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Behavior of RC T-Beam Hollow and Solid Section with Reactive Powder Concrete under Pure Torsion

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Abstract

Ten of reactive powder concrete (RPC) T- beams, 1300 mm length, 100 mm web width and 160 height, with different type of section (hollow and Solid) tested under pure torsion to study the significant effect of concrete core and steel fiber percentage on crack and ultimate torsional capacity. An increase of 191% and 64% for solid section and 174% and 59% in for hollow section respectively was achieved when increasing steel fibers percentage to concrete mix from zero to 2%, as longitudinal and transverse reinforcement ratios were kept constant (ρ_l=0.01, ρ_s=0.02). The result indicate that the concrete core has no significant effect on the ultimate torsional strength and beam elongation.

Key Words: RPC, Torsional Capacity, Hollow, Solid, Steel Fiber

سلوك العتبات الخرسانية المسلحة ذات المقاطع المجوفة والصلدة والمحتوية على خرسانة المساحيق الفعالة تحت عزم لي صافي

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الخلاصة

عشر عتبات خرسانية مسلحة من خرسانة المساحيق الفعالة ذات مقطع T بطول 1300 ملم وعرض للجذع 100 ملم وارتفاع 160 ملم بمقاطع مختلفة مجوفة وصلدة فحصت تحت تاثير عزم لي صافي فقط ولقد تبين من النتائج الزيادة النسبة المئوية من 0 الى 2% من الالياف المعدنية الى الخلطات يزيد من مقاومة اللي ومقاومة التشقق بمقدار 191% و 64% للمقاطع الصلدة و 174% و59% للمقاطع المجوفة على التوالي مع عند استخدام نسبة التسليح الطولي والعرضي ρl=0.01, ρs=0.02 لكل هذه العتبات . النتائج بينت عدم وجود اي تاثير كبير للبلب الكونكريتية للمقاطع على مقاومة التشقق ومقاومة اللي

1.Introduction

A new generation of Ultra High Performance Concrete (*UHPC*) named Reactive Powder Concrete (*RPC*) was developed in the last decades, which offers, superior strength, durability and ductility. One of the main differences between other concretes and RPC is that the latter requires mechanical models capable of taking tensile behavior into account for structural application to enable the material to be fully exploited.[1]

The term (RPC) has been used to describe a fiber-reinforced, superplasticized, silica fume-cement mixture with very low water-cement ratio (w/c) characterized by the presence of very fine quartz sand (0.15-0.40mm) instead of ordinary aggregate. The absence of coarse aggregate was considered by the inventors to be a key-aspect for the microstructure and the performance of the RPC in order to reduce heterogeneity between the cement matrix and the aggregate. However, due to the use of very fine sand instead of ordinary aggregate, the cement factor of RPC is as high as (900-1000 kg/m^3) [2].

Sherbrooke Pedestrian Bridge in Canada was the first pioneer structure built using RPC which was completed in July 1997, **Fig (1).** The bridge superstructure is a post-tensioned open-web space truss. RPC, with a compressive strength of 200 MPa, was used in the deck and top and bottom chord elements of the truss. The footbridge's effective thickness is 150mm. A comparative study showed that the same structure made by high performance concrete (HPC) would have required a thickness of 375 mm [3].

Fig. (1): Sherbrooke Bridge, Quebec, Canada[4]

Allawi (2006)[4] performed an experimental investigation and nonlinear analysis of reinforced concrete beams strengthen by CFRP in torsion. It was found that when the beam strengthened in the form of continuous wrapping, an increase of to 90% and 84% in the ultimate torque and an increase of 81% and 130% in cracking torque for reinforced concrete beams with solid and hollow sections, respectively have been achieved.

Hii and Al-Mahaidi (2006) [5] performed an experimental and numerical investigation on torsional strengthening of solid and box-section reinforced concrete beams using CFRP laminates. Enhancement up to 40% and 78% were recorded for cracking and ultimate torsional strength, respectively.

2. Significance of Torsion

If external loads act far away from the vertical plane of bending, the beam is subjected to twisting about its longitudinal axis, known as torsion, in addition to the shearing force and bending moment.

Torsion on structural elements may be classified into two types; statically determinate, and statically indeterminate. In **Figs.(2, and 3)** some examples of beams subjected to torsion are shown. In these figures, torsion results from either supporting a slab or a beam on one side only, or supporting loads that act far away transverse to the longitudinal axis of the beam. Shear stresses due to torsion create diagonal tension stresses that produce diagonal cracking. If the member is not adequately reinforced for torsion, a sudden brittle failure can occur.

