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Behavior of High Strength Self Compacted Hollow Section Reinforced Concrete Beams under Pure Torsion

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ABSTRACT

In this work, an experimental study has been conducted to investigate the behavior of high strength self-compacted concrete hollow beams under pure torsion.

In this work, the beams were implemented and tested under pure torsion load. A total of six beams were tested. All beams were of the same cross section, the same length, the same concrete mixture and quality control. All beams were of external dimensions (300x300mm) and the hollow dimensions (180 x180mm) and all the concrete beams have the same number of main reinforcement 4Φ12 at the top and 4Φ12 at the bottom, the main variable is the stirrups spacing to investigate the effect of stirrups amount on improving of hollow reinforced concrete beams resistance against torsional moments.

The six beams were subjected to pure torsion by using fabricated test machine to enable the application of the mentioned pure torsion load.

Experimental results showed that, many structural properties of the beams are improved, by decreasing the stirrups spacing. Highest improvement achieved for ultimate torsional moment (T_u) followed by cracking torsional moment (T_{cr}) and then by angle of twist (Ø) while the improvement of beam's concrete strain (ε) came at last.

The percentage of improvements of the mechanical properties of the beams due to decrease of the stirrups spacing according to the reference beam is:

- For T_u ranges between (25.7-254.3) %.
- For T_{cr} ranges between (25-200) %.
- For Ø ranges between (23.3-76.0) %.
- For ε (29.0-50.2) %.

The considerable increase in Ø and ε before failure makes the increase of stirrups preferable for safe life and attaining attention.

Keywords:_Self-compacted concrete, High-Strength Concrete, Cracking and Ultimate torsional moment, Hollow Concrete-Beam, Angle of twist, Strain of Concrete.

دراسة سلوك العتبات الخرسانية المسلحة المجوفة ذاتية الرص عالية المقاومة المعرضة لعزوم اللي الخالصة

الخلاصة

يتميز فشل الأجزاء الأنشائية تحت تأثير عزوم اللي بطبيعته الحدة والفجائية, وهذا النوع من الفشل يجب الحذر منه وذلك لتأثيره السئ على سلوك المنشأ. هذا البحث هو دراسة عملية للتحري عن سلوك العتبات الخرسانية المسلحة عالية المقاومة ذاتية الرص مجوفة المقطع تحت تأثير احمال اللي الخالصة. ست عتبات خرسانية تم فحصها بالكامل تحت تأثير هذه الاحمال. كل العتبات لها نفس ابعاد المقطع, الطول, تركيب الخلطة الخرسانية والسيطرة النوعية. جميع العتبات الخرسانية لها نفس ابعاد المقطع الخارجي (300×300 ملم) والتجويف الداخلي بأبعاد (180×180 ملم) كذلك جميع العتبات لها نفس التسليح الطولي بالقمة والقعر (ϕ412). المتغيرات الرئيسية في هذه الدراسة هي تقليل المسافات بين اطواق حديد التسليح لزيادة كميتها ولمعرفة تأثير هذه الزيادة على تحسين خواص العتبات

الخرسانية المجوفة المعرضة لعزوم اللي الخالصة. تم فحص العتبات الخرسانية السته وذلك عن طريق تسليط احمال لي خالصة عن طريق تحوير جهاز الفحص لتمكين الجهاز من تسليط هذه الاحمال. نتائج الفحص اظهرت تحسين العديد من الخصائص الأنشائية والتي تم الحصول عليها عن طريق تقليل تباعد اطواق حديد التسليح , ان اعلى نسبة تحسين تم الحصول عليها كان في (عزوم الالتواء النهائية يليه تحسن في (عزم تشقق الالتواء يليه تحسين في مقدار زاوية الالتواء (Ø) واقل تحسين كان في نسبة انفعال خرسانة العتبات.

في هذه الدراسة تم اعتماد العتبة الخرسانية الاولى كمرجع للمقارنة في تحسين الخواص وكانت نسبة التحسين من العتبة الثانية الى العتبة السادسة كالاتي: مقاومة الالتواء النهائية كانت نسبة التحسين تتراوح بين (25.7-254.3)%،عزم تشقق الالتواء نسبة التحسين تتراوح بين (25-200)%.زاوية الالتواء(Ø) تتراوح نسبة التحسين بين (23.3-76.0)%. انفعال خرسانة العتبات (ε) بين (29-50.2)%. ان الزيادة المعقولة لزاوية الالتواء ولانفعال الخرسانة قبل الفشل يجعل زيادة الاطواق مفضلة ,لاهميتها في اعطاء انذار قبل الفشل.

الكلمات الدالة: خرسانة ذاتية الرص, خرسانة عالية المقاومة, عزوم التشقق والالتواء النهائية, العتبات الخرسانية المجوفة, زاوية الالتواء, انفعال الخرسانة.

Introduction

In actual structure, torsion forces are usually combined with moments, shear, and axial forces, but in some structures, such as bridges, the torsion can become very important for the design. Furthermore, the design procedure based on force interactions need to know the behavior under pure torsion (1). Because HSC and hollow beams are frequently being used in bridges, a research program on the behavior of HSC hollow beams under torsion is very important (1). During recent years, it has become necessary to take account of torsion effects in member design because of the increasing use of structural members for which torsion is a central feature of behavior, examples including an end beam in a floor panel, a spandrel beam receiving load from one side [1].

