Journal of Engineering and Sustainable Development
www.jeasd.org
Vol. 21, No.03, May 2017
ISSN 2520-0917

TORISIONAL BEHAIVORE OF REACTIVE POWDER CONCRETE T-BEAM WITH WEB OPENING

Dr. Ali Sabah Alamli[1], Dr. Hayder Abdulameer Mehdi[2], *Reem Hatem Ahmed[3]

1) Assist Prof., Civil Engineering Department, Al-Mustansiriya University, Baghdad, Iraq.
2) Assist Prof., Civil Engineering Department, Al-Mustansiriya University, Baghdad, Iraq.
3) M.Sc. student., Civil Engineering Department, Al-Mustansiriya University, Baghdad, Iraq.

Abstract: Ten T section reinforced concrete beams by use Reactive Powder Concrete (RPC) beams with square and circular web perforation tested under pure torsion . The geometry and main reinforcement of all specimens are same. The main parameters taking into account in present paper are circular opening size, location of openings and number of openings. The torque caused the ultimate crack was recorded, and the angle of twist generated from these torques is calculated. Test results indicate that, torque that causes failure (ultimate) is affected by opening size, opening locations, opening numbers, the presence of web cut – outs reduces ultimate torque capacity of section, such that the increase in web opening size reduces the ultimate torque, when the web openings increase that leads to reduction in the torque capacity، the opening eccentricity makes no uniformity of shear stress distribution through web and leads to reduce the torque capacity. Then, angle of twist depends on the opening location at crack or ultimate stages, the twisted angle depends on torque magnitude because of beam span, shear modulus and geometry of T sections which are the same and the cracks start from support and then take a spiral shape around the beams up to flange so the number of cracks increases as the presence of openings.

Keywords: *Torque, cracks, RPC, Web Opening, T Section.*

سلوك اللي للعتبات ذات شكل T وذات خرسانة المساحيق الفعالة والحاوية على فتحات في الجذع

الخلاصة : عشر عتبات من خرسانة المساحيق الفعالة المسلحة ذات مقطع T حاوية على فتحات مربعة ودائرية فحصت تحت تأثير عزم لي صافي . الشكل و التسليح هو نفسه لكل النماذج . المتغيرات الرئيسية التي اعتمدت في هذا البحث هي حجم الفتحات الدائرية, موقع الفتحات و عدد الفتحات . عزم اللي الذي سبب التشقق النهائي تم تسجيله وكذلك زاوية اللي قد تم حسابها ايضاً. النتائج بينت أن عزم اللي الذي الفشل النهائي قد تأثر بحجم وموقع وعدد الفتحات، فوجود الفتحات في الجذع أدى الى تقليل مقاومة المقطع لعزم اللي النهائي، وكذلك زيادة حجم الفتحات يقلل من مقاومة عزم اللي, كما اظهرت زيادة الفتحات الى الحد من قدرة عزم اللي، إن الفتحات تعمل على عدم توحيد توزيع اجهادات القص خلال الجذع (WEB) ويؤدي الى التقليل من قدرة عزم اللي (الدوران) , وكذلك زاوية الألتواء تعتمد على موقع الفتحات عند مرحلة اللي الابتدائي او النهائي , تتأثر زاوية الالتواء بمقدار عزم اللي المسلط وعزم الجسائة والقصور الذاتي للمقطع وذلك لعدة اسباب منها طول العتبة ,معامل القص وشكل مقطع العتبة. إن التشققات تبدأ من المساند وتأخذ شكل حلزوني حول العتبة لتصل الى الجناح حيث تبلغ الشقوق ذروتها بوجود الفتحات.

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*Corresponding Author reem almula@yahoo.com

1. Introduction

There are many types of beams has many types of mode failure, mainly classified as shear, flexural and torsion failure, Because of concrete is a granular material so that it is brittle material, so that the main reinforcement resists the flexure failure, the stirrups resists the shear failure, and both closed stirrups with longitudinal reinforcement used to resists the torsional cracks.

A reinforced concrete beam has cracked in torsion, its torsional resistance is provided primarily by closed stirrups and longitudinal bars located near the surface of the member [1]. In ACI – 318 – 2014 there was a full explanation of how to analyze and design of reinforced concrete beams against torsion, but there were few researchers that taken in consideration the web perforations. Abdul-Hussein (2010) [2] investigated the torsional capacity of tested reinforced concrete "RC" beams as a function of various variables like fibers amount, with and without openings, and reinforcement ratio in each directions (transverse and longitudinal).

