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TORSIONAL PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED USING HYBRID FIBERS SIFCON JACKETING

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Abstract

The main aim is to investigate the influence of hybrid fiber Slurry Infiltrated Fiber Concrete (SIFCON) strengthening of beams loaded under pure torsion. The volume percentage of fiber was constant at 5%. Seven beams underwent pure torsion testing after being cast., two beams were taken as a reference (The first one without torsional reinforcement and the second beam with torsional reinforcement), and five beams were strengthened by a SIFCON jacket, One beam fully jacketed, and four beams with three-side jacket. Different types of fiber (Steel, Glass, and Hybrid) used to cast SIFCON. It found that the increase in ultimate torsion by about (163 - 537) % for strengthened beams (no torsional reinforcement) and (46 - 254)% for beams with torsional reinforcement. Finally, the fully jacket-strengthening beam with 5% from steel fiber was the most effective among strengthening beams to improve torsion strength. In addition, the results of cracking torque, twist angle, Energy Absorption (Toughness), Torsional Stiffness, and torsional strength appear enhanced when using SIFCON different types of fiber in strengthened beams.

Keywords:

Torsion
Strengthening beams
Slurry-infiltrated fiber concrete
SIFCON
Steel fiber
Glass fiber
Hybrid fiber
Toughness
Stiffness

1 Introduction

Early in the 20th century, research on the torsion of reinforced concrete beams began. However, it must be noted that there is little research on torsion compared to bending and sharing. There are developed theoretical concepts that are divided into two groups: Skew-Bending theory and Analogy of the Space Truss. The American code depended on the skew-bending principle from 1971 to 1995; after that, the space truss analogy depended. Additionally, since 1978, the European code has relied on the space truss analogy. To standardize the torsion design of large, small, and prestressed concrete sections, a variable Angle truss model was developed (for instance, small elements in building structures and big sections in bridges), which is the most modern theory [1].

Steel fiber is used to increase the ultimate load and decrease deflection [2]. Normal concrete has a toughness of 0.2–4% and a tensile strength of 0.01-0.1%, making it a brittle material with a limited carrying capacity in terms of tension, compared to steel structures. Steel Fiber may be added to concrete to enhance its capacity to absorb energy and flexural strength, which can help solve the problem of brittle concrete [3]. steel fiber is used to increase load capacity, ductility, and toughness and reduce cracking [4].

Concrete with hybrid fiber has the greatest strength and flexural toughness [5].increase fiber volume led to another type of concrete, So Lankerd at the New Mexico Engineering Research Institute (NMERI) discovered a new form of concrete in 1983, known as Slurry Infiltrated Fiber Concrete (SIFCON) [6], [7].

SIFCON is included in fiber at a volume-relative rate of 5–30% [8]. To prepare SIFCON, the fiber is placed on a mold's bed and then penetration with cement-based slurry. To decrease permeability and increase strength in concrete, SIFCON replaces part of cement with a mineral additive, such as silica fume [9]. Although there are many different forms of steel fiber used to prepare the SIFCON, crimped fibers and hooked ends are the most often used varieties. The straight and deformed fibers are also used, albeit less apparent [10]. It is a good idea to use hybrid fiber because a high percentage of fibers can be used at a lower cost than if steel fibers were used alone [11]. In addition, good design lies in safety, economy, and serviceability [12].

This study aimed to study the effect of strengthening reinforced concrete beams using hybrid fibers (steel and glass fibers) under torsional loading.

2. Previous Studies

AL-Rousan et al (2018) [13] investigated how employing SIFCON as a repair material may improve beam shear capability. Four of the experimentally constructed beams were SIFCON-jacketed after being tested under third-point stress until they failed. There were fourteen reinforcing concrete beams totaling 2000 mm in length that were cast for the experiment. The outcomes demonstrated a 25–50% increase in shear strength and prevented the brittle failure of shear in the restored beam.

Gilani (2007) [14] Various characteristics of SIFCON and the effect of mix type, steel fiber geometry, and fiber content on SIFCON durability were studied. Slurry and mortar were the matrices utilized for SIFCON in addition to a mix of plain concrete. Two distinct steel fiber types—hooked and crimped—as well as three altered fiber volume fractions—(7, 9.5, and 12) percentage—were used to create each SIFCON blend. The cylindrical samples were 135 millimeters in height and 68 mm in diameter. The results showed that SIFCON produced with mortar had acceptable durability qualities despite its apparent significant water absorption. Additionally, SIFCON's higher steel fiber produced greater outcomes.

