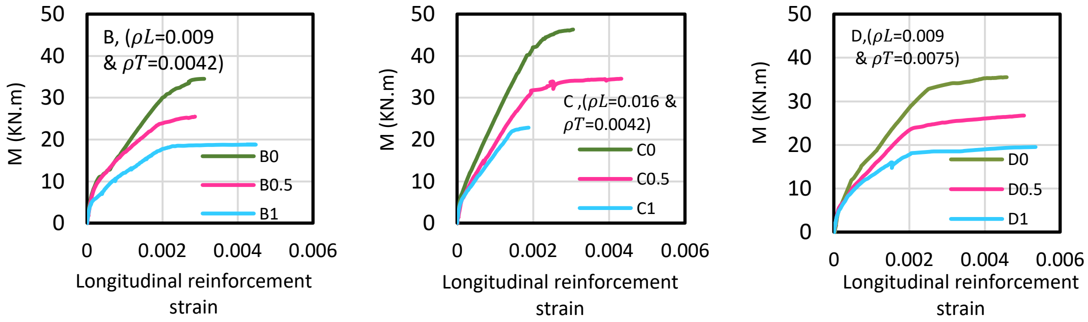

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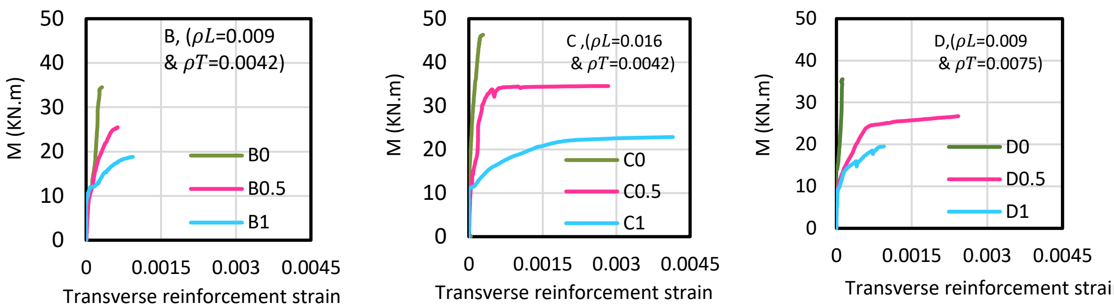
Figure 9. Moment – longitudinal strain for groups (1) B; (2) C; (3) D.

The effect of (T/M) ratio on the relation between moment- transverse reinforcement strain for groups B, C, and D is shown in Fig. 10. Increasing (T/M) ratio makes the response softer, and this effect is larger in advanced loading stages. Increasing (T/M) ratio from 0 to 0.5 has slight effect on the response, while increasing (T/M) ratio from 0 to 1 leads to a significant difference in transverse reinforcement strain values especially after the first cracking. Effect of increasing (T/M) on softening the response is larger with increasing longitudinal reinforcement and smaller with increasing transverse reinforcement.



1 2 3

Figure 10. Moment – transverse strain for groups (1) B; (2) C; (3) D.

4.3. Effect of longitudinal reinforcement ratio on behavior and capacity of RCP beams

4.3.1 Effect of long reinforcement ratio on cracking and ultimate capacities

From Table 11 it can be noticed that increasing the longitudinal reinforcement ratio from ρ_L=0.009 to ρ_L=0.016 slightly improved the cracking bending moment capacity. The maximum improvement is in case of pure bending by 11.5%, while the effect is convergent for the rest cases of (T/M).

Table 11 Effect of longitudinal reinforcement ratio on cracking capacity

Case of combination	B,(ρ_L=0.009)		C, (ρ_L=0.016)		Improvement %
	M_{cr}	T_{cr}	M_{cr}	T_{cr}	
T/M=0	11.70	-	13.05	-	11.5
T/M=0.5	9.75	4.88	10.20	5.10	4.6
T/M=1	7.35	7.35	7.50	7.50	2.0
T/M= ∞	-	7.95	-	8.40	5.7

From Table 12 it can be noticed that increasing the longitudinal reinforcement ratio significantly improved the ultimate capacity by 34.16%, and 35.54% in cases of (T/M) =0, and 0.5 respectively, while the minimum effect is in case of pure torsion by 13.8%.

