Tikrit Journal of Engineering Sciences (2023) 30 (3): 49-58
DOI: http://doi.org/10.25130/tjes.30.3.6

IRAQI
Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES
Tikrit Journal of Engineering Sciences

Novel Torsional Reinforcement of Concrete Beams Utilizing Cross-Rod Steel Reinforcement

Adnan Ibrahim Abdullah, Assim M. Lateef*
Civil Engineering Department, Engineering College, Tikrit University, Tikrit, Iraq.

Keywords:

Concrete; Cross-Rod (CR); Crack width; Normal Strength Concrete; Torsion.

ARTICLE INFO

Article history:

Received	07 Feb.	2023
Received in revised form	01 Aug.	2023
Accepted	28 June	2023
Final Proofreading	28 July	2023
Available online	04 Sep.	2023

Citation: Abdullah AI, Lateef AM. **Novel Torsional Reinforcement of Concrete Beams Utilizing Cross-Rod Steel Reinforcement**. *Tikrit Journal of Engineering Sciences* 2023; **30**(3): 49-58.
http://doi.org/10.25130/tjes.30.3.6

****Corresponding author:***

Adnan Ibrahim Abdullah
Civil Engineering Department, Engineering College, Tikrit University, Tikrit, Iraq.

Abstract: External strengthening of reinforced-concrete beams is challenging because of the building system complexity or the beam geometry. The major challenge is choosing an appropriate strengthening method to overcome its low torsion strength. Therefore, the main objective of this research is to ascertain how likely it is to suggest or adopt a particular internal in-plane approach to increase the torsional strength. In the present paper, the concept (technique) of adding internal concrete cross-rods (CR) in a transverse direction is adopted. Five concrete beam specimens with 200-, 200-, and 1500-mm dimensions for width, depth, and length, respectively, were poured and tested. One was a reference beam(B-R) without enhancement, while the other four (B-3CR, B-5CR, B-7CR, and B-9CR) were enhanced with three, five, seven, and nine internal cross-rod, respectively. The compressive strength of the concrete was (35MPa) at (28) days (normal strength concrete). This research intends to show how internal cross-rods (CR) and their number affect torsional capability. The experimental findings revealed significant improvements in the ultimate torsion strength capability by about 11.65%, 18.95%, 21.24%, and 27.77%, respectively, compared to the reference beam. The ultimate twisting angle and reinforced beams' toughness increased by (4.25%-28.36%) and (24.12%-94.48%), respectively, due to the increase in the number of internal cross-rods compared to the reference beam. It was concluded that interior cross-rods would enhance the torsional strength capacity of the reinforced concrete beams. The extent of enhancement depended mainly on the number of internal cross-rods (CR) deployed.

التعزيز الالتوائي الجديد للعتبات الخرسانية من خلال استخدام التسليح بقضبان الحديد المتقاطعة

عدنان ابراهيم عبدالله، عاصم محمد لطيف
قسم الهندسة المدنية / كلية الهندسة / جامعة تكريت / تكريت – العراق.

الخلاصة

يمكن أن تشكل التقوية الخارجية للعتبات الخرسانة المسلحة تحديًا في بعض الأحيان بسبب تعقيد نظام البناء أو تفاصيل تصميم الهندسي للعتبة. تتمثل الصعوبة الرئيسية في اختيار تقنية التقوية المناسبة للتغلب على قوة الالتواء الضعيفة للمادة تحت اجهادات داخل وخارج العتبات. في ضوء ذلك، فإن الهدف الرئيسي لهذا البحث هو التأكد من مدى احتمالية اقتراح أو اعتماد نهج تقوية داخلية مناسبة لزيادة قوة الالتواء. في هذا البحث، يتم تقديم دراسة تجريبية لسلوك العتبة الخرسانية المسلحة تحت تأثير الالتواء، معززة بقضبان بشكل متقاطع. في العمل التجريبي تمت دراسة خمس عتبات بأبعاد 200 و200 و1500 ملم للعرض والعمق والطول، وكان أحدها عبارة عن عتبة مرجعية بلا تقوية (B-R)، بينما الأربعة الأخرى (B- 3CR وB-5CR وB-7CR و B-9CR)، تم تعزيزها باستخدام ثلاثة، وخمسة، وسبعة، وتسعة قضبان متقاطعة داخلية، على التوالي. نوع الخرسانة والتسليح الفولاذي هي نفسها لجميع العتبات. يهدف هذا البحث إلى إظهار كيفية تأثير القضبان الحديد المتقاطعة الداخلية وعددها على القدرة الالتوائية. اظهرت النتائج التجريبية عن تحسينات كبيرة في قدرة قوة الالتواء النهائية البالغة 11.65٪، 18.95٪، 21.24٪، 27.77٪، على التوالي، مقارنة بالحزمة المرجعية. زادت زاوية الالتواء القصوى وصلابة الكمرات المقواة بنسبة (4.25٪ -28.36٪) و(24.12٪ -94.48٪) نتيجة زيادة عدد القضبان العرضية الداخلية حسب العتبة المرجعية. واستنتج إلى أن استخدام القضبان العرضية الداخلية سيعزز قدرة مقاومة الالتواء لعتبات الخرسانة المسلحة. يعتمد مدى التعزيز بشكل أساسي على عدد القضبان المستعرضة الداخلية (CR) المنتشرة.

الكلمات الدالة: خرسانة، قضبان متقاطعة، عرض الشقوق، الخرسانة ذات القوة الاعتيادية، اللي، المتانة.