The researcher founded that adding one percent of steel fiber increased the torque and reducing cracking. Khalel (2013) [3] investigated RC beams under pure torsion in case of high strength concrete type. Forty three specimens was adopted by author from literature review and applied regressions method to suggest an empirical equations, cracked due to pure torsion and resistance or torsional capacity as a function of concrete compressive strength, geometry longitudinal and transverse reinforcement . Al-Saraj (2013) [4] investigated RPC beams subjected to pure torsion by tested the strength capacity and torsional cracks of beams experimentally and theoretically. The experimental work consists of twenty two T- section of RPC with various fiber steel ratios and silica fume subjected to pure torsion.

Theoretical approach using tests results and proposed empirical equations represent cracking torque as a function of properties of RPC and another proposed equation to estimate maximum torsion relay on the properties of RPC. Tests result indicated that in presence and using of RPC up to (2% fiber steel ratio) increased the cracking torsion and then after increased in full torsional capacity. Mahdi (2015) [5] investigated the behavior High Strength Self Compacted "HSSC" of hollow section RCC beams under pure torsion. The total six beams was tested has same geometry and length, so the main variables was the stirrups spacing. The experimental tests result indicated that the torsion beams resistance increased by decreasing of stirrups spacing, also, the improvements of ultimate torsional capacity compared with reference beam up to two hindered fifty percent and for torsional cracks up to two hindered percent. Al-Hassani et al (2015) [6] suggested an empirical formula by using regression method to estimate torsional capacity in case of presence steel fiber.

The two proposed formula deals with codes formula and derived from tests result. Waryosh et al (2015) [7] studied the ultimate strength of hollow RC beams under pure torsion. The investigation consists of solid and hollow section (circular 18%,rectangular 18% and 27% of the total cross section area of beams. Torque – twist and opening effects on it and on the full behavior of RC beams discussed by authors. It was concluded that the full capacity torque of hollow section in case of circular is greater than in case of rectangular hollow when compared with solid section. Al-Hassani et al (2015) [8] tested and investigated the behavior of ten reinforced concrete specimens of T sections with and without hole along the span under pure torsion and using reactive powder. It was focused on the effects of holes and steel fibers on the cracks and full capacity of T sections under pure torsion. By results from experimental tests, increased in capacity for solid section is more than if compared with hollow section in case of presence of steel fibers but the core has no effect on the ultimate torsion capacity.

The objective of present paper was to investigating experimentally the torsional behavior of reinforced reactive powder concrete (RPC) T-section beams with square and circular web opening**.**

2. Specimen's Details

The dimensions of T- section beam used in present study are as follows; (bw=100mm, h=280mm, bf=320mm. tf=80mm), with length of (1300 mm). The reinforcement for beams with stirrups as distributed with bottom reinforcement 2Φ10, top reinforcement 2Φ 6, shear reinforcement Φ6 @ 200 mm. The total tested beams were ten beams which have the same geometry and steel reinforcement as shown in Fig (1).

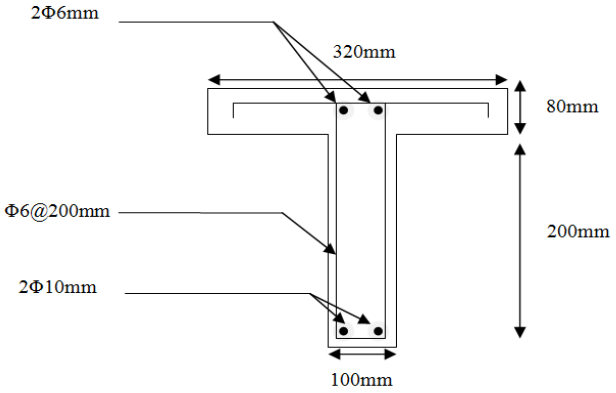

Figure 1. Details of Beam

2. Experimental Program

The main variables adopted in the experimental work were as follow; reactive powder concrete (RPC) and modify reactive powder concrete (MRPC), Eight T-section beams made of (RPC) and two T-section beams made of (RPC and MRPC) one of beam made of (RPC) in web and (MRPC) in flange , while another beam made of (MRPC) in web and (RPC) in flange. Monolithic and non-monolithic beam: Nine T-section beams cast monolithically and One T-section beam made of (RPC) cast non-monolithically. Web openings in this study inncluded many variables (shape, dimension, location, number) as given below.

3. Opening layout

The openings layout and configurations in the web of the T-section beams, one solid beams without web opening were made of (RPC), and nine other beams with different locations and sizes that perforated in web openings as given in Table (1).

Table (1). Details of beams and web openings.

