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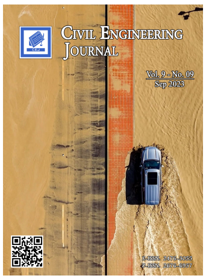

Effect of Openings on the Torsional Behavior of SCC Box Beams Under Monotonic and Repeated Loading

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Abstract

Repeated Torsional loading occurs in many concrete structures, such as offshore structures, freeways, multistory parking garages, and other structures; however, repeated torsional loading is still poorly understood. This study aims to investigate the effect of openings on the ultimate and cracking torques, angle of twist, and modes of failure of self-compacted R.C. box beams under monotonic and repeated loading. Two groups of eight half-scale box beams with different numbers of circular openings in the web with a diameter of about 30% of the hollow box dimension were investigated. The first group (I) included four beams: one was the control box beam without openings, whereas the rest of the beams were hollow with one, two, or three openings in the web tested under monotonic loading. The second group (II) consisted of the same details as the first one tested under repeated loading. The range of the repeated loading was about 30% and 60% of the ultimate load of the monotonic tests. The study showed that the cracking and ultimate torques and the angle of twist of the tested beams were significantly reduced due to openings in the web. Results revealed a more pronounced effect for monotonic loading, with a maximum reduction of 20% and 26.8% in cracking and ultimate torsional strength, respectively, compared to monotonic loading. Moreover, results revealed that repeated loading causes inelastic deformations in proportion to the number of loading cycles.

Keywords: Torsion; Repeated Loading; Box Beams; Web Opening; Self-Compacted Concrete.

1. Introduction

Many structural elements, including curved bridge girders and structural members with curved plans, are subject to a torsional moment. Due to its uncontrolled failure without any prior warning indicators, torsional failure is one of the more severe types of collapse. It is well known that an opening in any concrete member is considered a source of weakness, and the problem with torsional members becomes more complicated [1]. A concrete beam with a side web opening has been considered in structural design. Making an opening, such as round, square, rectangular, or any shape, is advantageous for passing service pipes, cables, or pipes. Web openings alter the stress distribution within the web, which in turn alters the failure mode or collapse behavior. The shape, size, and location of the openings in the web determine the purpose of the openings; in contrast to a solid web, the openings lessen the beam's rigidity and permit more deflection [2].

Hollow sections are primarily known for their economic advantages in long-span bridges. They are used to construct cast-in-place hollow-core slabs and prestressed concrete elements with voids designed to decrease weight and cost. In addition, it can be used for hidden electrical or mechanical wiring [2, 3]. Many structures, such as bridges, ports, multi-story parking garages, and airport facilities, are exposed to repeated loading, including repeated torsional loading. This

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type of loading is critical to structures because it exhibits greater deflection than the other types of loading. With the increasing number of load cycles, the deflections are also increased. Despite that, repeated torsional loading is still poorly studied in detail. Moreover, studying the deformation, modes of failure, cracking, and twist behavior under repeated torsional loading gives a clear vision of concrete beam behavior under this loading, enhances the quality and reliability of the design, and contributes to resolving any challenges not covered by any codes and standards. Constructing hollow box concrete members using normal concrete leads to many problems due to its poor flowability, such as voids, segregation, weak bonds with reinforcing bars, and holes in its surface. Therefore, the S.C.C. is more appropriate for casting these members. Self-consolidating concrete, also known as S.C.C., fills the whole formwork by releasing trapped air without vibrating and navigating around obstructions like reinforcement. This is advantageous for complex prestressing tendon patterns and inaccessible regions close to anchorages [4].

Bhatt & Ebireri (1989) [5] tested twelve hollow and solid beams under bending and torsional loads. Solid beams were built as hollow ones with the presumption that the exterior 50 mm thickness would resist torsion. Their research showed that beams with dominant bending crashed above design loads, whereas solid and hollow beams with pure torsion failed below design loads. Alnuaimi et al. (2008) [6] discussed the results of seven hollow reinforced concrete beams and seven solid reinforced concrete beams under a load combination of bending, torsion, and shear. It was found that the tested beams were affected differently due to the applied loads. A solid beam behaves like it is hollow under high torsion, whereas the core resistance is activated by large bending moments. Therefore, the concrete core contributes to the behavior and strength of the beams under this load combination and cannot be ignored.

Abdul-Hussein et al. (2010) [7] examined the torsion behavior of rectangular beams constructed from reinforced reactive powder concrete. Tests on fifteen concrete beams with solid and hollow cores were performed in this work. The cracking and ultimate torques of concrete were found to be dramatically increased by the use of 1% steel fibers in the concrete mix. It enhanced the cracking torque by 43% and 66% for solid and hollow beams and the ultimate torque by 57% and 53%, respectively. Bernardo & Lopes (2013) [8] investigated the plasticity and twist resistance of hollow beams made of high-strength concrete. Results showed a considerable loss in the test beam's plastic twist capacity with an increase in reinforcement ratio. They also found that an increase in concrete's compressive strength seems to result in a modest decrease in plastic twist capacity. Al-Khafaji et al. (2016) [9] experimentally examined the torsional behavior of reinforced self-compacting concrete beams. Test results revealed that the ultimate torsional moment is higher by 10% than the cracking torsional moment in the beam with steel fiber content equal to 0.8% when using high-strength S.C.C. Cracking and ultimate torsional moment increased by up to 125%. For normal-strength S.C.C., the cracking torsional moment of hollow beams is higher than that of solid normal-strength S.C.C. beams.

El-HakimKhalil et al. (2015) [10] examined how reinforced concrete box beams behaved under pure torsion. Tests were conducted on ten reinforced box beams, both with and without web openings. The first group of five beams was cast without a transverse opening, while the second group of five beams was cast with a transverse opening. The study focused on the transverse opening dimensions and prestressing direction. The researcher concluded that strengthening raises longitudinal bar strain by ratios ranging from 60–80% and increases torsional capacity by 58%. Jabbar et al. (2016) [11] investigated the torsional effect on reinforced concrete hollow beams with web openings and compared it with a hollow beam without openings by utilizing high-strength concrete and ultra-high-performance concrete. The opening's center-to-center measurement was 500 mm for all models. The findings showed that increasing the transverse opening's size significantly reduced its torsional capability. Ma et al. (2018) [12] studied the prediction of the maximum torque of the CFRP-bonded reinforced concrete box beam. Four reinforced concrete beams with box cross-sections were used in this research program and tested under pure torsion. The beam's best strengthening efficiency was the one that had been enhanced with two-ply U-jackets and longitudinal strips, and the experiment confirmed that the cracking angle mostly waved at 45° to the longitudinal axis of reinforced concrete specimens. Also, they noticed an increase in stiffness and cracking torsional moment in the tested beams.

Ajeel et al. (2018) [13] conducted an experimental study on the behavior of R.C. beams with air voids subjected to combined bending and torsional moments. Five specimens were cast and tested in this study; two were solid, the other two contained a number of plastic balls, and one had a single plastic pipe. The experimental results showed that the ultimate strength of the voided beams decreased by about 13–23% of the solid one; the cracking load of the concrete voided beams was not affected by the combined loading. Torsional stiffness was less than flexural stiffness; therefore, the angle of twist is more visible than deflection. The plastic pipes made the beam more deformable than the beams with plastic balls under a combined moment. Oukaili et al. (2018) [14] studied the behavior of open web-expanded steel-concrete composite beams under combined bending and torsion. The researchers used two strengthening techniques: using steel stiffeners in the web sections and external prestressing after providing steel stiffeners to the web. Six beams were tested and divided into two groups; each group contains three beams according to the type of strengthening. The researchers concluded that using the steel stiffeners increased load-carrying capacity by 16.36% and 33.33% for castellated and cellular specimens, respectively, and increased torsional stiffness by about 27.58% for castellated specimens.