1.INTRODUCTION

A structure's reinforced concrete members are made to withstand axial, flexural, shearing, torsional, and a combination of all these forces. Torsional forces attempt to rotate the element around its axes but rarely operate alone. Torsion strength is a key factor when studying and designing various structures, including spiral staircases and curved bridges [1]. Torsional failure may be considered one of the most dangerous failure types than other types of failure because it is uncontrolled and gives no warnings before happening. A sudden brittle failure may happen if the element is inadequately reinforced for torsion [2]. Several techniques can be used to avoid torsional failure, such as adequately designing transverse and longitudinal reinforcement, exploiting suitable strengthening, and repairing techniques. One of the following techniques may be used to strengthen the concrete members to resist torsional stresses:

1. Iincreasing the area of the member's cross-section.
2. Transversal reinforcement included.
3. Using steel plates with external bonds.
4. Using external prestressing to apply an axial load to the member [3,4].

Typically, concrete structures show in one manner or the other deficit throughout a lifetime. Therefore, they require strengthening or repair. Such requirements may arise from errors in construction or poor building design, functional alterations, design code updates, an absence of maintenance of the modifications to the structural systems, an increase in pass volume, and earthquakes and fires [5]. Civil engineering infrastructure renewal has received significant attention during the previous two decades and continues to do so. The question of whether or when to repair faulty or damaged structures is one that many people are particularly interested in. Reinforcing or repairing is frequently preferred for financial reasons [6]. There are various purposes and techniques used in structural strengthening. It is possible to achieve strengthening using section enlargement, externally bonded steel elements, concrete with textile reinforcement and external post-tensioning (TRC), composites made of fiber-reinforced polymer (FRP), and near-surface mounted (NSM) technology. In any of these methods or a combination of techniques, the construction functionality can be maintained for its estimated useful lifetime [7]. Mahdi [8] studied the performance of six box beams with reinforced high-strength self-compacting concrete under pure torsion. To investigate the effect of stirrup amount on improving hollow reinforced concrete beams' resistance against torsion moments, the spacing of stirrups was considered the main adopted variable. The experimental results showed that by decreasing the spacing of the stirrups, many structural properties of the beams were improved. The beams mechanical properties improvements percentage according to the reference beam were: -

1. For (T_u), it ranged between (25.70-254.30%).
2. For (T_{cr}), it ranged between (25.0-200.0%).
3. For (θ), it ranged between (23.30-76.00%).
4. For (ε), it ranged between (29.00-50.20%).

The substantial increase in the values of (θ) and (ε) prior to the failure made the increase of stirrups preferable for a safe life and attaining attention. Abdullah [9] studied how steel fiber-reinforced hollow and solid portions of reinforced concrete beams behaved under pure torsion. Twelve reinforced concrete beams with square sections were cast and tested under only torsion, with dimensions of (1000 mm) in length and (160 mm) in height. The results revealed that the ultimate and crack torsional capacities increased by 98.2% and 178% for solid sections and by 91.3% and 163% for hollow sections when the percentage of steel fibers increased from zero to 2.5%. Aziz and Muhammed [10] studied the strengthening of four self-compacting concrete (SCC) box beams using internal-framed steel stiffening ribs (FSSRs) and tested them under pure torsion until failure. The four specimens included one reference beam, which had no strengthening, and three beams strengthened internally with one, three, and five FSSRs of closed sections. The results from experimental work showed that the ultimate torsional capacities of the specimens strengthened with one, three, and five FSSRs increased by 45.7%, 75.5%, and 122.4%, respectively, compared to the reference beam. It was concluded that the internal transverse FSSRs could improve the torsional capacity of the reinforced SCC box beams. Saba [11] studied the high-performance concrete T-beams behavior with slots under net torsional loads. The experimental work involved casting and testing ten beams subjected to torsional moments. One was a geogrid-enhanced reference beam; the second was a reference beam without geogrid. The other eight beams were reinforced by the geogrid and contained slots of various shapes, sizes, and locations. The parametric study included the effects of opening size, opening shape (round and square), and opening location (distance from support, Lc/2, and Lc/3) for beams reinforced by geogrid. The experimental results showed that using geogrid to strengthen concrete T-beams under torque significantly improved the torsional capacity, with an increase of 28% compared to the control beam. Aziz and Abdullah [12] investigated the torsion strength of reinforced concrete box beams reinforced internally by in-plane steel bracing of a K-shape. Four beams were constructed and loaded to failure under pure torsion, with nominal cross-sectional measurements of 0.3 m × 0.3 m and a total length of 2.1 m. The results from experimental work showed that the failure torsion of reinforced beam specimens with K-shaped steel bracings increased up to 82% greater than the reference beam, and the twist angle reduced up to 35.5%, while the axial elongation reduced by 53%. Internal in-plane K-shaped steel bracing was an effective and simple way to increase the ultimate carrying torsion. Ibrahim et al. [13] studied the influence of continuous rectangular spiral stirrups, a transverse reinforcement with a configurable pitch (P) and inclination angle (α), on the torsional behavior of rectangular solid and hollow shapes RC beams has been investigated experimentally. Torque-locked spirals onto each specimen. Ten normal-strength RC beam specimens were tested, two solids with closed and spiral rectangular stirrups. One beam had closed stirrups, while seven had rectangular spiral stirrups with different reinforcing ratios. The experimental results showed that the inclined spiral rectangular stirrups in reinforcing RC solid and hollow beams increased torsional capacity by 16% and 18%, respectively, compared to normal closed stirrups. This approach also increased the strain energy by 27% and 16% for solid and hollow beams, twist angles, and ductile failures, respectively. Jasim and Abdulrahman [14] studied the torsion strength of reinforced concrete beams with steel wire rope. The dimension and strength of every beam were the same. Different steel wire rope arrangements were used to reinforce nine of these beams; three were reference beams, i.e., not reinforced. The experimental results of the study showed that a beam's torsional strength increased while its torsion angle decreased when the amount of steel wire increased (decreasing the distance between wires). All strengthened beams showed great resistance to repeated loads, particularly constant repeated loads. The improved torsional capacity in constant repeated load beams increased to 181.12% compared to the related monotonic load beam. Tais and Abdulrahman [15] studied the behavior of reinforced concrete hollow beams strengthened with a strip of carbon fiber reinforced polymer (CFRP) in various configurations using the externally bonded reinforcement (EBR) method when exposed to monotonic and repeated torsion. Eight beams, 250×350×3000 mm, were cast and tested up to failure under pure torsion. Two of these beams were unreinforced. Other beams were strengthened with varied configurations of CFRP strips. Test beams reinforced with two continuous CFRP stripes demonstrated a significant increase in the ultimate torsional moment than beams strengthened with other CFRP stripe configurations. Beams tested under repeated torsion showed less torsional strength degradation than those tested under monotonic torsion moment. External strengthening for beams can occasionally be challenging due to the system complexity or the geometry of the beam. Therefore, the necessity for internal reinforcing through straightforward mechanisms was created. Placing an interior cross-rod (CR) within the beams is among the better methods. The novel concept is to use this technique to enhance the torsion resistance of reinforced concrete, placing an interior cross-rod inside the beams.

