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Innovative Method for Reinforcing Beams with Different Types of Concrete Using Cross-Rod Steel Bracing Under Pure Torsion

Adnan I. Abdullah [1*], Assim M. Lateef [1]

[1] *Department of Civil Engineering, College of Engineering, Tikrit University, Tikrit, Iraq.*

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Abstract

This study aimed to investigate the effectiveness of an innovative way to reinforce the concrete beams using cross-rod steel bracing under pure torsion. The experimental program consists of casting and testing eighteen concrete beams made of three types of concrete in the form of three groups, with the same dimensions for all beams (200×200×2000) mm. The parameters of the study included concrete types (normal strength, high strength, and steel fiber), as well as the number of internally cross rods (4, 8, 12, 16, 20). The experimental results showed that the number of internally cross-rod reinforcements and concrete type had an effect on ultimate torque, crack width, toughness, and stiffness. The torsional capacity of all concrete beams increased with the increase in internally cross-rod reinforcement. The ultimate torque of normal-strength concrete beams, high-strength concrete beams, and steel fiber concrete beams reinforced with twenty internally cross rods increased (88.34%, 53.20%, and 40.60%), respectively, compared to beams without cross rods in each type of concrete beam. Increasing the internally cross rod in all concrete beams effectively inhibited the development of crack width and improved torsional stiffness, especially in fibrous concrete beams that contained steel fiber. The torsional toughness of all concrete beams increased with the increase of internally cross-rod reinforcement, and it was higher in steel fiber concrete beams. The steel fiber concrete beams reinforced with internally cross-rod steel bracing have better torsional properties compared to ordinary concrete beams and high-strength concrete beams.

Keywords: Cross-Rod Steel Reinforcement; Normal Strength Concrete Beams; High Strength Concrete Beams; Steel Fiber Concrete Beams; Ultimate Torsional Capacity; Torsional Stiffness; Torsional Toughness.

1. Introduction

In recent years, there has been a notable increase in the complexity and irregularity of building and bridge structures. This is particularly evident in the presence of beams that are exposed to significant torque, particularly canopies, frontier beams, and curvature structures. Under these particular scenarios, it is imperative for the beams to possess a significant level of torsional capacity and ductility, particularly in regions that are susceptible to typhoons or earthquakes. This circumstance adds new complexities to the torsional behavior of the beam [1–3]. Numerous researchers and specialists in the field have conducted extensive studies on the flexural and shear behavior of concrete members [4–7]. However, comparatively less emphasis has been placed on investigating the torsional performance of such members. Historically, the augmentation of stirrups and the longitudinal reinforcement ratio have served to counteract the torsional forces exerted on structural elements. The building components are currently undergoing advancements in terms of their properties, specifically in the areas of weight reduction, enhanced strength, and ease of assembly, due to the progress and utilization of novel materials. The architectural design of buildings has evolved to incorporate increased height, complexity, and flexibility. The issue of torsion in the components must not be disregarded.

* Corresponding author: adnan.i.abdullah43807@st.tu.edu.iq

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For torsion in concrete beams, Rahal et al. [8] presented a straightforward model to determine the torque capacity of concrete elements subjected to torsion. This model incorporates the effects of longitudinal reinforcement, stirrups, concrete compressive strength, and cross-sectional area. Nevertheless, the limited tensile strength and brittleness of conventional concrete and high-strength concrete impose restrictions on their use in torsion members. The incorporation of steel fibers into concrete results in the formation of fiber concrete, which effectively enhances the strength of the tensile force and reduces the fragility of the material. Rao et al. [9] observed that the incorporation of fibers made of steel led to enhancements in both torsional strength and ductility. This conclusion was drawn based on the results obtained from conducting torsional tests on concrete beams. Okay et al. [10] conducted an analysis on the impact of longitudinal reinforcement content, fiber length and width ratio, and steel fiber under torsion behavior for concrete members. A study finding indicates that the presence of steel fiber has a notable impact on the energy absorption capacity. The inclusion of steel fiber in concrete induces distinct mechanical properties when subjected to torsional forces. Yang et al. [11] observed that the torsion capacity of concrete beams showed a rise as the amount of steel fiber, stirrup proportion, as well as longitudinal ratios of reinforcement were increased. Fehling [12] experimentally demonstrated that a steel content of fibers over 0.9% is necessary for establishing an efficient bearing load mechanism following the occurrence of cracking, together with the presence of longitudinal reinforcements.

Improving the ability of reinforced concrete (RC) beams to resist twisting while keeping the cross-sections cost-effective and efficient is a practical difficulty in their design. Developing and testing cost-effective methods to improve the torsional strength of beams is an important focus. The continuous spiral reinforcement system is a technology that has demonstrated promising results in improving concrete sections' torsional performance. Moreover, in recent years, there has been a growing recognition of the benefits associated with the utilization of continuous spiral reinforcing (SP) as opposed to conventional stirrups. These advantages primarily pertain to the enhancement of both the load-carrying capacity and the ability to undergo deformation without fracturing structural elements. The utilization of structural strengthening techniques, specifically the implementation of spiral reinforcement (SP), has been found to greatly enhance the shear behavior of beams as well as improve the capacity for deformation and dissipation of energy in column-beam connections. Furthermore, the application of SP reinforcement has been shown to enhance the seismic strength and bearing load capability of walls that shear [13–17]. As a result, studies on the use of SP in twisting beams have been carried out gradually.

Ibrahim et al. [18] studied how rectangular spiral stirrups improve the torsion performance of solid and hollow concrete beams as transverse reinforcement. Results indicated that utilizing an inclined spiral rectangular stirrup in reinforcing solid and hollow concrete beams significantly increased the torsional capacity by approximately 16% and 18%, respectively, in comparison to conventional closed stirrups. Shatarat et al. [19] developed the concrete beams by using three forms of spiral reinforcements, then investigated the effect of spiral reinforcement shape on beam torsion ability. The continuous circular spiral stirrup demonstrated the greatest increase in ultimate torque, followed by the continuous SP, the advanced rectangular spiral reinforcement, and the conventional stirrups. However, circular spiral stirrups were rarely used in beams, while researchers devoted more attention to rectangular spiral reinforcement. Hadhood et al. [20] studied the influence of spiral stirrup distances on concrete beam torsion effectiveness. It was shown that when the stirrup spacing increased, the beams' ultimate torque and stiffness decreased. Simultaneously, the spiral stirrup has a restriction that prevents it from efficiently increasing the cracking torque of the beams [19, 21]. The presence of torsional cracks has been observed to decrease both torsional performance and durability [22–24]. Yang et al. [11] and Zhou et al. [25] have shown that the use of steel fibers in ultra-high-performance concrete beams leads to an increase in both cracking torque and ultimate torque. Kwahk et al. [26] performed torsion tests exclusively on hollow concrete beams. Their findings showed the effects of steel fibers on cracking torque exceeded the impact of the stirrups. Muhammed et al. [27] utilized internally framed steel stiffness ribs (FSSRs) to enhance the torsional strength of reinforced concrete hollow beams. The study evaluated the influence of FSSRs and their number on torsion performance. The study found that the torsional ability capacity increased by 32.7%, 59.2%, and 93.9% when using one, three, and five FSSRs to strengthen beams, compared to the reference beam without strengthening.

In fact, according to the studies that preceded us in this field above, beams are often internally reinforced against torsion, either through rectangular stirrups or longitudinal steel or by adding additives such as steel fibers, spiral stirrups, internal steel ribs, or diagonal stirrups. Due to the geometry of the beam or the complexity of the system, performing external reinforcement on concrete beams is challenging despite the use of internal reinforcement. The study gap is to find a method of reinforcement for beams that is more practical than the previous reinforcements and can be implemented in practical applications of structural engineering because some of the previous anti-torsion reinforcements for beams are considered complex and difficult to implement. The study aims to use an innovative method to resist the torsional forces of concrete beams using internal cross-rod steel bracing. Internal reinforcement of beams with internally cross-rod steel bracing is innovative to the best of our knowledge and research in this study. Constructing this reinforcement with ordinary steel is straightforward and not complex, unlike the challenging implementation of spiral stirrups or other types in practical applications. The study will investigate the torsional behavior of concrete beams to determine the effectiveness of this reinforcement with the different variables adopted in this study, including the number of internal cross rod steel braces and the type of concrete used: normal strength concrete (NSC), high strength concrete (HSC), and steel fiber concrete (SFC).

