Information Sciences Letters

Volume 12
Issue 3 *Mar. 2023*

Article 1

2023

Torsional Behavior of RC beams Strengthened by Near Surface Mounted-Steel Wire Rope Under Repeated Loading

Israa Kh. Jasim
Department of Civil Engineering, The University of Tikrit, Tikrit, Iraq, israa.abc95@gmail.com

Mazin B. Abdulrahman
Department of Civil Engineering, The University of Tikrit, Tikrit, Iraq, israa.abc95@gmail.com

Information Sciences Letters
An International Journal

http://dx.doi.org/10.18576/isl/120301

Torsional Behavior of RC beams Strengthened by Near Surface Mounted-Steel Wire Rope Under Repeated Loading

Israa Kh. Jasim and Mazin B. Abdulrahman*

Department of Civil Engineering, The University of Tikrit, Tikrit, Iraq

Received: 22 Sep. 2022, Revised: 19 Oct. 2022, Accepted: 11 Nov. 2022.
Published online: 1 Mar. 2023.

Abstract: In this paper, the torsional behavior of strengthened beams, which were subjected to constant and incremental repeated loads is studied. Repeated loads have a negative effect on the strength of beams as they reduce the beam's resistance to external loads. External strengthening is usually used to increase the strength of beams for different applied loading. The near-surface mounted technique is a type of strengthening recently used to improve the strength of beams. The experimental program includes testing of twelve beams. All beams have the same dimensions and the same reinforcement. Nine of those beams are strengthened with different configurations of steel wire rope, and three beams are non-strengthened (reference beams). The results show that the decreasing of the spacing between wires (increasing the amount of steel wires) leads to an increase in the beam torsion strength and a decrease in the twist angle of beams. All strengthened beams show high resistance to the repeated load, especially constant repeated load, the increased torsional capacity has reached to 181.12% in beams under constant repeated load compared to the related beam subjected to monotonic load.

Keywords: torsion of reinforced concrete beam, repeated loading, NSM strengthening, steel wire rope, monotonic load, constant repeated load, incremental repeated load.

1 Introduction

Both steel and concrete are subjected to high numbers of stress changes, for example, in highway bridges. Steel, like concrete, becomes fatigued in the same conditions. One or more small cracks occur after the cyclic stress has been applied a large number of times. The remaining un-cracked cross-sectional area is reduced to the point where it can no longer resist the imposed force. The member suddenly and brittle collapses at this point (Darwin, D. et al, 2016) [1].

Sometimes, the reinforced concrete structures are exposed to torsional moments, and the strength for torsion needs to be increased. Therefore, the ways for these member strengthening in torsion are necessary [2,3,4], to strengthen concrete (RC) structures, the strengthening materials can be applied in two main different manners:(1) externally bonded reinforcement (EBR), in which the strengthening materials are adapted externally to the concrete surface; and (2) near surface mounted (NSM), in which the strengthening materials are integrated into the concrete surface in pre-cut grooves (Askandar, N.H. and Mahmood, A.D.,2020) [5].

The reinforced concrete members subjected to torsion strengthened using externally fiber reinforced polymer has been in abundance previously [6,7,8,9,10,11,12].

Fiber reinforced composites is used for such application for many advantages like its high strength, resistance to corrosion, good flexibility and ease of application which make this material an appropriate for structural strengthening [13,14].

However, the FRP have many disadvantages, like its relatively low elevated temperature resistance, difficulty in fixing in low temperature or on wet surfaces, as well as its paucity of vapor permeability [15].

Steel wire rope, which featured with good flexibility as well as its availability and its cheap price is suitable for use as a strengthening material for many structural members [16,17].

(Askandar, N.H. and Mahmood, A.D., 2020) [5] investigate the properties of RC beams subjected to the combined actions of torsion and bending moment when strengthened by spiral NSM steel wire rope in various configurations. The experimental study included cast and investigated six rectangular RC beams, one of these beams is considered as a control beam (without strengthening), while the others were reinforced with spiral NSM steel wire rope with a 45° spiral inclination. Experimental results show that all beams strengthened by NSM method have better torsional resistance than the control beam. Also, when reducing the distance between the spirals NSM steel wire ropes, the ultimate torsional and bending moments are improved.

*Corresponding author e-mail: israa.abc95@gmail.com

(Askandar, N.H and Mahmood, A.D, 2020) [18] studied in their work the properties of seven RC beams subjected to the combined actions of torsion and bending moment. These beams are strengthened by NSM steel bars (10mm) in various configurations. One of these beams is considered as a control beam (without strengthening). The experimental results show that all NSM steel-bar-strengthened beams have a greater torsional resistance. Also, the 90° inclination of NSM steel bars configuration was found to be a more effective system for strengthening RC beams in terms of torsion resistance than the 45° inclination of NSM steel bars because the diagonal NSM steel bars have a direction parallel to the spirally cracks at that face , for this reason, the diagonal NSM steel bar didn't really work at that face.

(El Mostafa, H. and Elkateb, M., 2011) [7] conducted an experimental work to study the influence of combined loading of flexure, shear, and torsion on the torsional behavior of RC beams reinforced with externally bonded CFRP sheets (wraps). Five rectangular RC beams were used in the experiment. The study results show that when using CFRP wraps to strengthen beams improves their torsional strength capacity up to 116.7% over their non-strengthened value and increases their torsional stiffness by 66.4% over their non-strengthened value.