Zhu et al. (2019) [15] executed an experimental investigation on a double-deck prestressed concrete box girder to analyze the structural behavior and mode of failure of the box girder under axial compression, transverse bending, and torsion. They concluded that stiffeners and the top and bottom of the specimen should be thicker to increase its torsional strength and reduce cracking. Ultimately, the box girder experienced lateral bending damage, substantially distorting the support's cross-section. There were observable nonlinear strain changes following the stress redistribution phenomena that led to the box girder's cracking. Hussain 2019 [16] examined the torsional response of variable-section fiber-reinforced self-compacting concrete beams. The results of the experiments demonstrated that adding fibers makes S.C.C. less workable. This reduction enhanced the T500 duration for slump flow and J-ring while decreasing the slump flow diameter and blockage ratio. The reference mix's compressive strength, splitting tensile strength, elastic modulus, and flexural strength were all increased by the addition of steel fiber to the concrete. The torsional strength has been significantly improved by adding steel fibers.

Obaidat et al. (2020) [17] conducted an experimental and finite element model on the torsional behavior of R.C. beams strengthened by NSM and CFRP strips. Seven RC beams were cast and tested under pure torsion. The researcher found that all strengthening schemes improved torsional capacity and delayed the cracking of the specimens. The strengthening by using NSM-CFRP strips with a 45-degree inclination improved torsional strength more than vertical strengthening strips. Oukaili et al. (2019) [18] studied the effect of repeated loading on partially prestressed concrete beams. Six full-scale R.C. beams were cast. The range of repeated loads was between “0.4 to 0.6” of the ultimate load from the static test. The researcher concluded that the ultimate load of the beams tested under repeated loading was the same as the ultimate load of the beams tested under monotonic loading. The deflection, crack width, and crack spacing were increased in cycle 5 of the repeated test; there was no slipping in the bonds between concrete and steel for all the specimens; and finally, the partially prestressed beams were less affected by the repeated loading.

Shalaby et al. (2020) [19] investigated the torsional behavior of repaired R.C. beams with openings. The specimens were repaired using the steel plate technique. The parameters investigated were the steel plate configuration, its thickness, and the opening width. The ultimate torque increased by 38% and 11% when using full steel plates and steel strips, respectively. Moreover, the ultimate torque decreased by 6% when the opening width reached 30% of the tested beam span and decreased to 44% when the width of the opening reached 50% of the tested beam span. Abdulrahman et al. (2020) [20] conducted an experimental study on five T-beams with circular openings under pure torsional load. One beam was solid as a reference beam, and the others contained circular openings with different dimensions and locations. The researchers found that the increase in opening diameter caused a decrease in cracking and ultimate torque capacity, as well as an increase in the angle of twist compared to the reference beam. The torque capacity was reduced by 23% and 30% for circular openings with a dimension of 100 mm when the opening is at the center and the clear span of the beams, respectively.

Lin (2020) [21] conducted an experimental study on composite steel-concrete beams under combined negative bending and torsion. Two beams were used in this study, and the variable was the difference in the amounts of applied negative bending and torsion on the tested specimens. The researcher found that the presence of torsion will decrease yield and ultimate bending moment capacities; normal strains are greater than shear strains for the stud shear connectors; and the slip near the 1/4 span was larger than at both ends of the tested specimens. Hassan et al. (2020) [22] studied the torsional behavior of hollow R.C. beams reinforced with different types of fibers. They found that the torque capacity for hollow beams decreased by about 3.1% when compared with solid RC beams. Also, using ST.F. (steel fiber) and SY.F. (synthetic fiber) improved the torsional behavior of the tested beams, and the torque capacity raised 5.5% when they used ST.F. The researchers suggested using SY.F with normal-strength concrete due to the fiber's effect on torsional performance.

Moatt (2020) [23] examined self-compacting reinforced concrete box beams to explore torsional strength enhancement when near-opening strengthening techniques (NOSTs) were used to strengthen web openings. Thirteen R.C. box beams were cast and tested experimentally under a pure torsion test. The following variables were considered in this study: the existence or absence of the web opening, its location, and the presence or absence of strengthening. The researcher concluded that the web opening position in the first quarter and the middle of the specimens led to a reduction by about 34.7% and 45.3%, respectively. Compared with the reference beam, it was increased by about 20% to 57.14% for beams strengthened by NOST using one-face localized steel plates. Bernardo et al. (2020) [24] studied experimentally the behavior of high-strength concrete hollow beams under pure torsion to investigate the effect of longitudinal prestress. Analysis was done on the initial, post-cracking, and final behavior. They evaluate the rule of the longitudinal prestress to delay cracking and improve torsion resistance. They concluded that longitudinal prestressing levels alter failure mode, and concrete cracking significantly reduces prestressing force. Mures et al. (2021) [25] studied experimentally how hollow cross-section reinforced concrete beams strengthened with steel fibers (end-hooked and corrugated) would respond under pure torsion. Ten steel fiber-reinforced concrete specimens with low longitudinal reinforcement ratios served as the subject of an experimental investigation to examine the torsional behavior under pure torsion. They showed that adding steel fibers will increase T_{cr} and T_u, corrugated steel fibers have a lower torsional resistance than end-hooked steel fibers, and adding steel fibers to concrete mixtures will increase torsional ductility.

In the previous survey, considerable research work was performed on the performance of R.C. members with web openings in the last decades, and most of these studies were related to static loading [26]. However, no research work or experimental investigation was reported in the literature on the behavior of reinforced concrete members under quasi-static torsion, such as repeated torsion, especially for reinforced concrete hollow beams with or without openings in the web. This study aims to address this gap in the research field and to highlight the performance of R.C. box beams under monotonic and repeated torsion, with emphasis on the effect of web opening on ultimate and cracking torques, torque-angle of twist behavior, and failure modes. To achieve the goals of this study, prototype RC hollow core beams with openings in the webcast were tested experimentally. The performance of these beams was evaluated by considering the key parameters for their response and comparing their static and repeated torsional behavior. Results were presented and evaluated for conclusions and recommendations.

2. Experimental Program

Eight self-compacting reinforced concrete box beams with web openings were cast and tested under monotonic and repeated loading up to failure. The tested beams were divided into two groups; the first group (I) included four beams (the control beam was a hollow beam without openings). The second beam was hollow with one opening, the third hollow beam had two openings, and the fourth hollow beam had three openings tested under monotonic loading. The second group (II) consists of the same details as the first one tested under repeated loading. The experimental program details are listed and given as a flow chart in Figure 1.