2. Research Methodology

2.1. Materials

- ***Cement:*** this study used normal cement in accordance with Iraqi standard (I.O.S. No. 5/1984) [28].
- ***Fine aggregate:*** natural sand from Tikrit region was used in the concrete mixture. It conforms with Iraq's NO. 45/1984 specification.[29] . It has modulus of fineness 2.68.
- ***Coarse aggregate:*** The concrete mixture used Tikrit-sourced crushed river gravel. Conforms to Iraqi specifications No. 45/1984 [29] with maximum size aggregate 12.5mm. Crushed gravel plays a major role in obtaining high compressive strength concrete that is used in this study.
- ***Water (W):*** clean tap water was used for both, mixing and curing.
- ***Superplasticizer (SP):*** a superplasticizer used throughout this study was (Sika® Visco Crete®-180 GS, and manufactured by sika Construction Chemicals, Iraq), with nominal dosage 1 liter per 100 kg of cement).
- ***Steel Fiber:*** hooked-end steel fibers (Bekaert-Dra mix® ZP305) of length 50 mm and diameter 0.5 mm. It has an aspect ratio of 100 and a density of 7860 kg/m3. It is used in this study to make fibrous concrete with a constant content of the volume fraction of steel fibers (Vf = 1.0%), as shown in Figure 1. A ratio of 1% steel fiber provides sufficient workability without segregation, while a ratio of more than 1% steel fiber causes issues during implementation [30].
- ***Steel Reinforcement:***
  - Steel bars: steel reinforcement bars with deformed surfaces were used in all specimens, with diameters of (10 mm) for main reinforcement and (6 mm) for closed stirrup reinforcement. Table 1 shows the tensile results for all reinforcement rebars that tested in accordance with American Standard (ASTM A615-09) [31]. The steel reinforcement is shown in Figure 2.
  - Cross-rod steel bracing: stirrups in the form of internal cross rod of steel with a diameter of 8 mm. This steel reinforcement is used as an innovative way to reinforce concrete beams against torsional forces in this study. Table 1 shows the tensile results for steel bracing rods tested according to American Standard (ASTM A615/A615M-09)[31]. The internal cross rod (CR) of steel bracing is shown in Figure 2.

Figure 1. Granulation diagram for the materials used to cast concrete beams

Table 1. Properties of reinforcing bars

Bars diameter (mm)	Function	Yield strength (f_y) MPa	Ultimate strength (f_u) MPa	Elongation %
6	Stirrup	520	544	7.08
8	Cross-rod	442	589	11.2
10	Longitudinal rebar	583	672	12.32

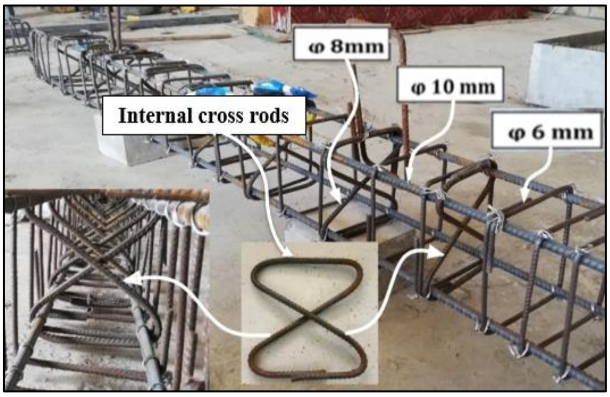


Figure 2. Internal cross rod of steel bracing and steel bars reinforcement

2.2. Mixtures

Three kinds of concrete mixtures have been utilized in this study for casting concrete beams: ordinary concrete, high-strength concrete, and fibrous concrete using steel fibers. The quantities of materials used to produce the three concrete mixtures are shown in Table 2. For each concrete, its compressive strength was tested by casting cylinders (150×300) mm according to ASTM C39 specifications. The splitting tensile strength was also tested according to ASTM C496 by casting cylinders (150×300) mm. The modulus of rupture was also tested by casting prisms (100×100×500) mm according to ASTM C293. All tests were performed 28 days after casting the samples. The properties of ordinary concrete, high-strength concrete, and steel fiber concrete are shown in Table 3. Figure 3 shows the flowchart of work.

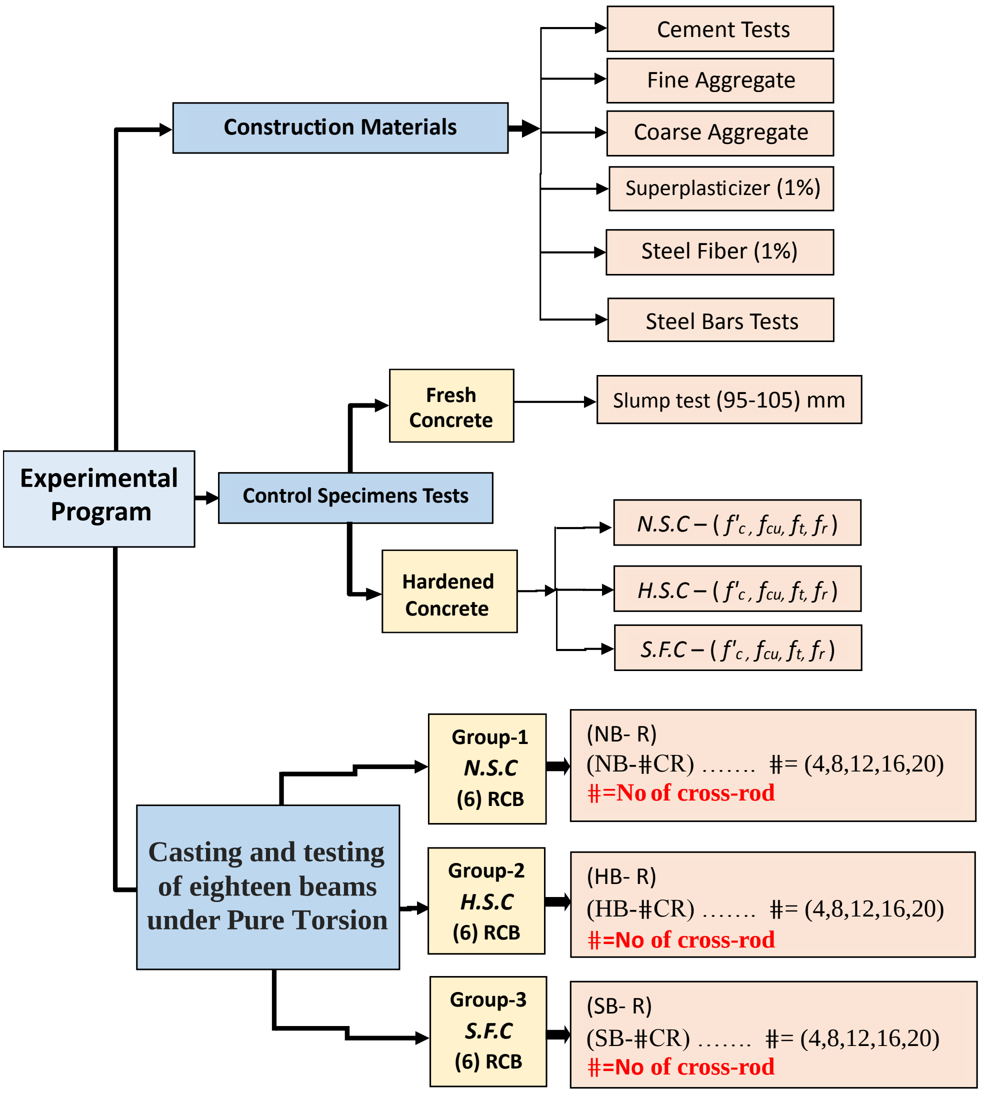


Figure 3. Flowchart of the work

Table 2. Quantities of materials used in the concrete mixes

Mixture type	W/C	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Steel fiber (kg/m^3)	Density (kg/m^3)
Normal strength concrete (NSC)	0.46	427	797	910	197	-	-	2311
High strength concrete (HSC)	0.3	480	740	986	140	4.8	-	2346
Steel fiber concrete (SFC)	0.3	480	740	986	140	7.2	79	2425

Table 3. Concrete characteristics

Mixture type	Compressive strength (MPa)	Splitting strength (MPa)	Flexural strength (MPa)
Normal strength concrete (NSC)	34.21	3.1	5.12
High strength concrete (HSC)	62.13	4.9	6.97
Steel fiber concrete (SFC)	65.52	7.55	9.75

2.3. Details of the Specimens

Eighteen reinforced beams were cast for testing under pure torsion. These beams were divided into three groups. Group-1 includes six beams made of normal strength concrete. Group-2 includes six beams made of high-strength concrete. Group-3 includes six concrete beams made of steel fiber. The dimensions of all beams were (200×200×2000) mm in (width × height × length), as shown in Figure 4. All of these beams were reinforced longitudinally with 2Φ10 mm bars at the top and bottom in cross section of beam. Each of the beam was transversely reinforced by stirrups Φ6mm@90mm. Design of both transverse and longitudinal reinforcement of beams according to ACI 318 torsion code requirements [32]. As for the steel bracing for the internally crossing rod using Φ8 mm, they were placed at different spaces (0, 75, 95, 125, 175, 320) mm, represented by the six beams for each of the three groups. Table 4 shows the reinforcement details for all concrete beams. Figure 5 shows the mechanism of reinforcement and distribution of internal cross rod for concrete beams, which was applied to each concrete group of the three groups.