2 Problem Statement

There are some beams that may be exposed to torsional moments and repeated loads at the same time, as in bridges, where the torsional moments are caused by the eccentricity in loads while the repeated loads are caused by the passage of vehicles. In previous studies, near-surface mounting has been extensively used to increase the shear or flexural strengths of reinforced concrete beams. Despite that some researches have concentrated on torsional strength, none of them have looked into the repeated loads. In this study, the effect of using steel wire rope – NSM technique to strength the RC beams subjected to pure torsion under repeated loading will be investigated.

3 Materials

The characteristics of the materials are shown below.

-Cement: Ordinary Portland Cement (Type 1) that meets the requirements of (ASTM C150/C150M-19a) [19] is used.

-Sand: for all the concrete mixes, natural sand meeting the (ASTM C778-17) [20] specifications with a maximum size of 4.75 mm are used.

-Gravel**:** the normal coarse aggregate meeting the (ASTM C33/C33M-18) [21] specifications with maximum size (14 mm) are used.

The quantities of materials used in the concrete mixture are shown in the table (1).

Table 1: The quantity of materials used in the concrete mixture

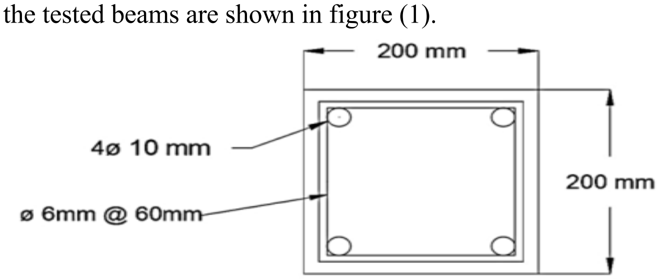
Cement (kg)	Sand (kg)	Gravel (kg)	Water (kg)
379	797	910	172

-Strengthening material: the material used for strengthening the RC beams is steel wire rope (Ø4mm in diameter) which inserted into the grooves and filled with epoxy with f_y= 416MPa and f_u=520Mpa

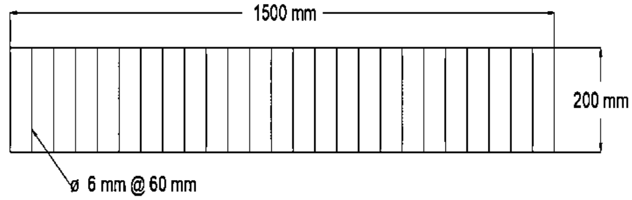
-Epoxy Glue: Sikadur®-330 is used as an adhesive to bind the steel wire rope (in the grooves) with concrete beams by NSM technique.

-Steel Reinforcement: reinforcing steel bars are used with a nominal diameter of 10 mm with yielding stress 583 MPa for main reinforcement and 6 mm with yielding stress 520 for transverse reinforcement which satisfy with the (ASTM A615/A615M15a) [22] and (ASTM C 1018/18) [23] specifications.

The reinforcement details of the tested beams are shown in figure (1).



(a)



(b)

Fig. 1: (a) and (b) Beam reinforcement details

4 Experimental Program

The main effects parameters that have been investigated throughout this study are:

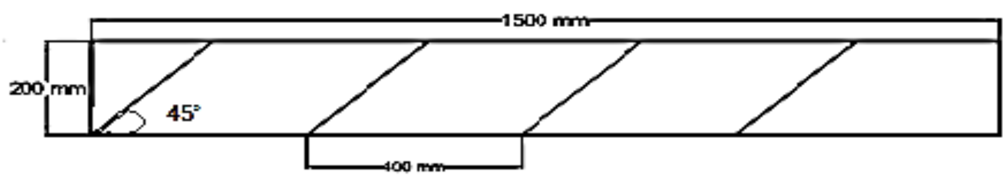
1- Type of load: monotonic and repeated (constant repeated load and incremental repeated load).

2- Strengthened configuration: with spiral NSM steel wire rope in different configurations.

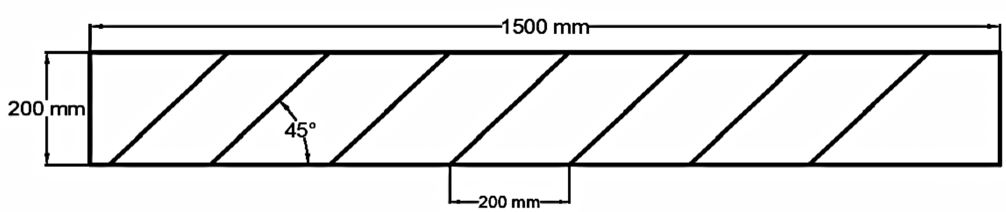
Twelve RC beams were casted and tested. Three of them are considered as control beams, and nine of them are strengthened by the NSM method in different configurations with an angle equal to 45° using steel wire rope. All of the beams have the same dimensions of (200*200*1500) mm and have the same reinforcement. Table (2) and figure (2) show the main properties and variables of the tested beams.