2. STUDY SIGNIFICANCE

Since reinforced concrete beam torsional reinforcement is typically done externally, the concept of an approach to reinforcing the internal torsion of concrete beams using various methods is relatively new. The major objectives of this study can be briefly stated as follows:

1. Studying the significance of using internal cross-rods (CR) in enhancing reinforced concrete beams experimentally.
2. Study the effect of the cross-rods (CR) numbers on the amount of torsional strength enhancement and cracks' number and width.

3. EXPERIMENTAL PROGRAM

3.1. Details of Beam Specimens

In this study, five beam specimens were cast and tested; one acted as a reference beam and was represented by (B-R). Internal cross-rods (CR) were used to strengthen four beam specimens represented by (B-#CR), where (#) refers to the number of interior cross-rods. Each specimen was cast. The transverse and longitudinal reinforcing design immediately incorporated the ACI318 M-14 torsion code requirement [16]. The top and bottom of each beam specimen were strengthened with (2φ10mm) bars. The transverse reinforcement consisted of (φ6@60mm) stirrups at the ends and (φ6@90mm) stirrups in the center. The major adopted variables included the number of internal cross-rods (three, five, and seven). For the reference beam (B-R), an internal cross-rod reinforced the remaining beam specimen. Table 1 and Figs. (1- 5) provide the designation, dimensions, and information for the examined beams and details of internal cross-rod steel reinforcement, as shown in Plate 1.

Table 1 Details of the Beam Specimens.

Designation of Beam	Dimensions (mm) D	W	L	Number of Internal Cross-Rods
B-R				0
B-3CR				3
B-5CR	200	200	1500	5
B-7CR				7
B-9CR				9

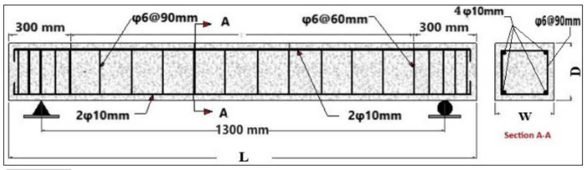


Fig.1 Beam Specifications and Reinforcement (B-R).

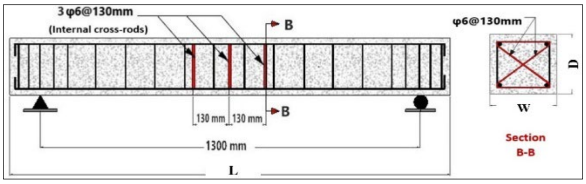


Fig.2 Beam Specifications and Reinforcement (B-3CR).

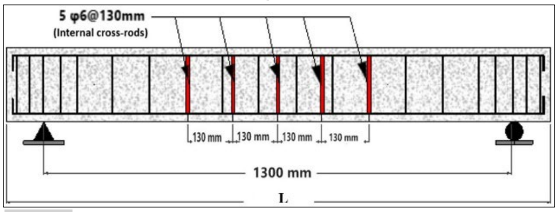


Fig.3 Beam Specifications and Reinforcement (B-5CR).

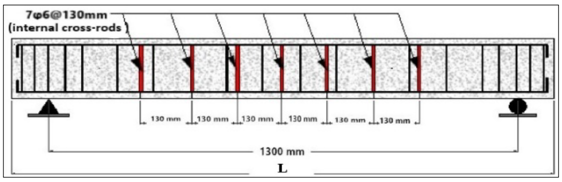


Fig.4 Beam Specifications and Reinforcement (B-7CR).

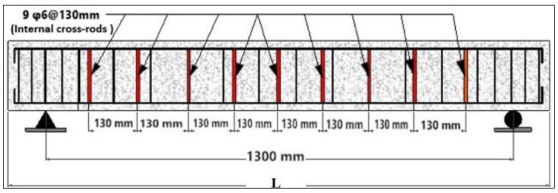


Fig.5 Beam Specifications and Reinforcement (B-9CR).

Plate 1 Internal Cross-Rod Steel Reinforcement Details.

3.2. Materials

3.2.1. Cement

Ordinary Portland Cement (Type1) was used in this study. It conforms with the Iraqi specifications (I.O.S.No.5.1984).

3.2.2. Fine Aggregate

In this research, natural sand was used, as it is in all concrete mixtures. The fine aggregate sieve analysis is shown in Table 2. It conforms with the Iraqi specifications (I.O.S. No.45, 1984).

Table 2 Fine Aggregate Sieve Analysis.

	Sieve size	Cumulative Passing %	Limit of IQS NO. 45/1984 for zone No. 3
1	4.75-mm (No.4)	90.95	90-100
2	2.36-mm (No.8)	88.62	85-100
3	1.18-mm (No.16)	78.55	75-100
4	600-µm (No.30)	66.96	60-79

5	300-µm (No.50)	16.74	12-40
6	150-µm (No.100)	4.34	
Fineness modulus =2.42			

3.2.3. *Coarse Aggregate*

In this study, crushed gravel with a maximum size of 12.5 mm was used. Table 3 shows the grading of coarse aggregate and the limitations imposed by the Iraqi specifications (I.O.S. No. 45, 1984).