Fig. (2): Reinforced Concrete Members Subjected to Torsion.[3]

3.Test Program

The experimental part of the present research testing ten RPC T-beams with both solid and hollow sections under pure torsion. The tested beams were simply supported with 1300 mm length, 100 mm web width and 160 height. The beams were tested under pure torsion. **Fig.(4**)

Two types of cross sections were used for the test beams (solid and hollow cross sections). This was followed to assess the effect of the type of cross section on the torsional strength of RPC T-beams.

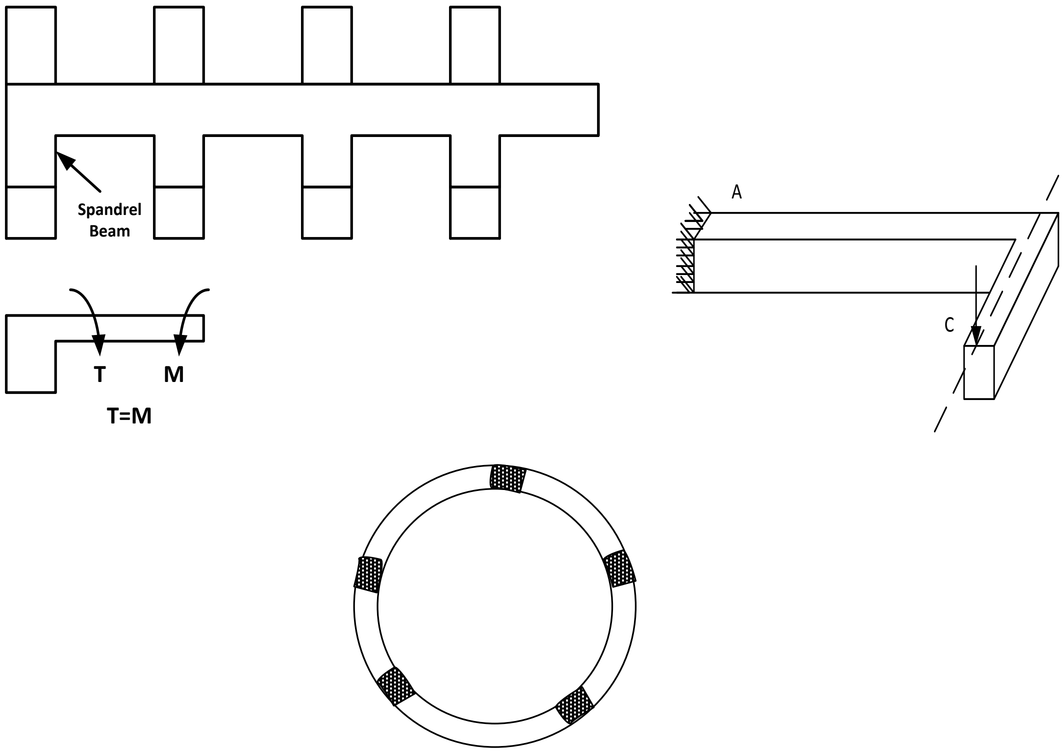


Fig. (3): Reinforced concrete members subjected to torsion:

The variables included in this study are focused mainly on beam type and on the different volume fraction of fibers that influence the torsional capacity of the beam. To study the effect of the volume fraction of fibers (V_f) on the torsional strength of RPC T-beams, four values of (V_f) (0%, 0.5%, 1.0%, and2.0%) were used in casting the beams. Taking into consideration the aspect ratio of the fibers used and the type of concrete mix

4. Materials

Ordinary Portland cement (**type I**) produced in Iraq of united cement component (UCC) as trade mark was used in casting all the specimens. Al-Grabia glass sand shown in **Fig. (5**) was used as fine aggregate. This type of sand is a byproduct of Al- Ramadi Glass Factory. The grading of original fine aggregate is shown in **Table (1**) column B. For RPC, very fine sand with maximum size 600μm was used, with the particles size greater than 600 μm were removed. This sand was separated by sieving, column C, its grading satisfied the fine grading in accordance with the B.S. specification No. 882/1992[7].