The Advantages of Hollow Cross Section [1]

1. Saving in weight, which affects especially the cost of transport, handling and erection for pre-cast cross sections.
2. Substantial reduction of material quantities, the materials required are usually much less than those needed for other conventional systems and they are little more than those required for continuously curved shells, with the advantage of utilizing relatively simple formwork (1).

In this study high strength self-compacting concrete was used as a construction material because this type of concrete enables faster construction and decreased labor requirements, as well as a number of health and safety benefits, such as reduced noise, and avoiding white finger syndrome due to holding vibrators for long periods.

Aim of the Study

There are very limited researches studying the behavior of hollow section reinforced concrete beams under pure torsion. Therefore, the aim of this study is to find the effect of different spaces between the stirrups on the pure torsional resistance for high strength self-compacted reinforced concrete beams of hollow section.

Experimental Work

1. Dimensions and Internal Reinforcement

All beams were of external dimensions (300x300mm) and hollow dimensions of (180x180mm); see Figure (1).

All the concrete beams have the same number of main reinforcement 4Φ12 mm at top and 4Φ12 mm at the bottom; the variable is the spacing between the stirrups. Each beam was less than the one before by 25 mm as shown; see Figure (2).

2. Materials

2.1 Cement

Ordinary Portland cement type (Cresta) complies with the Iraqi standards was used (IQS No.5/1984)[2].

2.2 Fine aggregate

Natural sand of (Tuz-khormato) region was used for this study passed from sieve (4.75 mm). Physical and chemical properties and the grading properties with the limits of the Iraqi specification No.45/1984 [3].

2.3 Coarse aggregate

The coarse aggregate was supplied from (Tikrit) area. The maximum size was 14mm which is suitable for self-compacting concrete. The physical and chemical properties, and the grading properties with the limits of the Iraqi specification No.45/1984 (3).

2.4 Water

Through this work tap water was used for making and curing all concrete specimens.

2.5 Superplasticizer

The product Structuro 502 was used in this work. It was used due to its benefits in producing SCC.

2.6 Silica Fume

We used type (MEYCO® MS610). It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. Because of its extreme fineness and high silica content, silica fume is a very effective pozzolanic material. Standard specifications for silica fume used in cementitious mixtures are ASTM C1240-03[4].

2.7 Steel Bars

The diameter of the steel was measured by the method described in (ASTM A 615)[5]. Table1 describes the mechanical properties of the steel bars.

4. Producing SCC

4.1 Trail mix for reference concrete

We adopted EFNARC [6] design method in producing self-compacting concrete. The method used for producing the self-compacting concrete was the changing in the superplastisizer's dose while keeping the w/p ratio fixed. Details of trial mixes are shown in Table 2. The slump flow and T_{50} test methods are used to evaluate the fresh SCC properties, the results of the trial mixes to examine the slump flow test and the time required to reach (50 cm) diameter are shown in Table 3 below. Three cubes were casting for each trial mix, compressive strength of the cube were done after 7 days and select the trial mix that identical with SCC properties and gives a higher compressive strength, after we choose The higher strength mix (V, L) tests were done for this mix to see if its match with SCC properties. In this study we selected (Trail 7) because this mix gives (36.33 Mpa) in (7 days) and identical with SCC tests. SCC test results of (Trial 7) shown in Table (4) below.

5-Casting and Curing

Plywood molds were used in this work to cast the hollow beam specimen, the mold is formed from two parts; external parts and internal part to make the hollow shape in concrete section see Fig.3. A steel tape were used for this work to surrounding and tied the specimens molds, the steel tape ensures the stability and the alignment of the plywood mold and keeps the section dimensions constant along the length of the beam see Fig.4.The construction process were done vertically see Fig.5.

The reinforcing steel was tied together firmly as shown in Fig.6). Steel cages installation was done vertically as shown in Fig.7. Three concrete cylinder of D=150 mm, h=300mm were cast for each beam and then tested to determine the value of concrete compressive strength at the time of testing the beams. All the specimens were curing by immersing into a steel pool manufactured by the researcher.

6- Test Preparations

6.1 Supports and Loading Condition

The Laboratory in which the beams have been tested is not supplied with a machine that can directly impose a pure torsional loads and the available testing machine is not designed to apply torsional loads. Thus, accessories were fabricated to enable the available 3000 kN machine for the application of the pure torsion load to the beams. See Figs. 8 and 9. Torsion was applied by means of torsion arm fixed to each end of the beam. The torsion arm was in wedge shape made of very heavy steel plates; see Fig. 10.The net torsion lever arm was 0.65m. Two rectangular steel plates (45mm in thickness) sat tight on both sides of the beams by four screws to fixation the arm of the test. 2mm thick wood sheets were used as soft contact between the beam and the steel plates and between the beams and screws to prevent local stress concentration; see Fig.10.

