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Torsional Behavior of RC Beams with Transverse Openings Strengthened by Near Surface Mounted-Steel Wire Rope Subjected to Repeated Loading

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ABSTRACT

The openings' presence negatively affects the beams' strength. The openings act as a weak point because of the sudden change in the cross-section of a beam. So, it becomes necessary to strengthen beams to resist the effect of the openings and improve the beams' strength, especially when the beams are subjected to repeated loads because of their effect on the strength at the failure. The present paper studies the effect of the openings on beams subjected to repeated loading and determines the extent of the strength increase of the beams when strengthened by the Near Surface Mounted technique (NSM). The experimental program included casting and testing fifteen RC beams. Six were considered control beams without openings (three with strengthening and three without strengthening), and nine had circular transverse openings in different locations and were strengthened by the NSM technique. Each beam was tested under three different types of loads, i.e., monotonic (for control beams), constant repeated load, and incremental repeated load. All beams had similar dimensions and reinforcement. The results showed that all beams with transverse openings were affected by repeated loads, as the ultimate torque decreased and the twist angle increased. The openings had a noticeable effect on reducing the ultimate torque, whereas the percentage of the ultimate torsional capacity reduction reached 43.83% in the beam where the opening location was closest to the support (at a quarter of the clear span) and subjected to constant repeated loads. The ultimate torque was significantly improved when the opening position was moved away from the supports. Also, strengthening reduced or eliminated the influence of openings on the ultimate torque compared with non-strengthened beams.

تصرف اللي للعتبات الخرسانية المسلحة الحاوية على فتحات والمقواة بالحبال الحديدية بتقنية التقوية القريبة من السطح تحت الاحمال التكرارية

إسراء خليل جاسم، مازن برهان الدين عبد الرحمن، ميسر محمد جمعة/ قسم الهندسة المدنية/ كلية الهندسة / جامعة تكريت.
بلال الصباري/ قسم الهندسة المدنية ، كلية الهندسة ، كلية ميامي في جامعة هنان ، كايفينغ ، هنان ، الصين.
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الخلاصة

ان وجود الفتحات الجانبية يؤثر سلبا على قوة العتبات حيث تعمل كنقطة ضعف بسبب التغير المفاجئ في المقطع العرضي للعتبات لذلك أصبح من الضروري تقوية العتبات لمقاومة تأثير الفتحات وتحسين قوة العتبات، خصوصا إذا تعرضت العتبات لأحمال تكرارية حيث تعمل تلك الاحمال على تقليل مقدار الحمل عند الفشل. تضمن هذا البحث دراسة تأثير الفتحات على العتبات المعرضة لأحمال تكرارية ومعرفة مقدار الزيادة في قوة العتبات عند تقويتها بتقنية التقوية القريبة من السطح. تضمن البرنامج التجريبي صب وفحص خمس عشرة عتبة خرسانية مسلحة، ست عتبات منهن اعتبرن كعتبات مرجعية (ثلاث عتبات مقواة وثلاث غير مقواة) بينما تحتوي التسع عتبات المتبقيات على فتحات دائرية بمواقع مختلفة ومقواة بتقنية التقوية القريبة من السطح. كل نوع من انواع العتبات فحص تحت ثلاث انواع مختلفة من الاحمال (تزايديه، تكرارية ثابتة وتكرارية متزايدة). كل العتبات تمتلك نفس الابعاد والتسليح. اظهرت النتائج ان كل العتبات التي تحتوي على فتحات تأثرت بالأحمال التكرارية حيث قلت قابلية الالتواء القصوى وزادت زاوية الدوران. ان وجود الفتحات له تأثير ملحوظ على تقليل قابلية الالتواء القصوى حيث ان نسبة النقصان في قابلية الالتواء القصوى وصلت الى 43.83% في العتبة التي يكون موقع الفتحة فيها الاقرب الى المسند (ربع الفضاء الصافي) ومعرضة لأحمال تكرارية ثابتة، وان قابلية الالتواء القصوى تحسنت بصورة ملحوظة كلما ابتعدت الفتحات عن موقع المساند. بالإضافة الى ان وجود التقوية قد قلل او ألغى تأثير الفتحات على قابلية الالتواء القصوى مقارنة بالعتبات غير المقواة.

1.INTRODUCTION

The fatigue strength of concrete, like all other materials, is much lower when it is subjected to fluctuating rather than steady loads. Plain concrete in compression has a fatigue limit of 50% to 60% of its static compressive strength after 2,000,000 cycles of stressing from zero to maximum stress. The fatigue limit is around 55% of the relevant static strength for various forms of applied stress (Darwin, D et al, 2016) [1-4]. Actually, web openings in beams are common to ease the passage of environmental services. These openings can come in various forms and sizes (Amiri, S and Masoudnin, R, 2011) [5]. Because an opening causes a sudden change in the size of the beam's cross-section, transverse openings change the beams' simple behavior into a more complicated behavior. Usually, the failure plane passes through the opening because it indicates a point of weakness. Ultimate strength, shear strength, crack width, and stiffness may all be impacted (Abdulrahman, M et al, 2020) [6].