Beam No.	MATERIAL	SHAPE OF OPENING	DETAILS OF OPENING
B1	solid beam made of (RPC) cast monolithically	———	without opening
B2	made of (RPC) cast monolithically	circle	Φ 100mm @ center of the span beam
B3	made of (RPC) cast monolithically	square	(100*100mm) @ center of the span beam
B4	made of (RPC) cast monolithically	circle	Φ 100mm @ 1/3 of the span beam
B5	made of (RPC) cast monolithically	square	(100*100mm) @ 1/3 of the span beam
B6	made of (RPC) cast monolithically	circle	Φ 100mm @ center of the span beam and Φ 100mm @ 1/3 of the span beam
B7	made of (RPC) cast monolithically	circle	Φ 150mm @ center of the span beam
B8	made of (MRPC)in flange and (RPC) in web cast monolithically	circle	Φ 100mm @ center of the span beam
B9	made of (RPC)in flange and (MRPC) in web cast monolithically	circle	Φ 100mm @ center of the span beam
B10	made of (RPC) cast non monolithically	circle	Φ 100mm @ center of the span beam

4. Material

Two types of concrete mixes are used Reactive Powder Concrete (RPC) and Modified Reactive Powder Concrete (MRPC). The (RPC) and (MRPC) mixes production requires high quality materials. Usually chemical admixtures are employed to obtain a low water–cement (w/c) ratio with acceptable workability.

4.2 *Cement*

Ordinary Portland cement type (I) Mass (Sulaymaniyah-Iraq) was used for both (RPC) and (MRPC). Tables (2) list the results of physical properties of the cement. Results indicate that the available cement conforms to the Iraqi Specification (IQS) No.5/1984[9].

Table (2). Physical properties of cement

PHYSICAL PROPERTIES	TEST RESULT	LIMIT OF IRAQI SPECIFICATION NO.5/1984
Specific surface area (Blaine Method), m^2/kg	383	230 (min)
Setting time (vicat's method)	1:55	00:45 (min)
Initial setting, hrs: min	4:25	10:00 (max)
Final setting, hrs: min		
Compressive strength, MPa	25.85	15.00 (min)
3 days	28.00	23.00 (min)
7 days		
Autoclave expansion %	0.01	0.8 (max)

4.2 *Fine Aggregate*

Very fine sand with maximum size 600μm was used for (RPC) and (MRPC) Mixes. The grading of used fine sand conform to the Iraqi specification(IQS) No.45/1984[10]

4.3 *Coarse Aggregate*

Crushed gravel from AL-Nibaey(Iraq) region was used for modified reactive powder concrete (MRPC) mixes with a maximum size of 5mm. This crushed gravel was washed, then stored in air for surface drying, and then stored in a saturated surface dry condition before using.

4.4 *Silica Fume*

The silica fume (SiO_2) reacts with this calcium hydroxide to form additional binder material (calcium silicate hydrate (C-S-H)) which is very similar to the calcium silicate hydrate formed from the Portland cement . In present paper, Silica fume has (20%), cement mass for (RPC) and (10%), cement mass for (MRPC). The chemical composition of this silica fume conforms to the ASTM 1240-04 [11]. High range water reducing agent (HRWRA) based on poly carboxylic ether is used. One of the new generation of polymer based super plasticizer Glenium 51 is used, the normal dosage for is (0.5-0.8) L/100kg of cement mass. It is free from chlorides and complies with ASTMC494 [12] types A and F.

4.5 Steel Fibers

Hooked ends short steel fibers were used in this work with volume fractions of (V_{sf} =1%) The properties of the used steel fibers are shown in Table (3).

Table (3). Properties of steel fiber

PROPERTY	SPECIFICATIONS
Relative density	7860 kg /m^3
Yield strength	1130 MPa
Modulus of elasticity	$200x10^3$ MPa
Strain at portion limit	$5650x10^{-6}$
Poisson's ratio	0.28
Average length L_f	32 mm
Nominal diameter D_f	0.4 mm
Aspect ratio(L_f/D_f)	80

5. Steel Reinforcement

Longitudinal reinforcement with diameters (Φ10mm) used for main reinforcement and (Φ6mm), which are used for stirrups. The bars have been tested in the material laboratory of the Civil Engineering Department at Al-Mustansiriyah University, test the results of steel bars conform to (ASTM A615/615M-13) [13], and the results are listed in Table (4).

Table (4). Properties of steel bars

Nominal Diameter (mm)	Measured Diameter (mm)	Modulus of Elasticity(E_s) (GPa)	Yield Stress(f_y) (MPa)	Ultimate Stress(f_u) (MPa)
6	6.17	200	385	550
10	9.53	200	484	719

6. Mixing

Reactive powder concrete consisting of cement , fine sand, silica fume, steel fibers , super-plasticizers and water were used to cast the RPC beams, as well as the control specimens (cubes ,cylinders and prisms) of RPC. The composition of RPC with a water to cement ratio of 0.2, percentage of silica fume was (20%) by weight of cement, and very fine sand was used with maximum particles size of (600μm), Table (5) list concrete mix for (RPC).