7- Dial Gages

Two dial gages at two portions of the beam were installed. Each one installed at (30mm) from the beginning of the beam. See Fig.11 shows the dial gages and Table 5 summarizes the locations of the dial gages.

8- Hardened Concrete Tests

8.1 Compressive strength

Compressive strength were tested according to (ACI 318M-11)[7] code. Three concrete cylinder D=150mm, h=300mm were casted and tested for each beam to determine the average compressive strength in 28 days measured from the moment I add the mixing water to concrete components. Table 6 shows the compressive strength for all tested beams.

Results and Discussion

In the present work, beams are tested under pure torsional moments gained by subjecting load at arm with long of 650mm from the center of the two ends of the tested beam. The torsion moment is applying using a hydraulic testing machine applied load with 5 kN increments on the tested beam. The test continues up to failure, and this failure mode leads to excessive twisting angle and cracking as shown in

Fig.12.The torsion moment, angel of twist and concrete strain determined from tests are listed in Table 7. At torque, Torsional cracks occur, before that no cracks are appeared, is referred as cracking torsional moment (T_{cr}), while the torque that leads to failure is called ultimate torsional moment (T_u).Two dial gages are positioned at the points of maximum torsional actions to measure the angles of twist. Vertical and horizontal demec points forms are positioned at the top and in one side of the tested beam to measure the average of concrete strain of the beam due to stresses and propagation of torsional moments.

1. Cracking and Ultimate Torsional Moments

The cracking torsional moment (T_{cr}) is the torque through cracking began to appear and reflects exceeding the applied stress of the tension strength of the section. However, the ultimate torsional moment (T_u) reflects the load carrying capacity of the tested beam, after that drop in machine reading appears with rapidly deformation of beam. Fig.13 shows these values for the tested beams. It is obvious from Fig.13 that, both T_{cr} and $T_u$values are increased with decreasing of stirrups spacing, therefore, the cracking resistance and carrying capacity of beam B6, which has the smallest stirrups spacing , are the highest among all the tested beams. So, increase the stirrups amount means strengthening the beam against torsion to gain improvement in beam behavior. Table 8 and Fig.14 illustrate the effect of increasing the stirrups amount on improvements of T_{cr} and T_u of the tested beams in comparison with beam B1, the beam of the greatest stirrups spacing.

2. Angle of Twist

The angle of twist (Ø) represents the two dimensional deformation in the direction of torsional moment action. The average of two angles of twist in each tested beam is graphed vs. the torsional moment as in Fig.15. The maximum twisting angle of the beam increase according to its ultimate torsional moment value, therefore; the area under the curve becomes greater with stirrups amount increase, and the area under the curve of beam B6 is the greatest among the all. However, comparison among the beams at a specific torsional moment reflects less of twist angle from beam B1 to beam B6 that means increasing the stirrups amount leads to decrease the value of angle of twist of the beam clearly and resulting in increasing the stiffness of the beam against deformation. In the case of the angle of twist, the improvement is decreasing in value which reflects the deformation in the member. Decreasing in angle of twist of any beam will be compared with the angle of twist of the weakest beam in this work which it is beam B1 at applied torsional moment equals11.38 kN.m (11.126 deg.) and results as shown in Table (9). From Table (9), that is clear, the angle of twist can be improved by increasing the amount of stirrups, therefore; the decrease in the angle graduated according to stirrups amount rising to be highest improvement by (76%) for beam B6. Fig.(16) shows Improving of angle of twist for the tested beams.

3. Beam's Concrete Strain

The beam's concrete strain (ε) is a unit less deformation transversely to the beam longitudinal axis and represents the average of the concrete compression diagonals strains on the top and side face of each tested beam. Fig.17, show the average beams strain against torsional moment. By comparison among the tested beams at a specific applied torsional moment, beam's concrete strain decreasing when the stirrups amount increase, by continuing in increase the stirrups amount of the beam; the beam exhibits fewer strains and that explains the reason of the less strain of beam B6. When the tested beam exhibits less strain that means increase in stiffness; and by noticing all the beams, the stiffness is increased from beam B1 to beam B6 and the beam B6 have highest stiffness among them. On the other hand, from beams B1 to beam B6, the strain at failure becomes greater and the area under the curve magnifies, that means increase in ductility and strain energy which is preferable property in structural design to safe life and attaining attention. As in angle of twist, in the case of the concrete beam's strain, the improvement is achieved by decreasing its value. Decreasing in beam's concrete strain of any beam will be compared with the failure beam's concrete strain of the weakest beam in this work which it is beam B1 at applied torsional moment equals 11.38 kN.m corresponds (0.00320 of strain) and their results are shown in Table 10 to demonstrate the effect of stirrups amount on improving the concrete strains against torsional stresses, by counting in decreasing the stirrups spacing, the beam's concrete strain can be decreased therefore, there is a gradual decrease in this property from beam B2 (29.0%) to the beam B6 and Fig.18 shows these results.