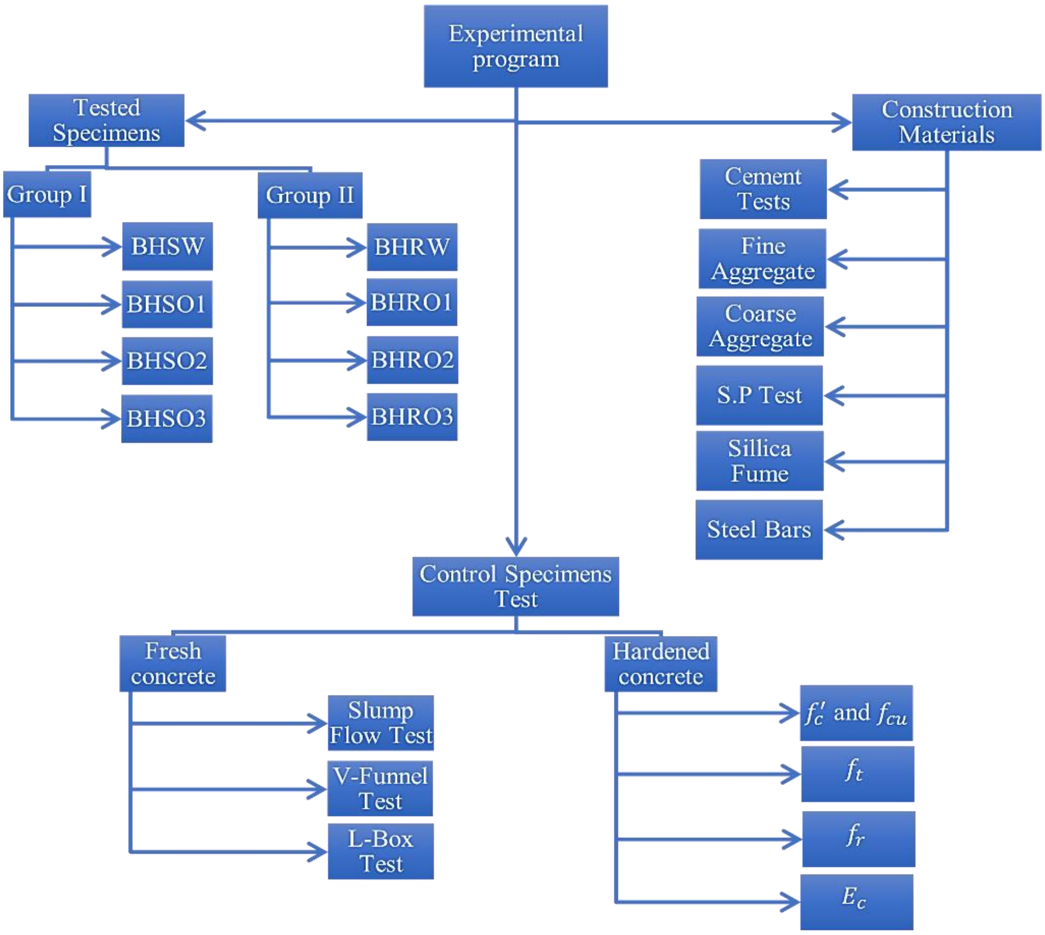


Figure 1. Experimental Program Details

2.1. Tested Specimens Details

The thin-walled tube truss analogy was adopted in this research's design of concrete members according to the A.C.I. code 2019 [27]. The design steps were completed according to the code requirements, and the test result was almost the same as the design assumed loads. The beams were tested after completing 28 days of curing. Table 1 shows the parametric of the details of tested beams, explained by the following: B = Beam, H = Hollow, S = Static, R = Repeated, and W = without openings, O = with Openings, 1, 2 or 3 = the number of openings. All details are provided in Figure 2.

Table 1. Tested Specimens details

Beam designation	Type of Load	No. of Cycles	No. of Transverse Opening
BHSW	Monotonic	-	None.
BHSO1	Monotonic	-	1
BHSO2	Monotonic	-	2
BHSO3	Monotonic	-	3
BHRW	Repeated	7 Cycles	None.
BHRO1	Repeated	7 Cycles	1
BHRO2	Repeated	7 Cycles	2
BHRO3	Repeated	7 Cycles	3

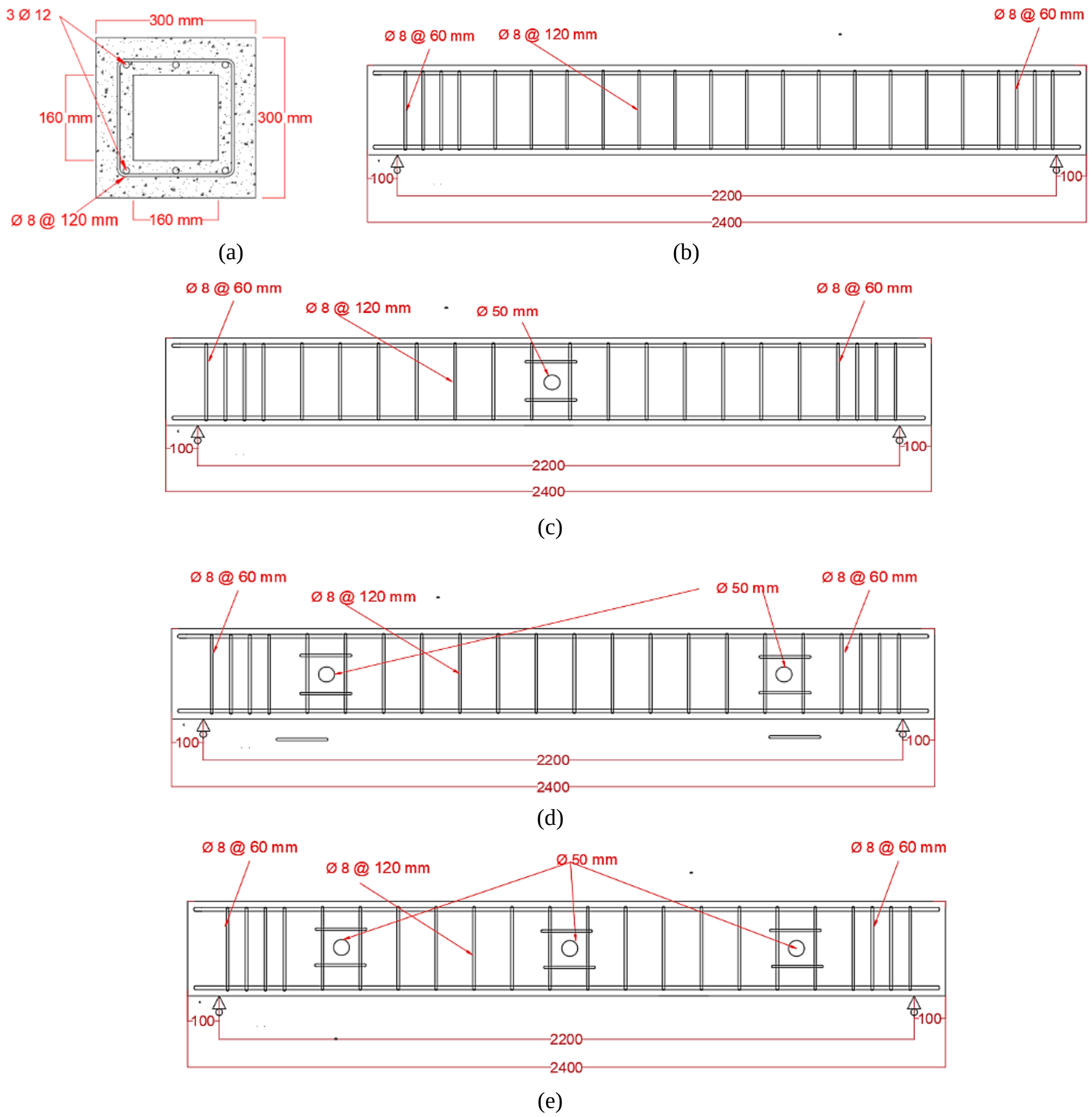


Figure 2. Details of beam specimen (all dimensions in mm): a) beams cross-section, b) (BHSW, BHRW), C) (BHSO1, BHRO1), d) (BHSO2, BHRO2), e) (BHSO3, BHRO3)

2.2. Materials

Materials used to construct the self-compacting concrete mix design and steel reinforcement properties are shown in Table 2. The S.C.C. mix was designed according to the requirements of EFNARC [28]. For producing S.C.C., the method we used was changing the superplasticizer dose while keeping the w/p ratio fixed. Details of the adopted mixture are shown in Table 3.