Furthermore, the openings' presence causes discontinuities or changes in the normal flow of stresses, resulting in stress concentration and fast cracking in the location of the opening. Special strengthening or enclosing of the opening near its periphery, similar to any discontinuity, should be supplied in sufficient quantities to limit crack widths and prevent early beam failure. Web openings are classified depending on the size and location into small and large openings, and the ideal place for each is determined by its size. The forms of web openings have been discovered to be circular, rectangular, diamond, triangular, trapezoidal, and even irregular. Round and rectangular openings are the most common (Ahmed, A et al., 2012) [7]. When reinforced concrete structures are subjected to torsional moments, the torsion strength must be increased. So, torsion member strengthening techniques are required. [8-10] One of these techniques is the near-surface mounted NSM technique, when the strengthening materials are embedded into the concrete surface in grooves that have already been created. Typically, the NSM systems are installed in grooves cut into the concrete cover. During the groove-cutting process, the existing steel reinforcement must not be affected. Before placing the beam, the soundness of the concrete cover must be checked. The inside sides of the groove should be cleaned to establish a good connection with the concrete. The groove resulted should be clear of laitance and other chemicals that might interfere with bonding. The moisture content of the parent concrete should be managed to suit the adhesive's bonding characteristics. The glue should be filled into the grooves. The glue should be recommended by the manufacturer of the NSM system [11-13]. Steel wire rope is suitable as a strengthening material for several structural elements because of its exceptional flexibility, availability, and low cost. [14-18]. Al amli, AS et al., 2017 [16] investigated the torsional response of reinforced reactive powder concrete (RPC) T-section beams with square and circular web openings. The experimental study included casting and testing ten T-beams with square and circular web openings using reactive powder concrete (RPC) beams with similar dimensions. The results showed that when the size of the opening increased, the ultimate torques decreased, and the crack density increased and became non-uniform. Also, the torque capacity was reduced because the opening eccentricity made non-uniformity in the shear stress distribution through the web. Hasan, SS, 2020 [19] investigated the behavior of high-performance concrete T-beams with a transverse opening under a pure torsional moment. The experimental work included testing ten beams under a torsional moment. All beams had the exact dimensions and reinforcements. The experimental results showed that when compared to a solid beam, the T-beam with circular openings of diameter (100mm) at different positions (Lc/2 and Lc/3) had a lower torsional capacity by about 23% and 30%, respectively. Also, the HPC T-beams with circular openings of diameter (150mm) with different locations (Lc/2 and Lc/3) had lower ultimate torsional capacity by about (56 % and 61%) than a solid beam. For beams with square openings of dimension (132mm x132mm) with different locations (Lc/2 and Lc/3), the reduction in the ultimate torsional capacity was about (58 % and 66%). Hamzah, AS and Ali, AY, 2020 [20] focused throughout the experimental study on the shear behavior of RC beams with openings. Five square RC beams, one without an opening and four with an opening. All studied beams were the same size. The results showed that a vertical opening marginally decreased the ultimate load capacity. Also, it had a negligible impact on increasing the maximum deflection under service loads. On the other hand, the circular form of openings had a more negligible influence on decreasing the ultimate load capacity than square openings. The study found that using stirrups on each side of the opening in the longitudinal direction was sufficient to improve the ductility index and replace the lost strength. In addition, it was discovered that transverse openings significantly impacted the ultimate load more than vertical openings. Ling, JH et al., 2020 [21] experimentally investigated the behavior of RC beams with a circular opening. Eleven RC beams were studied in the work program, all of which had the exact dimensions. The results showed that the opening impacted the beam's stiffness, yield strength, ultimate strength, and ductility, especially in large openings. The diagonal bar reinforcing technique strengthened beams with a 1/3 beam height opening.

2.PROBLEM STATEMENT

Some beams, such as those in bridges, may be simultaneously subjected to torsional moments and repeated loads. In these cases, the torsional moments are brought on by the eccentricity of the loads, whilst the repeated loads were brought on by the passage of vehicles. To increase the shear or flexural strengths of reinforced concrete beams, previous literature has mostly concentrated on near-surface mounting. A few studies have concentrated on torsional strength, but none of them have studied the beam's behavior under repeated loads. This study investigated beam behavior under repeated loads and the impact of the repeated load on the beam's torsional resistance. The present investigation included the negative impacts of transverse opening on torsional behavior. Also, the work studied the role of strengthening steel wire by applying the NSM technology in increasing the torsional capacity of the beams.

3.MATERIALS

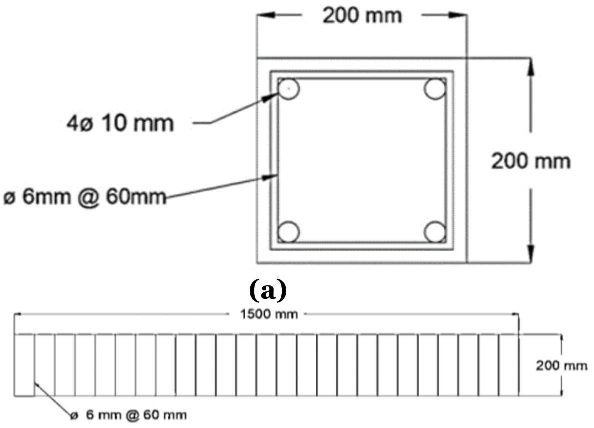
The characteristics of materials used in the present work are listed below.

