The effect of a circular hollow core on the torsional response of reinforced concrete beams subjected to repeated loading

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ABSTRACT

The loading on bridges, ports, multi-story parking garages, and airport facilities is typically repeated, so reinforced concrete beams are typically used to support these buildings. Under repeated loads, concrete behaves differently than it does under static stresses. Because of the way the truck is loaded and unloaded, some of the concrete pieces get crushed. This research aims to examine the behavior of reinforced concrete hollow beams subjected to repeated torsion loads. The experimental study involves the evaluation of four reinforced concrete rectangular beams of dimensions (length 3000 mm, height 350 mm, and width 250 mm) with identical reinforcing ratios and tested under pure torsion. There are two beam sections available: solid and hollow. The test program takes into account the influence of hollow shape and load type (monotonic and repeated). On the basis of torque-twist behavior, beam elongation, crack width, behavior and effect of hollow core cracking torque, ultimate torque, and failure mechanisms, test results were discussed. The results of the experiments showed that a circular cavity with a diameter of 10 mm in reinforced concrete beams has a small effect on the properties of reinforced concrete compared with solid-section beams, whether they are subjected to monotonic or repeated torque, with a reduction of the cracking and the ultimate torque of 6.09% and 5.58% for beams subjected to monotonic torque, and with a ratio of 6.6% and 6.03% for beams subjected to repeated torque.

Keywords: Torsion, Hollow beam, Repeated loads, Crack width, Energy Absorption, Angle of twist.

1. Introduction

Torsion is a brittle mechanism of failure in reinforced concrete beams when the beams are inadequately designed for torsion. Even now, not all torsional difficulties are completely understood. Other characteristics, such as shear and flexure, have received more attention than torsion. Torsion was not taken into account in the design of earlier buildings. Now that we know more, we should check older buildings for how well they stand up to twisting and how efficient they are **[1].**

Several structural elements in the construction of buildings and bridges are exposed to torsional moments that impact the structural design. Elements that are likely to twist include spandrel beams, beams in the frames of multi-deck bridges that are loaded unevenly, and curved box girder bridges **[2]**.

According to structural trends, there is a growing interest in adopting hollow core parts for both buildings and bridges. This is mostly owing to its advantageous structural and aesthetic design properties. Significant progress was accomplished **[3-4]**, but there are still places that require development. Most commonly, hollow core parts are employed to provide inexpensive solutions by lowering weight and expense. In other instances, their geometrical characteristics are functionally essential. In their study, several scientists examined the torsional behavior of hollow beams **[5].** The meagre data or design recommendations available in the literature indicate that hollow-section beams are subjected to torque. Mazen **[6]** The testing findings indicated that the ultimate torsional strength and beam elongation of the concrete core had not altered. Al-Attar et al. **[7]** studied the torsional behavior of self-compacting concrete beams reinforced with varied cross sections of steel fibers (solid and hollow). Recent findings indicate that the addition of steel fibers increased the torsional strength of all beams, with hollow beams benefiting more than solid beams. Rafea et al. **[8]** examined the torsion performance of hollow reinforced concrete beams reinforced with various fiber types. 5.5% was added to the ultimate load capacity of the (ST.F) reinforced concrete beam. Because (SY.F) has a big effect on torsional performance, it is suggested that it be used with regular concrete.

They were loaded into offshore projects, highways, and multi-story parking garages, among other constructions. Extensive theoretical and experimental research on reinforced concrete beams has given important techniques to design for serviceability under static loads for a very long period. However, cracking and deformation as a result of repeated stress on reinforced concrete beams are still uncommon and poorly understood. Compared to structures subjected to static loads, concrete structures subjected to repeated loads deflect more. This deflection has several permanent sets, and permanent deflections increase in proportion to the number of load cycles. Researchers have noticed this trend, but right now there isn't a lot of relevant experimental evidence **[9]**.

We conclude from what was previously mentioned that there has been a wide use in recent periods of hollow concrete sections in many buildings and structures. There have been a lot of studies done on this topic, but none of them looked at how hollowing affects the properties of concrete sections that are repeatedly subjected to momentary loads. To fill this gape, the main objective of this study is to look at how hollow concrete beams behave when subjected to monotonic and repeated torsional loads.

Experimental Program

1.1 Specimen Details

In the experimental program, four concrete beam specimens with a rectangular cross-section (350) mm deep, (250) mm wide, and (3000) mm long, and a circular hollow in the center of the concrete samples with a diameter of 100 mm for specimens with hollow cross section, were made out of ready-mixed concrete and tested under pure torsion up to failure.

Two huge cantilever steel arms deliver torque to the middle of the rectangular reinforced concrete beams in order to impart torque to the beam's ends. The rigid connection of test beams with huge blocks corresponds to the actual state of a beam with columns and a transverse beam at its ends in a frame structure. The test beam supports ensured that there was no frictional resistance to the applied torque, so this boundary condition had no effect on the beam's strength.

All beams were reinforced with (4 φ 12 mm) and (2φ 8 mm) longitudinal bars located around the beam's perimeter. The beams were designed intentionally to display torsion failure at their central parts. End zones of 0.4 m on each end of the beam were reinforced with (8 mm) stirrups spaced at 75 mm on the center to force failure in the mid-zone of the tested beam. The 2.2 m test region was chosen so that at least three complete spiral cracks at an angle of 45^{o} would form along its length, so it was reinforced with (8 mm) stirrups spaced at 150 mm on the center. Reinforcements in both transverse and longitudinal directions are given for torsion specifications to prevent the collapse of the beam at cracking. The steel reinforcement details and the beam cross-section dimensions used for each beam are shown in figure1. The tensile steel reinforcement was carried out on at least three specimens prepared from each type of steel reinforcing bar used in the tested beams. The yield strength of the (φ 8 mm and φ 12 mm) was determined experimentally and found to become equal to (475 & 410) Mpa, respectively.