Table 3 Coarse Aggregate Sieve Analysis.

No.	Sieve Size	Coarse Aggregate %	Iraqi specification No. 45/1984
1	(14 mm)	(100)	(90-100)
2	(10 mm)	(73.4)	(50-85)
3	(5mm)	(3.3)	(0-10)
4	(Pan)	(0)	-

3.2.4. *Water*

Clean tap water was used for mixing and curing.

3.2.5. *Steel Reinforcement*

The Steel reinforcement bars were determined using the procedure described in (ASTM A 615) [14]. The steel bars' mechanical characteristics are shown below in Table 4.

Table 4 Properties of Steel Reinforcement.

Bars diameters (mm)	Yield stress(fy) (MPa)	Ultimate stress (fu) (MPa)
6mm	521	544
10mm	585	672

Testing was carried out at the civil and chemical engineering labs in Tikrit University.

3.3. *Concrete Mixing*

The basic components were mixed using a rotating mixer, as shown in Plate 2(a), to create concrete for all specimens. The plywood molds with a size of (200×200×1500) mm were used to cast beams. The slumping test result before casting was (90 mm), as shown in Plate 2 (b). The casting of samples and dyeing of models after solidification are described in Plate 2 (c) and (d). Table 5 shows the mixture's specifications. The compressive strength of the concrete was determined using a compression machine of 2000 kN capacity. According to B.S. 1881 116-(1983), an average compressive strength of 3 cubic (150 mm) was used. Plate 3 shows the compressive strength test. The average cubic compressive strength "fcu " was 35MPa, as shown in Table 6.

Plate 2 (a) Rotary Mixer, (b) Slump Test, (c) Plywood Molds, (d) Painted Beams.

Table 5 The Mixture's Specifications.

Constituent	W/C	Water	Cement	Sand	Gravel
Amount (kg/m3)	0.52	197	379	797	910

Table 6 The Cubical Compressive Strength.

Cubes	Cube Strength f_{cu} (MPa)	Average Cube Strength f_{cu} (MPa)
1	34.80	35.00
2	35.68	
3	34.37	

Plate 3 The Compressive Strength Test.

3.4. *Test Setup and Instrumentation*

The specifics of the test setup are shown in Plate 4(a), (b), and (c). The testing machine was constructed to apply a torsion moment to beams. The torsional arm was created by tightly fastening steel frames to the beam specimens' ends, and it had a lever arm with a length of (420mm). The greatest twisted moment (torque) and resistance to cracking of all specimens were investigated using a hydraulic jack with a maximum load of 2000 kN, and the loading rate was 0.05 kN / sec. The beams were designed to be supported by just two bearing points, where the restraint on the beam sample was released by inserting the roller support beneath the bearing; due to its design, the beam could rotate easily while being subjected to applied torque throughout the test. The torque was produced using a hydraulic jack by applying a typical load through a spreader beam to the torsional arm.

Plate 4 (a) 3D Model of Testing Machine, (b) Loading Frame, (c) Test Machine.

3.5. *Twist Angle Measurements*

As the load was gradually applied, the twisting angle and maximum torsional capacities were calculated. A computer's user's data logger was used to record data, which transmits load and lateral displacement information via an LVDT sensor and load cells. To determine the twist angle at either of the beam's ends, the sensors recorded the uplifting and downward readings. The twist angles were calculated by dividing the recorded displacement from the LVDT readings by measuring the distances between the LVDT sensor and the beam center, i.e., 420mm. Then, the twisted angle was determined using Eq. (1):

The angle of the twist $=\tan^{-1}$ *(LVDT sensor reading divided by 420)* **(1)**

where (420 mm) is the distance in millimeters between the cross-center sections and the location of the load applied. Plate 5 shows the twist angle measuring method.

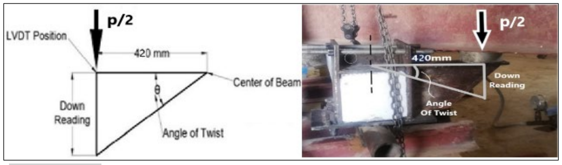


Plate 5 Measurements of the Twisting Angle.

4. RESULTS AND DISCUSSION

4.1. The Ultimate and Cracking Loads

The beam samples were tested under pure torsion by applying the load gradually. The loading process was continued until the final failure mechanism occurred. Both cracking and ultimate loads (Pcr and Pu) were recorded, then the torsional moments (torques) were calculated, as shown in Table 7 and Fig. 6. Compared to the reference beam, (R-B), the first cracking torsional moments (Tcr) were increased by about 12.38%, 15.44%, 31.78%, and 39.31% for the tested beams (B-3CR), (B-5CR), (B-7CR), and (B-9CR), respectively. This increase indicates that the interior reinforcing enhanced the torsion resistance and allowed the interior cross-rod to carry greater stresses.

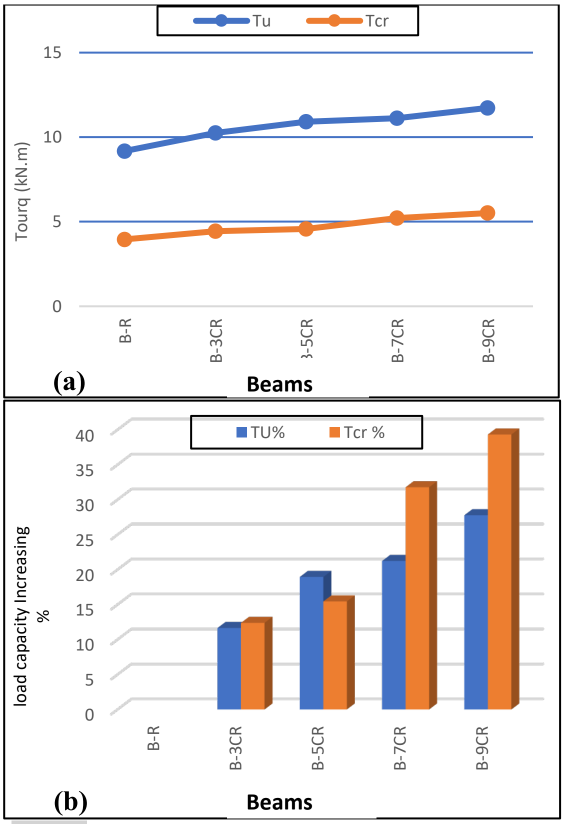


Fig. 6 (a) Ultimate and Cracking Torques, (b) Load Capacity Increasing.