Table 2: The variables of the tested beams

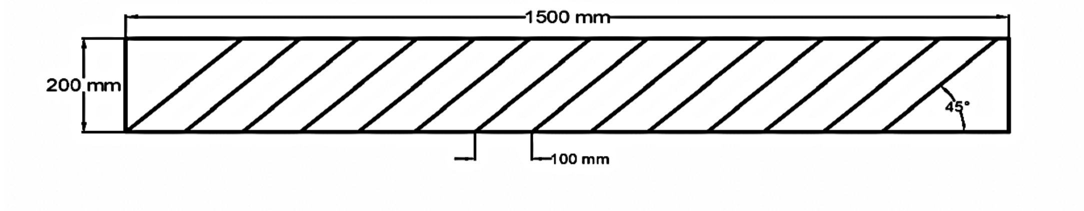
No.	Beam designation	Type of load	Spacing between wires (mm)
1	M	Monotonic	Un-strengthened
2	RC	Repeated Constant	Un-strengthened
3	RI	Repeated Incremental	Un-strengthened
4	MS100	Monotonic	100
5	MS200	Monotonic	200
6	MS400	Monotonic	400
7	RC-S100	Repeated Constant	100
8	RC-S200	Repeated Constant	200
9	RC-S400	Repeated Constant	400
10	RI-S100	Repeated Incremental	100
11	RI-S200	Repeated Incremental	200
12	RI-S400	Repeated Incremental	400



MS400



MS200



MS100

Fig. 2: Spacing between steel wire rope

5 Control specimens

For each concrete batch, three cylinders of dimensions (150 * 300) mm were cast and tested for tensile split test according to ASTM C496/C496M-17 [24], and three cubes of dimensions (150 * 150 * 150) mm were cast and tested for compressive test according to B.S. 1881 116-(1983) [25].

6 Beams strengthening process:

The Steps of strengthening process are as follow:

1-Grooves with a width of 10 mm and a depth of 10 mm are created in the concrete cover of the beams in various configurations (the minimum dimension of the grooves should be taken at least 1.5 times the diameter of the strengthening material (ACI 440.2R-08) [26]).

2-The grooves are smoothed and cleaned, steel wire rope used for strengthening is inserted into the grooves and filled with epoxy.

3-The beams are stored for 2 weeks to maintain the full hardening of the epoxy.

7 Test setup:

The beam permitted to slide and elongate freely by supporting the beam ends on roller at the unresisting support and the two ends of the steel arms are connect with steel girder, so that forces applied from the device are divided on both sides of the beam (because the applied load does not contact the beam from the middle and is only transferred to the edge of the beams by the girder, it is considered pure torsion). Then the force is transmitted from both sides of the steel arm to the beam in the form of torsional moment in opposite directions and the twist angle of the free end (the point of applying the torque) measured with the aid of the downward distance of the lever arm at that point by using a dial gauge. Fig. (3) shows the test setup.

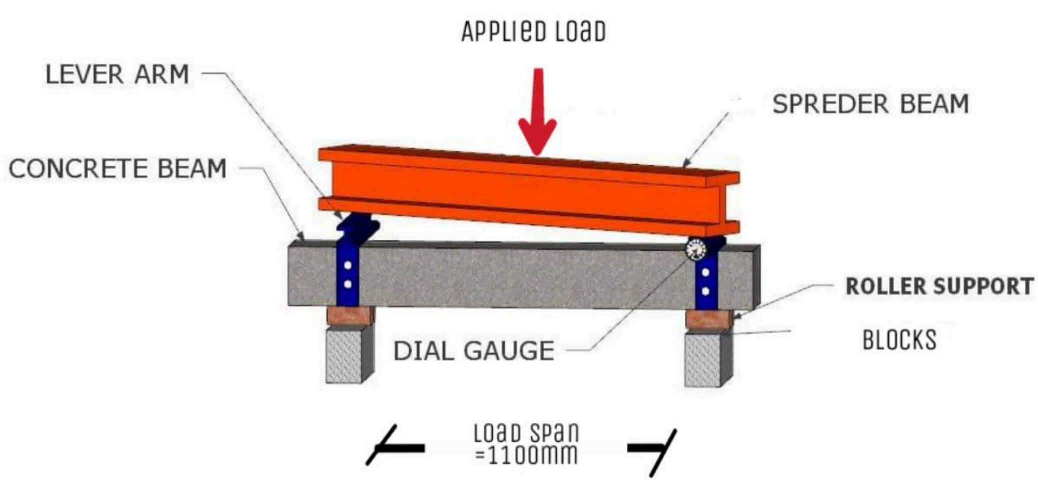


Fig. 3: Test Setup

Fig. 4: The loading frame

8 Loading Process

8.1 Monotonic Loading Test

Four beams were subjected to monotonically increase load.

8.2 Repeated Loading Test

1- Constant repeated load: four beams are repeatedly loaded at a constant rate. The loading level for each cycle is 60% of the ultimate load of a comparable monotonically tested beam. The beams are subjected to four loops of testing, and if the specimens did not fail, the load increased until failure.