Two sizes of steel reinforcing bars were used in the tested beams, deformed bars of size (φ5, φ6) mm were used as longitudinal reinforcement, and deformed steel bars of size (φ 8)mm were used as closed stirrups, as show in **Fig (5).**

Straight brass coated steel fibers 13 mm long with a diameter of 0.175 mm and an aspect ratio of 74 were used throughout the experimental program, which is brought from china and manufactured by Bekaert Corporation, **Fig (5).**

Asuperplasticizer commercially named Flocrete PC 260 which conforms to ASTM C494-99[8] type A&G was used in the mixes.

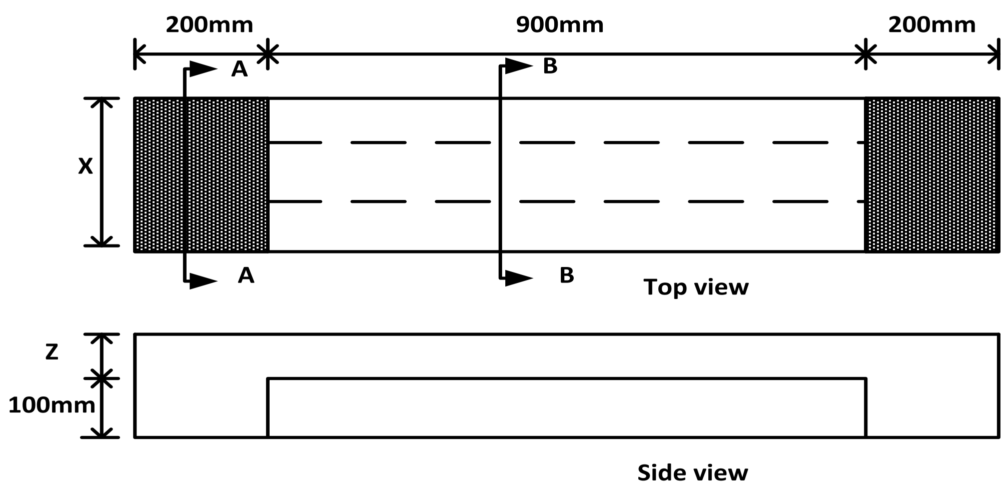


Fig. (4-a): Top and Side Views of Beam Specimen

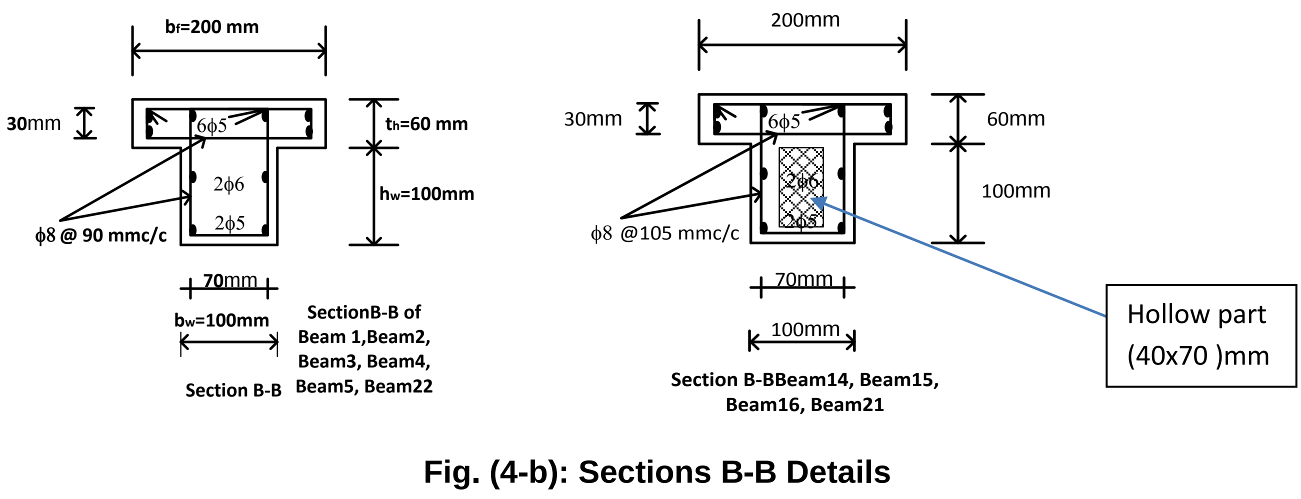


Fig. (4-b): Sections B-B Details

Table (1) Grading of Original Fine Aggregate Compared with the Requirement of B.S. 882: 1992