4. Achieved Improvements

The main variable of present work is decreasing the stirrups spacing to increase its amounts, and to investigate the effect of stirrups amount on improving of hollow reinforced concrete beams resistance against torsional moments and resultant stresses. From experimental observations of present tested beams, many structural properties are improved, these properties are: cracking torsional moment (T_{cr}), ultimate torsional moment (T_u), angle of twist (Ø) and beam's concrete strain (ε). The improvements of these structural properties were not in the same rate to the corresponding amount of stirrups, as cleared in Table 11 below, Fig.19.The highest improvement achieved with ultimate torsional moment (T_u) followed by cracking torsional moment (T_{cr}) and then by angle of twist (Ø) while the improvement of beam's concrete strain (ε) came at last. In general, it is clear that, increasing the stirrups amount improves the behavior of the beams, however; the improvement of (T_{cr} and T_u) is greater than the improvement of stiffness (resistance of Ø and ε).

Conclusion

Based on the results from the experimental works reported in this study, the following conclusions can be drawn. It is emphasized that these conclusions are limited to the studied variables:

1. Increase the stirrups amount of hollow reinforced concrete beam improves its behavior in resistance torsional stresses and deformations.
2. Highest improvement achieved for ultimate torsional moment (T_u) followed by cracking torsional moment (T_{cr}) and then by angle of twist (Ø) while the improvement of beam's concrete strain (ε) came at last.
3. The percentage of improvements from beam B2 to beam B6 is:

- For T_u ranges between (25.7-254.3) %.
- For T_{cr} ranges between (25-200) %.
- For Ø ranges between (23.3-76.0) %.
- For ε (29.0-50.2) %.

4. By continuing in increasing the stirrups amount in the section, the rate of increasing the carrying capacity (T_u) of the beam will be greater to be 5 times the concrete strain (ε) improvement.
5. Although improvement of beam torsional strength ($T_{cr}$and T_u) is better than the improvement of stiffness (resistance of Ø and ε), but the considerable increase in Ø and ε before failure makes the increase of stirrups preferable to safe life and attaining attention.
6. The relationships between of torsional moments and angles of twist and beam's concrete strains reflect the same response for all the tested beams, but the area under the curve magnifies to improve the strain energy of the beam by increasing its stirrups amount.

Recommendations

Based on the results of present tests and observations, the following recommendations are given for future works:

1. Effect of different walls thickness on behavior of the hollow beams subjected to torsional stresses.
2. Effect combined shear and torsion or combined bending, shear and torsion loads on the hollow reinforced concrete beams.
3. Effect of concrete compressive strength and steel fibers content as well as the external steel or (FRP) plates on hollow beam subjected to torsional stresses.
4. Effect of concrete compressive strength and steel fibers content can be tested in hollow concrete beams subjected to impact and cyclic loading.
5. Characteristics of longitudinal strain in hollow reinforced concrete beams subjected to torsional stresses.

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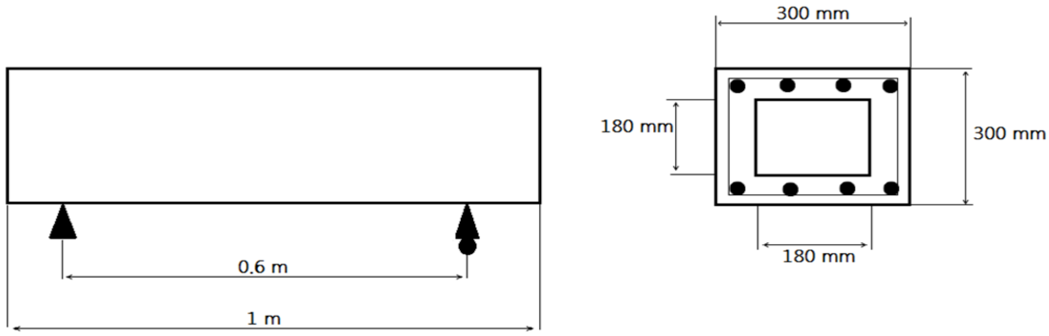


Fig.1 The hollow beam details.