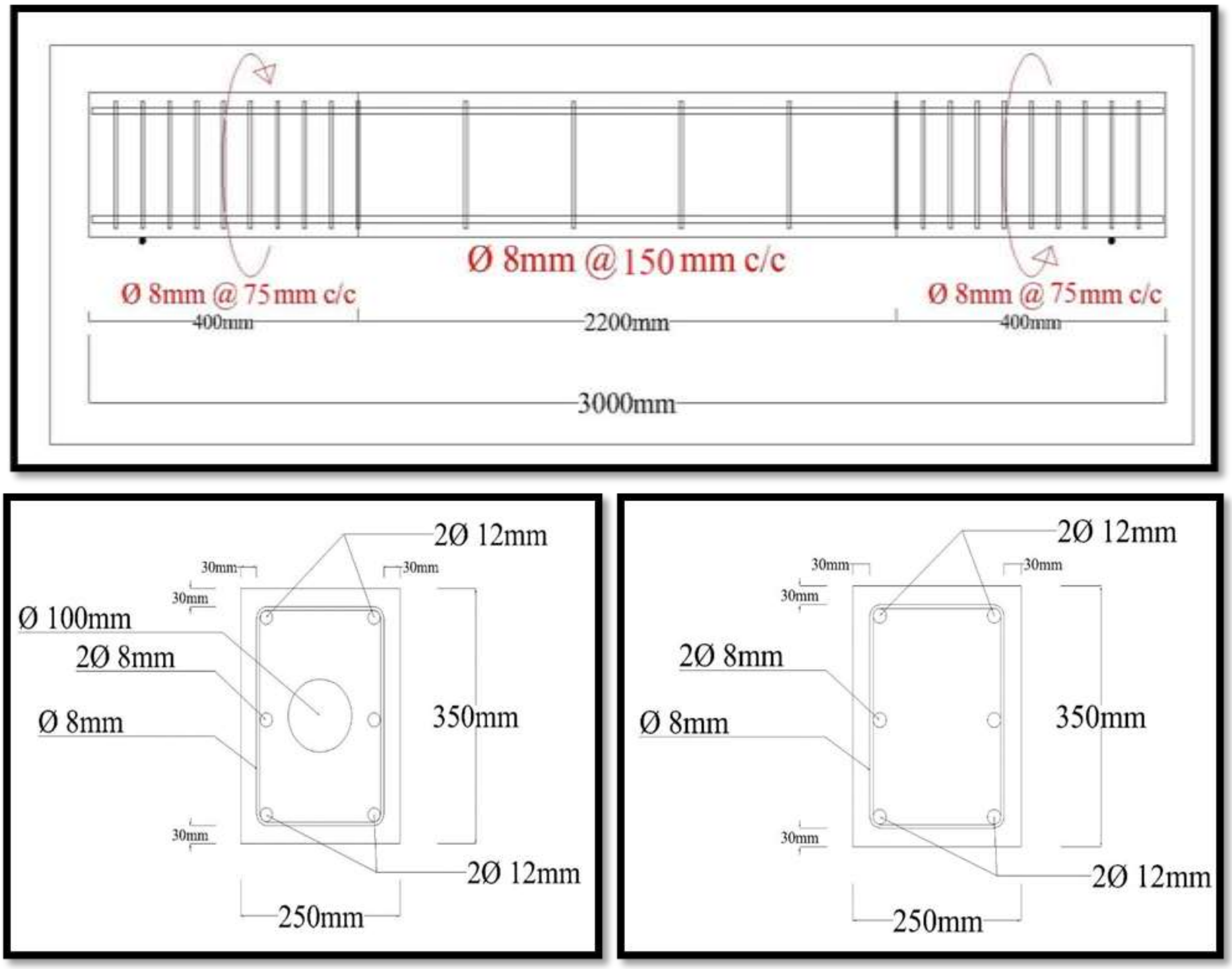


Figure 1: Dimensions and reinforcement details of the test beams.

Four plywood moulds were used to cast all the tested beams, including a base and four movable sides with plywood thickness (18 mm). The sides were fixed with screws and then fixed to the base with screws to form blocks at the ends. The assemblage is shown in figure 2. Before casting, the mould was oiled, and the mesh reinforcement was put in place. At the ends of the wooden mould, circular holes with a diameter of 100 mm were made so that the circular plastic tubes needed to make cavities along the sample could be held in place.

Figure 2: Molds and reinforcement steel used for casting sample

1.2 The material used for casting

Reinforced concrete specimens of the same size and reinforcement were made using a concrete mix that was designed to achieve an average compressive concrete strength cylinder (300 mm and diameter is 150 mm) strength of 30 MPa at 28 days (normal strength concrete), with a slump of around 100 mm.

Tables (1) show the characteristics of the concrete mixture and provide information about it. The employed combination creates concrete with excellent workability and homogeneous mixing without segregation.

Table 1: Concrete mix proportions

parameter	30 Mpa
W/C ratio	0.435
Water , kg/m^3	162
Cement , kg /m^3	413.8
Sand , kg/m^3	702
Gravel , kg/m^3	1021
Super-plasticizer , L/m^3	2.069

2.3 Beams designation details

Notable is the fact that they tested two beams for each condition of study (solid and hollow), one under monotonic load and the other under repeated load with seven cycles of service load at 60% of the monotonic load.

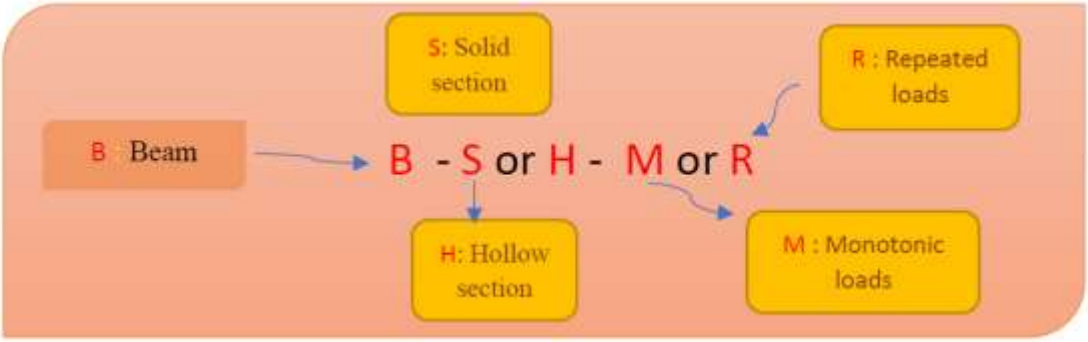


Figure 3: beams' designation and naming system for the tested specimens.