Table (5). Properties of concrete mix (RPC)

Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silica fume %	Silica fume kg/m^3	w/c	Super-plasticizer (L/m^3)	Steel fiber content %	Steel fiber content kg/m^3
1000	1000	____	20	200	0.2	5	1	78

The composition of MRPC with a water to cement ratio of 0.2, percentage of silica fume was (10%) by weight of cement, and very fine sand was used with maximum particles size of (600μm) and gravel of maximum size (5mm). The used super-plasticizer gives enough mixing time and permits to produce uniform mixing of concrete without any segregation, Table (6) list the concrete mix (MRPC).

Table (6). Properties of concrete mix (MRPC)

Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Silica fume %	Silica fume kg/m^3	w/c	Super-plasticizer (L/m^3)	Steel fiber content %	Steel fiber content kg/m^3
900	600	540	10	90	0.2	5	1	78

7. Test Procedure

All the beam specimens are tested in accordance of ACI-318-2014. Typically, (Ten)beam specimens representing a particular Test Group are tested under a load-control regime, that is fixed each 10 kN. At the start of each test, the load is initially applied slowly when the first crack of concrete appears the load continue apply up to failure of beams at the ultimate load, Loading is stopped on failure of beam. The load levels and the corresponding displacement as well as deflections are recorded at each increment of loading. For measurement of displacement, the strain dial gages of 0.01 mm accuracy are placed at many positions depending on the case of beam by the distribution and location of the opening.

While placing the specimens in the testing machine, care showed be taken to ensure that loading is at the end of the steel arm to produce pure torsion to the tested beams. The loads applied symmetrically as shown in Plate (1).

During application of load to the beam, single point load is applied to the top of steel arm and is transferred as pure torque to the top of the beam., loading is continued until severe cracking of the beam occurs.

The frame used in testing consists of two large steel clamps which work as arms for applied torque with separated faces to connect them over the sample by large bolts, where four bolts are used for each arm. High carbon steel plate is used to manufacture the frame with 10 mm in thickness and bolted by four 24 mm diameter bolts to prevent torque, as shown in Plate (2).

Plate 1. The moment arm

Plate 2. The test setup

8. Angle Of Twist Measurements

To measure the vertical strain due to applied torque, a dial gauge is fixed in a position. The methodology adopted to calculate angle of twist is by using the displacement measured from experimental tests,then divided it by horizontal distance by using trigonometric function.

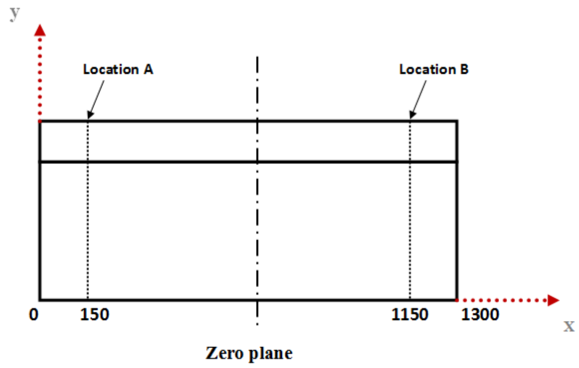

Plate 3. Angle of twist and location of zero plane angle

9. Test Results

9.1. *Effect of web opening*

In general the present of opening in transverse position make reducible in strength of RC beams against torsion because of reduced in cross sectional transverse area. The reduced in strength relay on position of plastic hinge in presence of openings.

The first beam, B1 represents solid web without opening (control beam), the maximum ultimate torque is (42.5 kN.m), with twist angle in radian (0.0177), beam B2 gives (37.5 kN.m) for ultimate torque with (0.02481) angle that corresponding the cracks width. When the principle maximum stresses reach the tensile strength of concrete, the cracks start to developed in concrete, so that in case of plain concrete fail but in reinforced concrete the closed stirrups play important parameter to prevent it. The presence of web opening reduces the beams torque capacity and increases angle of twist for the same value of torsion because opening makes inflection in the behavior of T sections because of reduction in polar moment of inertia due to decrease in geometry then the torsional rigidity becomes less.

Table (8) listed the comparisons between all tested beams with control as maximum torque at ultimate stage and twisted angle ratio.