Table 12 Effect of longitudinal reinforcement ratio on ultimate capacity

Case of combination	B,(ρ_L=0.009)		C, (ρ_L=0.016)		Improvement
	M_u	T_u	M_u	T_u	%
T/M=0	34.52	-	46.32	-	34.2
T/M=0.5	25.49	12.74	34.55	17.27	35.5
T/M=1	18.82	18.82	22.86	22.86	21.5
T/M= ∞	-	16.36	-	18.61	13.8

4.3.2 Effect of long reinforcement on moment-deflection and torque-rotation responses

The effect of increasing the longitudinal reinforcement ratio ρ_L in beams on moment-deflection response with different values (T/M) ratio is shown in Fig. 11. For cases of (T/M) = 0 and 0.5 increasing reinforcement ratio did not affect the response for large part of it and while its effect appears in advanced loading stages through decreasing the deflection values. For case of (T/M) = 1 the response became slightly stiffer and exhibited smaller values of deflection due to using larger reinforcement area, the difference in deflection values became significant at final load stages. This means that effect of longitudinal reinforcement on moment – deflection plot is larger with increasing (T/M) ratio.

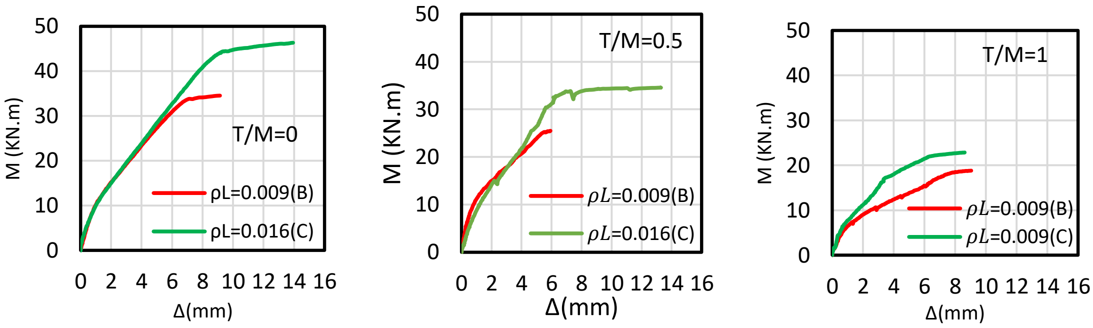


Figure 11 Effect of longitudinal reinforcement ratio on moment–deflection response.

The effect of increasing the longitudinal reinforcement ratio ρ_L in beams on the torque-rotation response with different values (T/M) ratio is shown in Fig. 12. For cases of (T/M) = 0.5 and 1 after the first cracking the response becomes stiffer due to using larger reinforcement ratio and this difference becomes larger with load increasing, the effect of longitudinal reinforcement in decreasing the beam rotation is due to its contribution in improving the torsional stiffness especially its role in decreasing cracking in tension zone. Maximum effect of it is more pronounced in case of (T/M) = 1

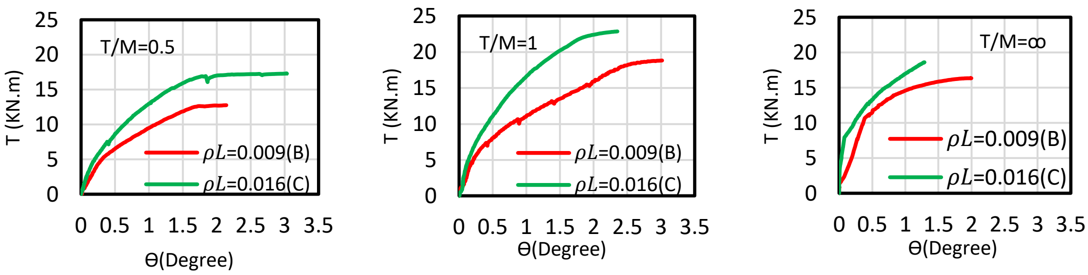


Figure 12 Effect of longitudinal reinforcement ratio on torque –angle response

4.3.3 Effect of long reinforcement ratio on strain in longitudinal bottom bars and transverse bars

Fig.13 shows the relation between moment-longitudinal bars strain at the middle of longitudinal bottom reinforcement within loading stages for groups B and C.