Abdul-Hussein (2010) [15] examined how reactive powder concrete (RPC) beams torsional behaved. The volume percentage of steel fiber content ranged from zero to 1 percent. In the experimental effort, fifteen beams with cross sections of (150x150) mm and lengths of 1020 mm, both solid and hollow, were examined. Various longitudinal and transverse steel ratios were applied. The findings showed that adding 1% fibers to the concrete mix increased the cracking torque for solid and hollow RPC beams by 43.3% and 65.6%, respectively, and the maximum torque for solid and hollow RPC beams by 57.7% and 53.2%. Cracking and ultimate torque have improved with the increase in transverse and longitudinal. Additionally, It was demonstrated that, at various points after cracking, the length of both solid and hollow RPC beams increases approximately linearly with the increase in applied torque.

Mohammed et al (2016) [16] examined the torsional performance of beams strengthened with ultra-high performance fibers-reinforced concrete (UHPFC) jacket for reinforced concrete. In the experimental work, cast beams with a cross-section of 100 by 200 mm and a length of 1600 mm were used without any transversal reinforcement, while other beams had strengthened, one beam was used as a control beam and was not strengthened. Except for the two sides (15 and 25 mm), the reinforcing was present on two, three, and four sides, and it varied in thickness using 10 to 15, 20, and 25 millimeters. Furthermore, finite element was performed in tandem with experimental work to evaluate and support the efficacy of the used repair method. When compared to control beams, the results showed that all strengthening beams had improved torsion behavior. Furthermore, the beam strengthened by four sides with a thin coating had the best torsion value. Ultimately, the findings of the experiment and the finite element analysis agreed rather well.

Hameed, et al (2020) [17] examined how the SIFCON layers employed as a retrofitting material behaved. This study's objective is to show how different steel fiber volumes (6.0, 7.5, and 9.0%) affect the response of toughness, prisms, ductility to the load-deflection relationship, and flexural of SIFCON when used in casting layers of different thicknesses (15, 25, and 35 mm). Following the aforementioned features, the location of the SIFCON layer (top, top, and bottom, and jacking) was also examined. It was revealed that the toughness, ductility, and load-carrying capacity of the prisms strengthened are improved by raising the SIFCON layer's thickness and the percentage of steel fibers in it. It took around 10 times as much energy to attain the maximum load as the control. The toughness surpassed the control by a factor of around 105. When the SIFCON layer was epoxy-bonded, the ductility was also improved.

Khalifah and Rasheed (2022) [18] the primary goal is to examine how strengthening beam sides affects torsion behavior. Concrete with slurry-infiltrated fibers (SIFCON) was used for the strengthening. SIFCON is thought of as a particular type of Fiber Reinforced Concrete (FRC). Steel fibers with hooked ends and an aspect ratio of 64 were used; their volume percentages were 8, 10, and 12%. Nine beams, including five strengthened by SIFCON and four used as references (two from ordinary concrete and two from SIFCON), have been cast and tested under pure torsion. Implemented strengthening on two sides, three sides, and four sides. The torsional capacity of reinforcing beams has reportedly increased. Additionally, the four-sided strengthening was superior to the two- and three-sided strengthening, which increased the torsion moment. Furthermore, the growth in steel fiber enhances the torsion strength of reinforcing beams.

Based on previous studies, there is a research gap concerned with hybrid fiber SIFICN jacketing to improve the torsional behavior for beam lack to resist such loads or have an error in its design. The torsion problems are very important and critical and may be studied.

3. Experimental Part

3.1 Experimental Work

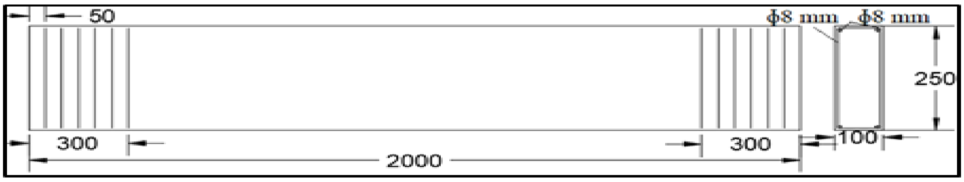
This study aims to examine and enhance the torsional behavior of rectangular beams subjected to pure torsion. Additionally, the effectiveness of the strengthening method and a comparison of results with beams that were not strengthened. Prisms, cylinders, and cubes were also utilized to assess the concrete's hardened properties. Several experiments were performed to compute the fresh SIFCON characteristics.