A	B	C	D
Sieve size (mm)	Original Cumulative Passing%	Final Cumulative Passing%	Limits of B.S 882:1992 fine grading
9.52	100	100	100
4.75	100	100	100
2.36	100	100	80-100
1.18	100	100	70-100
0.600	93.80	100	55-100
0.300	60.90	65.34	5-70
0.150	11.60	12.45	0-15

(a): Silica

(b) Reinforcement Steel

(c): Sand

(b) Steel Fiber

Fig. (5) Sample of Silica Fume, Steel Mesh, Sand,and steel fiber Used in Present Investigation

A grey densified grade 920 D silica fume (which is a byproduct from the manufacture of silicon or ferro-silicon metal) was used, which was imported from the Elkem company in UAE. Silica fume is an extremely fine powder, as shown in **Fig.(5**), its particles are hundreds of times smaller than cement particles.

Curing procedure adopted by Mahdi[9] was used here, where all specimens were kept in vapor bath and the temperature of the bath was increased gradually to reach 95°C ±5°C at rate of 20°C per hour. Specimens were kept in the bath for 48 hours then cooled gradually. Thereafter, they were immersed in water in laboratory climate temperature until age of 28 days,

The special clamping loading frame on each end of the beam used in this research is shown in **Fig. (6).** This frame consists of two large steel clamps which work as arms for applied torque with separated faces to connect them over the sample by large bolts; four bolts are used for each arm. This frame is made of thick steel plate (16 mm) with two steel shafts attached by screws.

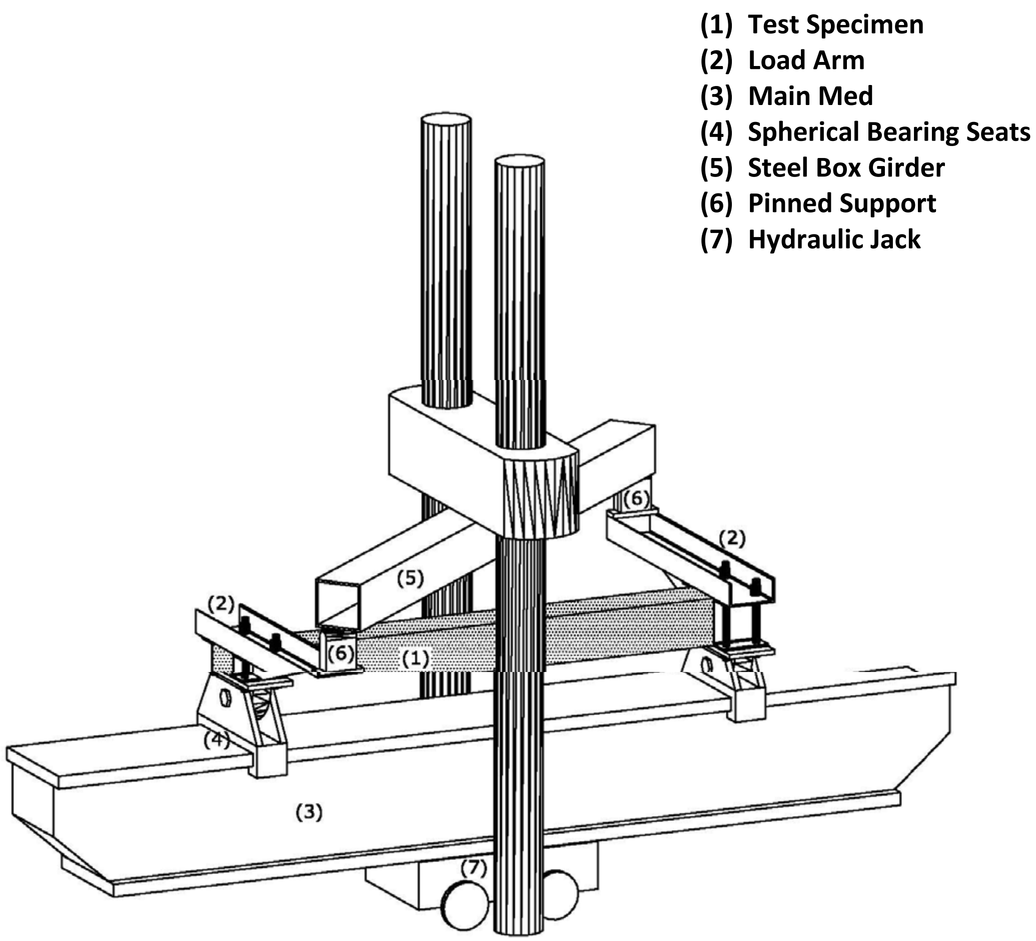


Fig. (6) Suggestions of load Arrangement Showing the Test Rig[4].