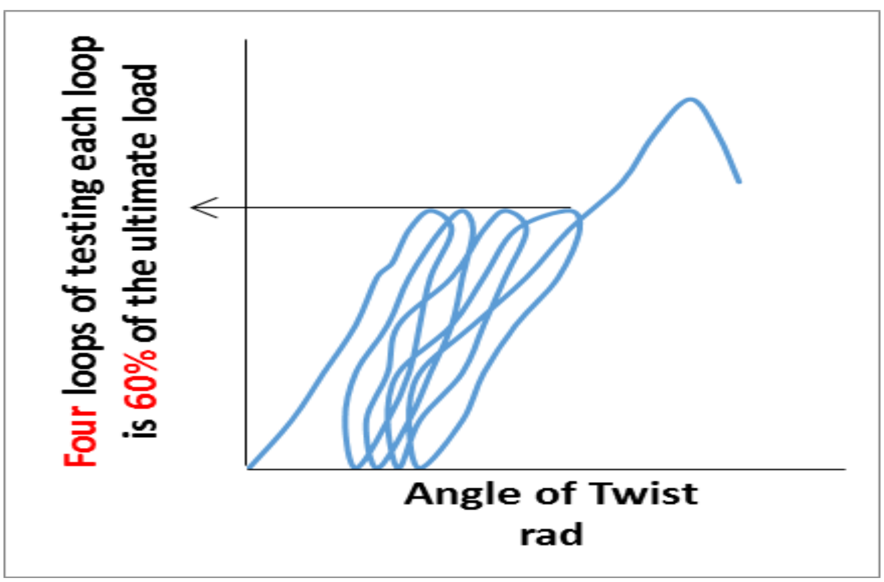


Fig. 5: Constant repeated load

2- Incremental repeated load: four beams are repeatedly loaded in small increments. The beams are subjected to four loops of testing. If the specimens did not fail, the load raised until failure. The loading levels of each cycle are 20%,40%,60%, and 80% of the ultimate load of a comparable monotonically tested beam, respectively.

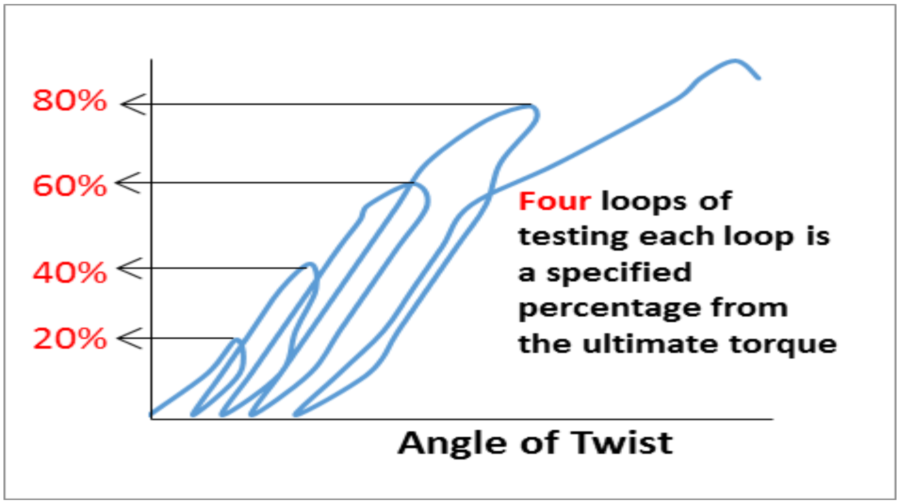


Fig. 6: Incremental repeated load

9 Angle of Twist Measurements

The vertical deflection at the edge of tested beams caused by applied torque is measured using a dial gauge. The dial gage is attached to the lever arms' bottom, one dial gage is used because when two dial gages are installed on the edges, they give the same or very close results. To calculate the angle of twisting, the recorded deflection from the dial gage reading is divided by the horizontal distance from the beam center to the dial gage (which equal to 400 mm).

10 Effect of Strengthening

10.1 Effect of Strengthening on The Cracking Load

The effect of strengthening on the cracking load for beams tested under different types of loads in this study is shown in table (3).

Table 3: The effect of strengthening on the cracking load

Beam Designation	Tcr* (kN.m)	Tcr /Tcr for M%**	Tcr /Tcr for RC%**	Tcr /Tcr for RI%**
M	5.12	100	-	-
MS100	7.51	146.77	-	-
MS200	7.17	139.98	-	-
MS400	6.04	118.09		
RC	4.25	-	100	-
RC-S100	6.96	-	163.76	-
RC-S200	6.50	-	153.12	-
RC-S400	5.58	-	131.36	-
RI	4.75	-	-	100
RI-S100	7.01	-	-	147.56
RI-S200	6.87	-	-	144.53
RI-S400	5.99	-	-	125.98

*Tcr= Cracking Torque

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

From table (3), it can be seen that all strengthened beams show an increase in the cracking torque compared with the related non-strengthened beams (control beams) under any type of loads. For the beams tested under monotonic load, the percentage of increasing in cracking torque reached to 147.77% (for beam MS100) while in beams tested under constant and incremental repeated load it reached to 163.74% (for beam RC-S100) and 147.56% (for beam RI-S100) respectively. This increase in strength is due to the using of steel wire (as a strengthening technique) as the steel wire direction is perpendicular to crack direction, which leads to arrest these cracks and breaks its continuity.

10.2 Effect of Strengthening on The Ultimate Torsional Capacity

The effect of strengthening on the ultimate torsional capacity for beams tested under different types of loads in this study is shown in table (4).

Table 4: The effect of strengthening on the ultimate torsional capacity

Beam Designation	Tu* (kN.m)	Tu /Tu for M%**	Tu /Tu for RC%**	Tu /Tu for RI%**	Angle of Twist (rad)
M	9.05	100	-	-	0.068
MS100	15.00	165.71	-	-	0.092
MS200	13.09	144.64	-	-	0.097
MS400	10.5	115.94			0.066
RC	6.69	-	100	-	0.089
RC-S100	12.13	-	181.12	-	0.113
RC-S200	11.17	-	167	-	0.136
RC-S400	8.24	-	123.19	-	0.074
RI	8.51	-	-	100	0.079
RI-S100	13.67	-	-	160.62	0.093
RI-S200	12.13	-	-	142.58	0.13
RI-S400	9.70	-	-	113.98	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- For the strengthened beams subjected to any type of load, the ultimate torsional capacity greatly increased, and the angle of twist significantly improved (decreased) compared to non-strengthened beams at the same applied load.