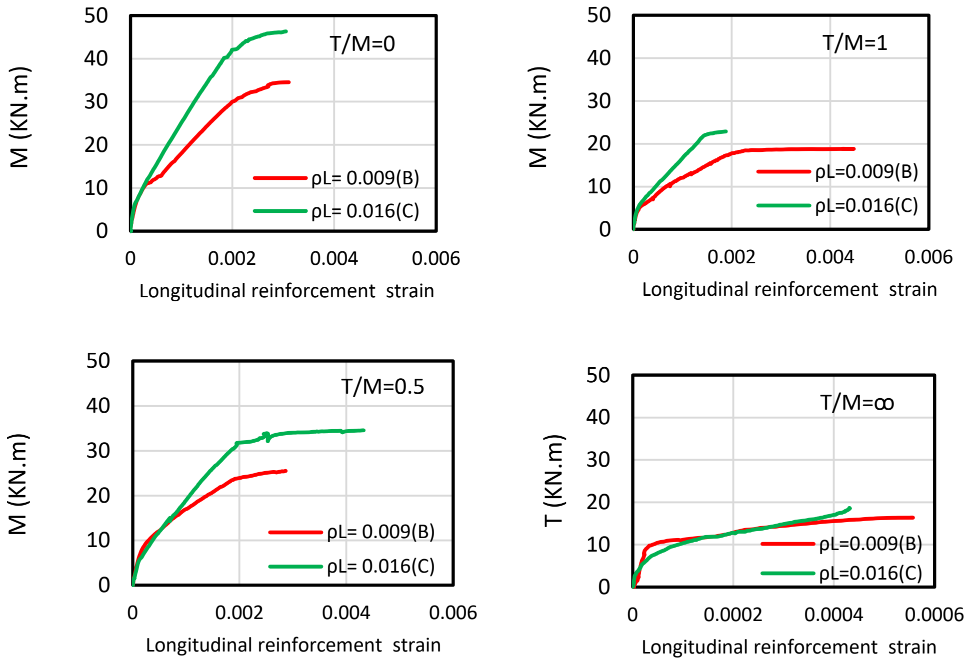


Figure 13 Effect of longitudinal reinforcement ratio on moment –longitudinal bars strain.

From this figure, it was noted that increasing the longitudinal reinforcement leads to a reduction in longitudinal bars strain value and the difference becomes large with progressing the load. The difference in longitudinal strain value reduced as the ratio of (T/M) increases. The maximum effect of it is in case of pure bending (T/M = 0).

In the case of pure torsion, the responses of beams have two ratios of ρ_L were fairly close in all loading stages, indicating that increasing the longitudinal reinforcement ratio ρ_L has approximately no effect on this response.

Fig. 14 shows the relation between moment-transverse reinforcement strain (in stirrups) within loading stages for groups B and C. At earlier stages, the response for two values of ρ_L are fairly close and the difference between them becomes slight for loading stages after cracking. This slight difference between the two responses is convergent for all (T/M) values.