9.2 Effect of opening location

Location of web perforation effects on the behavior, strength and twisted angle of RC T section. In case of central circular web opening beam B2, ultimate torque is (37.5 kN.m) with twisted angle (0.02481 rad.), same diameter but different position beam B4, ultimate torque is (30 kN.m) with twisted angle (0.0261 rad.), that means the eccentricity of web perforation affects the capacity or cracked torque and angle of twist because the eccentricity makes the T section weak against torque, and these eccentricity make the position of plastic hinge different from central because of the presence of web opening. The percent reduction in torque crack capacity for B4 if compared with B2 is (20%) because the eccentricity shear stresses distribution is unequal for all opening sides and make extra loading torque on the opening so that it becomes weak and cracked.

Beam B3, located at the center of the web if compared with B5 same opening size but B5 shafted from center. Beam B3 has ultimate torque (32.5 kN.m) and (0.04136 rad.) twisted crack angle but B5 ultimated at (30 kN.m) that less than B3 with angle of rotation (0.00965 rad.) which is smaller than B3. This is because when web perforation is shafted from center, the shear stress distribution and crack will be different and become non-uniform so that the weak point becomes near the opening and cracking starts to developed at low torque.

Table (8).Results of Torque and twist angle for tested beams

Beam mark	Maximum torque at ultimate stage (kN.m)	Maximum angle of twist at ultimate stage (rad.)	% (Crack torque) /(Ultimate torque)
B1	42.5	0.0177	76.47
B2	37.5	0.02481	66.67
B3	32.5	0.04136	69.23
B4	30.0	0.02619	66.67
B5	30.0	0.00965	66.67
B6	27.5	0.03929	72.72
B7	25.0	0.0193	60.00
B8	27.5	0.02836	63.63
B9	27.5	0.0455	54.54
B10	30.0	0.012153	58.33

9.3 *Effect of opening size*

The opening web sizes affect the behavior and strength of RC T section against torsion at ultimate stage. Beam B2 with 100 mm in diameter has ultimate torque crack (37.5 kN.m) and in case of B7 has 150 mm central web opening has(25 kN.m). so, when the opening size becomes large, the torque needs to produce ultimate cracks which become less because of losing in strength capacity due to reduction in web area.

Angle of twist to produce ultimate cracks in case of large beam opening becomes less, for B7 the twisted angle is (0.0193 rad.), but in beam B2 is (0.02481 rad.), this is due to reduction in polar moment of inertia of web area and reducible in torque resistance. In case of square opening at the center of beam B3, the equivalent square opening diameter is greater than B2, so the torque ultimate (32.5kN.m) is less than .

10. Torsion-Angle Of Twist At Ultimate Stage

Ultimate stage ranges from first crack torque up to ultimate capacity of RC T beams. This range means that all tested beams will behaved as nonlinear material and geometry if considered warping in the flange so that the geometry section not remain same before and after applied torque. Because of plastic hinge formulation due to extra applied torque, all tested beams become weak and starting to fail under the processing of applied torque. Figures (2) to (21), show the behaviors of all tested RC T beams and described the relationships between torque at ultimate stage with twisted angle and twisted angle with distance of applied torques.

The Figures indicated that when the first crack occurs, there was reduced in strength capacity and the cracks begin propagations from the position of plastic hinge that formulated from first crack. Equation for each curve was inserted as fitted to estimate the mathematical relationship between torque – twisted angle and between twisted angles – distance, the best fitting curve is defined by third degree polynomial and second polynomial for twisted angle – distance.

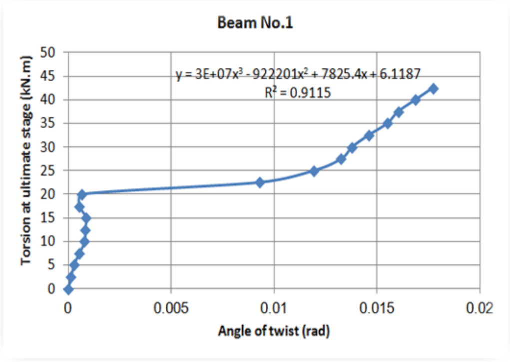

Figure 2. Torque – Angle of twist, B1.

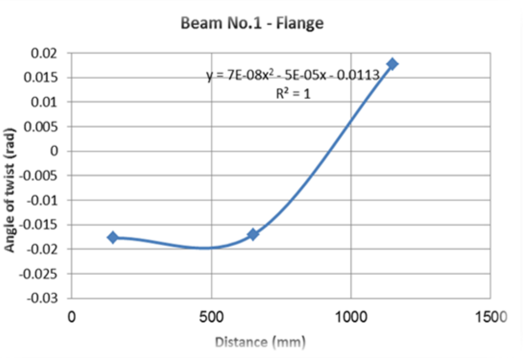

Figure 3. Angle of twist – Distance, B1.