2- The decreasing of the spacing between wires used for strengthening leads to increase in the beams strength and decrease in the twist angle of beams (at the same applied load) for the used three spacing (100,200 and 400) mm.

3- The increase in strength between beams having spacing grooves 10cm and 20cm is small (between 14% to 21%) compared to the fact that the strengthening in the beams with spacing grooves 10 cm is twice the second type, the reason of this behavior can be attributed to the increase in the number of grooves that make the concrete cover weaker, which in turn leads to a decrease in the ultimate torsional capacity of beams.

4- All of strengthened beams showed high resistance to the repeated load especially constant repeated load, the increase of torsional capacity has reached to 181.128% (in beam RC-S100) in beams under constant repeated load compare with beams under monotonic load.

5- At the same applied load, the improvement (decreased) in the twist angle for strengthened beams compared with non-strengthened beams reached 183% (for beams subjected to monotonic load), 329% (for beams subjected to constant repeated load) and 179% (for beams subjected to incremental repeated load).

10.3 Torque- Angle of Twist Response

Figure (7) to figure (13) present the relationship between the torque and angle of twist for control and strengthened beams.

Figure (7) shows torque- twisting angle relationship for beams tested under monotonic loading (M), (MS100), (MS200) and (MS400). It can be seen that the torsional capacity is significantly improved by an increase in the amount of steel wire rope. Under the same load, the control beam has a lower torque capacity and a larger twist angle than the beams there are reinforced by steel wire rope. The torque–twist curves for strengthened beams have similar behavior to control the beams with different changes at the last stage. However, before cracking, the slope of torque–twist curves did not have any significant changes. Due to the stirrup or steel wire rope reinforcement that resists the torque applied to the beams, all curves attempted to show a constant slope throughout the post-cracking stage.

Figure (8) to figure (10) show torque- twisting angle relationship for beams tested under constant repeated loading (RC), (RC-S100), (RC-S200) and (RC-S400). It can be seen that when the spacing between steel wires decreased, the torsional capacity is significantly improved by about 35% for the beam (RC-S200) and 47% for the beam (RC-S100) compared with the beam (RC-S400). The cracking happens in the first loop for all beams. At one beam, all loops are intertwined with each other, and the slope of all the loops is approximately equal, but when compared with other beams, the inclination of the loops decreases when the amount of steel wire rope increases (spacing between wires decreases). This means that the stiffness of beams (the ratio of torsional capacity to related twist angle) increases when the spacing between wires decreases. Under the same load, the control beam (RC) has a larger slope of the loops (lower torque capacity and a larger twist angle) than the strengthened beams.

Figure (11) to figure (13) show torque- twisting angle relationship for beams tested under incremental repeated loading (RI), (RI-S100), (RI-S200) and (RI-S400). It can be seen that when the spacing between steel wires was decreased, the torsional capacity was significantly improved by about 25% for the beam (RI-S200) and 41% for the beam (RI-S100) compared with the beam (RI-S400). The cracking happens in the third loop for all beams. At one beam, all loops are separated from each other, and the slope for each loop is different from another. Even when compared with other beams, the inclination of the loops doesn't take on specific behavior. But in spite of that, the stiffness of beams (the ratio of torsional capacity to related twist angle) increases when the spacing between wires decreases. Under the same load, the control beam (RI) has a lower torque capacity and a larger twist angle than the strengthened beams.

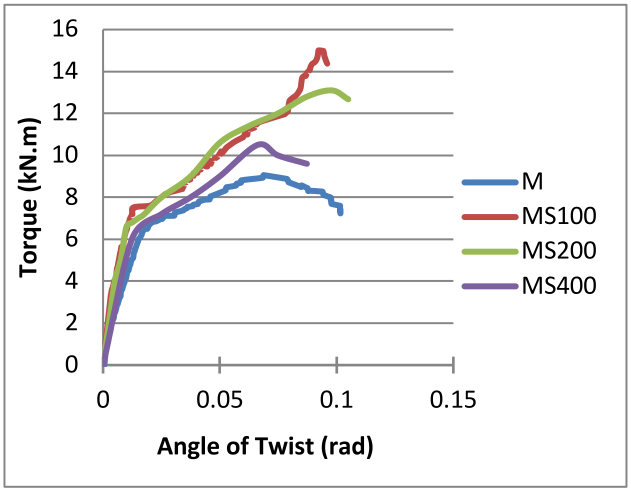


Fig. 7: Torque- Twisting angle Relationship for beams (M), (MS100),(MS200) and (MS400)

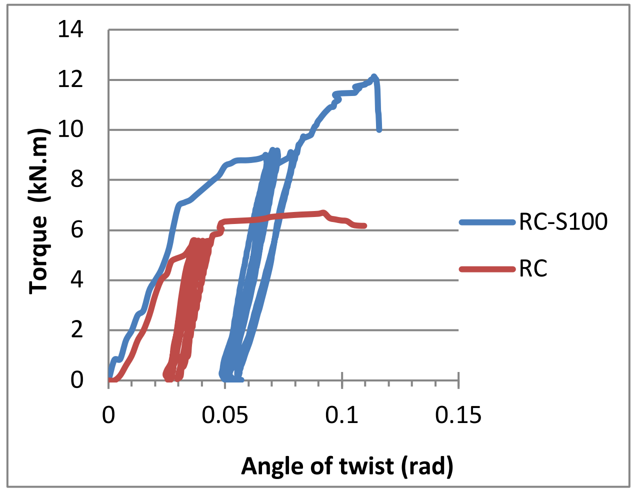


Fig. 8: Torque- Twisting angle relationship for beams (RC-S100) and (RC)