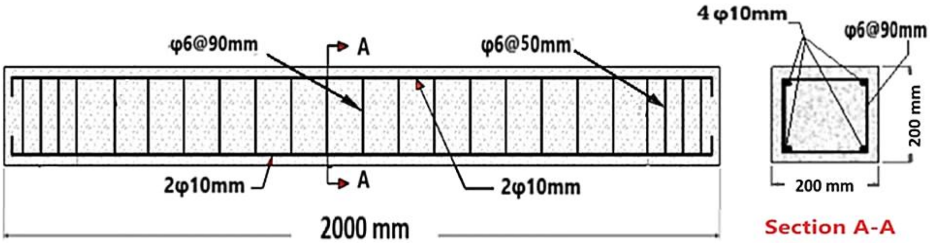


Figure 4. Specimen dimensions

Table 4. Reinforcements of concrete beams

Group No.	Beam designation	Cross-rod	No. of Cross-rod	Top reinforcing	Bottom reinforcing	Stirrups	Mixing type
Group-1	NB-R*	…….	0	2Φ10	2Φ10	Φ6@90mm	Normal strength concrete
	NB-4CR	Φ8@320mm	4				
	NB-8CR	Φ8@175mm	8				
	NB-12CR	Φ8@125mm	12				
	NB-16CR	Φ8@95mm	16				
	NB-20CR	Φ8@75mm	20				
Group-2	HB-R*	…….	0	2Φ10	2Φ10	Φ6@90mm	High strength concrete
	HB-4CR	Φ8@320mm	4				
	HB-8CR	Φ8@175mm	8				
	HB-12CR	Φ8@125mm	12				
	HB-16CR	Φ8@95mm	16				
	HB-20CR	Φ8@75mm	20				
Group-3	SB-R*	…….	0	2Φ10	2Φ10	Φ6@90mm	Steel fiber concrete
	SB-4CR	Φ8@320mm	4				
	SB-8CR	Φ8@175mm	8				
	SB-12CR	Φ8@125mm	12				
	SB-16CR	Φ8@95mm	16				
	SB-20CR	Φ8@75mm	20				

* Where: R is reference beam, NB is normal strength concrete beam, HB is high strength concrete beam, SB is steel fiber concrete beam, CR is cross -Rods steel bracing.

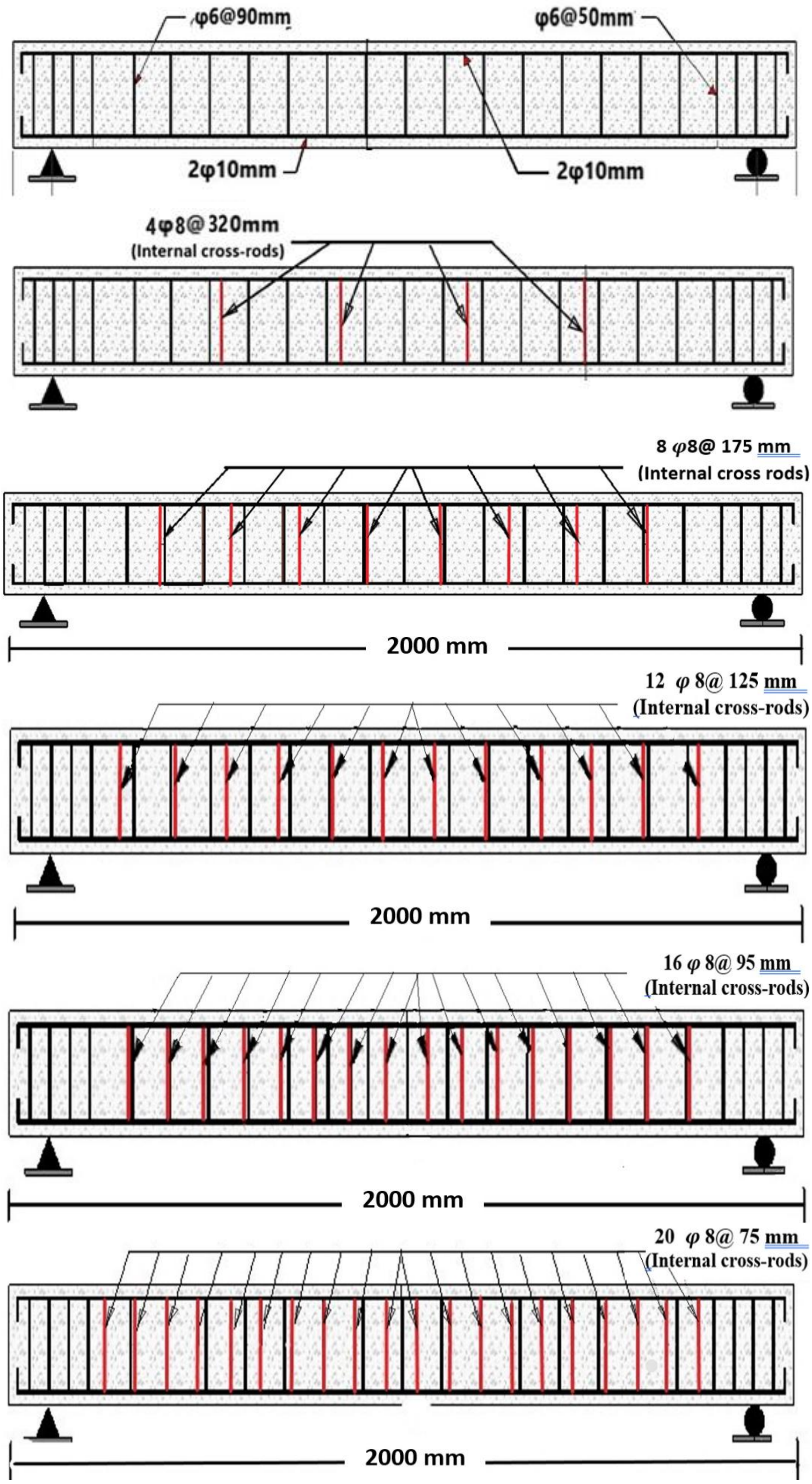


Figure 5. Reinforcement and distribution of internally cross-rod for concrete beams in each of the three concrete groups

2.4. Casting and Curing of Specimens

To cast concrete beams, a rotary mixer with a capacity of (0.07 m^3) was used. Molds were used according to the required sizes and dimensions (200 × 200 × 2000) mm to cast concrete beams. During the process of casting the beams, the mold was filled with three layers of the mixture, and each layer was compacted using an electric vibrator to shake the mixture and compact it in the mold. The surface of the specimens is levelled with a trowel, and all beams are left in their molds until they are dismantled after 24 hours. The specimens were treated with burlap bags that were continuously moistened with water for 28 days before the examination was performed. Figure 6 shows the casting and curing processes.

Figure 6. Casting and curing processes of concrete beams

2.5. Beams Test

All eighteen beams were tested under pure torque using a hydraulic testing machine with a load capacity of 3000 kN. The work of this machine is to stabilize the sample on one side and rotate the sample on the other side using the hydraulic arm. The hydraulic arm to rotate the sample is 200 mm (0.20 m). The main parts of the machine can be illustrated in Figure 7. In this study, reinforced concrete beams from the three groups were subjected to torsional loads until failure. Load readings are taken during the test using the load cell located below the hydraulic jack. These readings are recorded by the data logger on the computer and appear in Excel, as shown in Figure 8. To calculate the torsion angle of the beams, the vertical deflection recorded from the LVDT reading is divided by the horizontal distance from the center of the beam to the location of the gauge reading LVDT. Also, before testing the beams, the beams were painted with white dye so that it was easy to notice the crack patterns using a digital camera prepared for this purpose. The crack pattern was also observed at each loading stage. The locations and development of cracks were determined on all faces of the beam.