Table 7 Ultimate Torque in Relation to Cracking of All Specimens of Evaluated Beams.

Beam	Pcr (KN)	Pu (KN)	Arm (mm)	Tcr (kN.m)	Tcr Increasing according to B-R Beam (%)	Tu (KN.m)	Tu Increasing according to B-R Beam (%)	ρ
B-R	18,80	43.72	420	3.95		9.18		
B-3CR	21.14	48.80	420	4.44	12.38	10.25	11.65	
B-5CR	21.71	52.21	420	4.56	15.44	10.92	18.95	0.0054
B-7CR	24.81	53,13	420	5.21	31.78	11.13	21.24	
B-9CR	26.24	54.88	420	5.51	39.31	11.73	27.77	

T=(P/2) *Arm

The ultimate torque (Tu) improved by 11.65%, 18.95%, 21.24%, and 27.77% for specimens of tested beams B-3CR, B-5CR, B-7CR, and B-9CR, respectively, compared to the reference beam (B.R.). The results showed that the tested beams had the highest torsional strength of nine (CR), and the cross-rod was not separated from the concrete. When interior cross-rods were present, larger forces could be carried in the lateral direction inside the planes of torsional stresses due to increased torsional stiffness, increasing the beam section efficiency and improving the torsion capacity.

4.2.Torque-Angle of Twist Behavior

Figure 7 presents a relationship between the ultimate torque and the twisting angle for reference beams and reinforced beams with cross-rod. The internal cross-rod reinforcing can significantly alter beam deformation capacity. According to test data, the twist angle remained approximately constant at 0.48 degrees. Until the first cracks appeared, so it steadily increased until failure. At the same tension before the first crack, the twist angle of the reinforced beams with internal cross-rod was lower than the reference beams. The curves for torque-twist for reinforced beams are comparable to how reference beams behave, with a few outliers at the end; however, there were no notable changes in the slopes of the torque-twist curve. Because of the cross-rod (CR) presence, the torque applied to the beams was resisted, and every curve was made to have a constant slope after the crack stage.

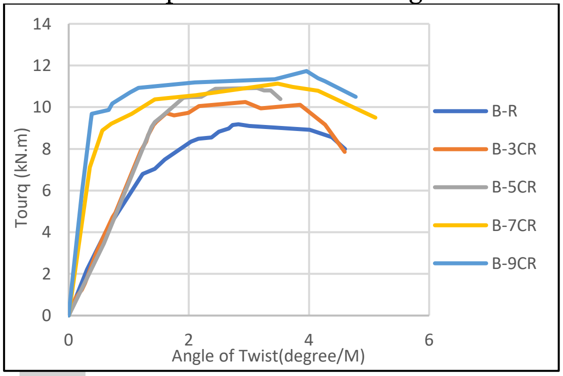


Fig.7 The Relationship Between Torque and Rotation Angle of the Tested Beams.

Table 8 shows the ultimate twist angle of the reinforced beams with cross-rod increased by 4.25%, 18.43%, 23.40%, and 28.36% for B-3CR, B-5CR, B-7CR, and B-9CR, respectively, compared to the reference beam (B.R), which might be a result of the transverse steel cross - rod inserted inside the beam, and that enabled greater torque to be carried. (θ) had a direct connection between (T) and (L) but a reversible relationship with (G) and (J), i.e., ($\theta = TL/GJ$), which in turn increased the corresponding twist angle.

Table 8 Ultimate Torque in Relation to Cracking of All Specimens of Evaluated Beams.

Beam	(Tu) (KN.m)	Arm (mm)	LVDT (mm)	[θu] (degree/m)	(%) Increase of [θu]
B-R*	9.18		20.68	2.82	-
B-3CR	10.25		21.54	2.94	4.25
B-5CR	10.92	420	22.99	3.34	18.43
B-7CR	11.13		25.51	3.48	23.40
B-9CR	11.73		26.52	3.62	28.36

4.3.Crack Width Response

Plate 6 shows how the crack widths were measured and recorded during the test using a micro-concrete crack width meter. The influence of the internal cross-rod reinforcing on the size of the cracks generated on their surfaces was one of the most important discoveries made when analyzing all models. When the crack width in the test was measured, the reinforcing beams B-3CR, B-5CR, B-7CR, and B-9CR reduced the crack width value; however, the expansion rate of the crack propagation was faster at the ultimate torque than the controlled beams (B-R). This result agrees with [17]. The crack width decreased by 12.42%, 13.21%, 22.24%, and 38.77%, which were reinforced internally by three, five, seven, and nine cross-rods for the examined beam samples B-3CR, B-5CR, B-7CR, and B-9CR, respectively, compared to the control beam (B.R). The crack widths of these beams were 3.65 mm, 3.22 mm, 3.17 mm, 2.87mm, and 2.25 mm, respectively, at a maximal load, as shown in Table 9 and Fig. 8 (a) and (b).