- **Cement:** Ordinary Portland cement (Type 1) meeting the requirements of (ASTM C150/C150M-19a) [22].
- **Sand:** natural sand meeting the requirements of (ASTM C778-17) [23] was used with a maximum aggregate size of 4.75 mm.
- **Gravel:** natural gravel meeting the (ASTM C33/C33M-18) [24] requirements was used with a maximum aggregate size of 14 mm. The quantity of materials used is shown in Table (1).
- **Strengthening material:** steel wire rope (Ø4mm) used as a strengthening material in all the beams with f_y=416MPa and f_u=520Mpa, as shown in Fig. (1).
- **Epoxy Glue:** Sikadur®-330 was used in all strengthened beams.
- **Steel Reinforcement:** the yielding stress for reinforcing steel bars used with a diameter of 10 mm and 6 mm was 583Mpa and 520 Mpa, which satisfies the (ASTM A615/A615M15a) [25] and (ASTM C 1018/18) [26] requirements. The reinforcement details are shown in Fig. (2).

Table 1. The weight of materials in a cubic meter

Cement (kg)	Sand (kg)	Gravel (kg)	Water (kg)
380	798	911	173

Fig. 1 Steel Wire Rope.



(a)

(b)

Fig. 2 Beam and Reinforcement Details

4.EXPERIMENTAL PROGRAM

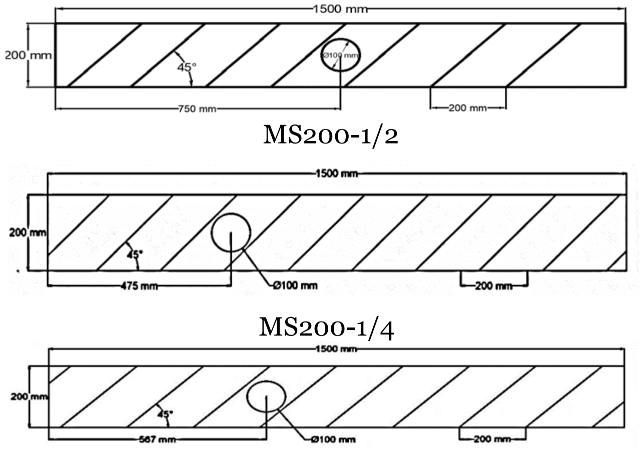
In this study, the main parameters are:

1. The loading type: monotonic and repeated (constant repeated load and incremental repeated load).
2. Location of transverse openings: in the quarter, one-third, and middle of the beam.

Fifteen RC beams were cast and tested, and six were considered control beams without openings (three with strengthening and three without strengthening). The rest specimens had circular transverse openings with a diameter of 100 mm in different locations and were strengthened by steel wire rope by NSM technique. All tested beams had the exact dimensions of (200*200*1500) mm and had the same reinforcement. Table (2) and Fig. (3) present the properties and variables of the tested beams.

Table 2. The Variables of the Tested Beams

No.	Beam designation	Type of load	Spacing between wires (mm)	Location of opening
1	M	Monotonic	Un-strengthened	Without openings
2	RC	Repeated Constant	Un-strengthened	Without openings
3	RI	Repeated Incremental	Un-strengthened	Without openings
4	MS200	Monotonic	200	Without openings
5	RC-S200	Repeated Constant	200	Without openings
6	RI-S200	Repeated Incremental	200	Without openings
7	MS200-1/2	Monotonic	200	Midspan
8	MS200-1/4	Monotonic	200	¼ of clear span
9	MS200-1/3	Monotonic	200	1/3 of clear span
10	RC-S200-1/2	Repeated Constant	200	Midspan
11	RC-S200-1/4	Repeated Constant	200	¼ of clear span
12	RC-S200-1/3	Repeated Constant	200	1/3 of clear span
13	RI-S200-1/2	Repeated Incremental	200	Midspan
14	RI-S200-1/4	Repeated Incremental	200	¼ of clear span
15	RI-S200-1/3	Repeated Incremental	200	1/3 of clear span



MS200-1/2

MS200-1/4

MS200-1/3

Fig. 3 The Location of the Openings.

5.CONTROL SPECIMENS

For each concrete batch and according to ASTM C496/C496M-17 [27], three (150 * 300 mm) cylinders were cast and tested for the tensile split test. Also, three (150*150*150mm) cubes were cast and tested according to B.S. 1881 116-(1983) [28] for the compressive test.

6.STRENGTHENING PROCESS

The steps of the strengthening process were:

1- In the concrete cover of the beams, grooves with a 10 mm width and 10 mm depth were made in a variety of configurations after the beams had cured (it is recommended that the grooves' minimum size should be at least 1.5 times the diameter of the strengthening material (ACI 440.2R-08) [29]).

2- After the grooves were cleaned and smoothed, epoxy adhesive was used to fill the grooves before steel wire rope was introduced for strengthening.

3- To keep the epoxy's full strength, the beams were stored for two weeks.

(a) (b)

Fig. 4 Strengthening Process of Beams.

7.TEST SETUP

By placing the beam ends on rollers at the unresisting support and connecting the two ends of the steel arms to a steel girder, the beam was allowed to slide freely and elongate while transferring the loads from the device equally on both sides of the beam. The force was then transferred from both sides of the steel arm to the beam as an oppositely directed torsional moment. Then the twist angle of the free end (the location of imparting the torque) was measured with the help of the downward distance of the lever arm at that location using a dial gauge. Figs. (5,6) shows the test setup.