5. Measuring Instruments

5.1 Angle of Twist Measurements

A simple method was used to estimate the angle of twist by using two dial gages attached at the bottom fiber of the end of beam at a point (90 mm) from the center of the longitudinal axis of the beam as shown in **Fig. (7)**. The dial gage on the right and on the left recorded the down values and then the average was used to find the twist angle in radians

5.2 Elongation Measurements

Two horizontal dial gages were fixed at the center of the beam ends to measure the axial displacement of the beam as shown in **Fig. (7).**

Fig. (7) Angle of Twist and Elongation Measurement

6. Test Results

In this pargraph show the following :

6.1 Effect of Volume Fraction of Fibers

Fig. (8) shows the behavior of solid RPC T- beams (B5, B22, B4, and B3) and hollow RPC T- beams (B16, B21, B15, and B14) with volume fraction of fibers (V_f) of 0%, 0.5%, 1.0%, and 2.0% respectively. In all these beams the silica fume content, transverse and longitudinal steel ratios were kept constant (*SF=25*%, ρ_s=0.02 , ρ_l= 0.01).

Table (2) Effect of Variation in Steel Fiber Ratio on Cracking and Ultimate Torque

Details	f_{yl}=555 MPa	f_{ys}=525 MPa	b_f=200mm, t_f=60 mm	SF = 25%	ρ_l=0.01	ρ_s=0.02
Beam No.	**f'_c MPa**	**V_f %**	**T_{cr} (kN.m)**	**%increase in T_{cr}**	**T_{ult} (kN.m)**	**% increase in T_{ult}**
Solid Section						
B5	99.5	0	4.3		19	
B22	115.4	0.5	8.55	99	23	21
B4	130.4	1	10.25	138	27.7	46
B3	154.2	2	12.5	191	31.12	64
Hollow Section						
B16	98.8	0	4.1		17.84	
B21	111.2	0.5	8.08	97	21.68	22
B15	126.1	1	9.75	138	25.68	44
B14	145.3	2	11.25	174	28.32	59

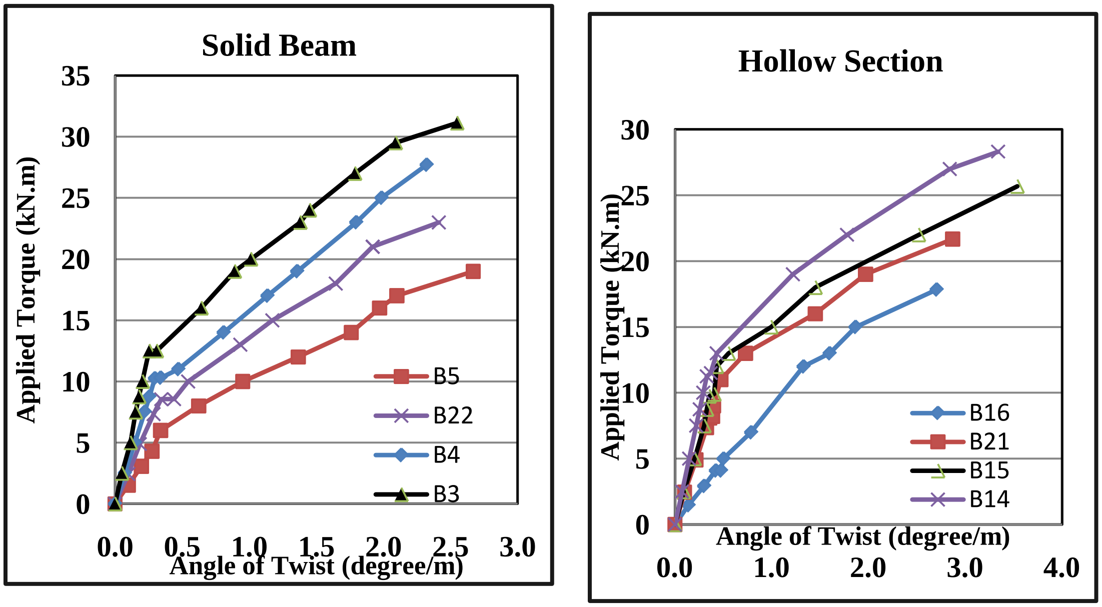
Table (2) shows that both the cracking and ultimate torque increase as the volume of fraction is increased. It was found that the ultimate torque of solid beam was increased by about 21%, 46% and 64% and crack torque increased by 99%, 138% and 191% as the volume fraction of fibers was increased from zero to 0.5%, 1.0% and 2.0% respectively. While for hollow beams, the ultimate torque was increased by about 22%, 44% and 59% and crack torque increased by 97%, 138% and 174 %as the volume fraction of fibers was increased from zero to 0.5%, 1.0% and 2.0% respectively.