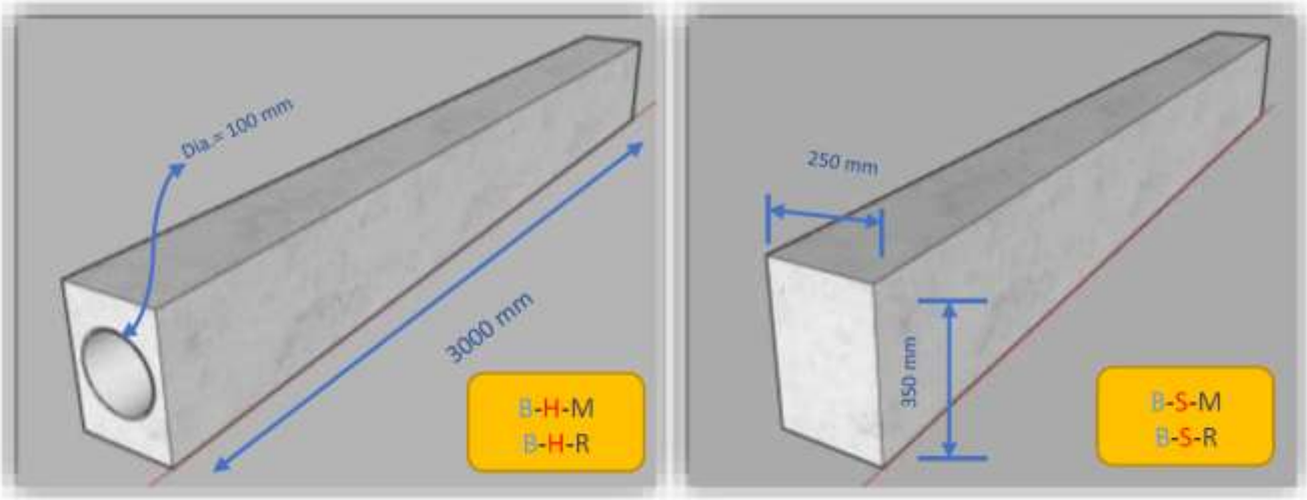


Figure 4: Beams Specimen with Dimensions

2.4 Instrumentation and Testing

In the structural laboratory of the university, all beams are tested in pure torsion until failure. Various eccentricities were applied torque by the use of two external arms attached at both ends. The load was delivered to the ends of the beam using a 2000 KN hydraulic jack through a 300 mm deep by 4000 mm long diagonal (I) section steel girder. Load cells were installed beneath the jack to measure the applied load. This frame consists of two enormous steel clamps that serve as torque-applying arms and are attached to the sample by three big bolts per arm. This frame consists of a 20 mm thick steel plate and two welded steel shafts. This concluding shape resembles a bracket. These arms could achieve an eccentricity of up to 500 mm relative to the longitudinal axis of the beam. To obtain pure torsion, the employed supports enable rotation about the longitudinal axis.

Two LVDT sensors were mounted to the bottom of each end of the beam at a location 30 mm from the beam's longitudinal axis. The sensors captured the uplift and down data to calculate the beam's twist angle at each end.

During testing, the primary characteristic of the beam's structural behavior was identified at each step of loading. The initial cracks and crack width of concrete were measured using a micro crack meter with (0.02 mm) precision, and the bigger cracks were measured using a digital meter vernier scale with a length of 15 cm and an accuracy of 1 mm. As the load was gradually applied, the ultimate torsion capacity and the angle of twist were determined. Readings were collected using the data logger attached to the device's computer, which sends data on loads and displacements from the load cell and LVDT sensors. In addition to the readings from the strain gauge mounted on the strengthened steel prior to casting, the torque was progressively raised until the beams failed. Failure is determined by decreasing the load capacity and increasing the beam's rotation. To measure the beam's elongation, dial gages were attached to the middle of one end of each beam. Figure 5 shows the test setup with the loading frame and a specific clamping loading structure on either end of the beam.

(a) Hydraulic Testing Machine.

(b) The Steel Arm.

(c) Angle of Twist Measurement used Lvdt.

(d) Data Logger.

Figure 5: Testing setup with the loading frame.

3. Results and discussion

In order to comprehend the behavior of reinforced concrete specimens with varying cross sections subjected to monotonic and recurrent torsion loads, the specimen's twist is recorded at regular intervals of torque till failure. Also noticed are the torques at the first crack and the final torque of each specimen. Table 2 shows the ultimate torque (**T_u**), ultimate twist angle (**θ_u**), and cracking torque (**T_{cr}**) of concrete beams.

Table 2: The Experimental results of the tested beams.

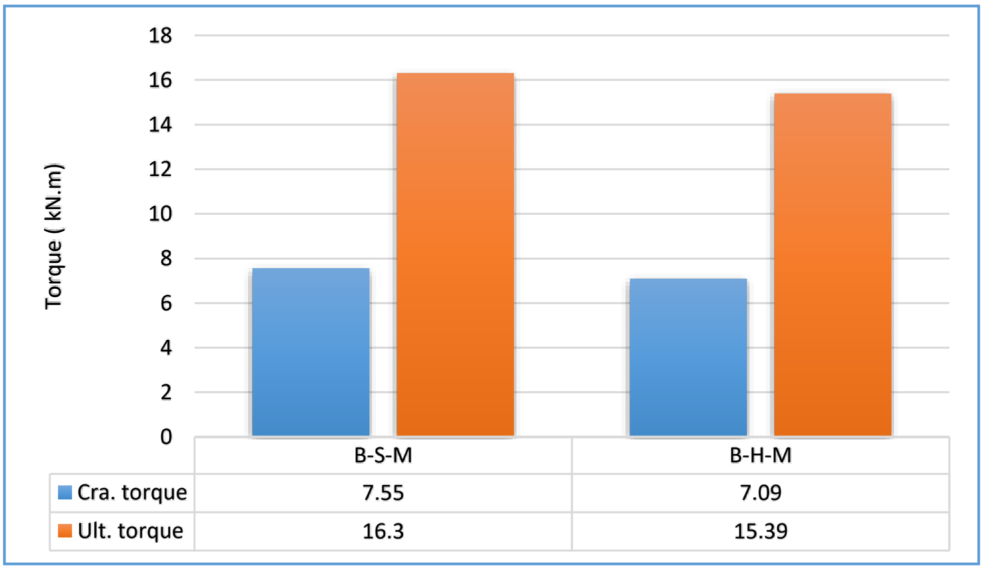
Beam Designation	Sec. Type*	Load type	T_{cr} (kN. m)	%decrease of T_{cr}	θ_{cr} (deg./m)	T_u (kN. m)	%decrease of T_u	θ_u (deg./m)
B-S-M	Solid	Monotonic	7.55	-	0.236	16.3	-	2.865
B-H-M	Hollow		7.09	6.09	0.2234	15.39	5.58	2.72
B-S-R	Solid	Repeated	7.5	-	0.2338	13.43	-	2.47
B-H-R	Hollow		6.99	6.8	0.22	12.62	6.03	2.338