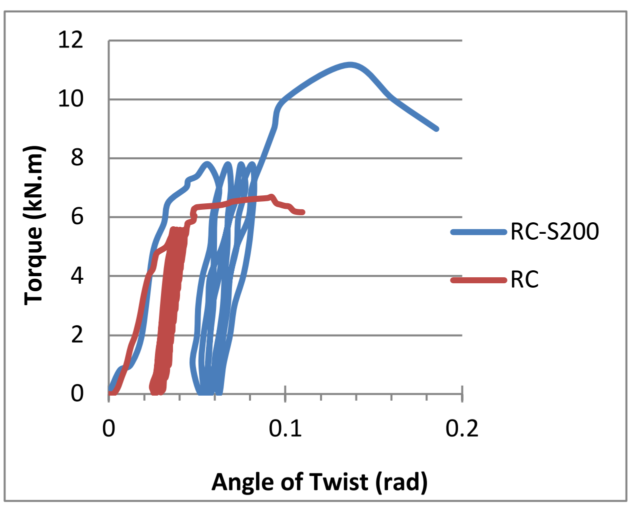


Fig. 9: Torque- Twisting angle relationship for beams (RC-S200) and (RC)

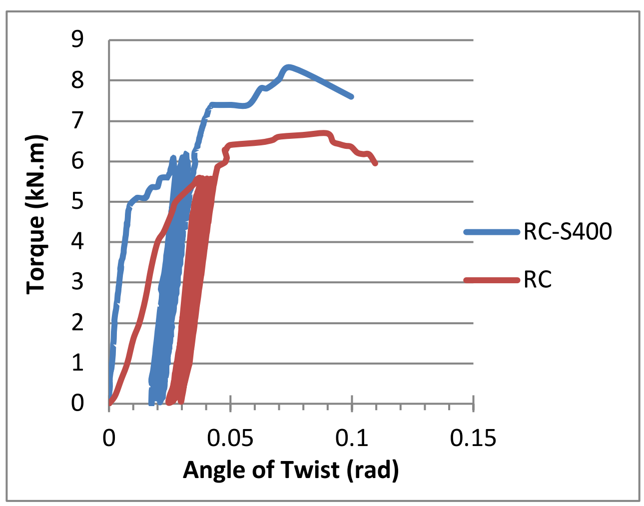


Fig. 10: Torque- Twisting angle relationship for beams (RC-S400) and (RC)

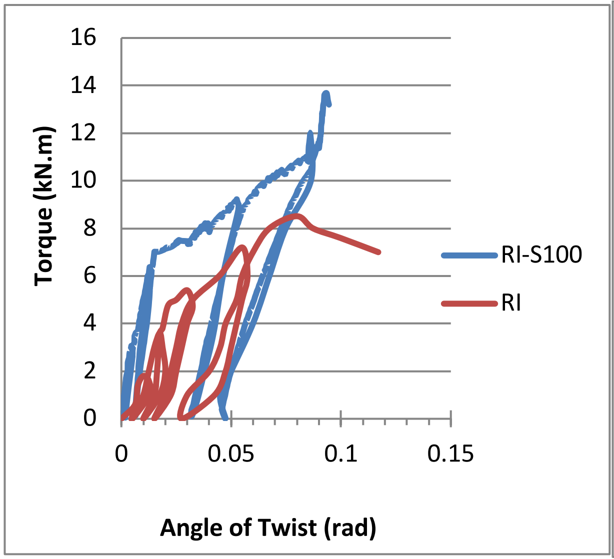


Fig. 11: Torque- Twisting angle relationship for beams (RI-S100) and (RI)

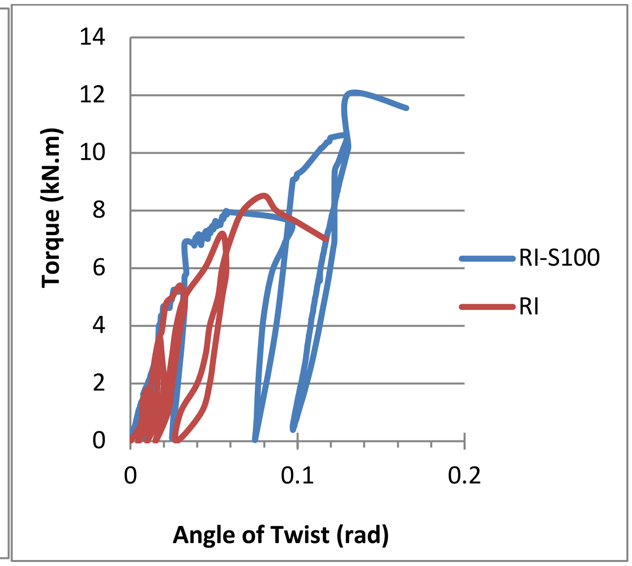


Fig. 12: Torque- Twisting angle relationship for beams (RI-S200) and (RI)