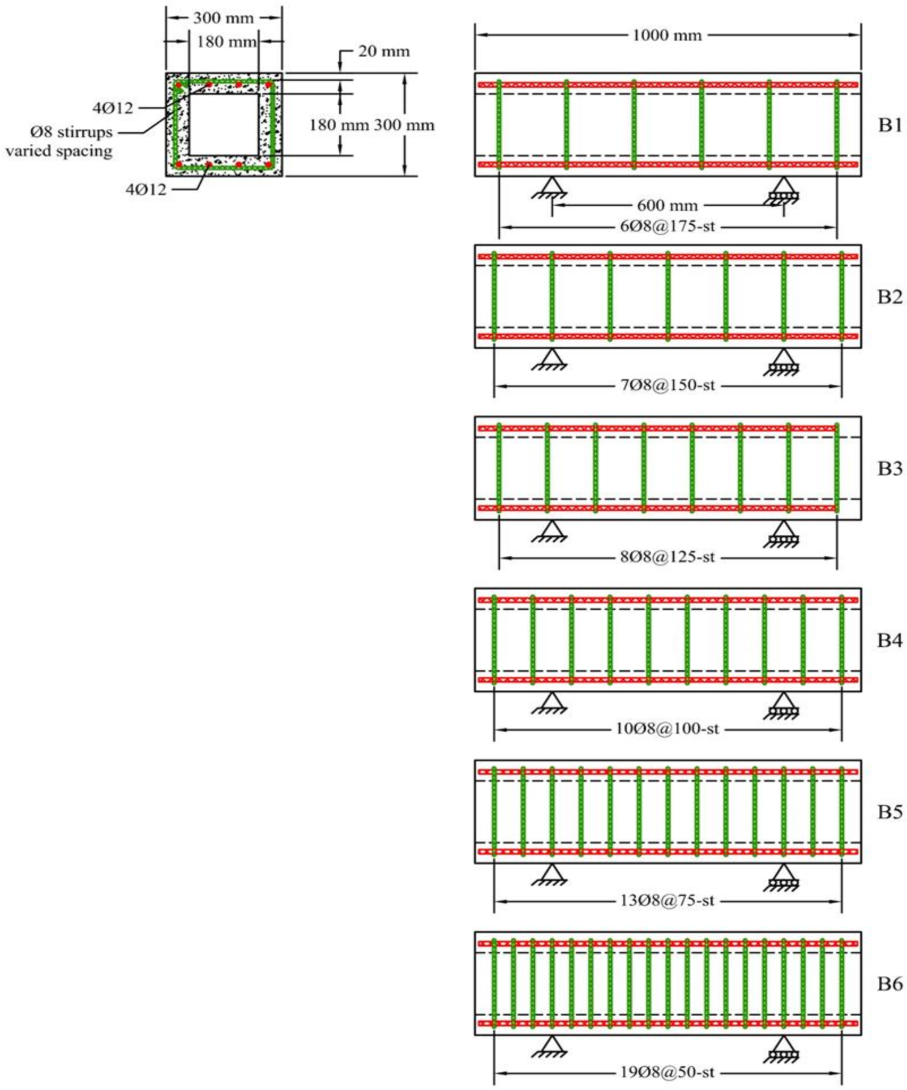


Fig.2 Reinforcement details.

a) External mold **b) Internal mold** **c) The whole mold**

Fig.3 Plywood molds.

Fig.4 The plywood molds and the Steel tape.

Fig.5 The vertical construction.

Fig.6 Steel cages.

Fig.7 Steel cages installation.

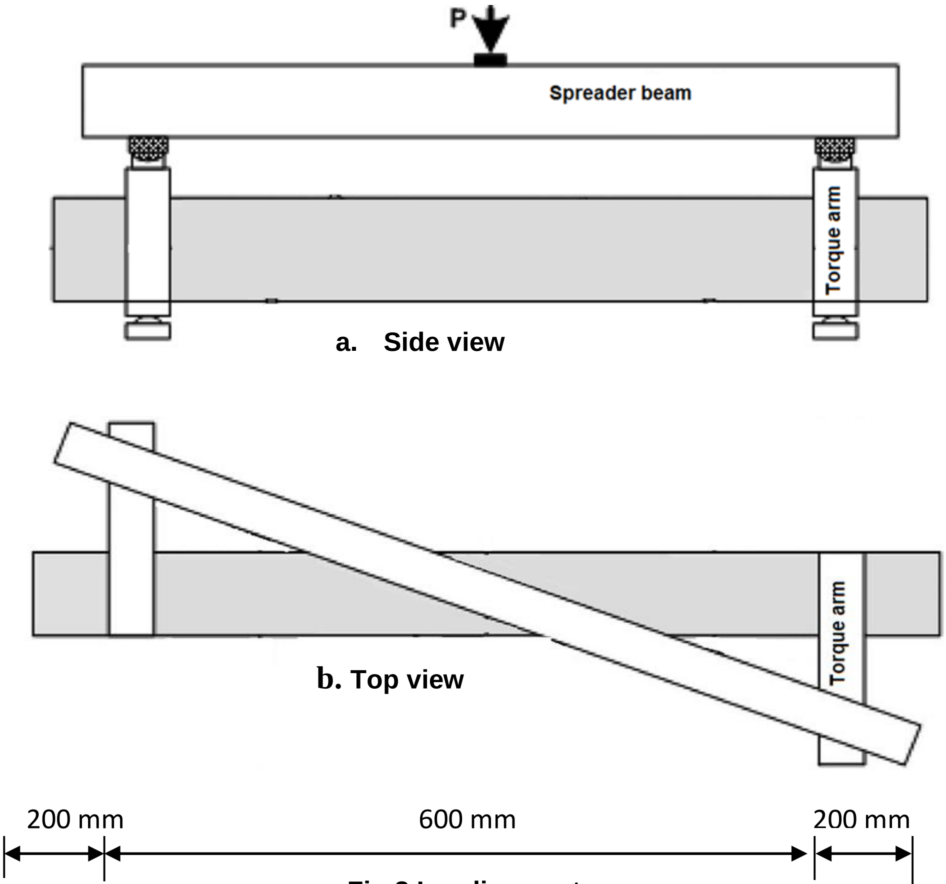


Fig.8 Loading system.