3.1 Cracking and Ultimate Torque Comparison

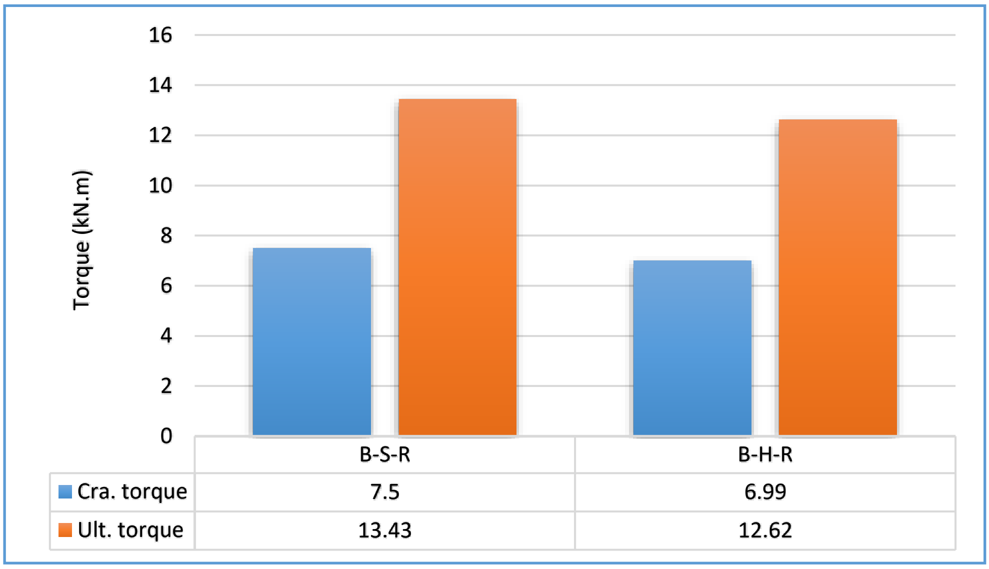
The cracking torsional moment (**T_{cr}**) is the torque at which cracking emerges and indicates that the tension strength of the section has been surpassed by the applied stress. However, the ultimate torsional moment (**T_u**) indicates the load-carrying capability of the tested beam, and the beam deforms fast once the machine reading decreases.

The cracking and ultimate torque strength of solid and hollow beam sections under monotonic and repeated torsion loads are listed in Tables 2. The solid beam (**B-S-M**) attained a maximum torque of 16.3 kN.m with a maximum rotation of 2.865° for the monotonic torque type, while the hollow beams attained a maximum torque of 15.39 kN.m with a twist angle of 2.72°. The tested beams (**B-S-R**) and (**B-H-R**) that were exposed to repeated load torque attained a maximum torque of 13.43 kN.m with a maximum rotation of 2.47°, and 12.62 kN.m with a maximum rotation of 2.338°, respectively.

Figures illustrate the first crack torque and ultimate torsional moment carrying capability of the control solid and hollow section beams under monotonic and repetitive loads.



(a) Beams tested under Monotonic loads.



(b) Beams tested under Repeated loads.
Figure 6: Ultimate torque and cracking for the tested beams

It can be noticed from figure 6 that the amount of decrease in the values of the ultimate torque and cracking torque for beams with hollow sections is minimal compared to the values of beams with solid sections and for both loading conditions (monotonic and repeated), where the decrease in the values of ultimate and cracking torque for hollow beam sections compared to solid beam sections was by (5.58% & 6.09%) for the beams examined under the influence of monotonic load, and (6.03% & 6.8%) for the beams examined under the effect of repeated load. This can be explained by the theorem (space truss analogy), which states that the concrete section exposed to torsion moments has stresses concentrated on the outer perimeter of the section, which reduces the contribution of the concrete in the middle area.

Figure 6 shows that the amount of decrease in the values of the ultimate torque and cracking torque for beams with hollow sections is minimal compared to the values of beams with solid sections and for both loading conditions (monotonic and repeated), where the decrease in the values of the ultimate torque and cracking torque for hollow beam sections compared to solid beam sections was (5.58% & 6.09%) for the beams examined under monotonic load, and (5.58% & 6.09%) for the beams examined under repeated load.

Under monotonic loading, all of the examined beams exhibited elastic behavior throughout the applied load and at the low load level, and the rotation at the ends of the beam specimens was minimal in relation to the applied loads. When the load is raised, the first crack appears, followed by other cracks in the area of the pure torsion moment. When specimens of beams are exposed to repeated loads, identical cracks are detected in the first monotonic cycle. In the loading phase of the first cycle, the same cracks quickly spread and moved diagonally down the beams. In the last cycle, the beams were loaded to the point where they broke.

Because of this, repeated loads do not modify the crack torsion moment characteristics of the tested beams compared to the identical beams tested under the effect of monotonous loads. But repeated loading from cycles of loading and unloading did lower the value of the ultimate torsional moments of the reference and reinforced beams when compared to beams that were evaluated under monotonous loads.

As indicated in Figure 7, the percentage decrease in the ultimate torsional moment carrying capacity of the solid beams (**B-S-R**) and hollow beams (**B-H-R**) under the impact of repeated loads resulting from cycles is 17.58% and 18.0%, respectively, as compared to the control-related beams. When it comes to repeated loads, solid parts are slightly better than hollow sections. This can be explained by the strength of the concrete in the middle area.