3.2 Description of Beams

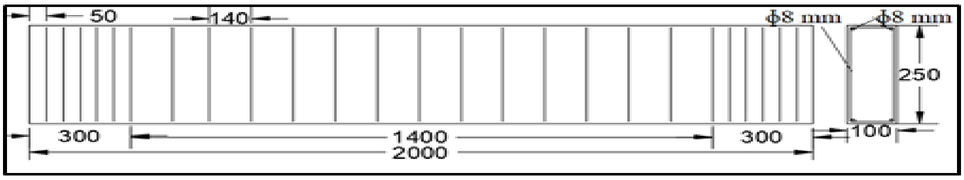
Testing was done on seven beams under pure torsion; Every beam was cast using normal concrete, and the first beam such as the references beam without torsional reinforcement. The second beam is a reference beam with torsional reinforcement. In addition, five beams were strengthened with SIFCON after being cast with normal concrete. The beam's length remained unchanged. at 2000 mm while the cross section was (250x100) first cast and then varied cross-section for strengthening, also there are other factors, such as the volume fractional of the (glass, steel, and hybrid) fibers and the quantity of warped sides, as indicated in Table 1. Transverse reinforcement (ϕ8) was not utilized other than before the support to function as a fixed support; instead, longitudinal reinforcement (4ϕ8), two at the top and two at the bottom was utilized to reinforce the beams, as indicated in Fig. 1.

Table 1: Details of Beams

Beams	**Description**	**Cross-section Dimension (b x h) [mm] After strengthening**
BN	Beam No torsional reinforcement and none strengthened (Reference beam 1)	100x250
BW	Beam With torsional reinforcement and none strengthened (Reference beam 2)	100x250
BSSFF	Beam without torsional reinforcement and Four sides strengthened with 5% steel fiber.	150x300
BSSFT	Beam without torsional reinforcement and Three sides strengthened with 5% steel fiber.	150x275
BSHFTa	Beam without torsional reinforcement and Three sides strengthened with 4% steel fiber and 1% glass fiber. (hybrid fiber)	150x275
BSHFTb	Beam without torsional reinforcement and Three sides strengthened with 3% SF and 2% GF. (hybrid fiber)	150x275
BSGFT	Beam without torsional reinforcement and Three sides strengthened with 5% Glass Fiber.	150x275



(a)



(b)

Fig. 1: Reinforcement Details of Beams: a) (BN, BSSFF, BSSFT, BSHFTa, BSHFTb,

(b) Reinforcement Details of Beam (BW)

3.3 Construction Material

In compliance with Iraqi Specifications Limitations (IQS) NO.5/1984, Ordinary Portland Cement (OPC) (Type-1) has been utilized [19]. Based on IQS No. 45/1984, the study's fine aggregate came from Iraqi specifications (zone 3) [20]. In this work based on polycarboxylate, a high-range water-reducing admixture (superplasticizer) was applied. The company went under the moniker GLENIUM51, based on Types F and A of ASTM C494M-99a [21]. To strengthen the beams, the SIFCON layer was bonded to normal concrete using an epoxy resin bonding agent. The brand was known as Sikadu® -32 LPAs to IQS No.45/1984, the largest size of coarse aggregate was 19 mm [20]. The water utilized for the specimens' casting and curing was regular tap water. The source of the silica fume was Sika. Silica fume chemical compositions correspond to ASTM C-1240-05 [22]. Microsteel fiber with a diameter of 0.2 mm and length of 20 mm an aspect ratio of 65 and tensile strength ≥2850 MPa was used. With different volume fractions of steel, fiber has been utilized in SIFCON. Alkali Resistant Glass Fiber Oscrete 12mm HP fiber is an alkali-resistant glass chopped strand fiber with 18 μm and tensile strength 1700MPa with different volume fractions of glass fiber that have been utilized in SIFCON.

3.4 Mixing and Casting

Normal concrete and the SIFCON combination were the two mixes employed in this experiment, as Table 2 illustrates. The material was mixed using rotary mixing. Wooden molds with dimensions of 18 mm in thickness and (2000x250x150) mm and a strengthening layer thickness of 25 mm were used. The molds follow their cleaning and addition of steel reinforcing. The beams were first cast as normal concrete beams and cured in the water for 28 days before being allowed to dry for one day. After that, five beams were prepared for strengthening using three processes (roughing, anchor bolts, and epoxy coating) before casting the strengthened as shown in Fig. 2. After using a hammer to scrape the stronger sidewalls, epoxy bonding, and strengthening paint was applied as shown in Fig. 3, thereafter 28 days of beam curing in a water tank.