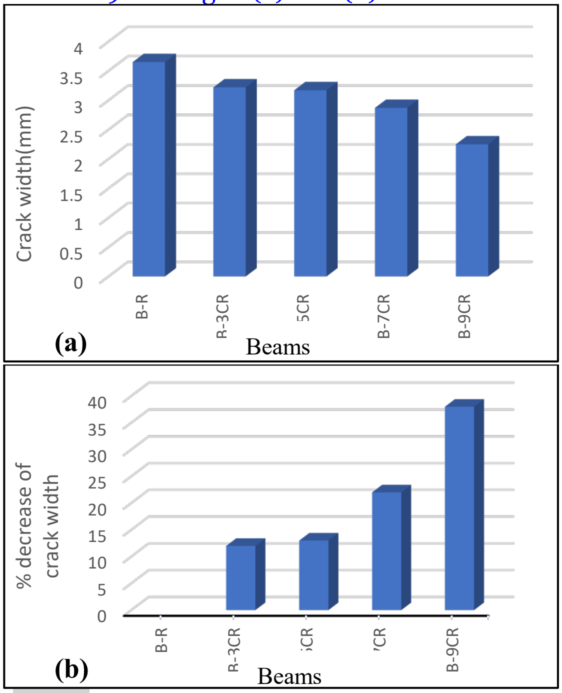


Fig. 8 (a) Crack Width, (b) Decrease of Crack Width.

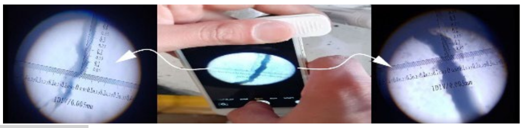


Plate 6 Measure and Note the Crack Widths.

Table 9 Crack Width with Maximal Load.

Beam	Pu (KN)	Crack Width (mm)
B-R	43.72	3.65
B-3CR	48.80	3.22
B-5CR	52.21	3.17
B-7CR	53.13	2.87
B-9CR	54.88	2.25

4.4.Toughness

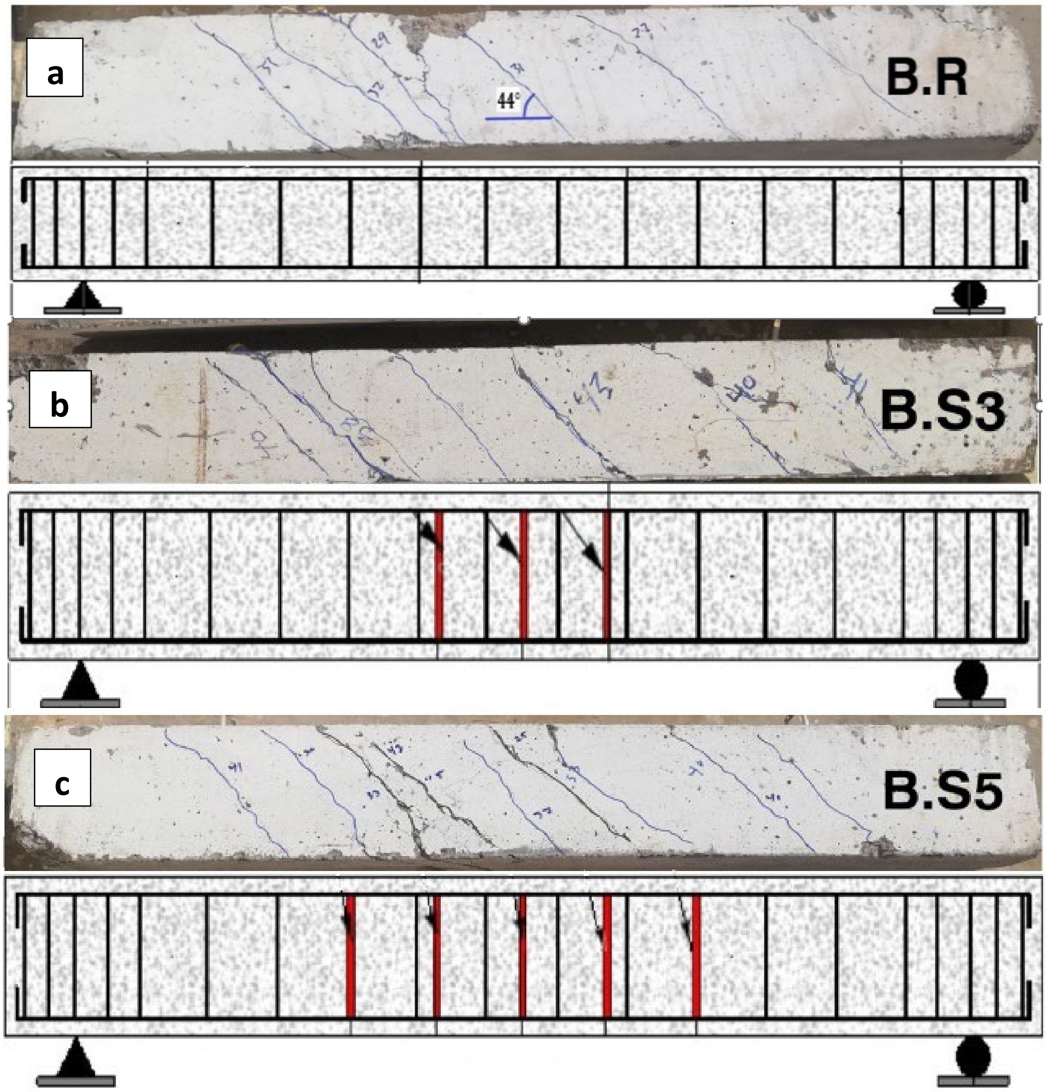
The area under the torque angle of the twisting curves was used to calculate the toughness of each specimen. The toughness of reinforced beams with cross-rods was higher. It increased by 24.12%, 32.42%, 56.71%, and 94.48% for B-3CR, B-5CR, B-7CR, and B-9CR, respectively, compared to the control beam (B.R.), as shown in Table 10 and Fig. 9 (a) and (b), which could be because the internal cross-rods used in reinforcing these beams increased their capacity for both torque and angle of twist, which in turn increased their toughness.