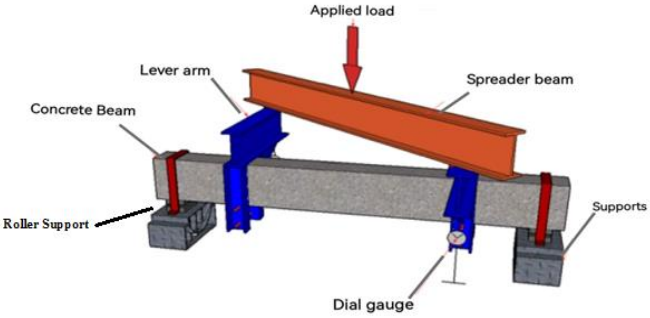


Fig. 5 Test Setup.

Fig. 6 The Loading Frame

8. LOADING PROCESS

8.1 *Monotonic Loading Test*

five beams were subjected to a monotonic load, where the load increased until failure.

8.2 Repeated Loading Test

8.2.1.Constant repeated load

Five beams were subjected to a constant repeated load, and each cycle's loading level was 60% of a comparable monotonically tested beam's ultimate load. The beams were subjected to four testing loops; the load was raised until failure occurred.

8.2.2.Incremental repeated load

Five beams were subjected to incremental repeated load. Each cycle's loading values were 20%, 40%, 60%, and 80% of a comparable monotonically tested beam's ultimate load. The beams were subjected to four testing loops, and the load was raised until failure occurred.

9. ANGLE OF TWIST MEASUREMENTS

A dial gauge was used to measure the vertical deflection of the tested beams brought on by the applied torque. The bottom of the lever arms was where the dial gauge was affixed. By dividing the recorded deflection from the dial gauge reading by the horizontal distance between the beam center and the dial gauge (400 mm), the twisting angle was determined.

10.EFFECT OF THE OPENING LOCATION

10.1.Effect of The Opening Location on The Cracking Load

The effect of the opening's location on the cracking load for beams tested under different types of loads in this study is shown in Table (3).

Regardless of the openings' locations, the presence of openings in strengthened beams significantly reduced the cracking torque that reached 47.09% (in beam RC-S200-1/4) in contrast to beams with the same type of strengthening and the same type of applied load. However, compared to the non-strengthened beams, it can be observed from Table (3) that the openings' effect was insignificant in some beams and had no effect on the other beams. Therefore, the strengthening reduced or eliminated the influence of openings on the cracking torque compared with the non-strengthened beams.

Table 3. The Effect of The Openings Location on The Cracking Load

Beam Designation	Tcr* (kN.m)	Tcr / (Tcr for M)**	Tcr/(Tcr for MS200)**	Tcr / (Tcr for RC)**	Tcr / (Tcr for RC-S200)**	Tcr / (Tcr for RI)**	Tcr / (Tcr for RI-S200)**
M	5.12	100	-	-	-	-	-
MS200	7.17	-	100	-	-	-	-
MS200-1/2	4.80	93.75	66.97	-	-	-	-
MS200-1/4	4.14	80.90	57.77	-	-	-	-
MS200-1/3	4.27	83.42	59.59	-	-	-	-
RC	4.25	-	-	100	-	-	-
RC- S200	6.50	-	-	-	100	-	-
RC- S200-1/2	4.30	-	-	101.36	66.19	-	-
RC- S200-1/4	3.44	-	-	81.01	52.90	-	-
RC- S200-1/3	3.70	-	-	87.27	56.99	-	-
RI	4.75	-	-	-	-	100	-
RI- S200	6.87	-	-	-	-	-	100
RI- S200-1/2	4.62	-	-	-	-	97.32	67.34
RI- S200-1/4	3.90	-	-	-	-	82.04	56.76
RI- S200-1/3	3.89	-	-	-	-	81.98	56.72

*Tcr= Cracking Torque

**Tcr/Tcr for M%, RC% and RI%=

$$\frac{\text{Tcr for each beam}}{\text{Tcr for control beams (M,RC and RI)}} * 100\%$$

10.2 Effect of The Opening Location on The Ultimate Torsional Capacity

The effect of the openings' location on the ultimate load for beams tested under different types of loads in this study is shown in Table (4).

Table 4. The Effect of The Openings' Location on The Ultimate Torsional Capacity

Beam Designation	Tu* (kN.m)	Tu/ (Tu for M%) **	Tu/ (Tu for MS200%) **	Tu / (Tu for RC%) **	Tu / (Tu for RC-S200%) **	Tu / (Tu for RI%) **	Tu / (Tu for RI-S200%) **	Angle of Twist (rad)
M	9.05	100	-	-	-	-	-	0.068
MS200	13.09	-	100	-	-	-	-	0.097
MS200-1/2	9.18	101.1	62.44	-	-	-	-	0.062
MS200-1/4	7.41	81.82	56.56	-	-	-	-	0.073
MS200-1/3	8.06	89.10	61.6	-	-	-	-	0.064
RC	6.69	-	-	100	-	-	-	0.089
RC- S200	11.17	-	-	-	100	-	-	0.013
RC- S200-1/2	7.74	-	-	115.62	69.23	-	-	0.072
RC- S200-1/4	6.28	-	-	93.81	56.17	-	-	0.083
RC- S200-1/3	7.04	-	-	105.16	62.97	-	-	0.069
RI	8.51	-	-	-	-	100	-	0.079
RI- S200	12.13	-	-	-	-	-	100	0.13
RI- S200-1/2	8.42	-	-	-	-	98.91	69.39	0.067
RI- S200-1/4	7.06	-	-	-	-	82.94	58.18	0.075
RI- S200-1/3	7.64	-	-	-	-	89.75	62.96	0.067