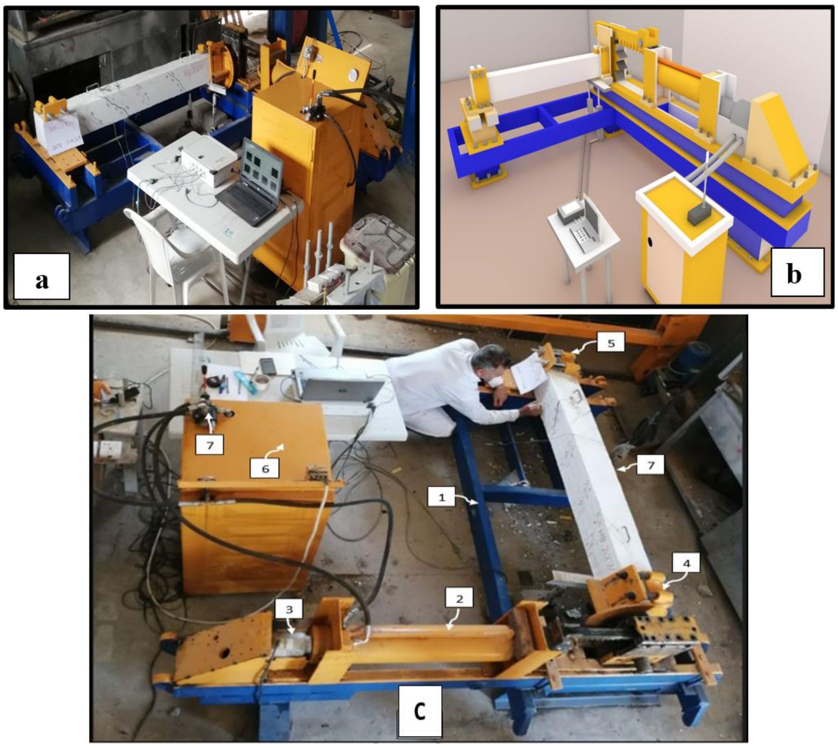
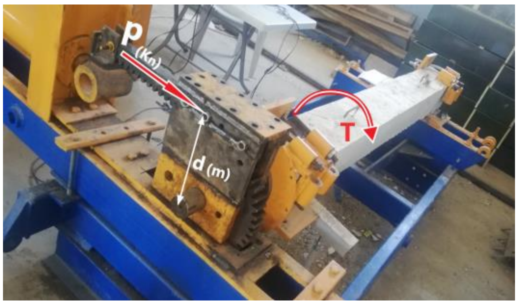
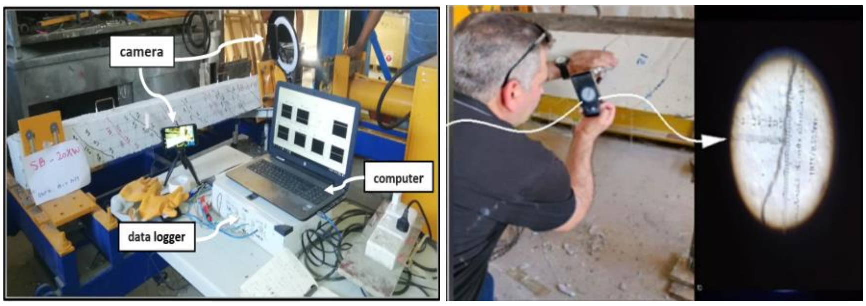


Figure 7. Diagram of beams test. (a) Loading Frame, (b) 3D Model of Machine, (c) Test Machine (1- Steel loading base 2- Hydraulic jack 3- Load cell 4- Rotating support 5-Fixed support 6- Control box 7- Hand shifter 8- Tested beam)



(a) Beam test

(b) LVDT, Angle of twist measurements



(c) Computer, data logger and micro crack width (camera system)

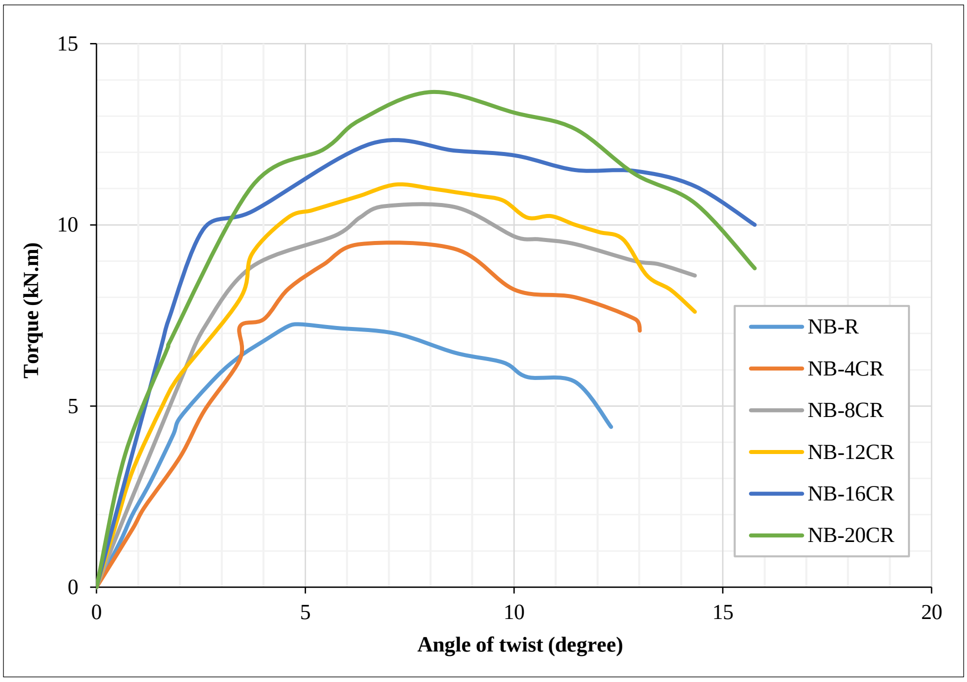
Figure 8. Testing of beams models

3. Results

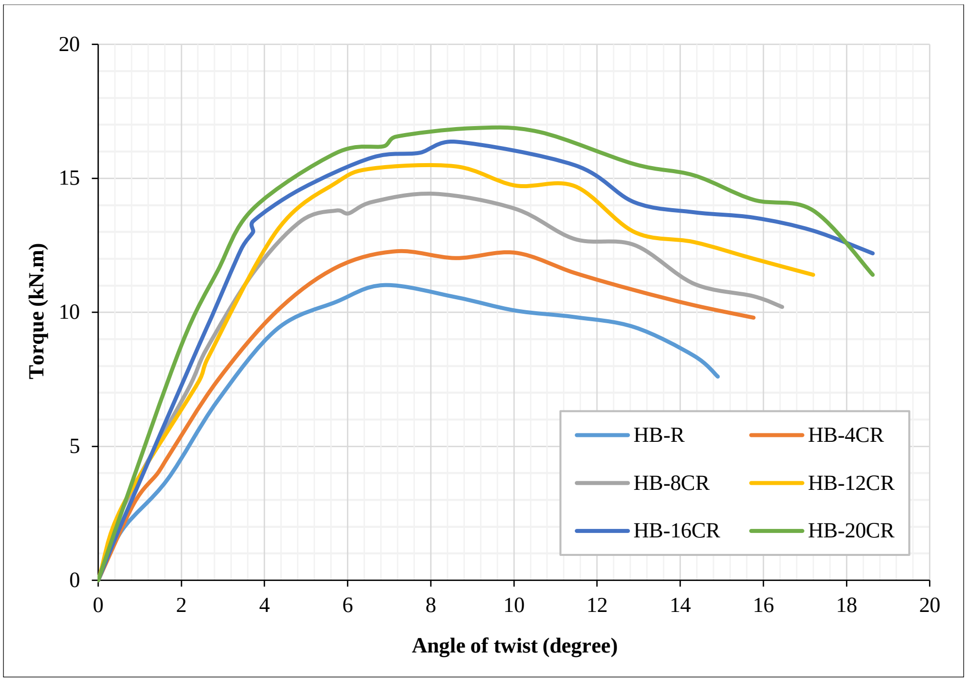
The characteristics examined involved torque of the initial crack, ultimate torque, twist angle at the crack's initial torque, twist angle at the ultimate torque, torsional stiffness, torsional toughness, crack pattern, and failure mechanism. In addition, torque-twist curves were drawn for the examined beams. The torque at which the first visible crack appeared was defined as the cracking torque. Figure 9 depicts the torque - twist of the tested specimens. Table 5 illustrates the results of all the concrete beams with different types of concrete reinforced with internal cross-rod steel bracing.

Table 5. Results of all the specimens reinforced using internally cross-rod bracing