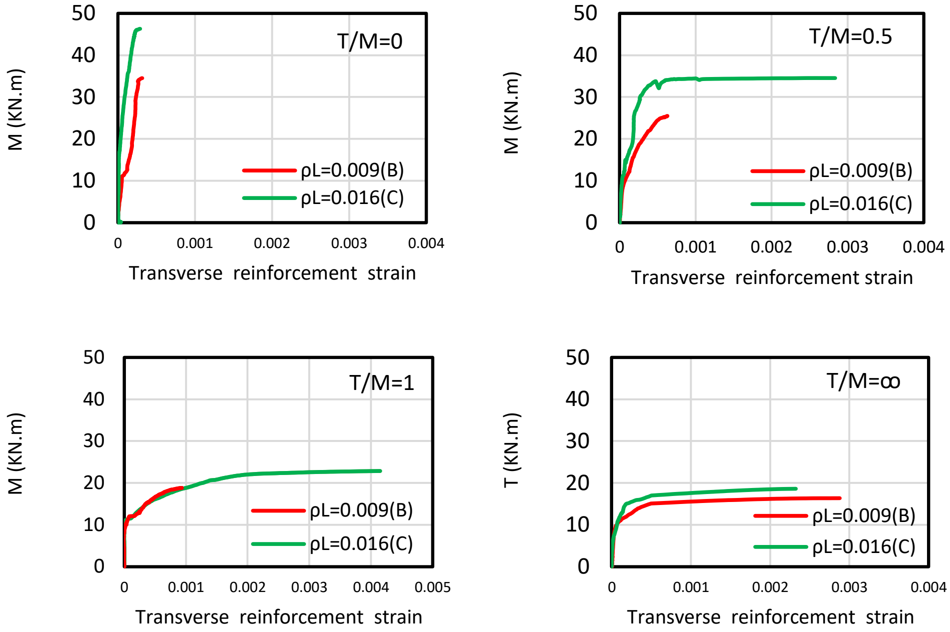


Figure 14 Effect of longitudinal reinforcement ratio on moment – stirrups strain.

4.4. Effect of transverse reinforcement ratio on behavior and capacity of RCP beams

4.4.1 Effect of transverse reinforcement ratio on cracking and ultimate capacities.

From Table 13 it was noticed that increasing the transverse reinforcement ratio from ρ_T=0.0042 to ρ_T=0.0075 slightly improved the cracking capacity where the maximum increasing was in case of (T/M) =1 by 12.2% while the minimum effect was in case of pure bending by 2.6%.

From Table 14 it can be noticed that increasing the transverse reinforcement ratio from ρ_T = 0.0042 to ρ_T = 0.0075 slightly improved the ultimate capacity where the maximum increasing was in case of pure torsion by 49.2 % while the minimum effect was in case of pure bending by 2.9%.

Table 13 Effect of transverse reinforcement ratio on cracking load.

Case of combination	B, (ρ_T = 0.0042)		D, (ρ_T = 0.0075)		Improvement %
	M_{cr}	T_{cr}	M_{cr}	T_{cr}	
T/M=0	11.70	-	12.00	-	2.6
T/M=0.5	9.75	4.88	10.50	5.25	7.7
T/M=1	7.35	7.35	8.25	8.25	12.2
T/M= ∞	-	7.95	-	8.78	10.4

Table 14. Effect of transverse reinforcement ratio on ultimate load.

Case of combination	B, (ρ_T = 0.0042)		D, (ρ_T = 0.0075)		Improvement %
	M_u	T_u	M_u	T_u	
T/M=0	34.52	-	35.53	-	2.9
T/M=0.5	25.49	12.74	26.74	13.37	4.9
T/M=1	18.82	18.82	19.53	19.53	3.8
T/M= ∞	-	16.36	-	24.41	49.2

4.4.2. Effect of transverse reinforcement ratio on moment-deflection and torque-rotation responses

Fig. 15 shows the effect of increasing the transverse reinforcement ratio ρ_T in RCP beams on moment-deflection response with different values of (T/M) ratio.

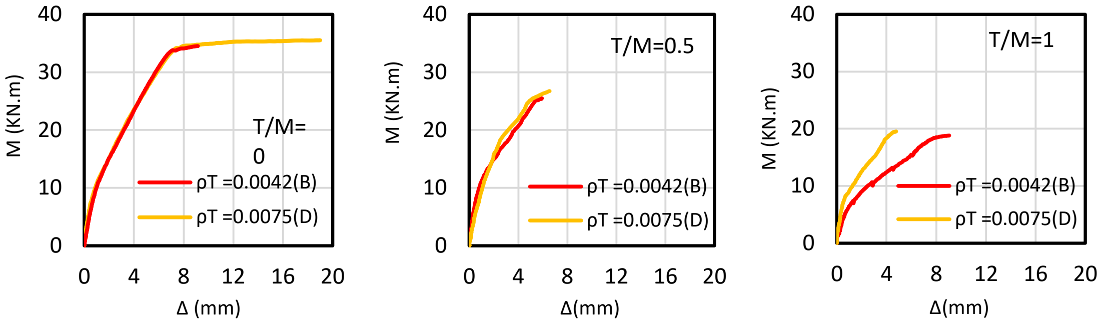


Figure 15. Effect of transverse reinforcement ratio on moment–deflection response.