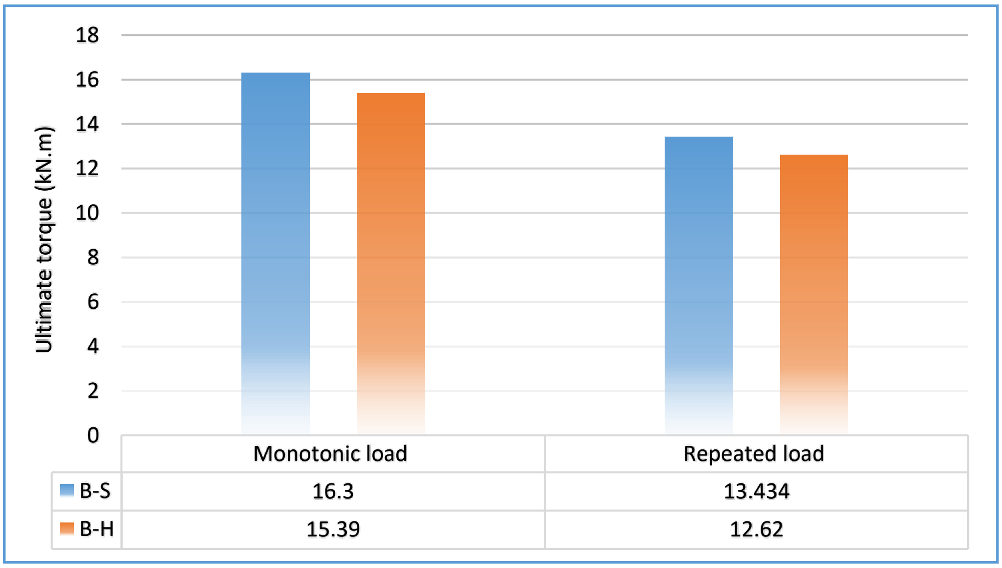
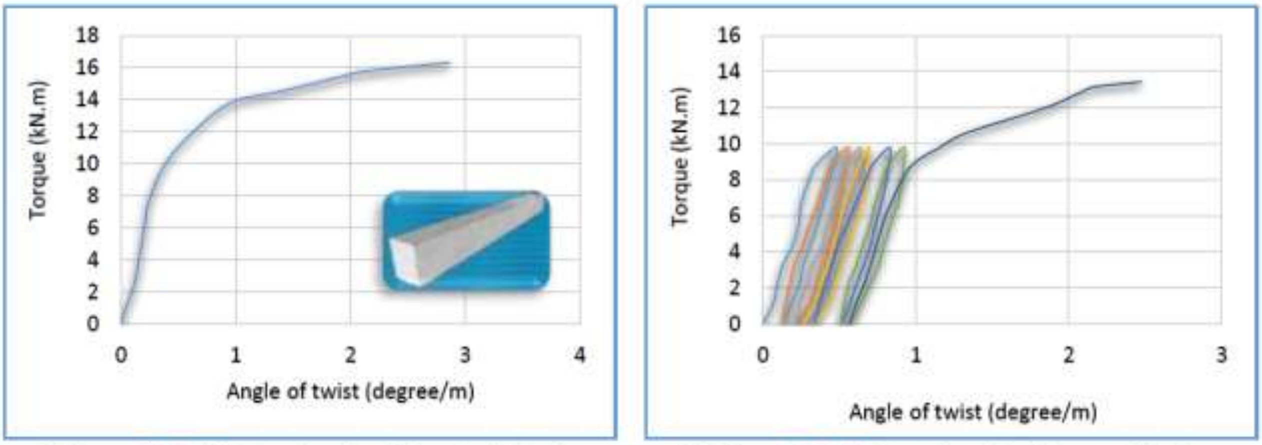


Figure 7: Ultimate torque value of tested beams under repeated and monotonic load (Solid & hollow section).

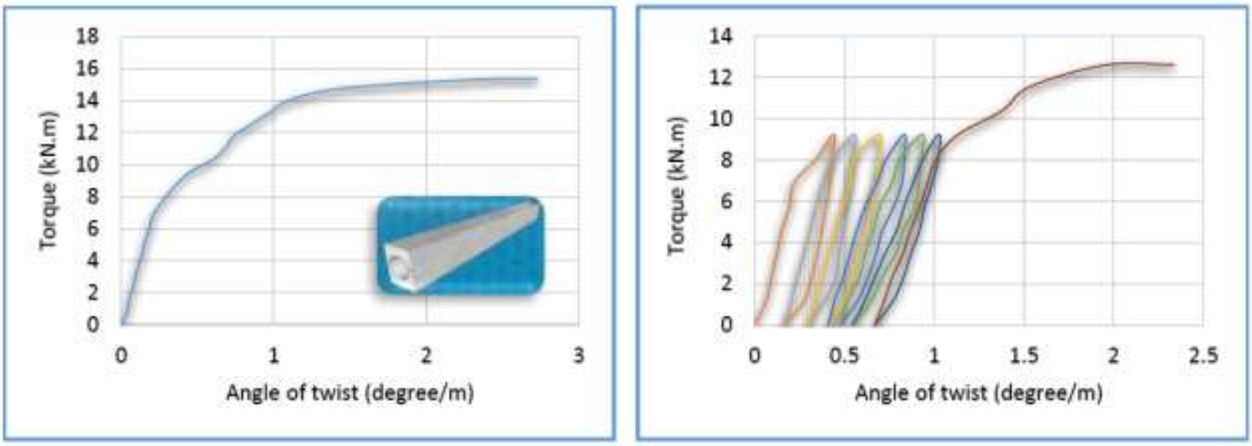
3.2 Torque–twist behaviour comparison

Figures 8 & 9 illustrate the applied torque versus twist per unit length relationship for solid and hollow beams under monotonic and repeated loads. In general, linear elastic behavior was first seen in all beams, followed by a substantial rise in twist angle and a progressive increase in torque up to failure. Using the torsion-twist curves, the crack and ultimate torques for each beam were computed, with the ultimate torque being the highest torque beyond which the beam fails and the crack torque representing the torque at which the first diagonal crack emerges. The torque against angle of the twist curve indicated the first crack, with the torque reducing abruptly at the first cracking point, followed by a shift in the slope of the torque-twist curve.



(a) Beam (B-S-M) tested under Monotonic loads. (b) Beam (B-S-R) tested under Repeated loads.

Figures 8: Torque - twist angle relationship of tested beams ((B-S-M) & (B-S-R)) under Monotonic and repeated loads.



(a) Beam (B-H-M) tested under Monotonic loads. (b) Beam (B-H-R) tested under Repeated loads.

Figures 9: Torque - twist angle relationship of tested beams ((B-H-M) &(B-H-R)) under Monotonic and repeated loads.

When a body is twisted, one half of the beam is rotated while the other half is rotated in the opposite direction. Two LVDTs were mounted to the steel plate at the end of the beams so that the twisting angle could be measured. The value of the graph shows that the torsional moment is plotted against the average of the two twist angles of each tested beam.

It was found that hollow-sectioned concrete beams didn't change the rotation angle much compared to solid-sectioned beams if the decrease in rotation angle is less than 5.06% for models tested under monotonic loads and less than 5.34% for models analyzed under repeated loads.

3.3 Longitudinal elongation response

Once the cracking torsional moment was achieved, all beams lengthened longitudinally due to the creation and enlargement of concrete fractures. During the test, we wrote down the values of elongation for each load until the maximum torque was reached **[10]**.

Comparing the value of the lateral displacement of hollow-section beams to the section of a solid beam reveals that the value of the final displacement at the maximum torque value increased by 3.35% for beams tested under monotonic loads and by 4.66% for beams tested under repeated loads.