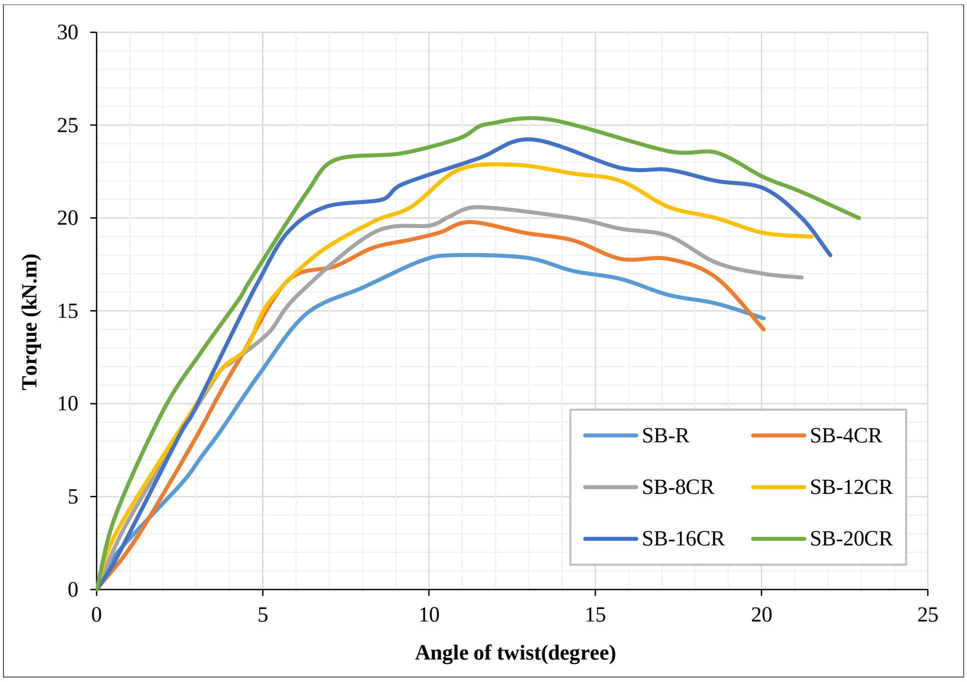
Group No.	Beam designation	Cracking Load Pcr (kN)	Cracking torque Tcr (kN.m)	Cracking twist θcr (deg.)	Ultimate Load Pu (kN)	Ultimate torque Tu (kN.m)	Ultimate twist θu (deg.)	Torsional stiffness K (kN.m/deg.)	Torsional toughness (kN.m.deg.)
Group-1	NB-R	14.49	2.898	1.43	36.28	7.256	4.872	1.489	23.952
	NB-4CR	23.32	4.664	2.01	47.33	9.466	6.37	1.503	27.768
	NB-8CR	24.44	4.888	2.13	52.56	10.512	6.88	1.528	38.067
	NB-12CR	26.11	5.222	2.21	55.56	11.112	7.16	1.552	50.260
	NB-16CR	31.78	6.356	2.32	61.23	12.246	7.33	1.671	60.438
	NB-20CR	33.43	6.686	2.89	68.33	13.666	8.13	1.703	69.484
Group-2	HB-R	18.77	3.754	1.66	55.08	11.016	6.87	1.603	41.974
	HB-4CR	24.53	4.906	1.89	61.39	12.278	7.13	1.729	45.706
	HB-8CR	32.88	6.576	2.29	72.12	14.424	8.08	1.785	60.132
	HB-12CR	36.94	7.388	2.47	77.23	15.446	8.53	1.817	79.867
	HB-16CR	44.04	8.808	3.41	81.83	16.366	8.89	1.841	91.679
	HB-20CR	52.63	10.526	3.72	88.35	16.877	8.97	1.881	102.455
Group-3	SB-R	33.77	6.754	3.43	89.99	17.998	10.71	1.680	111.034
	SB-4CR	46.53	9.306	3.75	98.92	19.784	11.23	1.762	136.762
	SB-8CR	57.88	11.576	4.98	102.94	20.588	11.42	1.806	143.623
	SB-12CR	62.94	12.588	5.07	115.32	23.064	12.61	1.829	183.239
	SB-16CR	69.04	13.808	5.21	121.15	24.23	13.09	1.851	190.876
	SB-20CR	71.63	14.326	6.01	126.53	25.306	13.61	1.909	236.227



(a) Normal strength concrete beams



(b) High strength concrete beams



(c) Steel fiber concrete beams

Figure 9. Torque-twist relationships of different groups of test beams

3.1. Torque−Twist Relationships

Figures 9-a to 9-c shows the torque-twist relations of all the beams. All of the figures illustrate the relationship among normal-strength concrete (NSC) beams, high-strength concrete (HSC) beams, and steel fiber concrete (SFC) beams, all reinforced with internally cross rods of different spacing. Table 5 shows the results for all these beams. For normally strength concrete beams, as shown in Figure 9 (a) and Table 5, the ultimate torque increases with the number of cross rod. The ultimate torque of normal strength concrete beams (NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) increased by (30.45%, 44.87%, 53.14%, 68.77% and 88.34%) respectively, compared to beams (NB-R) without cross rods. Also, the angle of twist for these beams increases with the number of cross rod. The angle of twist of normal strength concrete beams (NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) increased by (30.74%, 41.21%, 46.96%, 50.45% and 66.87%) respectively, compared to beams (NB-R) without cross rod.

Figure 9-b shows the torque-twist relationships of highly strength concrete beams. The ultimate torque increases with the number of cross rod. The ultimate torque of high strength concrete beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) increased by (11.45%, 30.93%, 40.21%, 48.56% and 53.20%) respectively, compared to beams (HB-R) without cross rods. Also, the angle of twist for these beams increases with the number of cross rod. The angle of twist of high strength concrete beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) increased by (3.78%, 17.61%, 24.16%, 29.40% and 30.56%) respectively, compared to beams (HB-R) without cross rod. When compared, these beams with (NSC) beams show that the ultimate torque and twist angle of (HSC) beams higher than (NSC) beams with the same reinforcement. This increase in torque was due to the high compressive strength of the concrete in these beams compared to beams with normal concrete strength with the same reinforcement.

For steel fiber concrete (SFC) beams, as shown in Figure 9-c, the ultimate torque increases with the number of cross rod. The ultimate torque of steel fiber concrete beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) increased by (9.92%, 14.39%, 28.14%, 34.62% and 40.60%) respectively, compared to beams (SB-R) without cross rod. Also, the angle of twist for these beams increases with the number of cross rod, as shown in Table 5. The angle of twist of steel fiber concrete beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) increased by (4.85%, 6.62%, 17.74%, 22.22% and 27.07%) respectively, compared to beams (SB-R) without cross rod.

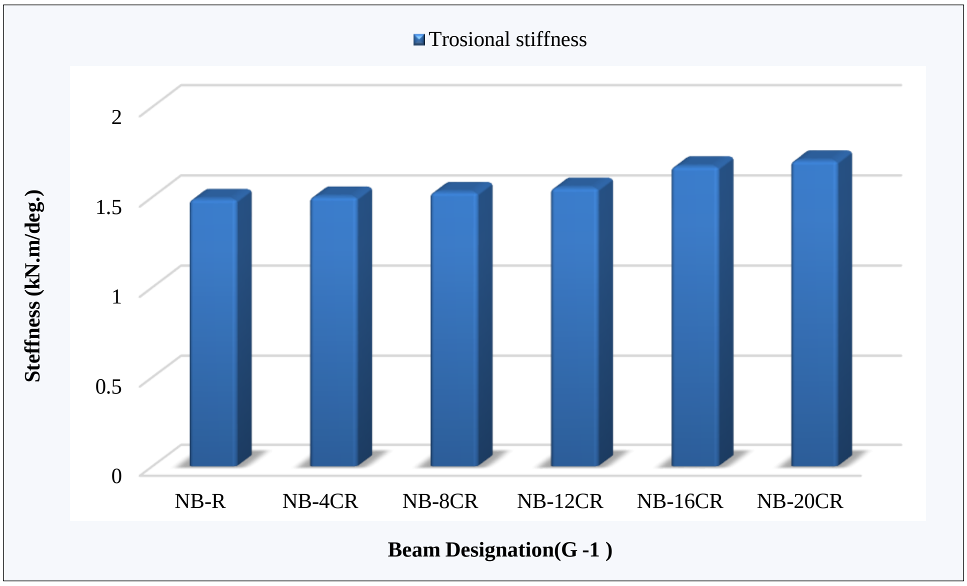
Comparisons between concrete beams show that the ultimate torque and twist angle of steel fiber concrete (SFC) beams higher than those of high strength concrete (HSC) beams and the normal strength (NSC) beams with the same reinforcement. The ultimate torque of steel fiber concrete (SFC) beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the high strength concrete (HSC) beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) by (63.38%, 61.13%, 42.73%, 49.32%, 48.05% and 49.94%) respectively, with the same reinforcement. The ultimate twist angle of steel fiber concrete (SFC) beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the high strength concrete (HSC) beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) by (55.89%, 57.50%, 41.33%, 47.83%, 47.24% and 51.72%) respectively, with the same reinforcement. The ultimate torque of steel fiber concrete (SFC) beams (SN-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the normal strength concrete (NSC) beams (NB-R, NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) by (148.04%, 109%, 95.85%, 107.55%, 97.86% and 85.17%) respectively, with same reinforcement. The ultimate twist angle of steel fiber concrete (SFC) beams (SN-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than the normal strength concrete (NSC) beams (NB-R, NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) by (119.82%, 76.29%, 65.98%, 76.11%, 78.58% and 67.40%) respectively, with the same reinforcement. The steel fibers had a greater influence on the ultimate torque of the beams. Steel fibers' influence on torque in the presence of cross rods, stirrups and longitudinal reinforcement is very clear in increasing the capacity of these beams. The reasoning is that the steel fibers in the concrete matrix improve its bridging effect. This indicates that when the steel fiber content in the concrete was high, agglomerations that collectively created clusters of steel fibers inside the concrete were the cause of the stress concentration inside the concrete [33]. The test beam's torque was enhanced as a result of the concrete's greater tensile strength. Since raising the reinforcement ratio could significantly increase the ultimate load capacity, the tensile strength of the reinforcement was greater than the tensile strength of the concrete. Furthermore, compared to the longitudinal reinforcement ratio, the impact of internally cross rods and stirrups on maximum torque was larger, similar to a result by Yang et al. [11]. This indicates that the ultimate load capacity of steel fiber concrete beams is effectively improved with steel fiber and internal cross rods, stirrups and longitudinal bars with reasonable strength. Using steel fibers improved the concrete's tensile strength in addition to the stirrups' tension strength. It's obvious which ultimate torque increases using steel fibers, and this agrees with Gao et al. [34, 35].