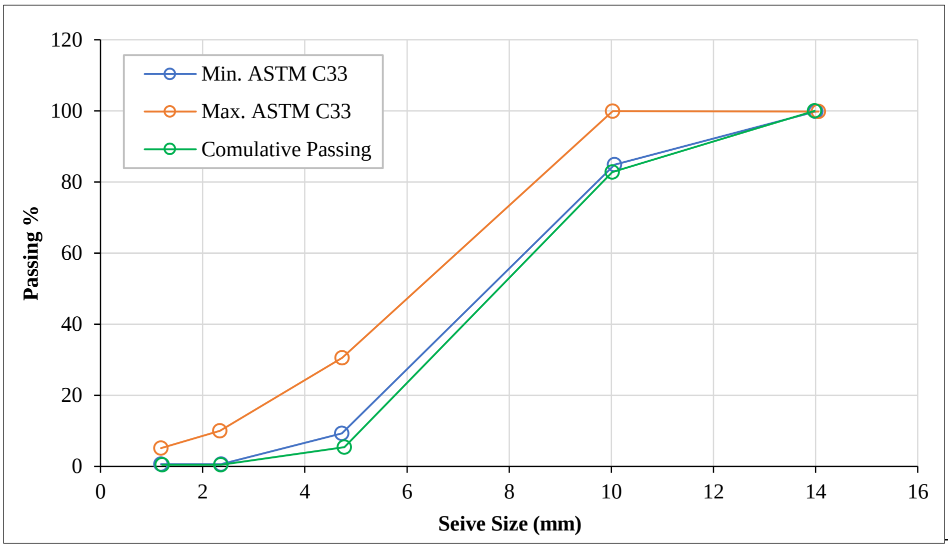
Table 2. Material properties

Material	Description
Cement	Ordinary Portland Cement (Type-I) (TASLUJA-BAZIAN)
Sand	Natural sand passing from a sieve size of (4.75 mm)
Gravel	Natural crushed gravel Size (14 mm).
Silica Fume	Type Mega Add MS(D) produced by CONMIX company.
Superplasticizer	Glenium 51
Water	Tap water
Reinforcing Bars [20]	(ϕ8 mm) deformed steel bar with a yield strength of (f_{yt}=410 MPa); and (ϕ12 mm) deformed steel bar with a yield strength of (f_{yl}=435 MPa).

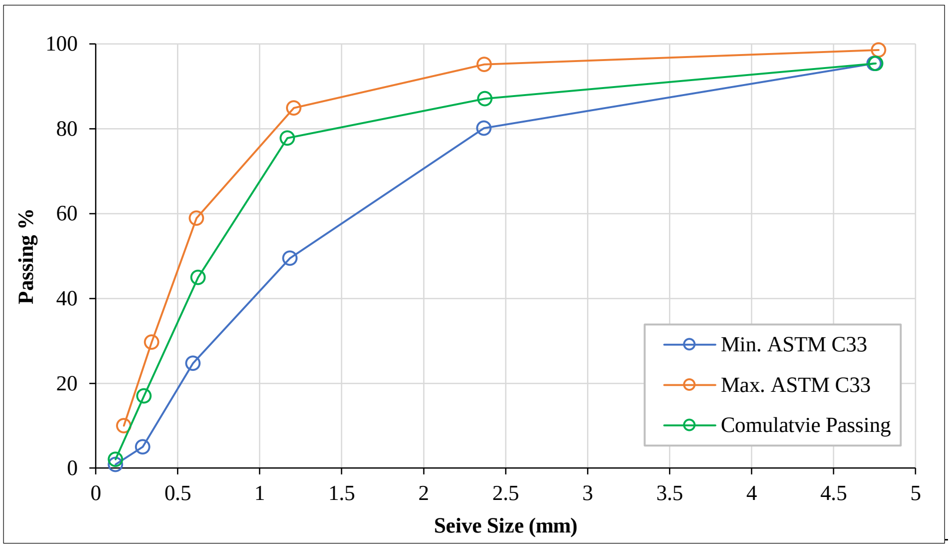
Table 3. Trial mix details of self-compacting concrete

Filler%	Glenium 51	Quantities of Mix Ingredients (Kg/m^3)							
		Water	Powder		W/P ratio	Sand	Gravel	Glenium 51	Density
			Filler Content	Cement					
9.2%	3.82%	179.83	44.00	473.24	0.34	777.1	888.1	19.8	2382.07

The grading properties of sand and coarse aggregate with the limits of ASTM C33/C33M-18 [29] are shown in Figure 3. This figure shows the sieve analysis of the fine and coarse aggregate used in this experimental work.



(a) Sieve analysis of the Coarse aggregate



(b) Sieve analysis of the fine aggregate

Figure 3. Sieve analysis of Aggregate

2.3. Mechanical Properties of Concrete

2.3.1. Test on fresh Self Compacting Concrete

Three tests have been conducted as control tests on fresh S.C.C., namely the V-funnel, L-box, and slump flow tests, which gave a good indication of filling ability, passing ability, and segregation resistance. Furthermore, all these tests were compatible with EFNARC requirements [28].

2.3.2. Hardened Concrete Properties

For each two-beam specimen, three 150×300 mm cylinders and three of 150×150×150 mm cubes were used for the compressive strength test according to ASTM A615/A615M-22 [30], three of 150×300 mm cylinders for the splitting tensile test according to ASTM C39/C39M-21 [31], three of 150×300 mm cylinders for the modulus of elasticity test according to ASTM C496-96 [32], three of 100×100×500 mm prisms for the flexural according to ASTM C469/C469M-22 [33], were tested to evaluate the mechanical properties of hardened concrete at the age of (28) days as given in Table 4.

Table 4. Mechanical properties of hardened concrete control specimen's test results

Beams Symbols	Properties				
	f'_c MPa	f_{cu} MPa	E_c MPa	f_{ct} MPa	f_r MPa
BHSW, BHSO1	43.62	56.67	24743.408	3.793	5.125
BHSO2, BHSO3	45	57.78	26542.771	3.83	5.2
BHRW, BHRO1	44.71	57	29789.322	3.805	4.212
BHRO2, BHRO3	44.8	56.8	25678.798	3.789	4.205

f'_c: Cylinder Compressive strength, f_{cu} : Cube Compressive strength, E_c : Modulus of elasticity, f_{ct} : Splitting tensile strength, f_r : Modulus of rupture.

2.4. Test Setup, Instrumentation, and Measurements

2.4.1. Instrumentation and Measurements

All beams have been tested using a universal testing M.F.L. machine model (8551 MFL system) with a 300-ton capacity. With a span of 2200 mm, the beams were set onto free-supported rollers at each end. Supports were designed to rotate about the beam's longitudinal axis, allowing free application of torsion. This was achieved by transferring the load from the universal machine to the two outer points representing the moment arm, which is equal to 500 mm from the applied load on steel arms to the center of the beam. The steel girder of 250 mm in depth and 2500 mm in length was used for load transmission from the universal machine to both arms, as shown in Figure 4. Details for the parts and dimensions of the fabricated loading steel arms are shown in Figure 5. The measurement of the angle of twist was performed by using two dial gauges attached to the bottom of the end of the specimens at a point laid at 230 mm from the center of the beam (see Figure 6).