*Tu= Ultimate Torque
**Tu/Tu for M%,RC% and RI%=

$$\frac{\text{Tu for each beam}}{\text{Tu for control beams (M,RC and RI)}} * 100\%$$

From Table (4). it can be noted that:

1- All beams with transverse openings (in the center, third, and quarter of the clear span) were affected by the repeated loads. The ultimate torque decreased while the twist angle increased. However, the value of this effect between different positions of openings was convergent. The decrease in ultimate torque was between 8% and 16%, and the increase in the twist angle was between 3% and 8%. The reason for this convergence, despite the difference in the openings' locations, was that the repeated load's effect was evenly distributed along the beam and was unchanged from one point to another.

2- Under any type of load, beams with openings in mid-span showed an increase in the ultimate torque and a decrease in the twisting angles, in contrast to those with openings in the quarter or third of the clear span. The different behavior due to the openings' location resulted from the eccentricity in terminal openings that led the plastic hinge location to move from the center because of the openings' locations.

3- The existence of openings significantly reduced the ultimate torque, which reached 43.82% (for beam RC-S200-1/4), and increased the angle of twist that reached 16% (for beam RC-S200-1/2) compared with beams that had the same strengthening and under the same type of loads. However, compared with non-strengthened beams, the effect of openings was insignificant in some beams and had no effect on the other beams. The insignificant effect was due to strengthening that reduced or eliminated the influence of openings on the ultimate torque compared to non-strengthened beams.

4- The beams with openings lying in the quarter of the clear span showed the weakest resistance against torque moment compared with other openings' positions because it was the closest to the support. The area near the supports had higher shear forces, so when the openings' position approached the supports, the beams' resistance decreased against torque moment and increased in deformations.

5- The difference in ultimate torque and angle of twist between beams with openings in a third of clear span and beams with openings in a quarter of clear span is little. For example, in a beam with an opening in a quarter of a clear span and under monotonic load, the ultimate torque was 7.41 kN.m, and the twisting angle was 0.073. In contrast, in a beam with an opening in the third of a clear span and under the same type of load, the ultimate torque was 8.069 kN.m, and the twisting angle was 0.064. The same behavior was observed in a beam under other types of loads. The reason for this behavior was that the difference between the quarter of a clear span and the third was slight.

10.3 Torque- Angle of Twist Response

Figs. (7-17) present the relationship between the torque and angle of twist for beams with openings. Fig. (7) shows the torque-twisting angle relationship for beams tested under monotonic loading (M), (MS200), (MS200-1/2), (MS200-1/3), and (MS200-1/4). It can be seen that the torsional capacity was significantly improved when the opening position was moved away from the supports. Under the same load, the control beam (MS200) had a larger torque capacity and a lower twist angle than the beams with transverse openings, while the control beam (M) had values of torque moment and twist angle close to that of beams with transverse openings. The torque–twist curves for beams with openings similarly behaved as the control beams with different changes at the last stage. However, before cracking, the slope of torque–twist curves had insignificant changes. Due to the stirrups or steel wire rope reinforcement that resisted the torque applied to the beams, all curves attempt to show a constant slope throughout the post-cracking stage. Figs. (8-12) show the torque-twisting angle relationship for beams tested under constant repeated loading (RC-S200-1/2), (RC-S200-1/3), and (RC-S200-1/4). It can be seen that the torsional capacity was significantly improved when the opening position was moved away from the supports by about 12% for the beam (RC-S200-1/3) and 23% for the beam (RC-S200-1/2) compared with the beam (RC-S200-1/4). The cracking happened in the first loop for all beams. At one beam, all loops were intertwined, and the slope of all the loops was approximately equal. However, compared with other beams, the inclination of the loops decreased when the opening was close to the mid-span. As a result, the stiffness of beams (the ratio of torsional capacity to related twist angle) increased when the opening was close to the mid-span. Under the same load, the control beam (RC-S200) had a lower slope of the loops (larger torque capacity and lower twist angle) than the beams with transverse openings, while the control beam (RC) had inclinations in the loops that were close to beams with transverse openings. Figs. (13-17) show the torque-twisting angle relationship for beams tested under incremental repeated loading (RI-S200-1/2), (RI-S200-1/3), and (RI-S200-1/4). It can be seen that the torsional capacity was significantly improved when the opening position was moved away from the supports by about 8% for the beam (RI-S200-1/3) and 19 % for the beam (RI-S200-1/2) compared with the beam (RI-S200-1/4). The cracking happened in the third loop for all beams. At one beam, all loops were intertwined, and the slope of all the loops was approximately equal. However, compared with other beams, the inclination of the loops decreased when the opening was close to the mid-span. As a result, the beams' stiffness increased when the opening was close to the mid-span. Under the same load, the control beam (RI-S200) had a larger torque capacity and a lower twist angle than the beams with transverse openings, while the control beam (RI) had torque moment and twist angle close to beams with transverse openings. However, the shape and slope of loops in beams (RI-S200) and (RI) differed from those in beams with transverse openings.