By studying Table 5, the cracking torque and crack twist angle of all concrete beams increase with the internally cross rods reinforcement. Table 5 summarises the cracking torques for all beams. Compared with normal strength concrete (NSC) beams, high strength concrete (HSC) beams and steel fiber concrete (SFC) beams, a cracking torque as well as twist angle of high strength concrete (HSC) beams were higher than those of normal strength concrete (NSC) beams. The cracking and crack twist angle of steel fiber concrete (SFC) beams were higher than normal strength concrete (NSC) beams and high strength concrete (HSC) beams. The cracking torque of steel fiber concrete (SFC) beams was strongly affected by steel fibres, in agreement with the conclusion of Kwahk et al. [26]. It was found that the fibers of steel prevented the formation of cracks and applied tension to the beams through the bonding force. Additionally, the steel fibers in the beams distribute tension, preventing stress concentration.

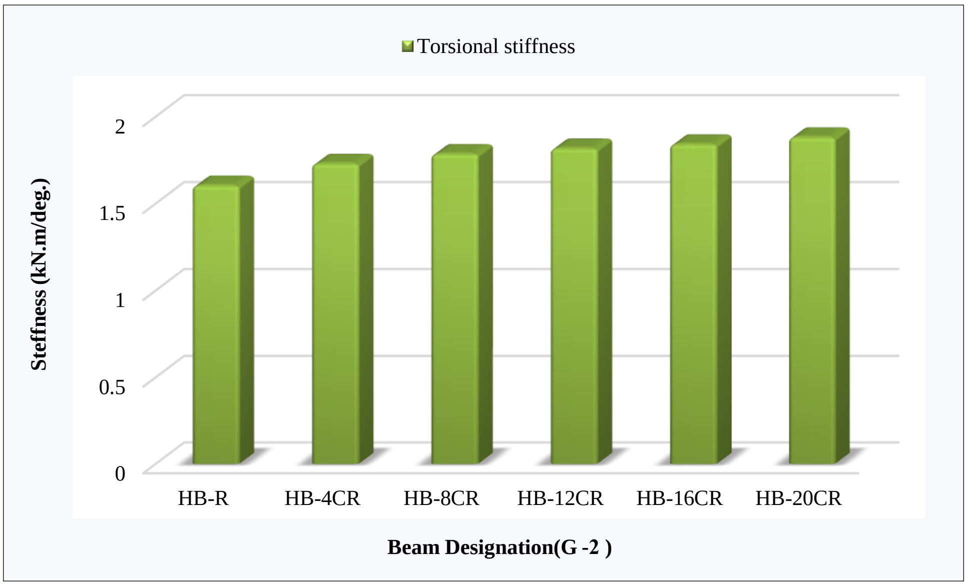
3.2. Torsional Stiffness

The ability of members of the structure to withstand deformations as a result of any applied load is defined as rotational stiffness. It is an indicator of rigidity (a material property). The ultimate torque divided by the ultimate twist angle determines the ultimate torsional stiffness of beams [20, 34–36]. Table 5 shows the torsional stiffness of all beams. The maximum torsional stiffness refers to the rigidity of the specimen until it fails. For normally strength concrete beams, the stiffness increases with the number of cross rod. The stiffness of normal strength concrete beams (NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) increased by (0.90%, 2.61%, 4.22%, 12.20% and 14.36%) respectively, compared to beams (NB-R) without cross rod, as shown in Figure 10-a.

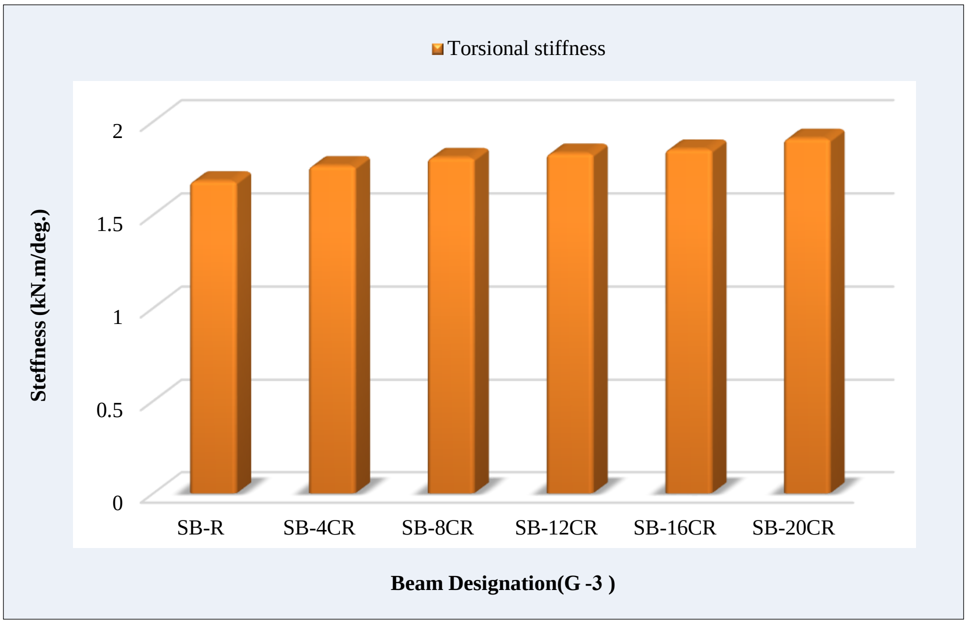
Figure 10-b shows the stiffness of highly strength concrete beams. The stiffness increases with the number of cross rods. The stiffness of high strength concrete beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) increased by (7.87%, 11.36%, 13.36%, 14.84% and 17.32%) respectively, compared to beams (HB-R) without cross rod. When compared, these beams with (NSC) beams show that the stiffness of (HSC) beams was higher than that of (NSC) beams with the same reinforcement. This increase in stiffness was due to the high compressive strength of the concrete in these beams compared to beams with normal concrete strength with the same reinforcement. For steel fiber concrete (SFC) beams, the stiffness increases with the number of cross rod. The stiffness of steel fiber concrete beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) increased by (4.86%, 7.49%, 8.87%, 10.18% and 13.60%) respectively, compared to beams (SB-R) without cross rod as shown in Figure 10-c. The stiffness of steel fiber concrete (SFC) beams was higher than that of high strength concrete (HSC) beams and the normal strength (NSC) beams with the same reinforcement. The stiffness of steel fiber concrete (SFC) beams (SB-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the high strength concrete (HSC) beams (HB-R, HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) by (4.80%, 1.87%, 1.16%, 0.65%, 0.54% and 1.48%) respectively, with the same reinforcement. The stiffness of steel fiber concrete (SFC) beams (SN-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the normal strength concrete (NSC) beams (NB-R, NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) by (12.83%, 17.24%, 18.19%, 17.85%, 10.79% and 12.08%) respectively, with the same reinforcement. Steel fibers increase the stiffness of concrete beams, as mentioned by many researchers, such as Rao et al. [37], Hassan et al. [38] and Gao et al. [34, 35]. The cause is because the fibers of steel weren't fully pulled out of the concrete's matrix during this level, as well as the fibrous concrete linked through internal cross rods, stirrups, longitudinal rebar, and steel fibers, which appeared to exhibit a pseudo-hardening phenomenon [39, 40].