Fig. (9) shows that both the cracking and ultimate torques increase as the steel fiber content is increased for both hollow and solid sections.

The presence of steel fiber improved the ductile behavior of beams by increasing the tensile strength of concrete. Diagonal cracks were observed at faces of all fibrous beams with relatively high percentage of fibers, which indicates that the fibers (after beam cracking) continue to resist increasing tensile stresses until the complete pullout of all fibers at a critical crack.

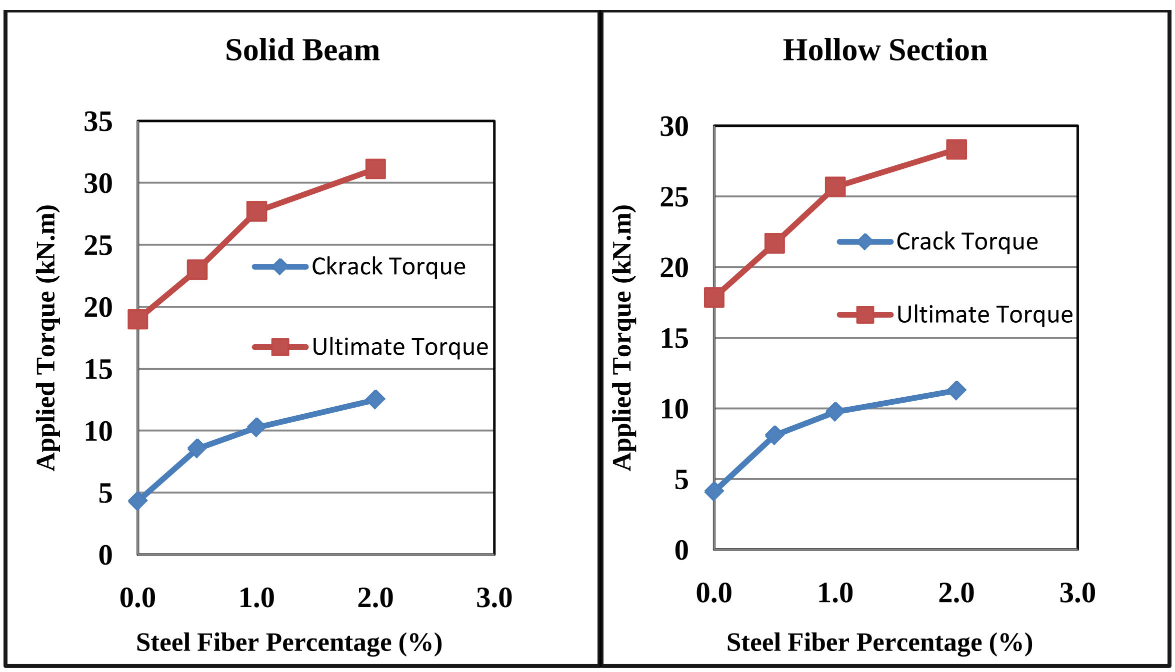
The experimental results indicate that the type of beam (solid or hollow) has no major effect on the angle of inclination of the cracks. In general, the number of cracks was larger in beams of hollow section than in the beams of solid section. All beams in both groups failed by forming extensive diagonal torsional crack in the flange due to high torsional shear stress.