For case of (T/M) = 0 increasing transverse reinforcement ratio did not affect the response in all loading stages, and leads to fairly close response in all loading stages for case of (T/M)= 0.5, while for case of (T/M) = 1, this increase in ρ_T makes the response stiffer and results in decrease in values of deflection, and the difference in deflection values becomes larger at advanced load stages. The increase in ρ_T due to decreasing the spacing between stirrups reduces the torsional cracks that lead to a large flexural stiffness, therefore the deflection is reduced.

Fig. 16 shows the effect of increasing transverse reinforcement ratio ρ_T in RPC beams on torque - rotation response with different values of (T/M) ratio.

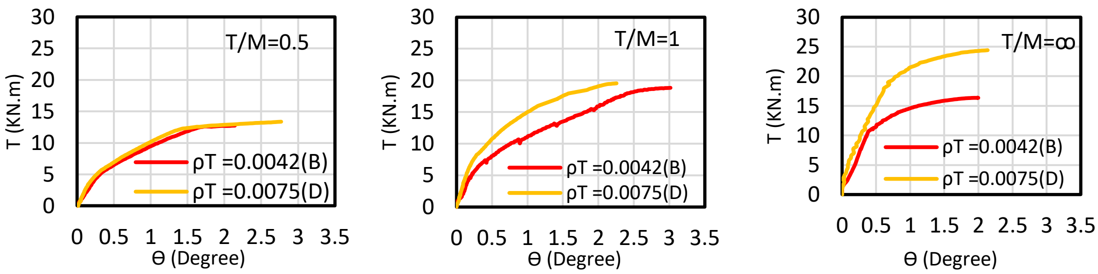


Figure 16. Effect of transverse reinforcement ratio on torque–angle response.

For case of (T/M) = 0.5 the responses of beams have two ratios of ρ_T were fairly close for all loading stages, while for (T/M) = 1, and ∞ increasing ρ_T slightly reduced the rotation values at earlier loading stages and then significantly reduced them at advanced loading stages especially in case of pure torsion.

4.4.3 Effect of transverse reinforcement ratio on strains in longitudinal and transverse bars

Fig. 17 shows the relation between moment-longitudinal reinforcement strain at the middle of longitudinal bottom reinforcement within loading stages for groups B and D. From this figure, it was noted that the response of beams have two ratios of ρ_T has a very close for all loading stages and for all values of T/M ratio. This means that increasing ρ_T has approximately no effect on the strain values in longitudinal reinforcement for all values of (T/M) ratios.