(a) Normal strength concrete beams



(b) High strength concrete beams



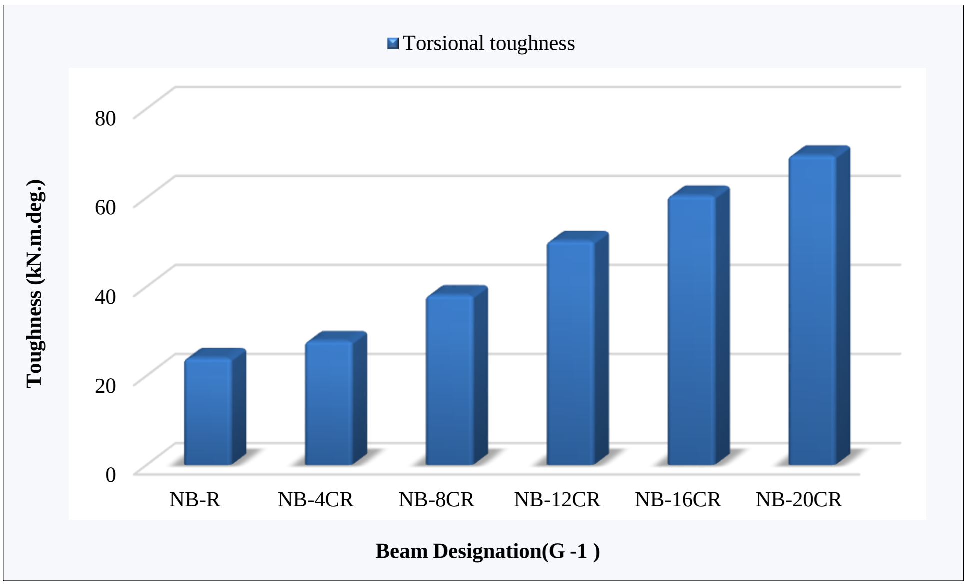
(c) Steel fiber concrete beams

Figure 10. Torsional stiffness of all the concrete beams

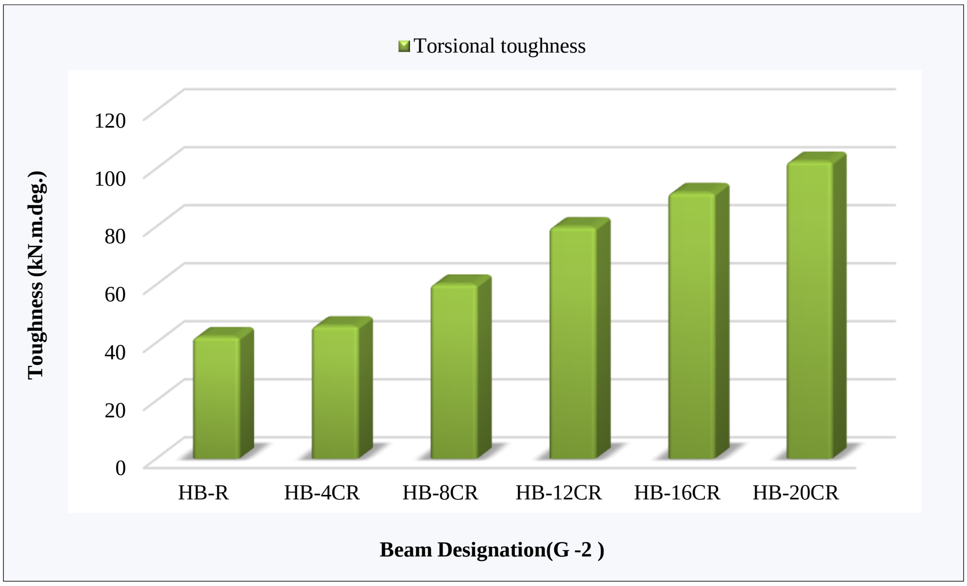
3.3. Torsional Toughness

Toughness can be expressed as the amount of energy needed to break the specimen. Toughness may be determined from the torque-twist curve to the ultimate torque since it is the area under the curve [37, 38, 41]. Table 5 reveals the torsional toughness of specimens. The ultimate torsional toughness denotes the toughness of the test beam until it fails. For normally strength concrete beams, the toughness increases with the number of cross rod. The toughness of normal strength concrete beams (NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) increased by (15.92%, 58.92%, 109.83%, 152.32% and 190.09%) respectively, compared to beams (NB-R) without cross rod, as shown in Figure 11-a. Figure 11-b shows the toughness of highly strength concrete beams. The toughness increases with the number of cross rod. The toughness of high strength concrete beams (HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) increased by (8.89%, 43.26%, 90.27%, 118.41% and 144.09%) respectively, compared to beams (HB-R) without cross rod. When compared, these beams with (NSC) beams show that the toughness of (HSC) beams was higher than that of (NSC) beams with the same reinforcement. This increase in toughness was due to the high compressive strength in these beams compared to beams with normal concrete strength with the same reinforcement. For steel fiber concrete (SFC) beams, the toughness increases with the number of cross rod. The toughness of steel fiber concrete beams (SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) increased by (23.17%, 29.35%, 65.02%, 71.90% and 112.75%) respectively, compared to beams (SB-R) without cross rod, as shown in Figure 11-c.

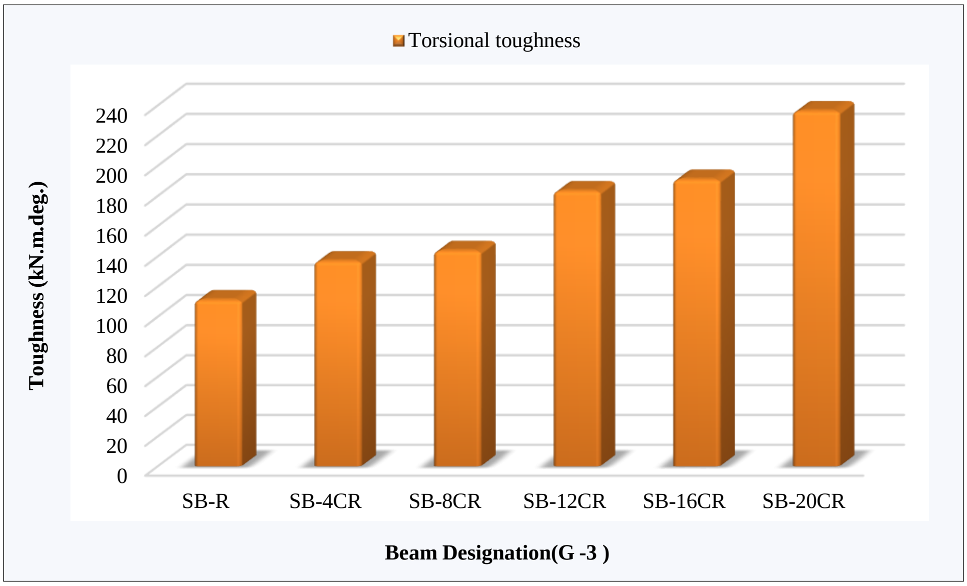
The toughness of steel fiber concrete (SFC) beams was higher than that of high strength concrete (HSC) beams and the normal strength (NSC) beams with the same reinforcement. The toughness of steel fiber concrete (SFC) beams (SB-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the high strength concrete (HSC) beams (HB-R, HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) by (164.52%, 199.22%, 138.84%, 129.42%, 108.20% and 130.56%) respectively, with the same reinforcement. The toughness of steel fiber concrete (SFC) beams (SN-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) higher than that of the normal strength concrete (NSC) beams (NB-R, NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) by (363.56%, 392.52%, 277.29%, 264.58%, 215.82% and 239.97%) respectively, with the same reinforcement. Steel fibers increase the stiffness of concrete beams, as mentioned by many researchers, such as Hassan et al. [38] and Gao et al. [34,35]. The highest torsional toughness was (236.227 kN.m.deg.) for the steel fiber concrete beam (SB-20CR) reinforced with twenty internally cross rod steel bracing. While for the same beam, but high-strength concrete beam (HB-20CR) and normal-strength concrete beam (NB-20CR), the energy was (102.455 kN.m.deg.) and (69.484 kN.m.deg.), as shown in Table 5. This could be because steel fiber concrete beams have a high tensile strength which increases the torque to twist curve area of these specimens.



(a) Normal strength concrete beams



(b) High strength concrete beams



(c) Steel fiber concrete beams

Figure 11. Torsional toughness of all the concrete beams

3.4. Crack Pattern and Failure Mechanism of Beams

Figure 12 depicts the torque-crack width relationship for each group of concrete beams. Figure 13 depicts the crack pattern as well as the mechanisms of failure of concrete specimens. For each group of concrete beams, the development of cracks was characterised by the addition of new cracks to the surface and the simultaneous development of multiple cracks. The cracks width grew gradually, as well as every crack width was comparable. The primary crack hadn't been determined. The crack widened significantly following every load, ultimately developing into its primary crack. The maximal crack had been roughly proportional to the torque. After the appearance of the main crack, the cracks rapidly entered the unstable phase. At the cracks in the fibrous concrete beams, a steel fibre was fully pulled out. When beams of concrete were damaged by an increase in torque, the crack width expanded significantly [9, 42].