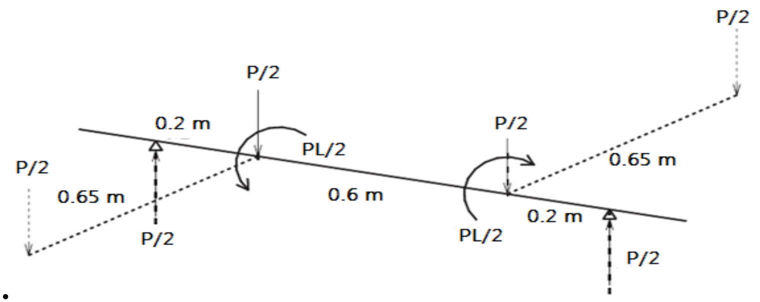
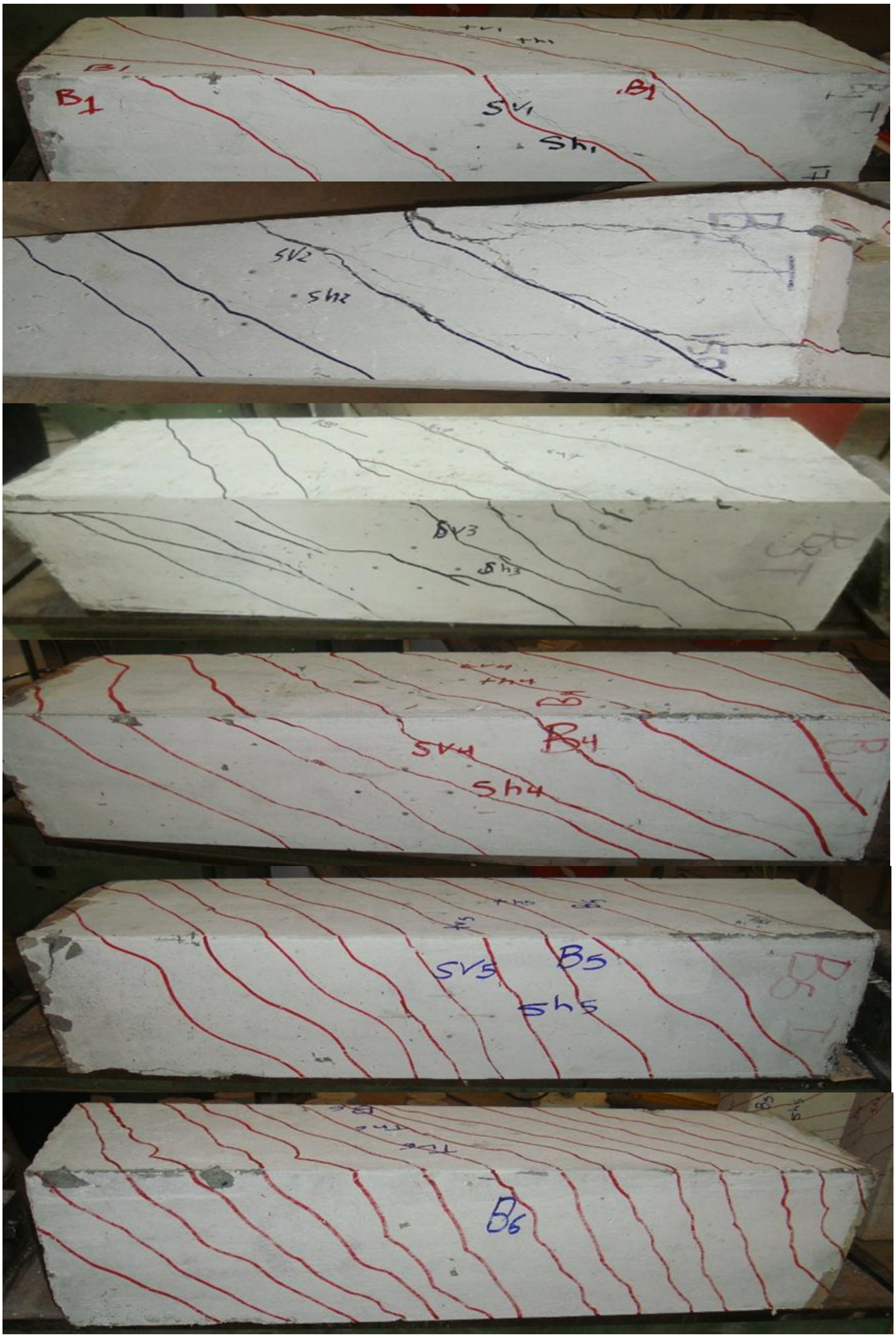


Fig.9 Schematic of the applied loading

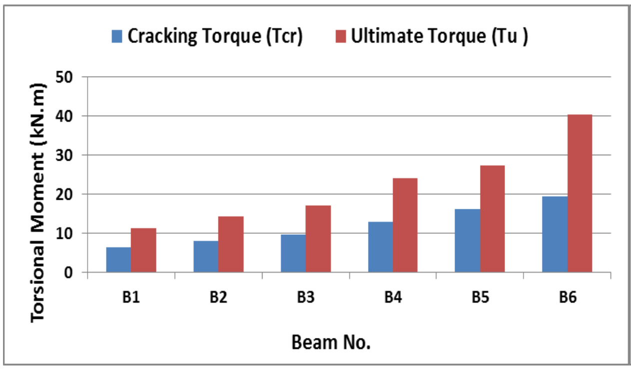
Fig.10 Beam installation for torsion test.