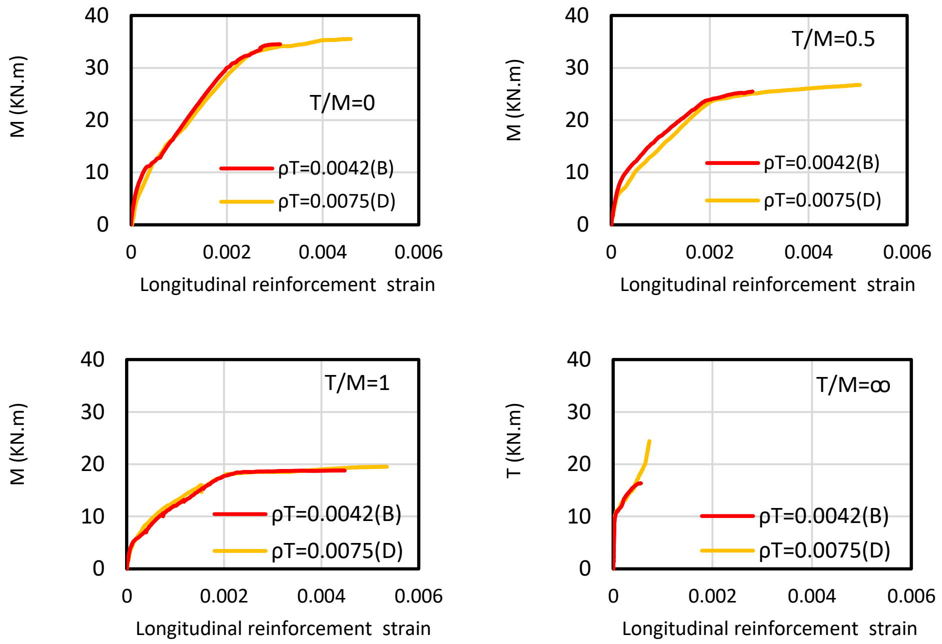


Figure 17 Effect of transverse reinforcement ratio on moment –longitudinal reinforcement strain

Fig.18 shows the relation between moment-transverse reinforcement strain (in stirrups) within loading stages for groups B and D. For cases of (T/M) = 0 , 0.5 and 1 the responses of beams two ratios of ρ_T were fairly close in all loading stages, while in case of pure torsion the response becomes stiffer after the first crack by using larger value of transverse reinforcement ratio (ρ_T=0.0075) where the strain values significantly decreases especially in advanced load stages.

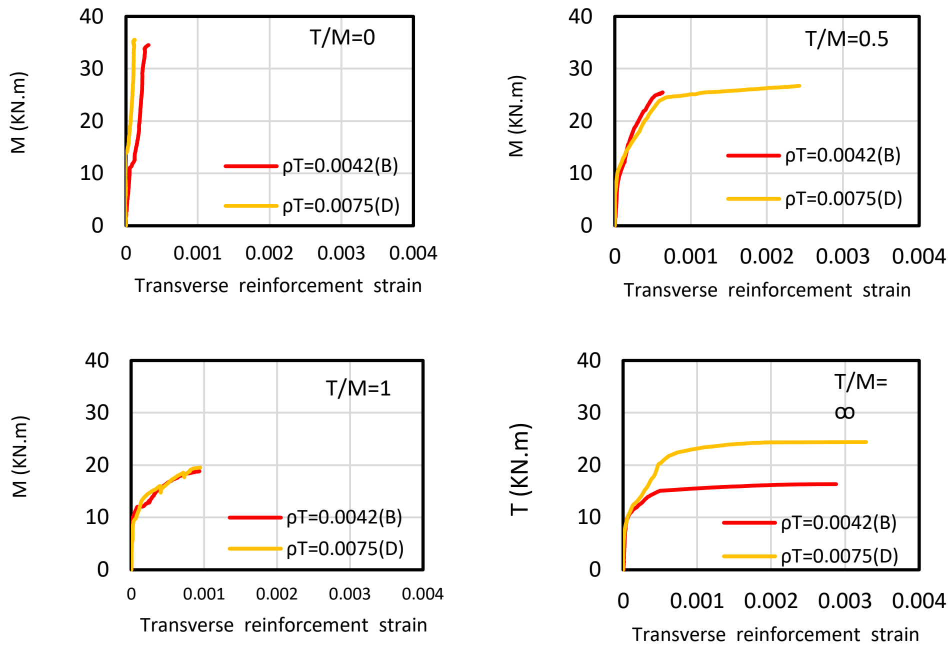
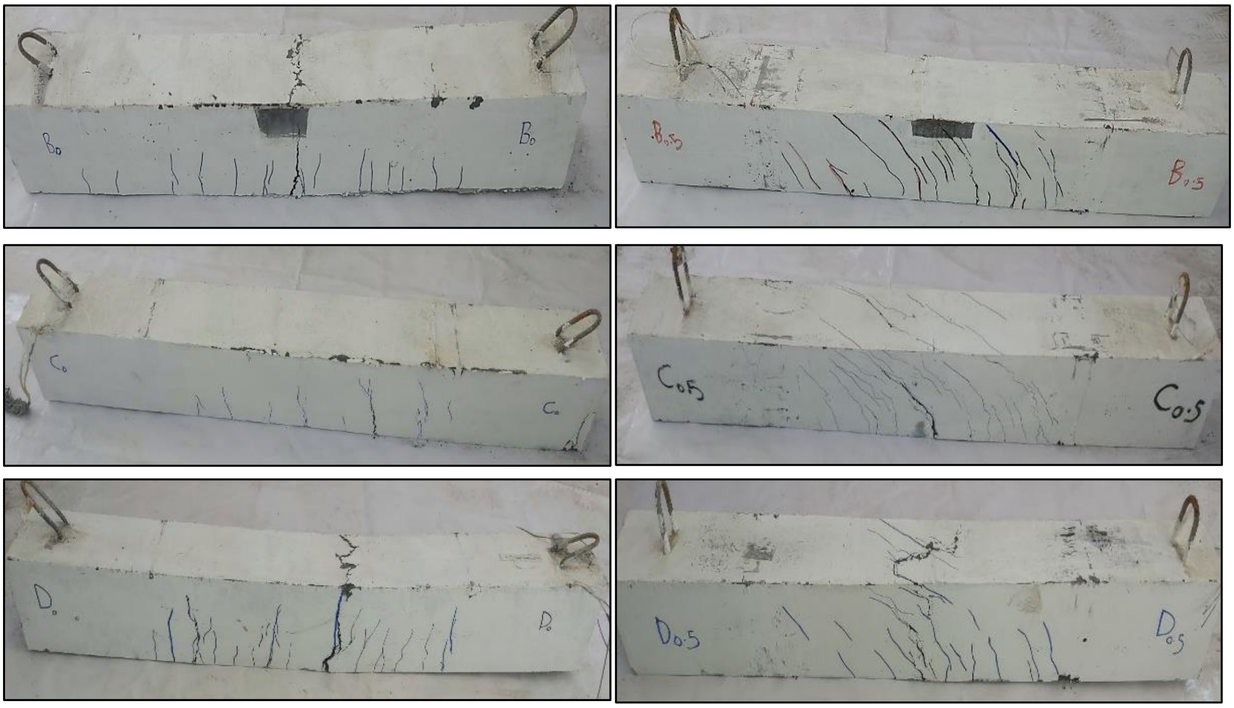