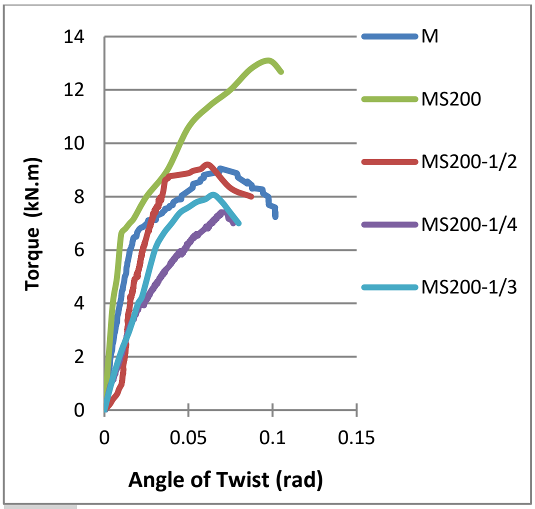


Fig. 7 Torque- Twisting Angle Relationship for Beams (M, (MS200), (MS200-1/2), (MS2001/3) and (MS200-1/4)

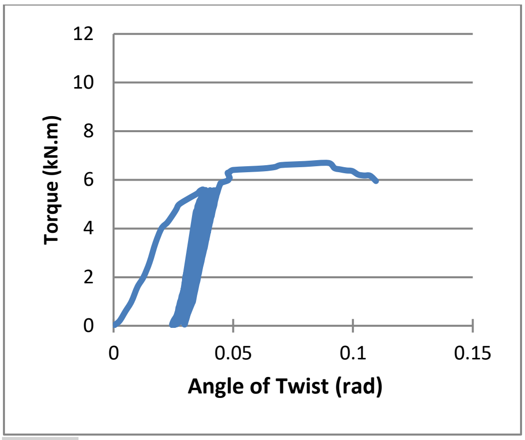


Fig. 8 Torque-Twisting Angle Relationship for Beam (RC).

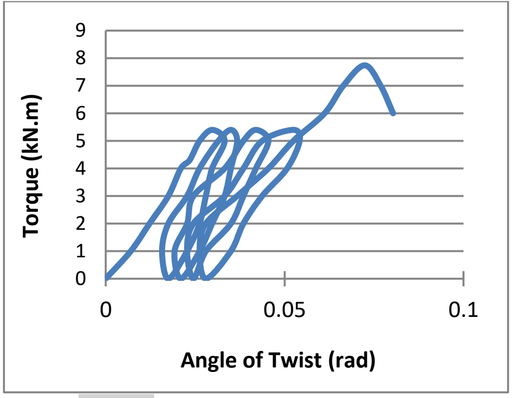


Fig. 9 Torque-Twisting Angle Relationship for Beam (RC-S200-1/2).

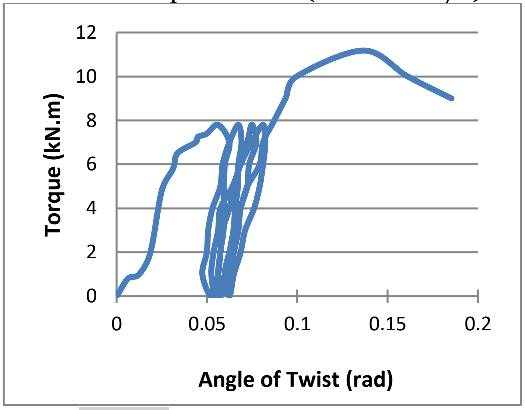


Fig. 10 Torque-Twisting Angle Relationship for Beam (RC-S200).

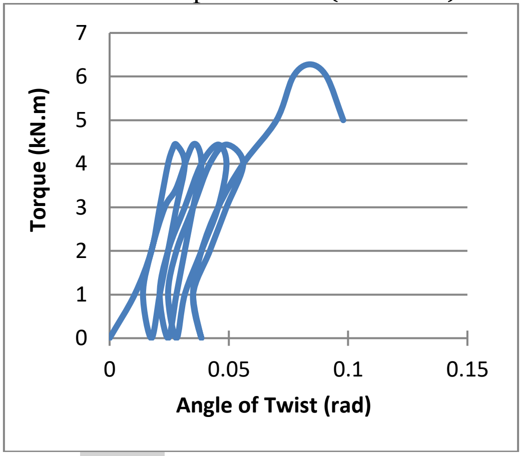


Fig. 11 Torque-Twisting Angle Relationship for Beam (RC-S2001/4).

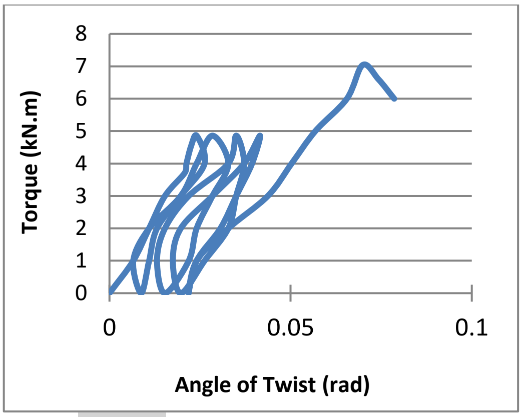


Fig. 12 Torque-Twisting Angle Relationship for Beam (RC-S200-1/3).