4.5 Mechanisms of Failure

All beams tested failed due to torsional moments. The initial crack started in the first third of the clear span of all tested beams; it gradually increased in length. The cracks on both vertical edges of the beam gradually spiraled within its axis due to increasing the torque moment's effects. The primary cracks were inclined around 40–50 degrees away from the lengthwise axes of the beam. While increasing the load after cracking. Furthermore, as it approached the failure stage, the capacity for carrying tension disappeared. The number of cracks and the type of penetration through the beams differed. The mechanisms for failure of the control beam (B-R) and enhanced RC beams under pure torsion are shown in Plate 7. It can be concluded that the number of cracks increased with the percentage of cross-rods (CR) in the beams under load. As a result of the increased tension, the reinforcing beams had much more cracks than the control beam (B-R), which agreed with the findings of [18]. The number of cracks in the control beam was less than seven; for beams enhanced internally by three, five, seven, and nine internal cross-rods, the number of cracks was more than seven. Also, the distribution of cracks on the beams was more uniform with the increased number of internal cross-rods (CR). This distribution was clearly shown in the beam containing nine internal stiffeners.

Table 10 The Toughness of Tested Beam Specimens

Beam	Tu (kN.m)	θu (deg./m)	Toughness (kN.m. deg.)	Increase of toughness (%)
B-R*	9.18	2.82	18.32	-
B-3CR	10.25	2.94	22.74	24.12
B-5CR	10.92	3.34	24.26	32.42
B-7CR	11.13	3.48	28.71	56.71
B-9CR	11.73	3.62	35.63	94.48



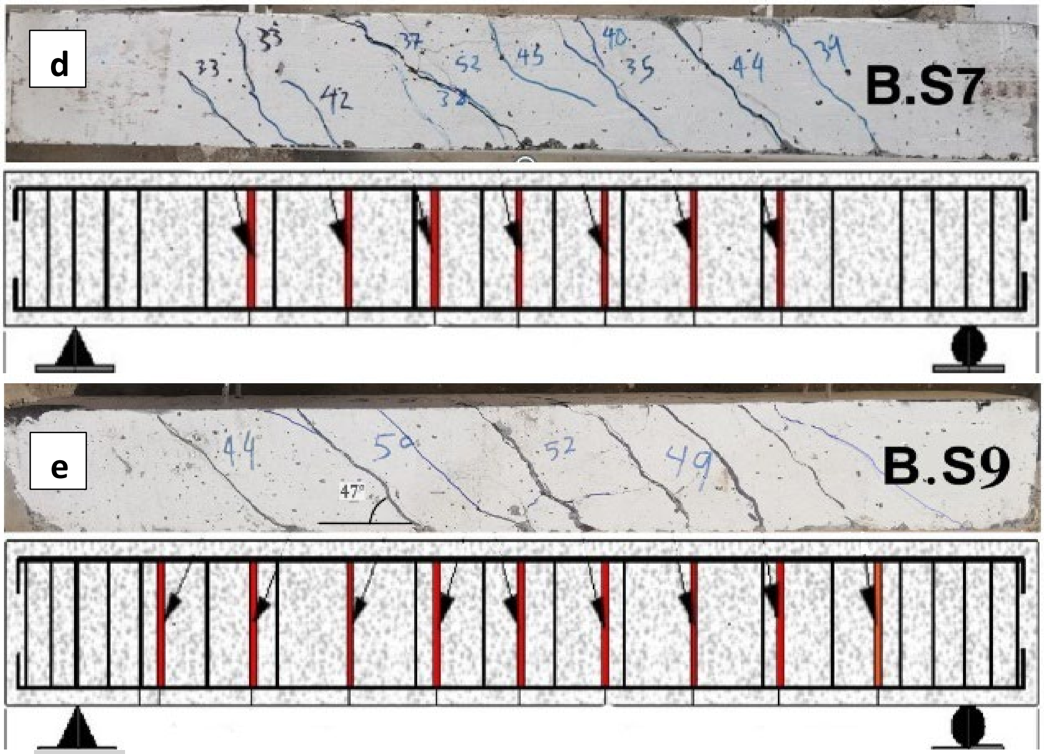


Plate 7 The Failure Mode for Samples Evaluated Under Torsion. (a) Control Beam, (b) B-3CR, (c) B-5CR, (d) B-7CR, and (e) B-9CR.

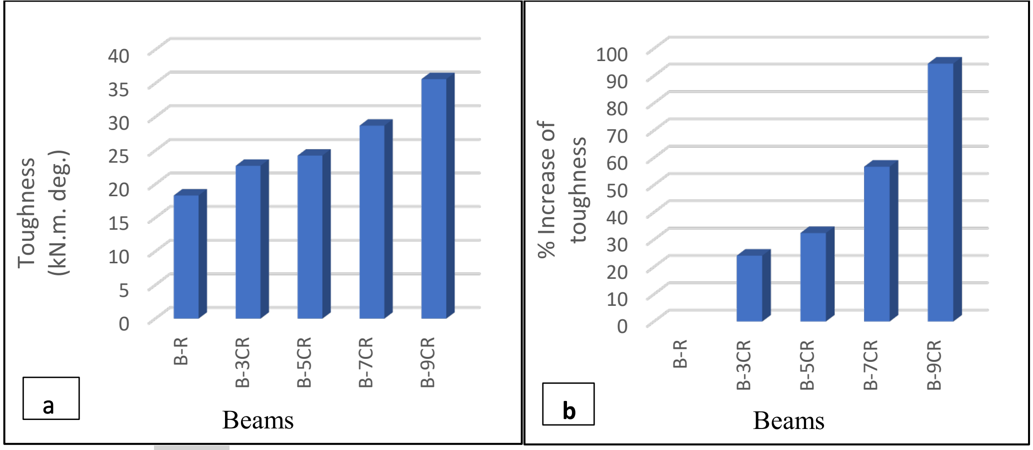


Fig. 9 (a) Toughness (kN.m. deg.), (b) Increase of Toughness.