Figure 18. Effect of transverse reinforcement ratio on moment – transverse reinforcement strain.

5. Mode of failure

Fig. 19 shows the crack patterns for the tested beams. For beams that failed in flexural mode (T/M)=0, the cracks were vertical while for the beams failed in torsional mode at (T/M)=∞ the main cracks were inclined at 45° approximately. When (T/M) =0.5 and (T/M)=1 the flexural -torsional failure mode is characterized by vertical cracks in the beams resulting from flexural effects and inclined cracks resulting from torsional effects. Also the crack inclination increases and moves from 0 to 45° as T/M ratio increased from 0 to ∞. Generally, a higher number of cracks were found in group C and D than in group B.



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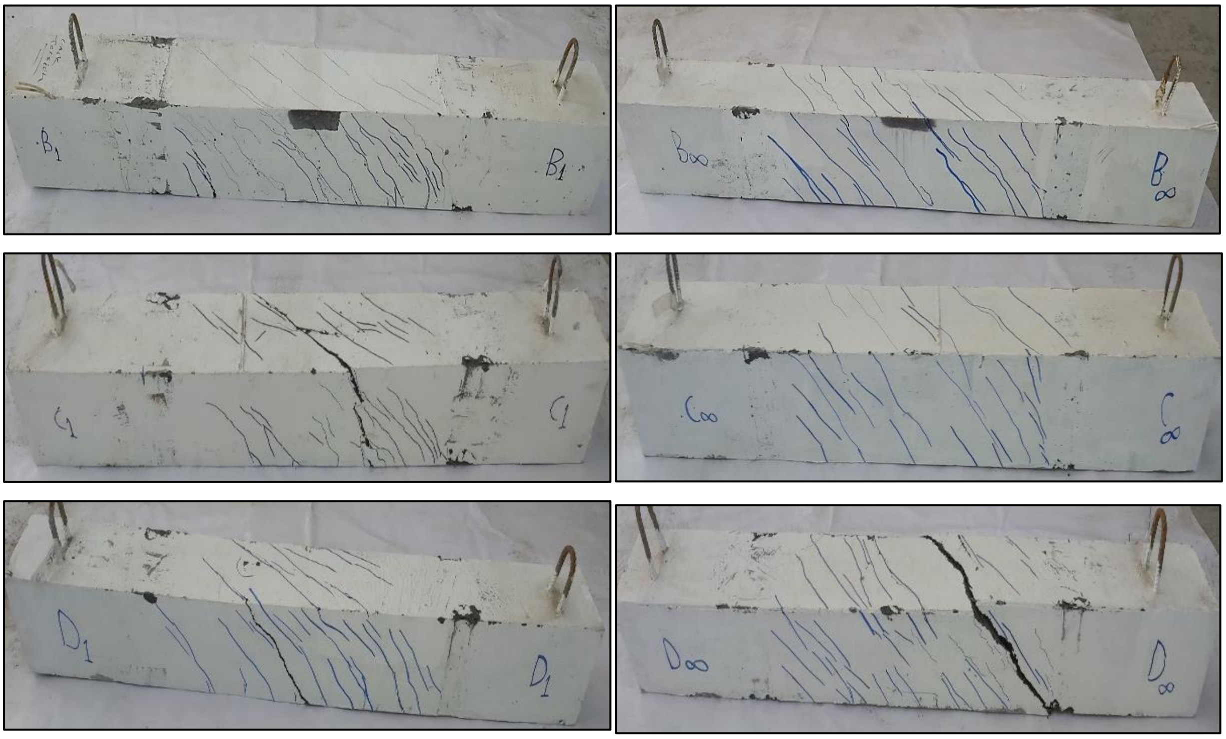