Fig.11 Location of the dial gages.

Fig.12



Failure mode of tested beams.



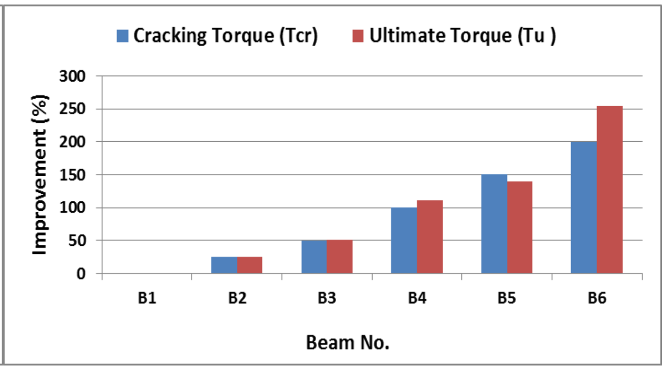


Fig.13 Load carrying capacity of The tested beams.

Fig.14 Improvement of cracking and Carrying capacity of the torque.

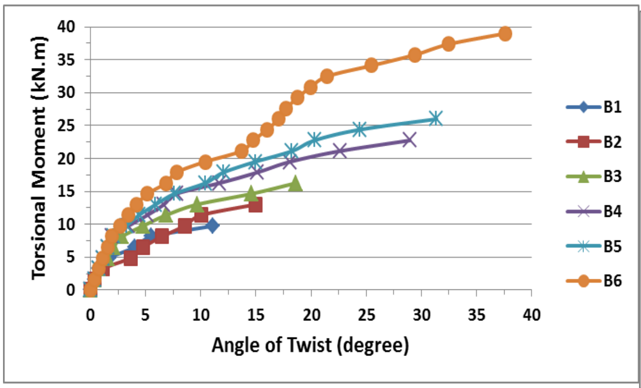
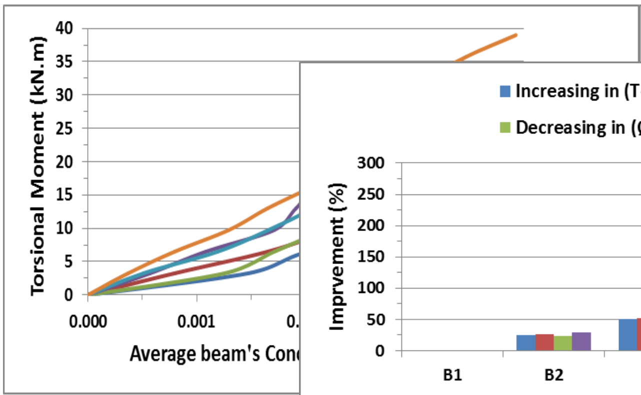
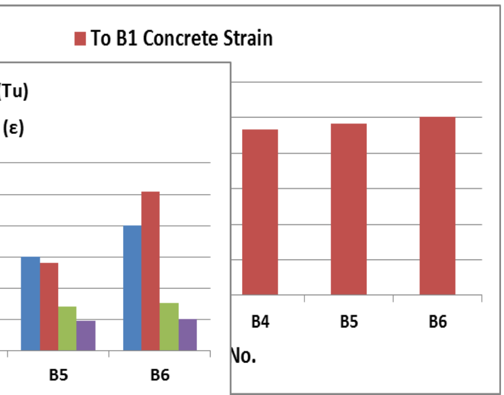


Fig.15 Torsional moment vs. angle beams.

Fig.16 Improving of angle of twist for the tested of twist for all tested beams.





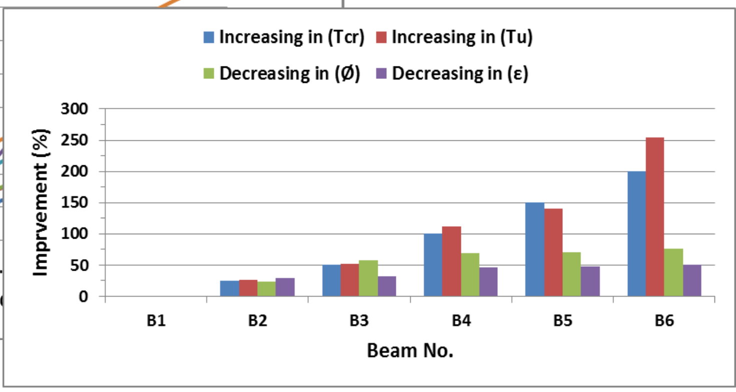


Fig.17 Torsional moment vs. strain

Fig.18 Improving of Beam's Concrete Strain for the tested beams.

For all tested beams.

Fig.19 Influence of stirrups spacing on the Improvement of the beams behaviors.

Table 1 Test results of the steel bars used for reinforcing the beams

Bars diameters (mm)	Yield stress (f_y) (MPa)	Ultimate stress (f_u) (MPa)	Elongation%
12mm	523	685	9.5
8mm	579	648	7.5

Table 2 Details trial mixes of concrete self-compacting reference.