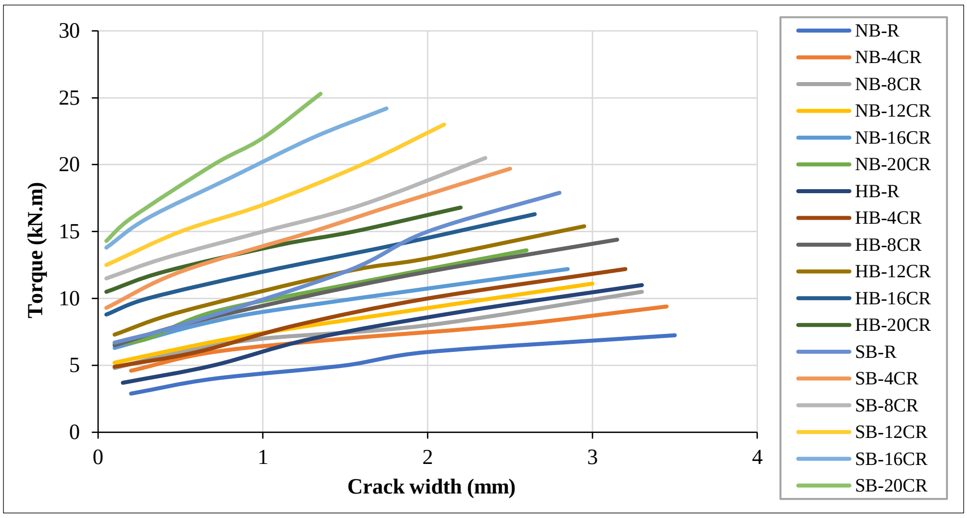
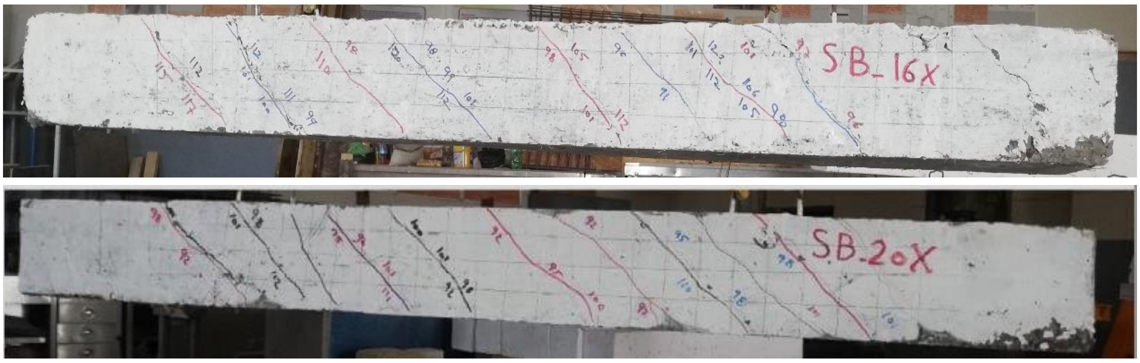


Figure 12. Totrue-crack width relationship for different of test beams

(a) Group-1 (Normal strength concrete beams)

(b) Group-2 (High strength concrete beams)



(c) Steel fiber concrete beams

Figure 13. Cracking patterns in beams reinforced by internally cross rods

Figure 12 shows the torque to crack width relationship of normal strength concrete beams reinforced with internally cross rod. With the same torque, increasing the internal cross rod reduced the crack width. Due to diagonal cracks on the surface, they intersected the internally cross rod and stirrups. The crack width for these beams (NB-CR, NB-4CR, NB-8CR, NB-12CR, NB-16CR and NB-20CR) was (3.5 mm, 3.45 mm, 3.3 mm, 3 mm, 2.85 mm and 2.6 mm) respectively at ultimate torque. The more densely the internal cross-rods and stirrups, the stronger the inhibition affects the crack formation following the crack. The primary diagonal crack angle is also shown in Figure 13. The diagonal cracks angles in these beams ranged from 43° to 47°. The presence of internally cross rods increases the ductility and deformations of these beams. Moreover, there was no big concrete falling off when the beams were damaged in the failure process of these beams.

Figure 12 shows the torque-crack width curves for high strength concrete beams. The influence of internally cross-rod reinforcement in these beams on crack width was different from that of normal strength concrete beams. The type of concrete had an influence on the maximum crack width. With increasing internally cross rods the crack width decreased more than normal strength concrete beams. The crack width for these beams (HB-CR, HB-4CR, HB-8CR, HB-12CR, HB-16CR and HB-20CR) was (3.3 mm, 3.2 mm, 3.15 mm, 2.95 mm, 2.65 mm and 2.2 mm) respectively at ultimate torque. The cracks began to appear in the portion somewhere in the middle and continued all the way to the edges of the beam. The primary diagonal crack angle is also shown in Figure 13. The average of diagonal cracks angle in these beams was 45°. The internally cross rods, stirrups and longitudinal bars increased the ductility and torsional deformation of these high strength concrete beams. Moreover, during the failure, there was no spalling on the surface of the high strength concrete beams.

Figure 12 shows torque-crack width curve of steel fiber concrete beams. As the width of the crack increased, the fiber in the cracks was progressively drawn out. After the first crack appeared, the crack became wider and soon caused damage to the beam. In fibrous concrete beams with steel fibers and stirrups, the influence of various in-situ cross-rod reinforcement states on the cracking process was slight. These beams' cracking behavior was documented, as seen in Figure 13. The initial audible diagonal crack appeared on the beam's side when the cracking torque was achieved. With each increment in torque, a continuous appearance of new diagonal cracks was observed, with their inclination remaining essentially unaltered. Along the surface of the beam, numerous diagonal cracks had developed spiral cracks as they extended to the top and bottom. Further diagonal cracks were not observed, and as the beam underwent increasing angles of twisting, the extent of the pre-existing diagonal cracks progressively expanded until its sustained damage.

The quantity of cracks in these beams developed in correlation with an increase in cross rods and steel fiber contents. This indicates that by increasing the internal cross-rod and steel fiber, the stress redistribution could be effectively enhanced, preventing the expansion of the crack width while fostering the tendency towards numerous cracks. The effects of the internal cross rod and the steel fiber were comparable, but the two components' mechanisms of action were distinct. By enhancing the internal cross-rod, the tension of the concrete was increased, resulting in an increase in the torque transferred to the concrete of the test beam. However, the fibers of steel effectively removed the concentration of stress in the concrete matrix and prevented the growth of crack width, promoting numerous cracks. Thus, failures of steel fiber concrete beams were classified as ductile failures. The utilization of the tensile properties of the longitudinal bars, stirrups, and internally cross rods prior to the crushing of the concrete is what caused this type of failure. In addition, there wasn't any concrete crashing off due to the existence of steel fibers when the specimen failed. Compared with ordinary concrete beams and high-strength concrete, this phenomenon appeared very different [43,44].

The crack width decreased with the number of cross rod steel bracing increased in these steel fiber concrete beams. The crack width for these beams (SB-R, SB-4CR, SB-8CR, SB-12CR, SB-16CR and SB-20CR) was (2.8 mm, 2.5 mm, 2.35 mm, 2.1 mm, 1.75 mm and 1.35 mm) respectively at ultimate torque. This is in agreement with Gao et al. [34,35] and Abdullah et al. [45], those who showed that the number of cracks is increased and their width the decreases with the increase in the stirrups and steel fibers in concrete beams. The primary diagonal crack angle of these beams is also shown in Figure 13. The test parameters had an effect on the primary crack inclination angle. This is because the crack's angle is determined by the direction of the major tensile stress, which is related with the stress condition of steel fiber as well as stirrups. The average of diagonal cracks angle in these steel fiber concrete beams was 45°. By comparing the beams of the three concrete groups, we conclude that concrete beam containing steel fibers and twenty internally cross rod (SB-20CR) are better at controlling the width and development of numerous cracks. The crack width was reduced by 38.6% for this beam compared to high-strength concrete beams with twenty internally cross rods (HB-20CR) and 48% compared to normal-strength concrete beam with twenty internally cross rod (NB-20CR).

4. Conclusions and Recommendations

The following conclusions can be drawn:

- The torsional capacity of all concrete beams increased with the increase in internally cross-rod reinforcement. The ultimate torque of normal-strength concrete beams, high-strength concrete beams, and steel fiber concrete beams reinforced with twenty internally cross rods increased (88.34%, 53.20%, and 40.60%), respectively, compared to beams without cross rods in each type of concrete beam.
- The ultimate torque and twist angle of steel fiber concrete beams are higher than those of high-strength concrete beams and normal-strength concrete beams with the same reinforcement.
- The stiffness of steel fiber concrete beams was higher than that of high-strength concrete beams and normal-strength beams with the same reinforcement.
- The torsional toughness of concrete beams improved as the internally cross rod reinforcing increased, as well as being higher in steel fiber concrete beams. The highest torsional toughness was (236.227 kN.m.deg.) for the steel fiber concrete beam reinforced with twenty internally cross-rod steel bracing. While for the same beam, but high-strength concrete beams and normal-strength concrete beams, the torsional toughness was (102.455 kN.m.deg.) and (69.484 kN.m.deg.), respectively. This is due to the high tensile strength of steel fiber concrete beams, which increases the torque-twist curve area of these beams.
- Increasing the internally cross-rod in all concrete beams prevented crack width progression as well as improved stiffness under torsional loads, especially in fibrous concrete beams that contained steel fiber. The crack width was reduced by 38.6% for this beam compared to high-strength concrete beams with twenty internally cross rods and by 48% compared to normal-strength concrete beams with twenty internally cross rods.
- The steel fiber concrete beams reinforced with internally cross-rod steel bracing have better torsional properties compared to ordinary concrete beams and high-strength concrete beams.

5. Declarations

5.1. Author Contributions

Conceptualization, A.I.A. and A.M.L.; methodology, A.I.A.; software, A.I.A.; validation, A.M.L.; investigation, A.M.L.; writing—original draft preparation, A.I.A.; writing—review and editing, A.M.L.; visualization, A.M.L.; supervision, A.M.L. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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