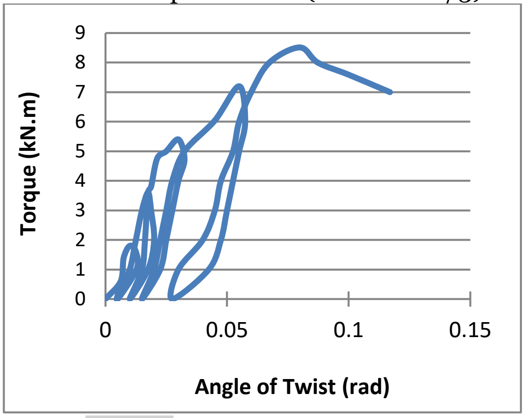


Fig. 13 Torque-Twisting Angle Relationship for Beam (RI).

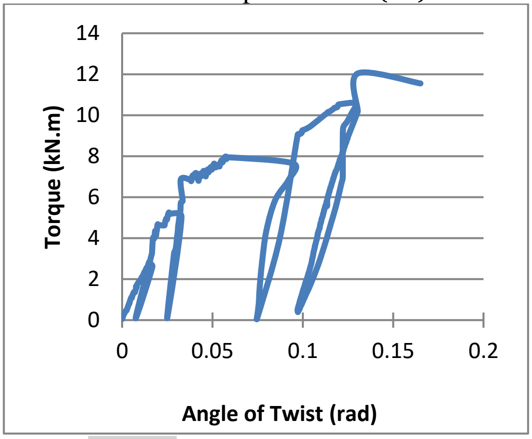


Fig. 14 Torque-Twisting Angle Relationship for Beam (RI-S200).

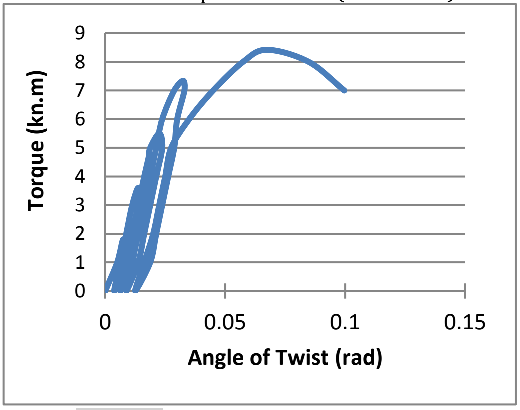


Fig. 15 Torque-Twisting Angle Relationship for Beam (RI-S200-1/2).

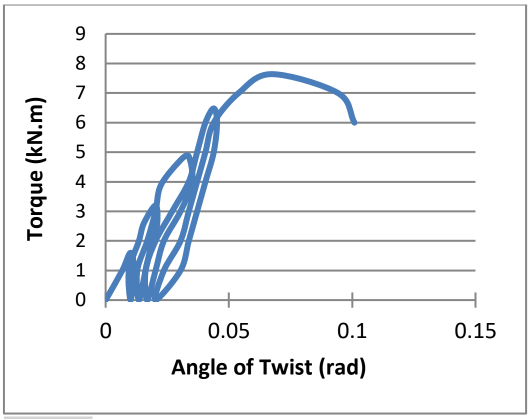


Fig. 16 Torque-Twisting Angle Relationship for Beam (RI-S200-1/3).

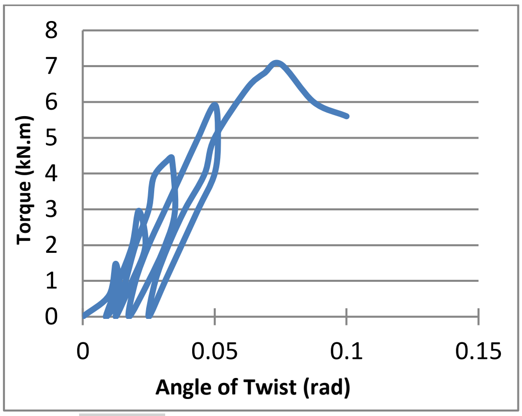


Fig. 17 Torque-Twisting Angle Relationship for Beam (RI-S200-1/4).

11. STIFFNESS

Torsional stiffness is the ratio between the ultimate torque and the related twist angle (Agarana, M. C. and Agboola, O. O., 2015) [30]. Table. (5) shows the torsional stiffness for tested beams.

Table 5. Stiffness at failure

Beam Designation	Stiffness (kN.m/rad)
M	133.17
RC	75.21
RI	107.74
MS200	135.04
RC-S200	82.19
RI-S200	93.36
MS200-1/2	148.06
RC-S200-1/2	107.5
RI-S200-1/2	125.67
MS200-1/4	101.50
RC-S200-1/4	75.66
RI-S200-1/4	94.13
MS200-1/3	126.07
RC-S200-1/3	102.02
RI-S200-1/3	114.02

From the obtained results, it is determined that:

1- The ultimate torsional capacity decreased, and the maximum twist angle increased due to repeated loading; as a result, the torsional stiffness of beams tested under repeated load was lower than the torsional stiffness of beams tested under monotonic load.

2- Beams with openings had lower torsional stiffness than beams without openings because the openings reduced ultimate torsional capacity and increased twist angle, reducing the torsional stiffness compared with beams without openings. The lowest torsional stiffness was for a beam (RC-S200-1/4) with an opening at the quarter of a clear span and tested under constant repeated load.

12. FAILURE MECHANISM

From the failure modes of tested beams shown in Figs. (18, 19), it can be noted that:

1- All tested beams experienced an initial crack that started at the clear span's first third and steadily grew in length. As the torque moment increased, cracks developed on the two vertical sides and eventually spiraled around the axis of the beam.