6. CONCLUSIONS

The experimental findings of the evaluated beams have led to the following conclusions:

1- The technique used (reinforcing by internal cross-rod (CR) steel reinforcement) was straightforward and more efficient in increasing the torsion capacity of the section.

2- The improvement rate in ultimate torsion capability was good compared to a few cross-rod steel reinforcements.

3- The ultimate torsion capability of reinforced concrete beams with cross-rods steel reinforcement increased by a percentage up to 27.77% more than the reference beam.

4- The ultimate twist angle of reinforced concrete beams with cross-rods steel reinforcement increased by a percentage up to 35.5% more than the reference beam.

5- Increasing the number of internal cross-rods (CR) played a significant role in providing a safe life and attracting attention due to the increase in the angle of torsion (θ) before failure occurs.

6- The beams of reinforced concrete with internal cross-rod steel reinforcement had greater toughness than reference beams because the internal cross-rods (CR) location did not provide any restraint against the beam rotation.

Abbreviation

ACI	American Concrete Institute
ASTM	American Society for Testing a Material
B.S.	British Standards Institute
B-R	reference beam
B-3CR	Beam with three cross-rods

B-5CR	Beam with five cross-rods
B-7CR	Beam with seven cross-rods
B-9CR	Beam with nine cross-rods
CR	cross-rods
FRP	Fiber Reinforced Polymer
IQS	Iraqi Specification
NSC	Normal Strength Concrete
SCC	Self-Compact Concrete

Symbols

H	Beam Depth	mm
ƒcu	Cube Compressive Strengtl	MPa
ƒu	Ultimate stress	MPa
ƒy	Yield Strength of Steel Bars	MPa
L	Beam Length	mm
Pcr	Cracked load	kN
Pu	Ultimate load	kN
Tcr	Cracking Torque Capacity	kN.m
Tu	Ultimate Torque Capacity	kN.m
W	Beam Width	mm
θ	Angle of Twist	degree
ϕ	Diameter of Steel Bars	mm
(ρ)	Steel reinforcement ratios	

REFERENCES

[1] Arthur HN, Charles WD. Design of Concrete Structures. 14th Ed, McGraw-Hill, Pp 421 2010.

[2] Jasem AA, Aziz AH. **Torsion Strength Enhancement of RC Hollow Beam Web Using Steel Diaphragms as In-Plane Technique**. *IOP Conference Series: Materials Science and Engineering* 2020; **870**(1): 012109, (1-13).

[3] Abeer AM, Allawi AA, Chai HK. **Theoretical Study on Torsional Strengthening of Multi-Cell RC Box Girders**. *International Journal of Civil and Environmental Engineering* 2013; **7**(2): 115–122.

[4] El-HakimKhalil A, Etman E, Atta A, Fayed S. **Torsional Strengthening of RC Box Beams using External Prestressing Technique**. *IOSR Journal of Mechanical and Civil Engineering* 2015; **12**(2): 30–41.

[5] Khalid Heiza AN, Meleka N, Tayel M. **State-of-The Art Review: Strengthening of Reinforced Concrete Structures–Different Strengthening Techniques**. *Sixth International Conference on Nano-Technology in Construction* 2014; **6**: 22–24.

[6] Bisby JH, Se P. (2002). "An introduction to FRP strengthening of concrete structures". ISIS Educational Mudule 4, p 1- 39.

[7] Alkhrdaji T, Thomas J. **Techniques and Design Considerations for Upgrade of Parking Structures**. *Parking: the Magazine of the Parking Industry* 2002; **41**(5): 1-6.

[8] Mahdi HM. **Behavior of High Strength Self Compacted Hollow Section Reinforced Concrete Beams under Pure Torsion**. *Tikrit Journal of Engineering Sciences* 2015; **22**(1): 9–23.

[9] Abdullah MD. **Behavior of Hollow and Solid Section of Reinforced Concrete Beams under Pure Torsion Strengthened by Steel Fiber**. *Journal of University of Babylon for Engineering Sciences* 2018; **26**(9): 344–355.

[10] Aziz AH, Muhammed SH. **Torsion Enhancement of Reinforced Self-Compacting Concrete Box Beams using Internal Framed Steel Stiffening Ribs**. *Journal of Engineering and Sustainable Development (JEASD)* 2020; **24**(4): 89-103.

[11] Saba SH. *High Strength Reinforced Concrete T-Beams with Web Opening under Pure Torsion*. MSc Thesis in Tikrit University 2020.

[12] Aziz AH, Abdallah MH. **Using Internal In-Plane K-Shape Steel Bracing as A Simple Strengthening Technique for RC Box Beams Failed in Torsion**. *IOP Conference Series: Materials Science and Engineering* 2021; **1076**(1): 012092, (1-13).

[13] Ibrahim A, Askar HS, El-Zoughiby ME. **Torsional Behavior of Solid and Hollow Concrete Beams Reinforced with Inclined Spirals**. *Journal of King Saud University-Engineering Sciences* 2022; **34**(5): 309–321.

[14] Jasim IK, Abdulrahman MB. Torsional Behavior of RC beams Strengthened by Near Surface Mounted-Steel Wire Rope Under Repeated Loading. 2023.

[15] Tais AS, Abdulrahman MB. **Improving The Torsional Strength of Reinforced Concrete Hollow Beams Strengthened with Externally Bonded Reinforcement CFRP Stripe Subjected to Monotonic and Repeated Loads**. *Information Sciences Letters* 2023; **12**(1): 427–441.

[16] Committee ACI. **Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary**. American Concrete Institute 2008.

[17] Hussain HK, Zewair MS, Ahmed MA. **High Strength Concrete Beams Reinforced with Hooked Steel Fibers Under Pure Torsion**. *Civil Engineering Journal* 2022; **8**(01): 92-104.

[18] Askandar NH, Mahmood AD, Kurda R. **Behaviour of RC Beams Strengthened with FRP Strips Under Combined Action of Torsion and Bending**. *European Journal of Environmental and Civil Engineering* 2022; **26**(9): 4263–4279.