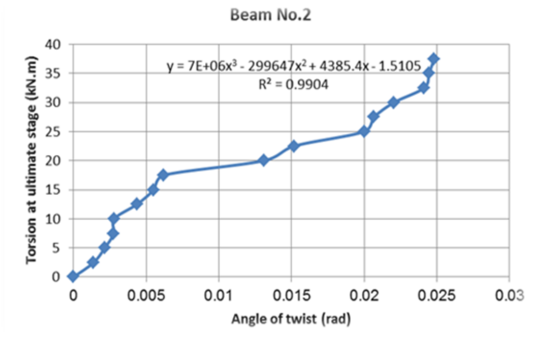

Figure 4. Torque – Angle of twist, B2.

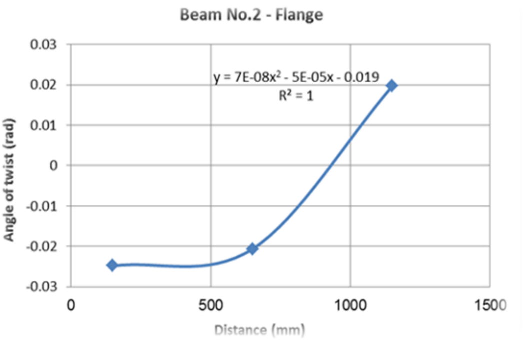

Figure 5. Angle of twist – Distance, B2.

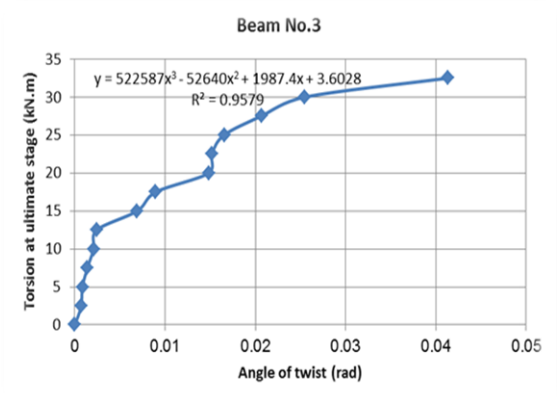

Figure 6. Torque – Angle of twist, B3.

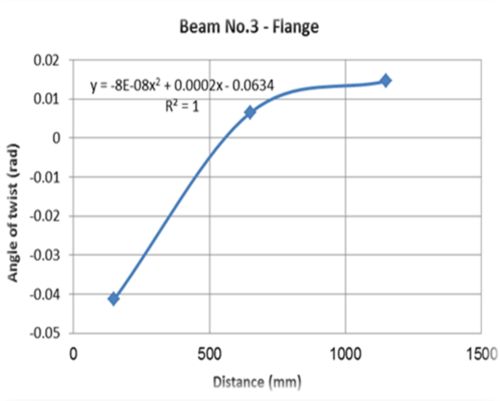

Figure 7. Angle of twist – Distance, B3.

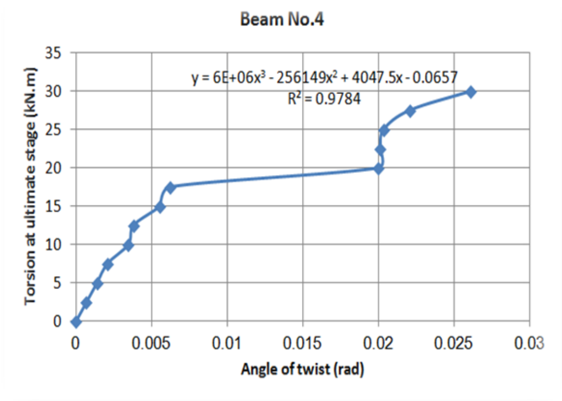

Figure 8. Torque – Angle of twist, B4.

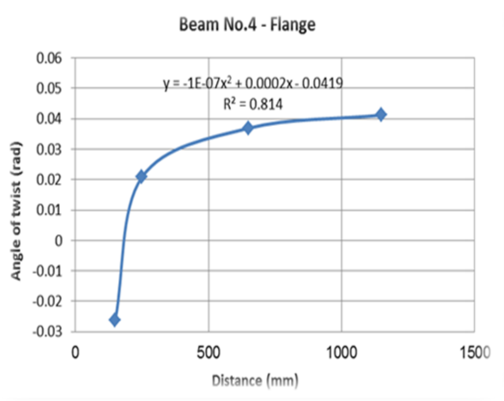

Figure 9. Angle of twist – Distance, B4.