Trail Mix #	Filler %	Str. 502 %	Quantities of Mix Ingredients (Kg/m³)								
			Water	Powder		w/cm ratio	FA	CA	Str. 502	Density Kg/m³
				Filler Content	Cement					
Trail -1	9.2%	0.95%	182.23	44.59	479.55	0.34	787.43	899.92	5	2398.72
Trail -2	9.2%	1.53%	181.74	44.47	478.27	0.34	785.32	897.51	8	2395.31
Trail -3	9.2%	2.3%	181.09	44.31	476.55	0.34	782.49	894.28	12	2390.72
Trail -4	9.2%	2.69%	180.76	44.23	475.68	0.34	781.07	892.66	14	2388.40
Trail -5	9.2%	3.08%	180.43	44.15	474.81	0.34	779.65	891.03	16	2386.07
Trail -6	9.2%	3.57%	180.02	44.05	473.72	0.34	777.86	888.98	18.5	2383.13
Trail -7	9.2%	3.82%	179.83	44.00	473.24	0.34	777.1	888.1	19.8	2382.07

Table 3 Trial mix properties and compressive strength.

Trail Mix #	Self Compactibility Properties		Compressive Strength (N/mm^2)
	Slump flow (mm)	T_{50} (Sec.)	7 Days
Trail -1	765	2.5	19.2
Trail -2	757	2.8	25.3
Trail -3	746	3.1	31.2
Trail -4	733	3.3	33.6
Trail -5	727	3.6	34.2
Trail - 6	715	3.8	35.5
Trail -7	710	4	36.33

Table 4 Tests conducted on (Trial 7).

Test Type	Test Result	Accepted SCC Range
Slump Flow by Abram's Cone	710 mm	650-800 mm
T50cm	4 sec	2-5 sec
L-box	0.96	0.80-1.00
V-funnel	10 sec	6-12 sec

Table 5 Locations of the two dial gages.

Dial Gage #	Location	Distance from End	Direction
1	Under the beam, and attached to the left corner	30mm	vertical
2	Under the beam, and attached to the right corner	30mm	vertical

Table 6 Compressive strength of concrete.

Beam No.	f'_c (MPa)	Age at test
B1	45.48	28 days
B2	45.05	28 days
B3	46.07	28 days
B4	44.54	28 days
B5	45.31	28 days
B6	44.80	28 days

Table 7 Overall results from tests.

Beam No.	Stirrups Spacing (mm) c/c	Cracking Torsional Moment (T_{cr}) (kN.m)	Ultimate Torsional Moment (T_u) (kN.m)	Maximum Angle of Twist (Ø) (degree)	Maximum Concrete Strain (ε)
B1	175	6.50	11.38	11.13	0.00320
B2	150	8.13	14.30	14.93	0.00302
B3	125	9.75	17.23	18.61	0.00316
B4	100	13.00	24.05	28.96	0.00314
B5	75	16.25	27.30	31.38	0.00336
B6	50	19.50	40.30	37.59	0.00393

Table 8 Improvement of cracking and carrying capacity.

Beam No.	Stirrups Spacing (mm) c/c	Cracking Torsional Moment (T_{cr}) (kN.m)	Increasing in(T_{cr}) according to B1 (%)	Ultimate Torsional Moment (T_u) (kN.m)	Increasing in(T_u) according to B1 (%)
B1	175	6.50	-	11.38	-
B2	150	8.13	25	14.30	25.7
B3	125	9.75	50	17.23	51.4
B4	100	13.00	100	24.05	111.4
B5	75	16.25	150	27.30	140
B6	50	19.50	200	40.30	254.3

Table 9 Improvement of angle of twist.

Beam No.	Stirrups Spacing (mm) c/c	Maximum Angle of Twist (Ø) (degree)	Decreasing in (Ø) according to B1 (%)
B1	175	11.13	-
B2	150	14.93	23.3
B3	125	18.61	57.2
B4	100	28.96	69.1
B5	75	31.38	70.9
B6	50	37.59	76.0

Table 10 Improvement of beam's concrete strain.

Beam No.	Stirrups Spacing (mm) c/c	Maximum Concrete Beam Strain (ε) (mm/mm)	Decreasing in (ε) according to B1 (%)
B1	175	0.00320	-
B2	150	0.00302	29.0
B3	125	0.00316	31.6
B4	100	0.00314	46.6
B5	75	0.00336	48.2
B6	50	0.00393	50.2

Table 11 Summary of structural improvements.

Beam No.	Stirrups Spacing (mm) c/c	Increasing in (T_{cr}) according to B1 (%)	Increasing in (T_u) according to B1 (%)	Decreasing in (Ø) according to B1 (%)	Decreasing in (ε) according to B1 (%)
B1	175	-	-	-	-
B2	150	25	25.7	23.3	29.0
B3	125	50	51.4	57.2	31.6
B4	100	100	111.4	69.1	46.6
B5	75	150	140	70.9	48.2
B6	50	200	254.3	76.0	50.2