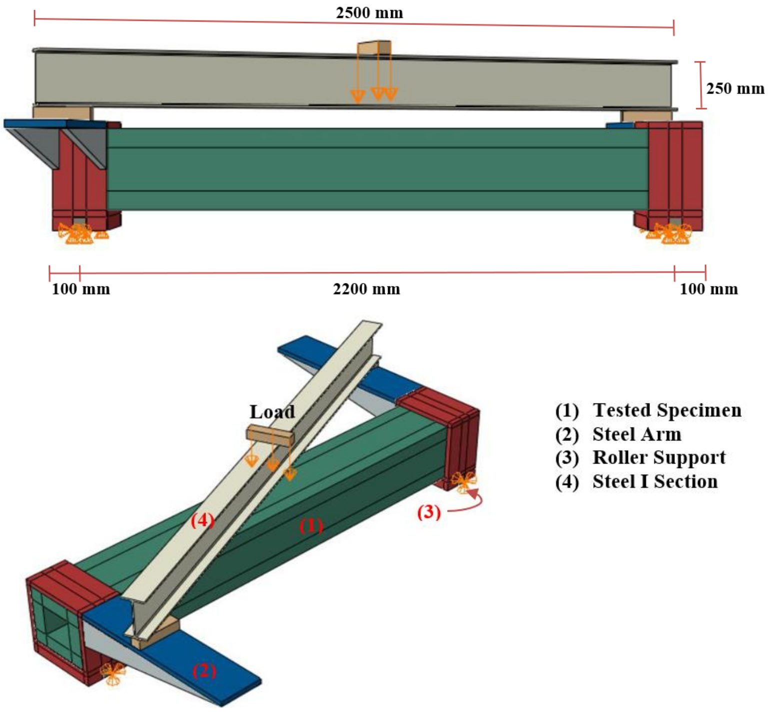


Figure 4. Schematic diagram of the test setup and the applied loading

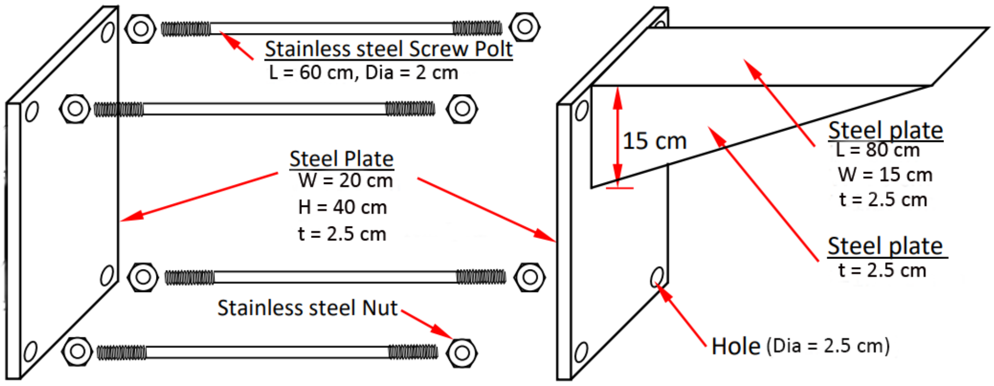


Figure 5. Loading steel arm details

Figure 6. Dial gage location in the tested beams

2.4.2. Test Procedure and Setup

Figure 7 shows the test setup in the lab. For the monotonic test in the first group (I), all beams were tested under an increasing 5 K.N. torque increment up to failure. For the repeated loading test, in the second group (II), 30% of the ultimate torsion of the beams failed under the monotonic loading for three cycles, followed by three cycles of 60% of the ultimate torsion load of specimens that failed under the monotonic load. The loading process was repeated for seven cycles until failure.

Figure 7. Test setup

3. Results and Discussion

3.1. Cracking and Ultimate Torsional Moment and Modes of Failure

Tables 8 and 9 show the experimental work's results. The cracks will appear on the surface of the concrete if the principal tensile stress reaches the tensile strength of the concrete. As shown in Figure 8, the crack had an inclination of about 45 degrees from all sides until failure and was connected from all sides of the tested specimens. For the repeated loading test, 30% of the ultimate torsion load of the other beams that failed under the monotonic loading was applied for the first three cycles, followed by three cycles with 60% of the ultimate torsion load of the other beams that failed under the monotonic loading. The loading process was continued for the 7th cycle until failure. No cracks appeared in the first three cycles; in the second three cycles, as shown in Figure 8, the crack pattern refers to the cracks that appeared in the 4th and 5th cycles. The green color refers to the cracks that appeared in the 6th cycle, whereas the red color refers to the cracks that appeared in the 7th cycle. The pattern of cracking and the mode of failure for the monotonic and repeated loading tests are shown in Figure 9.

Table 5. Cracking and Ultimate Torque for the tested Beams

Beam designation	Type of Load	Cracking Torque, T_{cr} (kN.m)	Ultimate Torque, T_u (kN.m)	T_{cr}/T_u %
BHSW	Monotonic	9.375	20.63	45.44
BHSO1	Monotonic	6.75	12.25	55.10
BHSO2	Monotonic	8.375	14.88	56.28
BHSO3	Monotonic	5	10.25	48.78
BHRW	Repeated	8.75	17.5	50.00
BHRO1	Repeated	5.625	9.25	60.81
BHRO2	Repeated	7.75	11.25	68.89
BHRO3	Repeated	4	7.5	53.33