Fig. (10) shows that increasing the steel fibers content resulted in a decrease in the elongation of the T- beams



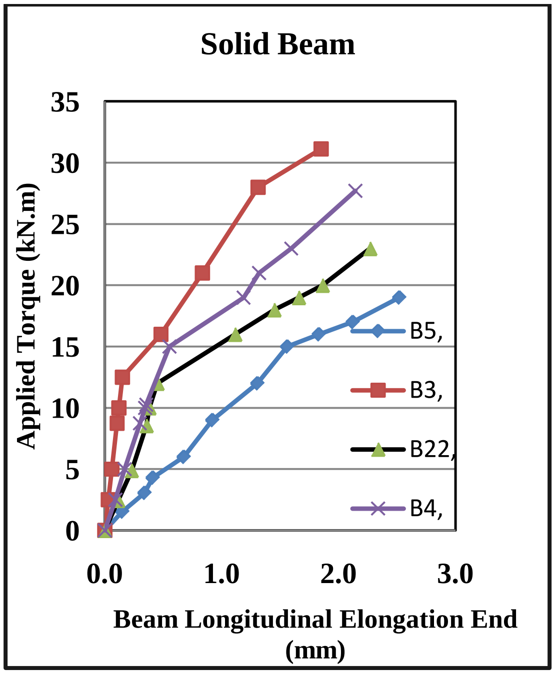
(a): Solid Beam **(b): Hollow Section**

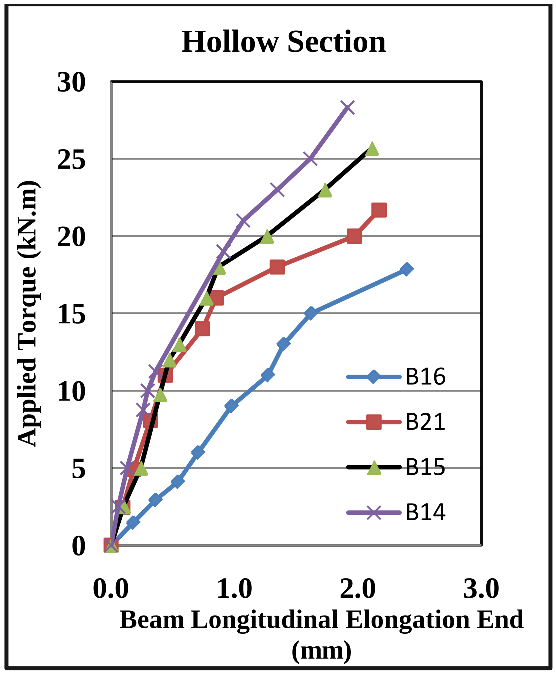
Fig. (8) Torque-Twist Behavior of with Different Steel Fiber RatioSolid Section



(a) : Solid Section **(b) : Hollow Section**

Fig. (9): Experimental Crack and Ultimate Torques





(a): Solid Section **(b): Hollow Section**

Fig. (10) Beam Longitudinal Elongation Behavior: Effect of Steel Fiber Content

6.2 .Effect of Cross Section Shape

Fig. (11) shows the torque-twist behavior of the plain RPC T-beams B8(hollow) and B12(solid). For the solid section beam B12, the first diagonal crack was observed at an applied torque of 10.1 kN.m and the beam reached an ultimate torque of 24.4kN.m and exhibited a ductile behavior. Ductility of beam B12 was mainly due to the amount of steel fibers provided. For the plain hollow section beam B8, cracking was recorded at a torque value of 9.25kN.m, while the ultimate torque was 23.44 kN.m. It can be seen that the post cracking torsional behavior of B8 was similar to that B12 and the failure surface was inclined at approximately 45 degree with respect to the longitudinal axis of beam at the front side and then turned gradually to 45 degree as it approached the opposite face and the beam failed by torsion. **Figs. (11 and 12)** indicate that the concrete core has no significant effect on the ultimate torsional strength and beam elongation.