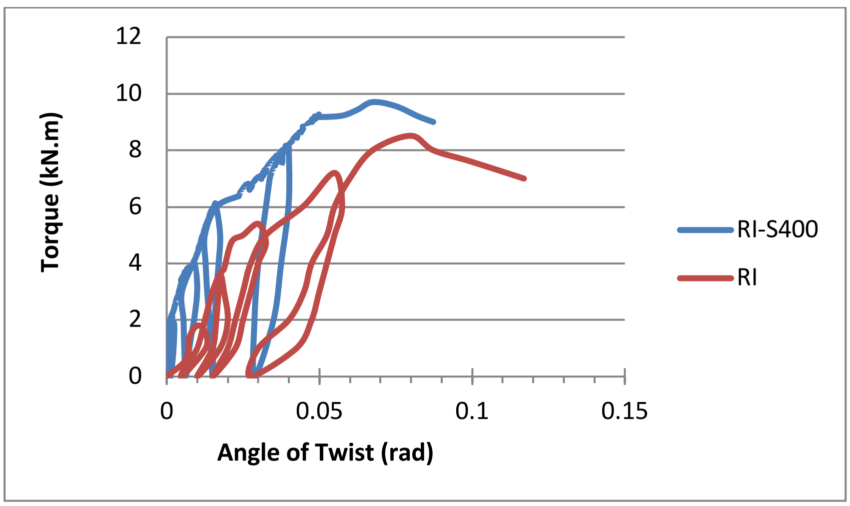


Fig. 13: Torque- Twisting angle relationship for beams (RI-S400) and (RI)

11 Stiffness

Torsional stiffness of a beam is a ratio of torsional moment to the related angle of twist [27, 28, 29]. Table (5) shows torsional stiffness of the tested beams.

Table 5: Rotational stiffness at failure

Beam Designation	Stiffness (kN.m/rad)
M	133.17
RC	75.21
RI	107.74
MS100	163.11
RC-S100	107.38
RI-S100	147.01
MS200	135.04
RC-S200	82.19

RI-S200	93.36
MS400	159.09
RC-S400	111.44
RI-S400	144.80

From the obtained results, it is determined that:

1- The repeated loading reduces ultimate torsional capacity and increases the maximum angle of twist. Therefore, the torsional stiffness of beams tested that are under repeated load is lower than the torsional stiffness of beams tested under monotonic load, where the decrease in the stiffness of beams reaches 56% (in beam RC).

2- Strengthened beams have a torsional stiffness higher than for those of non-strengthened beams because that the using of steel wire in the strengthened beams will increase the torsional capacity and reduce the angle of twisting, resulting a higher torsional stiffness. The higher torsional stiffness is for beam (MS100) which has groove spacing equals to 10 cm and tested under monotonic load.

12 Failure Mechanism

From the failure modes of tested beams that are shown in figures (14) to (16), it can be noted that:

1- The initial crack in all tested beams is developed at the first third of the clear span, and the length of it gradually increased. Cracks occurred on two vertical sides as the torque moment increased, later spiraling around the beam axis.

2- The primary cracks are inclined at a range of 40–60 degrees to the longitudinal axis of the beam.

3- Each beam shows a different number of spiral cracks and pervasion through the test region.

4- The width of cracks in beams tested under repeated load is wider than in beams tested under monotonic load. As well, the secondary cracks appeared from the main cracks in beams tested under repeated load specially when the beams tested under constant repeated load because the process of loading- unloading leads to a fluctuation in stresses and more damage to concrete.

5- Whenever the percentage of strengthening in the beams under any type of loads increased, the number of cracks and the width of cracks decreased. This is due to using of steel wire for strengthening perpendicular to the cracks, because it breaks the continuity of the cracks and decreases their width when compared with the non-strengthened specimen.

Fig. 14: Failure Mode for Beams under monotonic load

Fig. 15: Failure Mode for Beams under constant repeated load

Fig. 16: Failure Mode for Beams under incremental repeated load

13 Conclusion

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

1- Both types of repeated loading affected on the beams, where the reduction in the ultimate torsional capacity reached to 26.08% and the increase in the maximum angle of twist reached to 140% for beams subjected to constant repeated loading compared with those for monotonic loading.

2- The constant repeated loading type has higher effect on decreasing the ultimate torsional capacity and increasing the twisting angle compared with the incremental repeated loading type.

3- For strengthened beams under any type of load, the ultimate torsional capacity greatly increased, and the angle of twist significantly improved (decreased) compared with non-strengthened beams at the same applied load.

4- For the strengthened beams decreasing the distance between steel ropes leads to higher torsional capacity for the used three spacing between steel ropes (100,200 and 400) mm.

5- The increase in strength between beams having spacing grooves 100 mm and 200 mm is little (between 14% to 21%) compared to the fact that the strengthening in the beams having spacing grooves 100 mm is twice the second type

6- All strengthened beams show high resistance to the repeated load especially constant repeated load, the increase of torsional capacity has reached to 181.12% in beams under constant repeated load compared to the beams subjected to monotonic load.

7- At the same applied load, the improvement (decreased) in the twist angle for strengthened beams compared with non-strengthened beams reached 183% (for beams subjected to monotonic load), 329% (for beams subjected to constant repeated load) and 179% (for beams subjected to incremental repeated load).

Conflict of interest

The authors declare that there is no conflict regarding the publication of this paper.

14 References

[1] D. Darwin, C. Dalan and A. Nilson , *Design Of Concrete Structures*. The McGraw Hill Companies, New York USA: 56,(2016).

[2] M. Hatem,, A. Abdul Samad, N. Mohamad, G. Inn, and S. Abdulqader. A Review On NSM-CFRP Technique Using In Shear Strengthening Of RC Deep Beams. *Indian Journal of science and Technology*, **12(36)**, 1 (2019).