Figure 10 illustrates the torque-longitudinal elongation relationships for controlled (hollow and solid) beams evaluated under monotonic load. In the same way, figure 11 shows how the longitudinal elongation values of the tested beams (both hollow and solid) change when they are subjected to repeated loads compared to when they are subjected to monotonic loads.

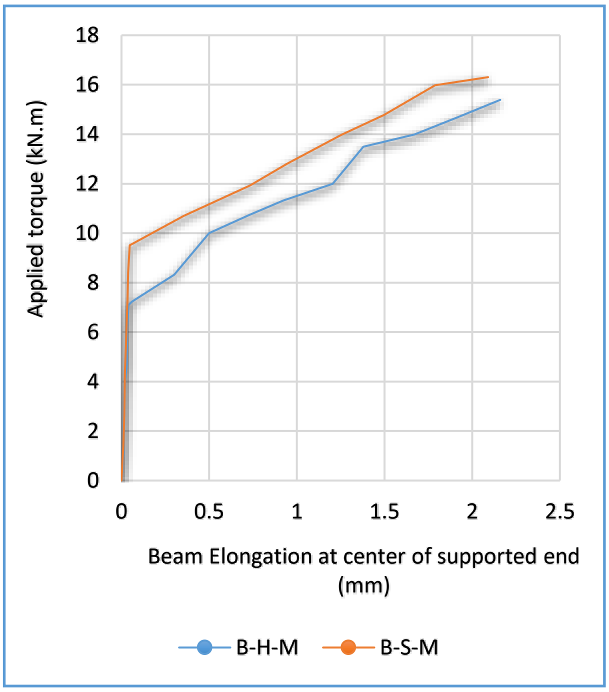


Figure 10: Torque – elongation curve for beams tested under monotonic loads (solid & hollow section).

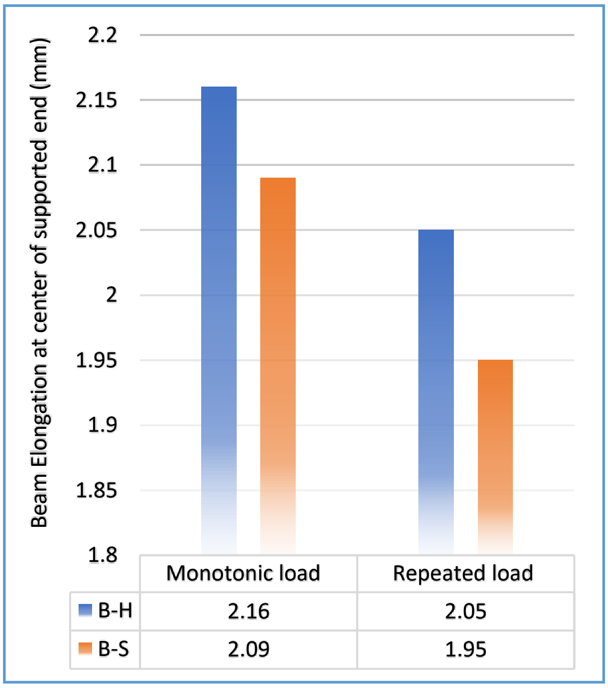


Figure 11: Beam longitudinal elongation value under monotonic and repeated loads (solid & hollow section).

3.4 Crack width response

The influence of the cross-section type (solid and hollow) and load type on the width of the cracks created in the beams during the test was one of the most important findings when analyzing each model. Figures 12 indicate that, in general, main cracks occur and form after midspan near the end of swivel brackets of samples. As the applied force increases, additional cracks appear. The number of cracks was observed to stabilize at 75% of the maximum load range. A digital concrete crack width meter was used to measure and record the crack width at each load increase during the test.

Figure 12: measure and record the crack width during the test.

Comparing the crack width values of beams with hollow sections to those of beams with solid sections reveals that the width of the cracks was not significantly impacted by the type of beam section nor by monotonic or repetitive loading conditions. Figures 13 and 14 illustrate the torque-crack width relationships for solid and hollow beams subjected to monotonic loading. In addition, compare the maximum crack width of the specimens (solid and hollow) subjected to monotonic static stress with the specimens subjected to a restricted number of cycles of repeated loading.

A thorough analysis of the preceding figures shows the following: The maximum width of the crack is proportional to the length of the inspection sample and is not always situated at the site of the initial fracture. Under the impact of repeated loading of the tested beam, a modest increase in crack width is attributed to the emergence of new large cracks generated by the applied cycles of repeated load and the reduction in ultimate load. In addition, repeated loading with limits had no significant impact on the number of cracks, how cracks propagated, or the number of cracks that formed in the beams.

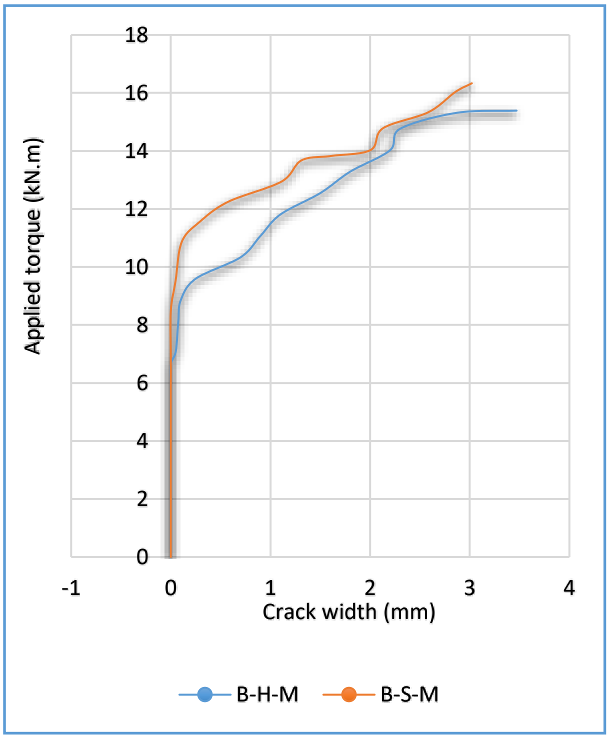


Figure 13: Torque-crack width relationship in beams (Solid & hollow section) tested under monotonic loads.