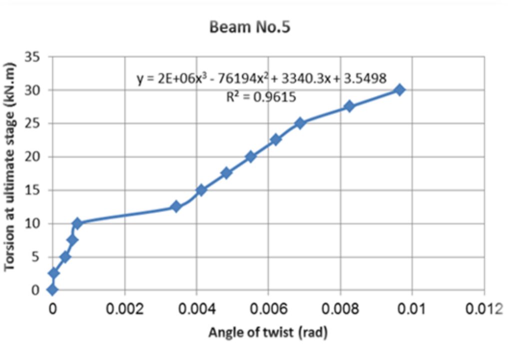

Figure 10. Torque – Angle of twist, B5.

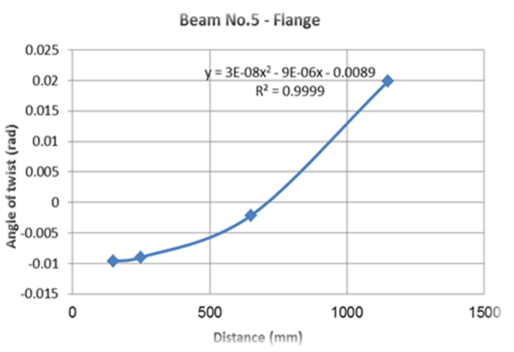

Figure 11. Angle of twist – Distance, B5.

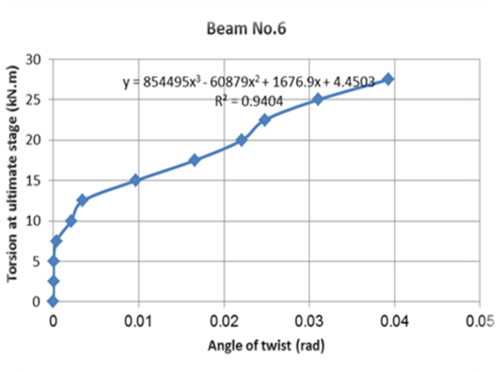

Figure 12. Torque – Angle of twist, B6.

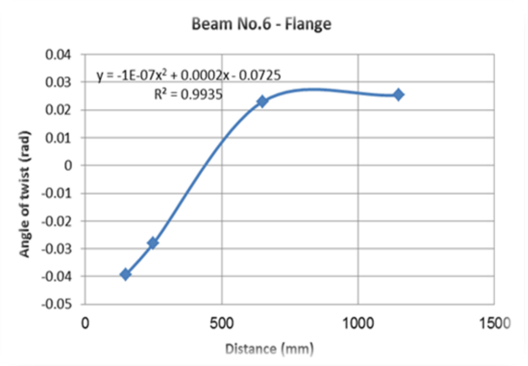

Figure 13. Angle of twist – Distance, B6.

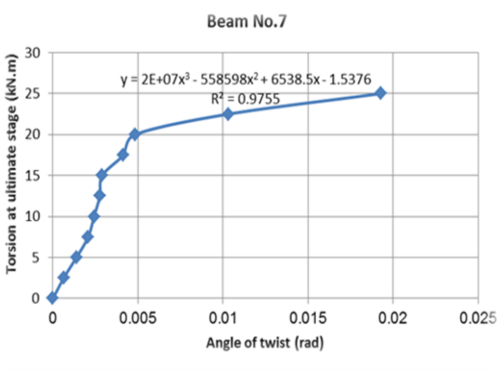

Figure 14. Torque – Angle of twist, B7.

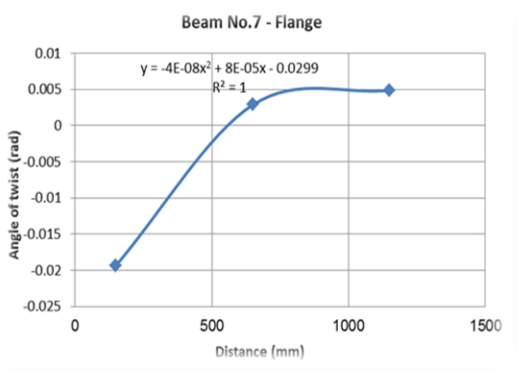

Figure 15. Angle of twist – Distance, B7.

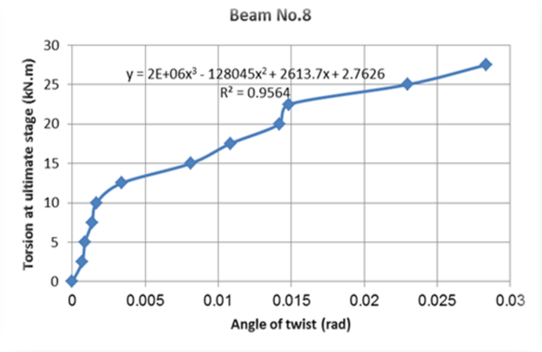

Figure 16. Torque – Angle of twist, B8.