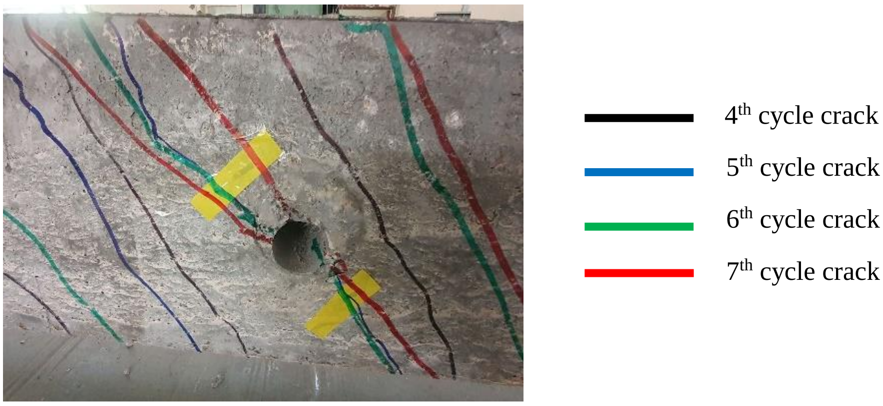


Figure 8. The sequences of crack appearance during the test loading

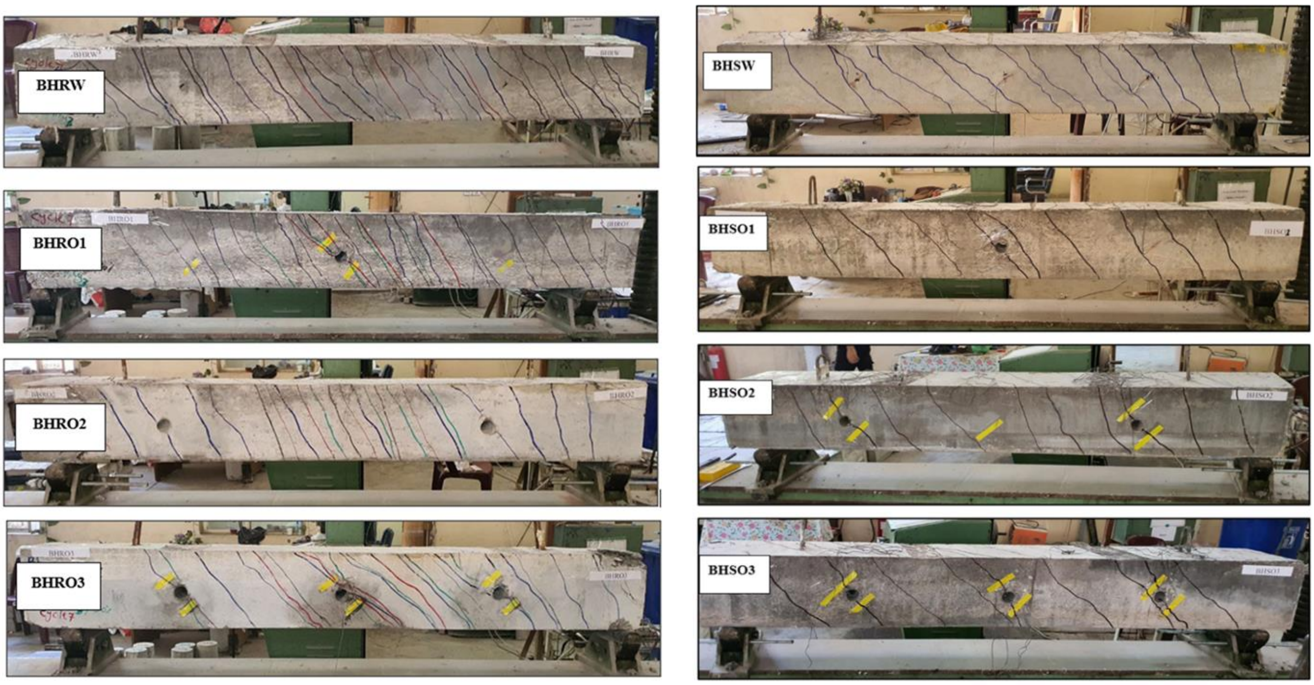
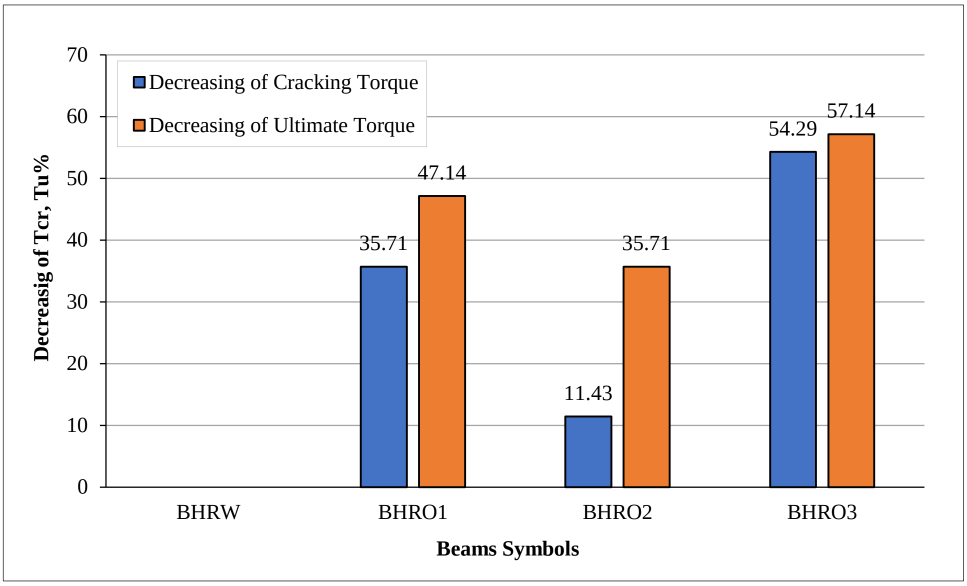


Figure 9. Cracks Pattern after Failure for Monotonic and Repeated Loading Test

3.2. The Effect of Opening on Cracking and Ultimate Torsional Strength

Due to the presence of the web openings, the cracking and ultimate torques, as shown in Table 5, showed the torsional strength of the tested box beams. For the monotonic loading test, the cracking and ultimate torques were reduced and decreased due to openings compared with the reference beam BHSW. The percentage decrease is shown in Figure 10. Moreover, the results presented in Figure 10 also indicated a reduction in the cracking and ultimate torque capacities for the repeated loading test specimens compared to the reference beam. The results presented in Figure 10 showed that the ultimate torque strength is more affected by the presence of the web opening as compared with the cracking torsion strength. For the monotonic and repeated loading tests, a maximum reduction in the ultimate torque moments of approximately 50.3% and 57.1%, respectively, is noted.



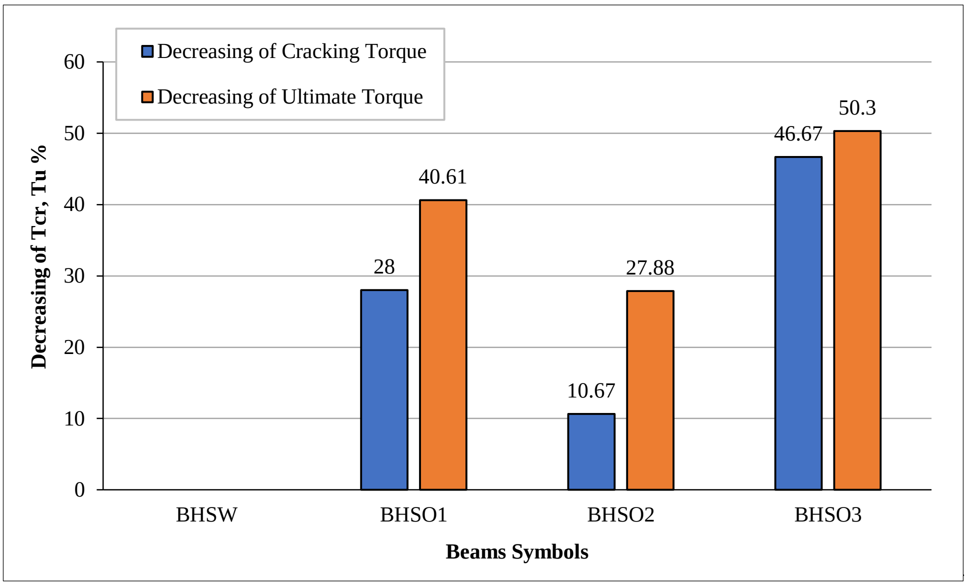


Figure 10. Percentage of decrease in the Cracking and Ultimate Torques due to the presence of opening for beams tested under Monotonic and repeated load

On the other hand, Figure 11 shows the comparison of the effects of repeated loading as compared with monotonic loading. Results indicated that the cracking and ultimate torque capacities for the repeated loading specimens decreased compared to the monotonic loading test. The results presented in Figure 11 also showed that the ultimate torque strength is more affected by the repeated load's action than the cracking torsion strength. A maximum reduction in the ultimate torque moments of about 27% is recorded compared with a 20% reduction in the cracking torque moments when the repeated loading effect is compared with monotonic loading for the box beam samples with and without openings.

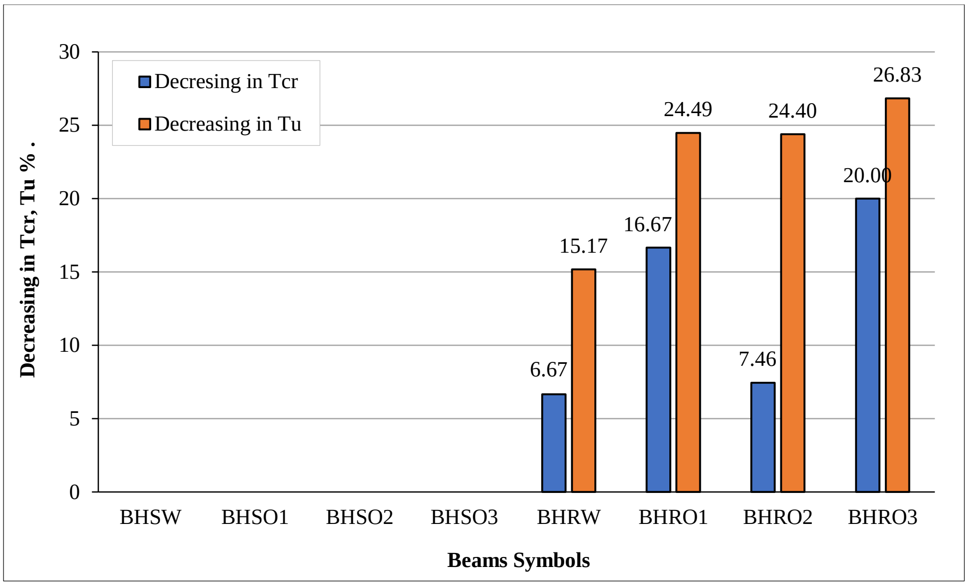


Figure 11. Comparison of the Cracking and Ultimate torque capacities for the repeated and Monotonic loading specimens