[3] S. Panchacharam, and A. Belarbi .Torsional Behavior of Reinforced Concrete Beams Strengthened With FRP Composites, *First FIB Congress*, **1**, 1-110 (2002).

[4] M. Ameli , H. Ronagh, and P. Dux.Behavior of FRP Strengthened Reinforced Concrete Beams Under Torsion. *Journal of Composites for Construction ASCE*, **11(2)**, 192-200 (2007).

[5] N.H. Askandar, and A.D. Mahmood. Torsional Strengthening Of RC Beams With Continuous Spiral Near-Surface Mounted Steel Wire Rope. *International Journal Of Concrete Structures And Materials*, **14:7,**1-7(2020).

[6] A. Ghobarah, M.N. Ghorbel, and S.E. Chidiac. Upgrading Torsional Resistance of Reinforced Concrete Beams Using Fiber Reinforced Polymer. *Journal of Composites for Construction ASCE*, **6(4),** 257-263(2002).

[7] H. El Mostafa, and M. Elkateb .*Strengthening of Reinforced Concrete Beams Under Torsion Using CFRE Sheets.* M.A. Thesis, Ain Shams University, Egypt, (2011).

[8] A.K. Hii and R. Al-Mahaidi .Experimental investigation on torsional behavior of solid and box-section RC beams strengthened with CFRP using photogrammetry. *J Compos Constr*, **10(4)**, 321–9(2006).

[9] A.K. Hii and R. Al-Mahaidi. An experimental and numerical investigation on torsional strengthening of solid and box-section RC beams using CFRP laminates. *Compos Struct*, **75(1)**, 213–21(2006).

[10] C.E. Chalioris. Torsional strengthening of rectangular and flanged beams using carbon fibre-reinforced-polymers experimental study. *Constr Build Mater* , **22(1)**, 21–9(2008).

[11] A. Deifalla, A. Awad, and M. Elgarhy. Effectiveness of externally bonded CFRP strips for strengthening flanged

beams under torsion: an experimental study. *Eng Struct* ,**56:2**, 65–75(2013).

[12] M.B. Abdulrahman, L.A. Al-Jaberi, and S.S. Hasan.The Effect of Opening Size and Location on The Performance of Reinforced Concrete T- Beam Under Pure Torque. *Tikrit Journal of Engineering Sciences*, **27(2)**, 47(2020).

[13] M. Al-Mashaykhi, B. Alsbari, M. Abdulrahman, and A. Hussein. Punching Strength of Reactive Power Reinforced Concrete Flat Slabs. *Tikrit Journal of Engineering Sciences*, **28(3)**, 36(2021).

[14] S.S.Hasan. *High Strength Reinforced Concrete T- Beams With Web Openings Under Pure Torsion*. M.A. Thesis, University of Tikrit, Iraq, (2020).

[15] M. Alabdullady, L. Sneed, and C. Carloni. Torsional behavior of RC beams strengthened with PBO-FRCM composite – An experimental study. *Engineering Structures Journal* , **27**, 394(2017).

[16] K.H. Yang, H.Y. Byun, and A.F. Ashour. Shear strengthening of continuous reinforced concrete T-beams using wire rope units. *Engineering Structures*, **31**, 1154–1165(2009).

[17] X. Li, G. Wu, M.S. Popal, and J. Jiang. Experimental and numerical study of hollow core slabs strengthened with mounted steel bars and prestressed steel wire ropes. *Construction and Building Materials*, **188**,456–469(2018).

[18] N.H. Askandar, and A.D. Mahmood. Torsional Strengthening of RC Beams With Near- Surface Mounted Steel Bars. *Hindawy Advances In Material Sciences and Engineering*, **16**, 2-9(2020).

[19] American Society for Testing and Materials. *Standard specification for Portland cemen*t. USA, ASTM C150, (2019),

[20] American Society for Testing and Materials. *Specification for standard (sand) fine aggregate*. USA, ASTM C778, (2017).

[21] American Society for Testing and Materials. *Standard Specification for Lightweight Aggregate for Structural Concrete*. USA, . ASTM C33/C33M, (2018).

[22] American Society for Testing and Materials. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. USA, ASTM A615 / A615M-15a, (2018).

[23] American Society for Testing and Materials. *Standard specification for Steel, Sheet and Strip*. USA, ASTM C 1018, (2018).

[24] British Standard, *Method of determination of compressive strength of concrete cubs*. Britain, B.S. 1881 116, (1983).

[25] American Society for Testing and Materials. *Splitting Tensile Strength of Cylindrical Concrete Specimens*. USA, ASTM C 496, (2017).

[26] American Concrete Institute. *Guide For The Design And Construction Of Externally Bonded FRP Systems For Strengthening Concrete Structures*.USA, ACI 440-2R(2008).

[27] M.C. Agarana, and O.O. Agboola. Analysis of Torsional Rigidity of Circular Beams With Different Engineering Materials Subjected to St. Venant Torsion. *International Journal of Research in Engineering & Technology,* **3(2)** , 33(2015).

[28] A.S. AlAli, M. B. Abdulrahman, and B.A. Tayeh,. Response of Reinforced Concrete Tapered Beams Strengthened Using NSM-CFRP Laminates. *Tikrit journal of Engineering Sciences*, **29**, 99-110(2022).

[29] A. I. Abdulla. Thermal properties of sand modified resins used for bonding CFRP to concrete substrates. *International Journal of Sustainable Built Environment*, **5** (1), 176-182 (2016).