Table (4) Effect of Cross Section Shape on Cracking and Ultimate Torque

	$\rho_s = 0.02$	b_f=200mm, t_f=60 mm	SF = 25%	V_f=2%	ρ_l=0.01
Beam No.	Section	T_{cr} (kN.m)	%increase in T_{cr}	T_{ult} (kN.m)	% increase in T_{ult}
B8	Hollow	9.25		23.44	
B12	Solid	10.1	9	24.4	4

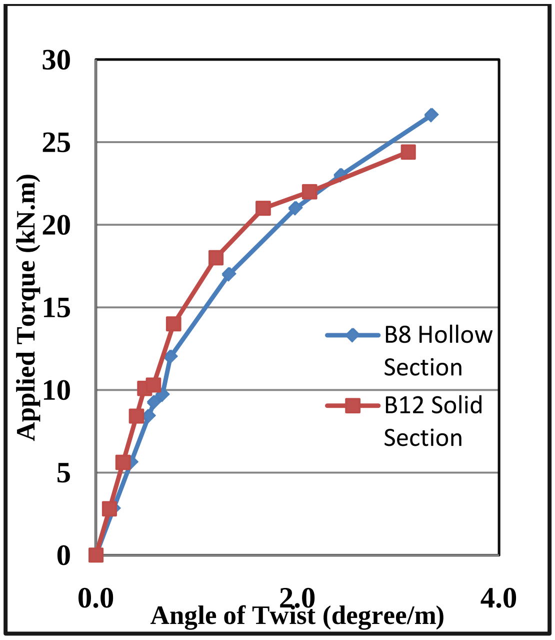


Fig. (11): Torque-Twist Behavior of Plain concrete

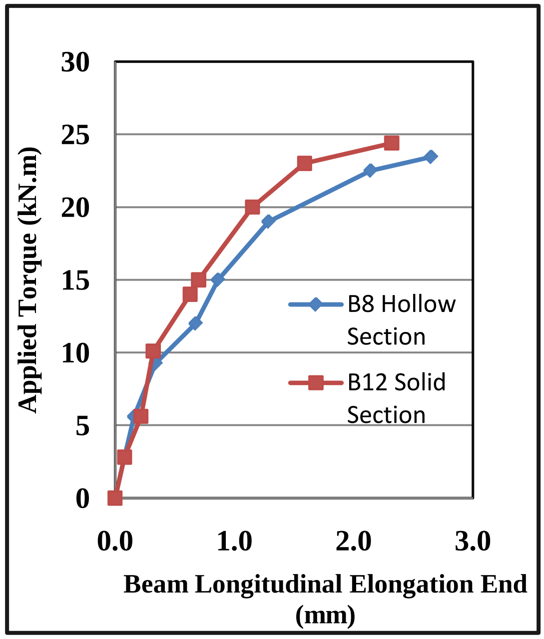


Fig. (12): Beam Longitudinal Behavior Plain concrete

7. Crack Patterns of Tested RPC T-Beams

For each tested beam with solid and hollow cross section, the total number of cracks and the maximum crack width at the onset of beam failure were found to proportional with the percentage content of steel fibers in beam. Initially, a crack formed at one side of web and with increasing the applied torque, other cracks developed at the other side of the web and both extended towards the flange to form a complete helical crack pattern around the beam. Failure of beams B5 and B16 was associated with concrete cover spalling at the edge of the flange, Figs. **(12 to 14).**

The two fibrous RPC T-beams, which were cast without steel reinforcement, namely the beam B12 solid section and the hollow section, beam B8 failed by the formation of extensive diagonal torsional cracks in the web with subsequent propagation to flange and accompanied by small crushing of concrete cover. In fibrous beam without reinforcement, the stresses were transferred to the fibers with crinkling sound heard which eventually ended with fibers pullout at the critical section resulting in failure of the beam, **Fig. (14).**

Fig. (12): Failure of Solid Specimens

Fig. (13) : Failure of Hollow Specimens

Fig. (14) : Failure of Group H Specimens

8. Conclusions

1. It was observed the total number of cracks counted in a fibrous RPC T-beam under pure torsion failure was greater and the crack width was lesser than those in identical non-fibrous beam for both solid and hollow section.
2. The steel fibers became effective after the cracks formation and continued to resist the principal tensile stresses until the complete pullout of all fibers occurred at one critical crack.

3. An increase of 64% and 59% in the ultimate torque T_n for solid and hollow RPC T-beams was obtained by adding 2% fibers to concrete mix. The corresponding increase in the cracking torque T_{cr} was 191% and 174 % for solid and hollow RPC beams respectively
4. The type of RPC beams (solid or hollow) was found to have no major effect on the angle of inclination of the cracks, cracking and ultimate torque and beam elongation. In general, the number of cracks was larger in the hollow sections than in the solid ones. All the beams in both groups failed by forming extensive diagonal torsional crack in the flange due to high torsional shear stress.

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