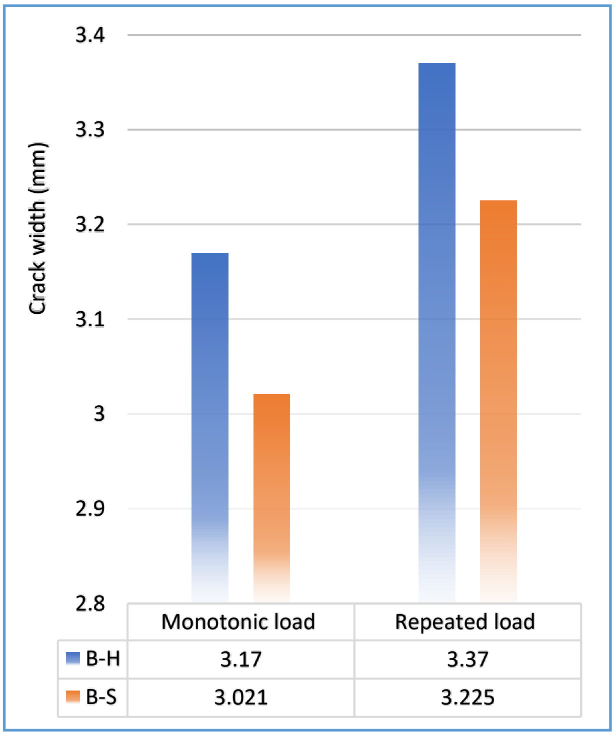


Figure 14: Crack width value of tested beams (Solid & hollow section) under monotonic and repeated load.

3.5 Torsional Stiffness

The property of stiffness is used to characterize the rigidity of a material. Therefore, torsional stiffness is the amount of resistance a member offers per degree of twist. The definition of torsional stiffness before cracking is stiffness before a crack (K_{pre}). It may be derived from the torque-twist curve as the pre-cracking tangent slope of this curve, as shown in equation (1), whereas stiffness after cracking is defined as a post-cracking stiffness (K_{post}) that is much lower than the pre-cracking stiffness. It reflects, as in equation (2), the tangent slope of the torque-twist curve following breaking **[11]**. This approach was utilized to determine stiffness in the current investigation.

$$k_{pre-cracking} = T_{cr}/\theta_{cr} \quad \text{............ (1)}$$

$$k_{post-cracking} = (T_{max}-T_{cr}) / (\theta_{max}-\theta_{cr}) \quad \text{............. (2)}$$

The figures 15 and 16 illustrate the relationship between the stiffness values (pre-cracking and post-cracking stiffness) for solid and hollow concrete beams under monotonic and repeated loading conditions. Based on these results, it can be inferred that the pre-cracking values for hollow sections are lower than those for solid sections, but the influence on post-cracking stiffness values is minimal.

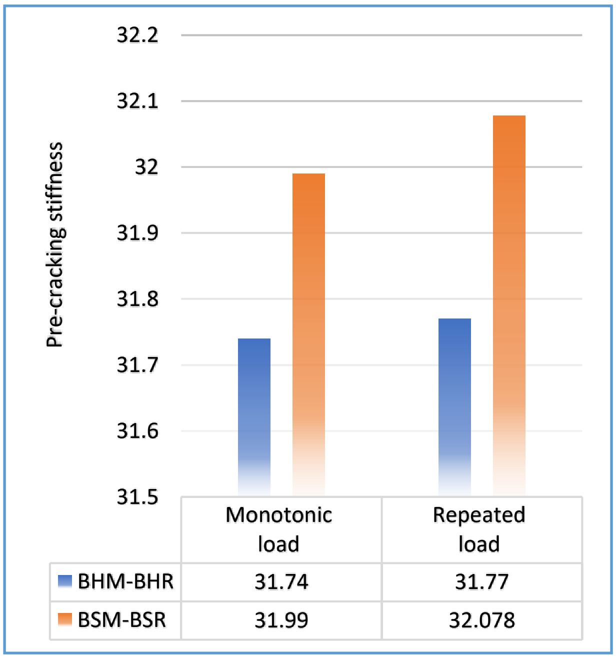


Figure 15: Effect of (Solid & hollow section) on pre-cracking stiffness value.

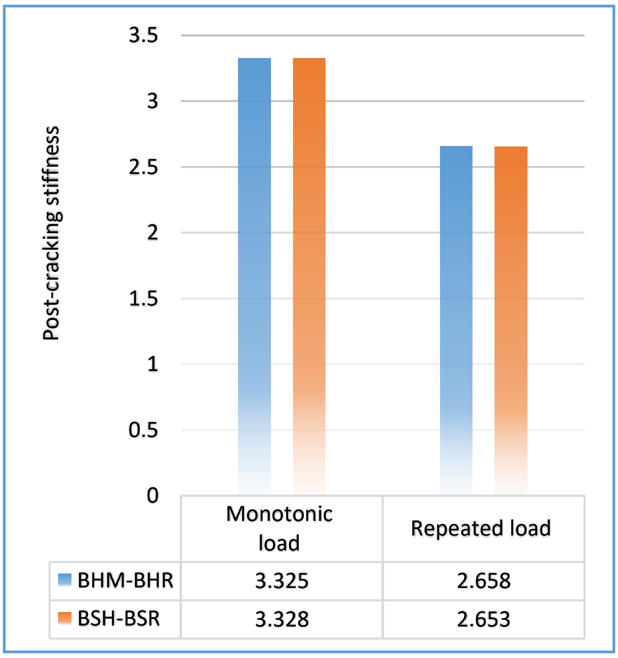


Figure 16: Effect of (Solid & hollow section) on post-cracking stiffness value.

When comparing the stiffness values of beams subjected to repeated loads to those subjected to monotonic loads, there is no discernible difference (pre-cracking and post-cracking stiffness).

3.6 The Energy Absorption and The Ductility

Mechanical energy is converted into internal potential energy by reinforced concrete members, and this is due to those members' inherent ductility and energy absorption. In addition, concrete members have to deal with a lot of complicated processes, like the fracture mechanics of concrete cracking and the deformations caused by elastic and plastic forces **[12].**

Numerous investigations have demonstrated that the ductility of reinforced concrete members is proportional to their energy absorption capacity. In this work, the areas under the energy absorption curves for all tested beams were calculated. This note calculates the energy absorbed at each cycle of the torque-twist curves of beams subjected to repeated loads, as well as the total energy absorbed for each girder.

When comparing the values of the ductility factor ratio of beams with hollow sections to beams with solid sections, as seen in figure 17, there is a modest drop of (4.52%) for beams exposed to monotonic loads and (4.78%) for beams subjected to repeated moments loads. Figures 18 and 19 depict the values of the energy absorbed by the tested beams and whether or not they were affected by monotonic and repetitive loads on the solid parts versus the hollow sections.