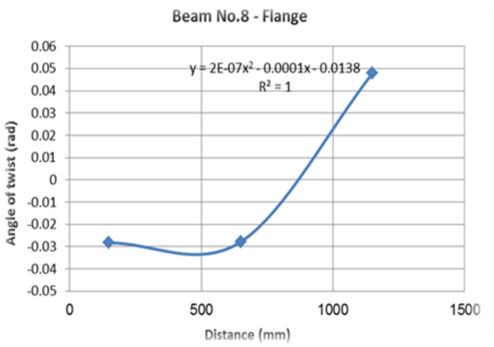

Figure 17. Angle of twist – Distance, B8.

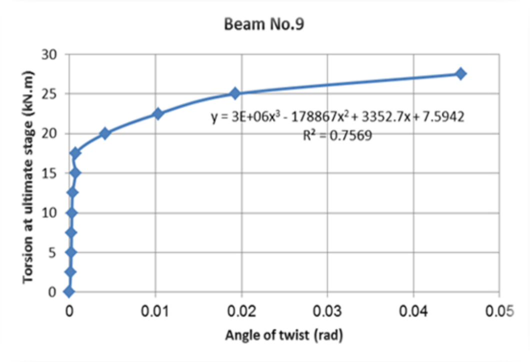

Figure 18. Torque – Angle of twist, B9.

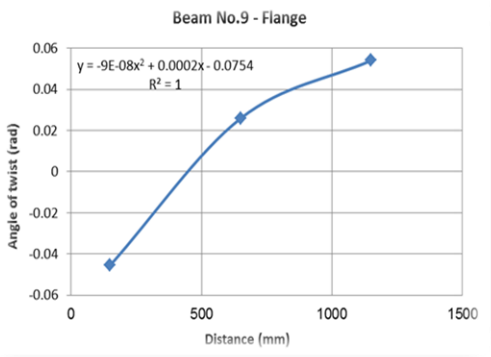

Figure 19. Angle of twist – Distance, B9.

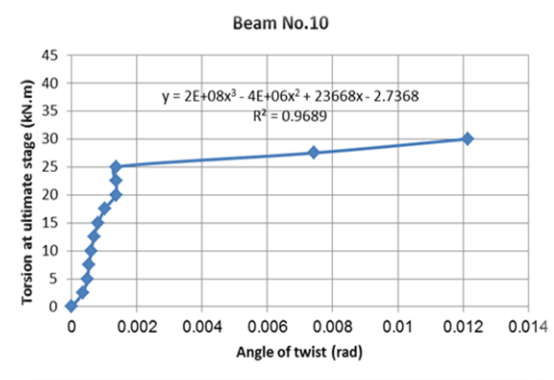

Figure 20. Torque – Angle of twist, B10.

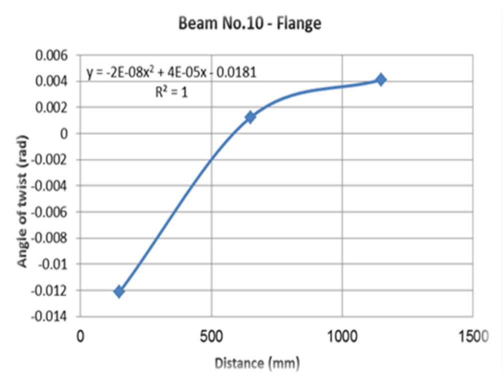

Figure 21. Angle of twist – Distance, B10.

11. Cracks Photo

Plates (4) to (13), show the cracks propagation for all tested RC T – section beams. All cracks starting from the bottom of the web with spiral form toward the flange. The shape of cracks similar that rounded and connected together to form spiral cracks in the direction of opposite applied torque. The cracks intensity around the web perforation because of the opening and round it is the weak regin.

Plate 4. Specimen beam B1 – after test.

Plate 5. Specimen beam B2 – after test.

Plate 6. Specimen beam B3 – after test.

Plate 7. Specimen beam B4 – after test.

Plate 8. Specimen beam B5 – after test.

Plate 9. Specimen beam B6 – after test.

Plate 10. Specimen beam B7 – after test.

Plate 11. Specimen beam B8 – after test.

Plate 12. Specimen beam B9 – after test.

Plate 13. Specimen beam B10 – after test.

12. Conclusions

According to the results from experimental tests, the following conclusions were drawn:

1. The ultimate torques decrease when the opening increased.
2. Cracks density increased as the opening increased and become non-uniform.
3. Opening eccentricity makes no uniformity of shear stress distribution through web and leads to reduction in torque capacity.

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