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Figure 19. Crack pattern for the tested beams (1) T/M=0;(2) T/M=0.5; (3) T/M=1; (4) T/M=∞.

6. Conclusions

1- Increasing T/M ratio reduces the cracking and ultimate capacities. The maximum effect of T/M ratio was decreasing the ultimate capacity by 50.6 % and decreasing the cracking capacity by 42.5 % in case of (T/M) = 1 at using a large value of longitudinal reinforcement ratio (ρ_L=0.016).

2- It is concluded that the presence of small bending moment can improve the ultimate torsional capacity in case of (T/M) = 1 where maximum increase was 22.8% at high longitudinal reinforcement ratio (ρ_L=0.016). But when the value of the bending moment is high (T/M = 0.5), it will weaken the torsional capacity where maximum decrease was 45.2 % at high transverse reinforcement ratio $\rho_T = 0.0075$.

3- Increasing the longitudinal reinforcement ratio from ρ_L=0.009 to ρ_L=0.016 slightly improves the cracking capacity and significantly improves the ultimate capacity. Maximum effect was in case of T/M = 0.5 where the improvement was 35.5 % while the minimum effect was in case of pure torsion where the improvement was 13.8 %.

4- Increasing the transverse reinforcement ratio from ρ_T=0.0042 to ρ_T=0.0075 slightly improves the cracking and ultimate capacities. The significant effect of it is only in case of pure torsion where the improvement was 49.2 % while the smaller effect was in case pure bending where the improvement was 2.9 %.

5- The moment – deflection curve for RPC beams is affected by T/M ratio where this curve is softer as T/M ratio increased. Effect of T/M ratio on M-Δ response is smaller with increasing ρ_L and ρ_T. Also this response slightly affected by increasing ρ_L and ρ_T that make it stiffer especially in case of T/M = 1.

6- The torque – rotation curve for RPC beams is affected by T/M ratio where this curve is softer as T/M ratio decreased. Effect of T/M ratio on T-θ response is smaller with increasing ρ_L. This response is stiffer with increasing ρ_L especially in case of T/M = 1, also it is stiffer with increasing ρ_T especially in case of pure torsion.

7- The strain in longitudinal reinforcement is larger with increasing T/M ratio. Increasing ρ_L reduces the strain values with maximum effect in pure bending case and very slight effect in case of pure torsion. While increasing ρ_T approximately does not affect the longitudinal reinforcement strain.

8- The strain in transverse reinforcement is larger with increasing T/M ratio especially in case of high longitudinal reinforcement ratio. Increasing ρ_L slightly reduces the strain values. While increasing ρ_T approximately does not affect the transverse reinforcement strain except in case of pure torsion where increasing it leads to smaller strain values especially after beam cracking.

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