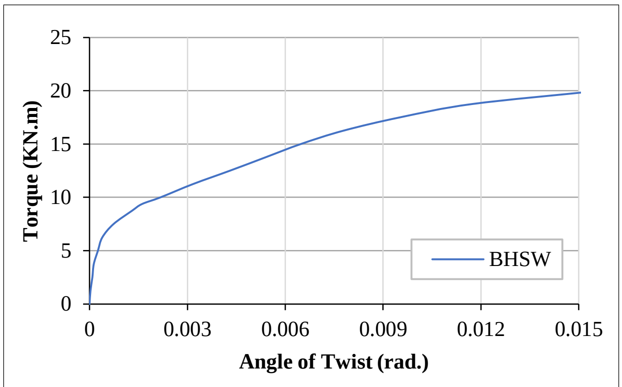
3.3. Torsion-Twist Angle Comparison

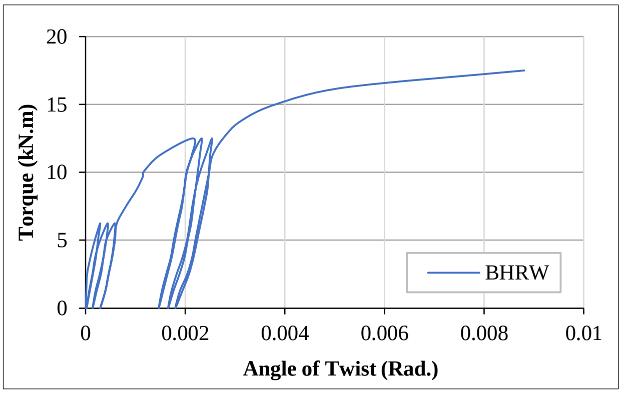
The angle of twist is defined as a two-dimensional torsional moment deformation. Table 6 shows the results of the twist angle of the tested beams.

Table 6. Experimental results of the Twist angle for the tested beams

Beam designation	Type of Load	Cracking Torque, T_{cr} (kN.m)	Cracking Angle of Twist ϕ_{cr} (Rad.)	Ultimate Torque, T_u (kN.m)	Ultimate Angle of Twist ϕ_u (Rad.)
BHSW	Monotonic	9.375	0.00161	20.63	0.01565
BHSO1	Monotonic	6.75	0.00083	12.25	0.00761
BHSO2	Monotonic	8.375	0.00090	14.88	0.00858
BHSO3	Monotonic	5	0.00070	10.25	0.00687
BHRW	Repeated	8.75	0.00103	17.5	0.00880
BHRO1	Repeated	5.625	0.00042	9.25	0.00410
BHRO2	Repeated	7.75	0.00056	11.25	0.00490
BHRO3	Repeated	4	0.00032	7.5	0.00342

As shown in Figure 12, the torsional moment is graphed against the average of two twist angles for each tested beam separately. The results presented for the monotonic and repeated loading tests indicated that the area under the curve becomes smaller for the tested beams with openings. This result shows that the beam samples with openings have less torsional stiffness and will decrease in the ultimate angle of twist. Figure 13 displays the percentage decrease for each test. However, as illustrated in Figure 14, the comparison of the tested beams at a specific torsional moment clearly shows an increase in the angle of twist with a decrease in rotational stiffness. Generally, a reduction in the angle of twist of about 45% to 60% is observed due to different numbers of openings under monotonic or repeated loading compared with box beam samples without openings.





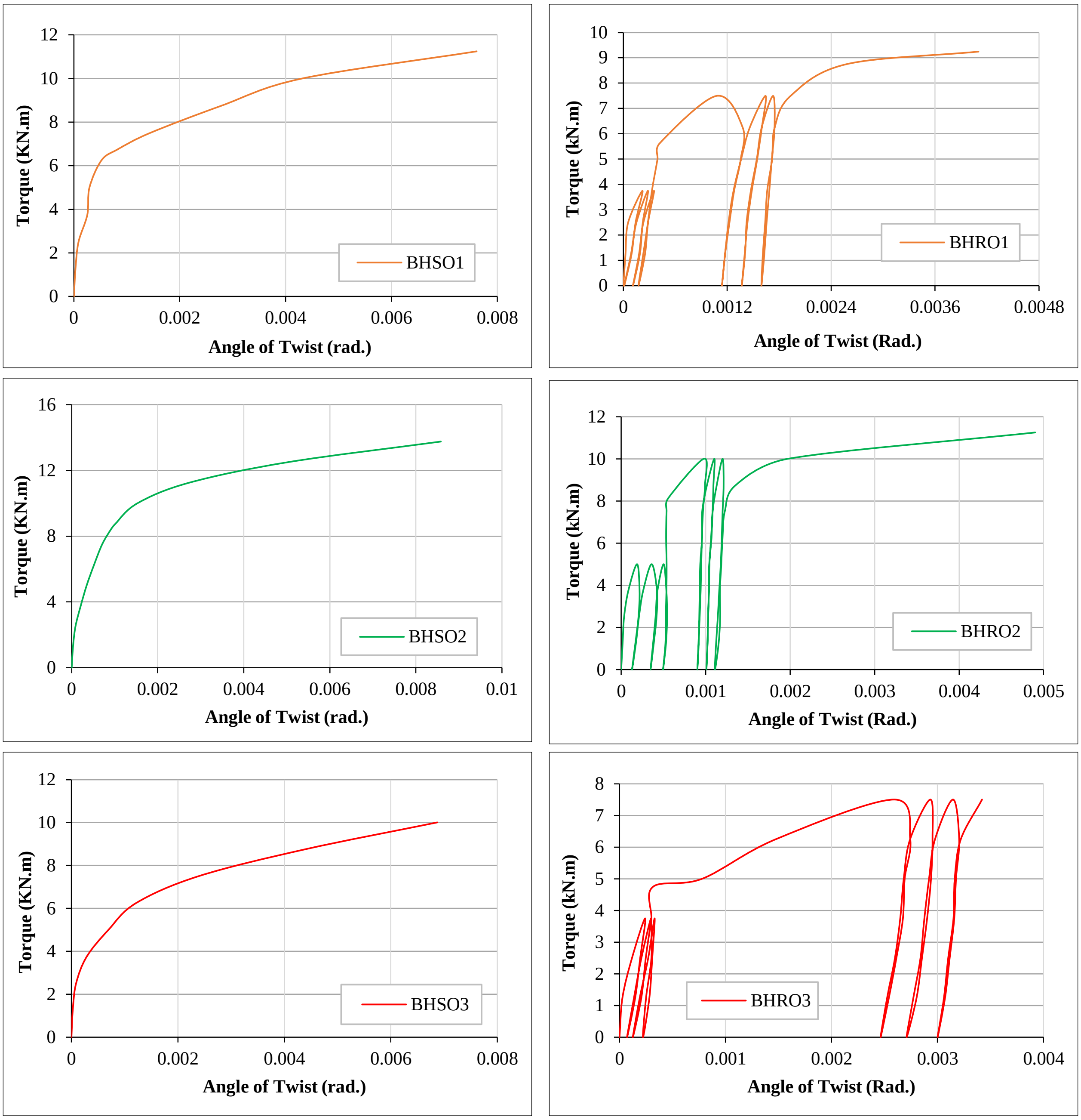


Figure 12. Torsional moment vs. angle of twist for beams under Monotonic and Repeated loading