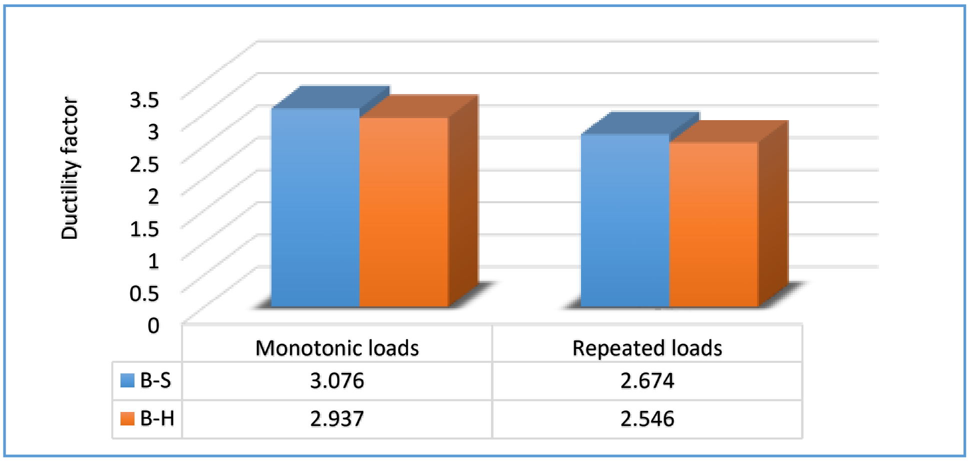


Figure 17: Effect of section type (Solid & hollow) on ductility factor.

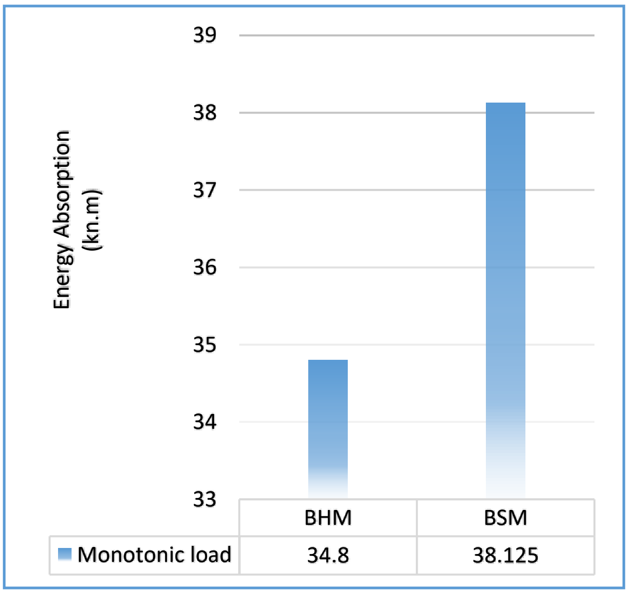


Figure 18: Energy absorption of beams (Solid & hollow section) tested under monotonic load.

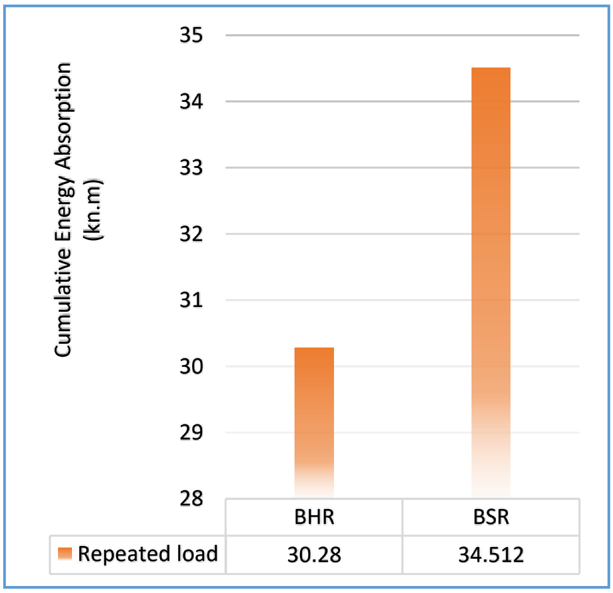


Figure 19: Cumulative Energy absorption of beams (Solid & hollow section) tested under repeated load.

The ductility factor of tested beams under monotonic load is greater than the ductility factor of tested beams under repeated loads after a cycle of loads due to the loss in stiffness of the beams when they are subjected to repeated loads, particularly in the last five or six cycles of the loading and unloading process.

3.7 Failure Mechanism

Due to torsional moments, all of the reinforced concrete beams that were tested failed. On all four sides of the testing span, diagonal cracks occurred in a spiral pattern on typical reinforced beams.

As the applied loading rose, the cracks grew larger at both ends and around the reinforced concrete beam's centroidal axis. The photograph shown in figure 20 demonstrates that most cracks in the reinforced beams were dispersed.

Figure 20: Failure modes of beams tested under monotonic and repeated loads.

The failure mechanism for each specimen exposed to repeated loading was similar to that of its counterpart subjected to monotonic static loading on the specimen.

4. Conclusions

1. The cracking (**T_{cr}**) and ultimate torque (**T_u**) for hollow beams made with (circular hollow in the center of a rectangular section with a 10 mm diameter) decrease by approximately 6.09% and 5.58%, respectively, under the effect of monotonic torque, and by approximately 6.8% and 6.03%, respectively, under the effect of monotonic torque, when compared to the cracking and ultimate torque strength for rectangular solid beams. The hollow core has a little impact on the crack and ultimate torque strength and the capacity to alter the mode of failure.
2. Under the effect of monotonic or repeated torque, the angle of twist for hollow beams is smaller than for solid beams.
3. Whether or not the torque is monotonic or repeating, when comparing solid-sectioned and hollow-sectioned beams, the concrete core has little effect on crack width and beam elongation.
4. In general, the crack width is less when beams are subjected to repeated loads as opposed to monotonic loading. This is mostly due to the repeated cycles of load application and the reduced ultimate load, which led to the formation of new big cracks.

5. The torsion stiffness of solid beams was greater than that of hollow beams.
6. We may assert that adopting hollow-section beams reduces energy absorption and ductility compared to solid beam sections if the applied torque is monotonic or repeated.
7. Both solid and hollow beam sections showed no noticeable effect on the inclination angle of the fractures. In general, hollow parts have a greater number of fractures than solid sections. Both failed beam types exhibited severe diagonal torsional fractures as a result of the high torsional shear stress.
8. According to tests, the slope of cracks under pure torsion is roughly 45°.
9. Failure mechanisms of specimens subjected to repeated loading were comparable to those of specimens subjected to monotonic static stress.

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