2- The primary cracks were inclined toward the longitudinal axis of the beam between 40 and 60 degrees.

3- Each beam had a different quantity of spiral cracks that permeated the test zone.

4- In comparison to beams tested under monotonic load, the width of cracks in beams tested under repeated load was significant. Additionally, the secondary cracks developed from the primary cracks in beams tested under repeated loads, mainly when the repeated loads were constant. This behavior was because the loading and unloading concrete process caused a variation in stresses, which resulted in significant concrete damage.

5- Most cracks and failures occurred at the openings' area, regardless of where the opening was located. In all cases, all the cracks and failures occurred just at the opening because the opening in the transverse position was considered a weak area due to the reduction in the cross-sectional transverse area. Also, the opening region had no strengthening, as the strengthening reduced the number of cracks in the area where there were no openings.

6- Only in beams with transverse openings and subjected to repeated loads, crushing and smashing occurred in the concrete cover of the opening region.

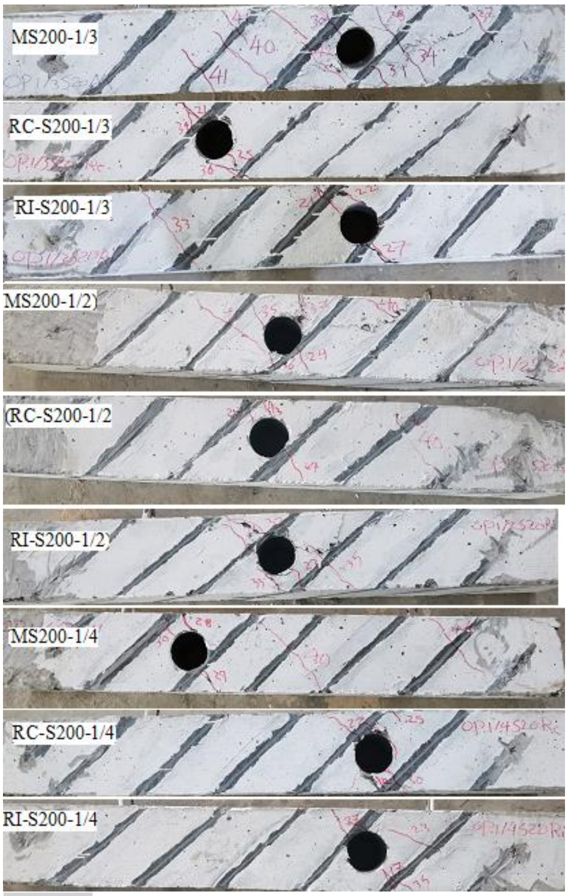


Fig. 18 Failure Mode for Beams with openings

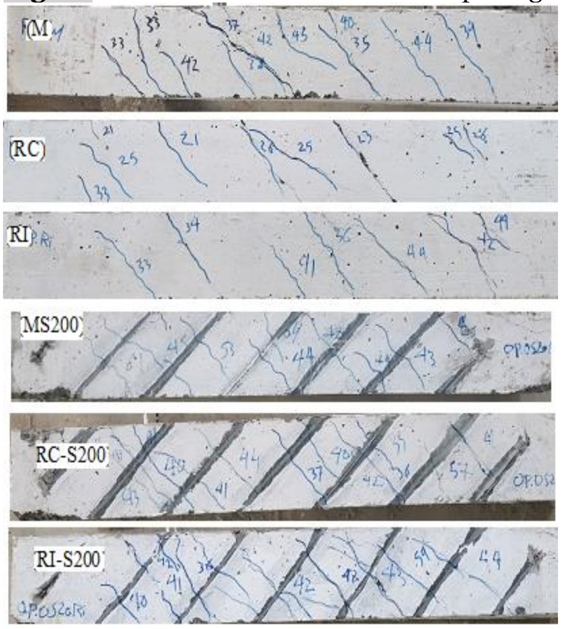


Fig. 19 Failure Mode for References Beam

13. CONCLUSIONS

The following conclusions are obtained from the experimental results of the tested beams:

1- Compared to monotonic loading, both types of repeated loading negatively affected the beams, increasing the maximum angle of twist and decreasing the ultimate torsional capacity to 26.08% and 140%, respectively.

2- Compared to the incremental repeated loading type, the constant repeated loading type significantly reduced the ultimate torsional capacity and increased the twisting angle.

3- Under any type of loads, beams with openings in the mid-span showed an increase in the ultimate torque and a decrease in twisting angles compared with beams with openings in the quarter or third of a clear span.

4- The existence of openings significantly reduced the ultimate torque; it reached 43.824% compared with beams with the same form of strengthening and under the same type of loads. However, compared to the effect of openings in strengthened and non-strengthened beams, the effect of openings was insignificant in some beams and had no effect on the other beams, so the existence of strengthening reduced or eliminated the influence of openings on the ultimate torque compared with non-strengthened beams.

5- The beams with openings in the quarter of clear span showed lower resistance against torque moment than with the other positions of openings.

6- The difference in ultimate torque and angle of twist between beams with openings in the third of clear span and beams with openings in the quarter of clear span was insignificant.

7- All beams with transverse openings (in the center, third, and quarter of the clear span) were affected by repeated loads where the ultimate torque decreased, and the twist angle increased. However, the value of this effect between different positions of openings was convergent; the ultimate torque's reduction was between 8% and 16%, and the twist angle's increase was between 3% and 8%.

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