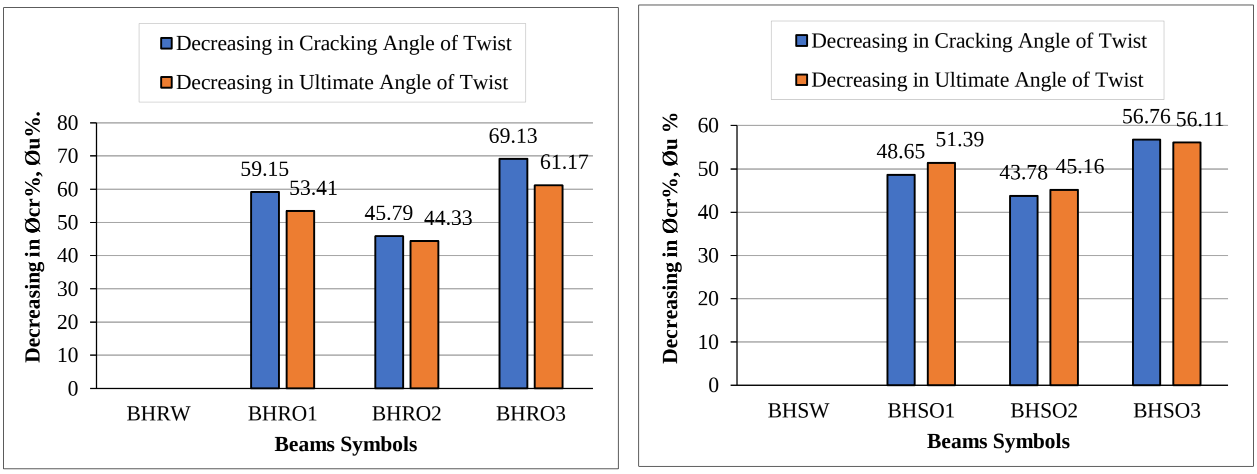


Figure 13. Decreasing in the Cracking and Ultimate Angle of Twist for Monotonic and Repeated loading Tests

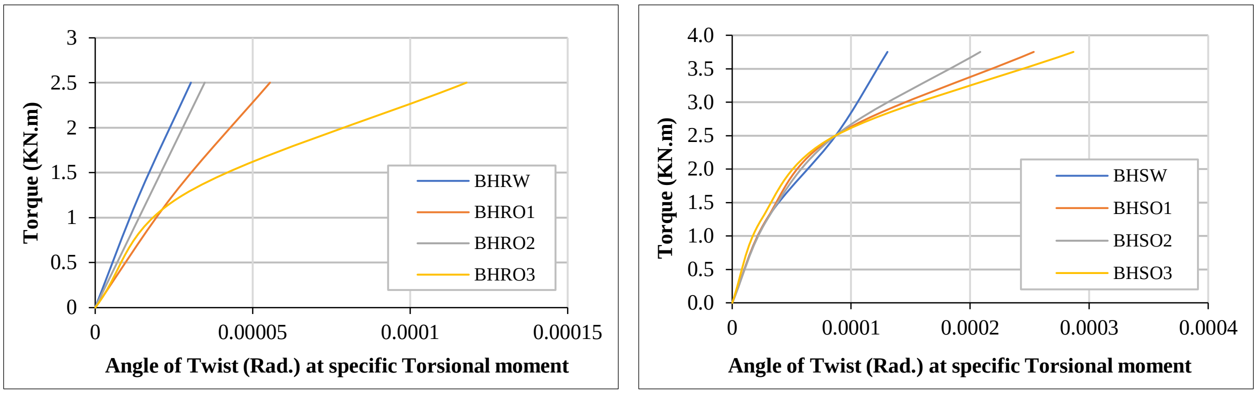


Figure 14. Increasing the Angle of Twist at a Specific Torsional moment

On the other hand, Figure 15 compares the effect of repeated loading on the decrease in the angle of twist as compared with monotonic test samples. Results showed that the twist's angle at cracking and torsion is more affected by repeated loading as compared with monotonic test samples. A maximum reduction in the angle of twist up to about 55% is recorded due to the action of repeated loads.

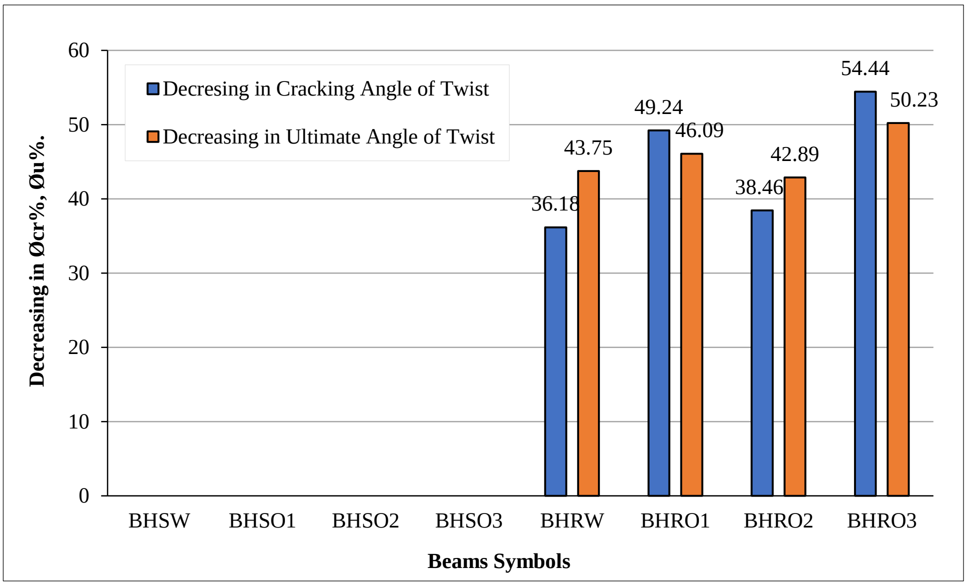


Figure 15. Decreasing the Twist angle of the tested beams under Repeated loading compared to the Monotonic loading test

4. Conclusion

The experimental results showed that the torsional strength of reinforced concrete box beams with transverse web openings was lower than that of the control specimen without openings. For the monotonic load test, the cracking torsional moment and the ultimate torsional strength were decreased for the tested beams with one up to three openings in the web by 10.7% to 46.7 and 27.9% to 50.3, respectively. As for the repeated torsional load test, the cracking torsion moment and the ultimate torsional strength were reduced by 11.4% to 54.3% and 35.7% to 57.1%, respectively, for the same configuration of openings in the web. Hence, for the tested beams with different configurations of openings, a maximum reduction of about 20% and 26.8% in the cracking and ultimate torsional strength, respectively, was observed due to the repeated loading effect compared to monotonic loading, indicating a more pronounced effect for the monotonic loading. Moreover, results revealed that repeated loading causes inelastic deformations in proportion to the number of load cycles. Also, the presence of openings resulted in a reduction in the angle of twist at the cracking and ultimate torsional moments because of the decrease in the tested beam's stiffness, with a maximum reduction of about 70% compared to the beam without opening, indicating less ductile behavior. As indicated for box beam torsional strength, the repeated loading case had a greater effect on cracking and ultimate torsional deformability. A reduction of about 38.5% to 54.4% and 42.9% to 50.2% in the cracking and ultimate torsional angle of twist, respectively, was recorded due to repeated loading compared to monotonic loading for the tested beams with different numbers of openings.

Further work is suggested to study the behavior of RC beams with various types of fiber (steel or hybrid) to improve torsional resistance or to study the performance of box sections with other section types such as T, L, and I sections.

5. Declarations

5.1. Author Contributions

Conceptualization, H.M.; methodology, H.M.; validation, H.M.; formal analysis, H.M.; investigation, H.M.; resources, H.M.; data curation, H.M.; writing—original draft preparation, H.M.; writing—review and editing, H.M. and R.M.; supervision, R.M.; project administration, H.M.; funding acquisition, H.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgments

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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