Table 2 Mixes of Concrete

Material	**Normal Concrete** [23]	**SIFCON** [24]
Cement [kg/m^3]	300	825
Sand [kg/m^3]	850	885
Gravel [kg/m^3]	1050	------
Silica fume [%]	------	10
Fiber [%]	------	5
Water [kg/m^3]	100	318
Superplasticizer [%]	1	1.5

(a)

(b)

(c)

Fig. 2: Strengthening Beams Preparation a) Roughening operations, b) Using anchor bolts, and c) Use Epoxy bounding coted

Fig. 3: Casting the Strengthening Beams

3.5 Test Procedure

Painted white to highlight cracks. Every beam specimen has been put through its paces in a hydraulic machine that is accessible at the Structural Engineering Laboratory-Al-Nahrain University. capacity of this machine (2000 kN) as shown in Fig. 4. subjected to pure torsion till failure. The beams were placed on the testing device, then the load was applied to both ends, in two different directions, and at a distance of one loading arm was 370 mm accepted for (BN&BW) equivalent to 345 mm to obtain the torsion of the beam. To determine the twisting angle, End arms loading has been supplied with two LVDT gauges. At every loading stage, the vertical displacement was recorded by the LVDT.

Fig. 4: Test Beams Machine

3.6 Result of Fresh and Hardened Properties

3.6.1 Fresh Properties of SIFCON

The SIFCON is categorized as a Self-Compacting Concrete (SCC). Slump-flow, T50, L-box, and V-funnel were the three tests used to identify fresh SIFCON characteristics [25]. Table 3 lists the results.

Table 3: Results of fresh properties for SIFCON

Test	Property	Result	EFNARK limitation [25]	Unite
Slump flow	Filling ability	705	650-800	mm
T50		3.2	2-5	sec
L-box	Pass ability	0.95	0.8-1	-
V-funnel	Ability to fill	10	6-12	sec

3.6.2 Hardened properties of concrete

This research comprised testing for splitting tensile strength (fct), compressive strength (fc' and fcu), modules of elasticity (Ec), and modules of rupture (fr) to determine the hardened characteristics of normal concrete Table 4 and SIFCON Table 5.

Table 4: Properties of Hardened Normal Concrete

Mix	Compressive strength(MPa)		f_r (MPa)	f_{ct} (MPa)	E_c (MPa)
	(f'_c)	(f_{cu})			
NC @28 day	25.10	31.2	3.100	2.873	28000
NC @60 day	28.35	35.64	3.344	3.203	30000

Table 5: Properties of Hardened SIFCON Concrete

SIFCON Mix	Compressive strength (MPa)		f_r (MPa)	f_{ct} (MPa)	E_c (MPa)
	(f_c)	(f_{cu})			
5% Steel fiber	57.56	70.23	7.525	6.910	37200
4%Seel Fiber+1%Glass Fiber	48.13	58.69	4.616	4.500	35250
3% Seel Fiber+2%Glass Fiber	44.97	54.85	3.781	3.825	34500
5% Glass Fiber	30.12	33.77	3.225	3.302	29750

4. Results and Discussions

4.1 Crack and Ultimate Torque

The applied load was subjected to tested beams until they failed. The cracking torque (Tcr) was calculated when the crack was viewed visually and the ultimate torque (Tu) was measured when failed and listed in Table 6 and Fig. 5.

Table 6: Cracking and Ultimate Torque

Beams	P_{cr} (kN)	P_u (kN)	arm (m)	T_{cr} (kN.m)	T_u (kN.m)	Increasing in T_{cr} with BN %	Increasing in T_{cr} with BW %	Increasing in T_u with BN %	Increasing in T_u with BW %
BN	5.54	7.81	0.345	0.956	1.347	Ref1	-	Ref1	-
BW	11.78	14.05	0.345	2.032	2.424	125	Ref2	80	Ref2
BSSFF	31.08	46.41	0.370	5.750	8.662	504	184	543	257
BSSFT	22.00	32.22	0.370	4.070	6.037	324	99	348	149
BSHFTa	14.62	26.00	0.370	2.705	4.528	192	37	236	87
BSHFTb	11.21	20.30	0.370	2.074	3.786	103	-5	181	56
BSGFT	14.05	19.16	0.370	2.599	3.504	170	27	160	45

Ref1 and Ref2 refer to references beam *T_{cr}= (P_{cr} /2) . (Arm) **T_u= (P_u /2) . (Arm)
% Increase in Cracking Torque with respect to $_{Ref}$ = $[(T_{cr} - (T_{cr})_{Ref})/(T_{cr})_{Ref}]$

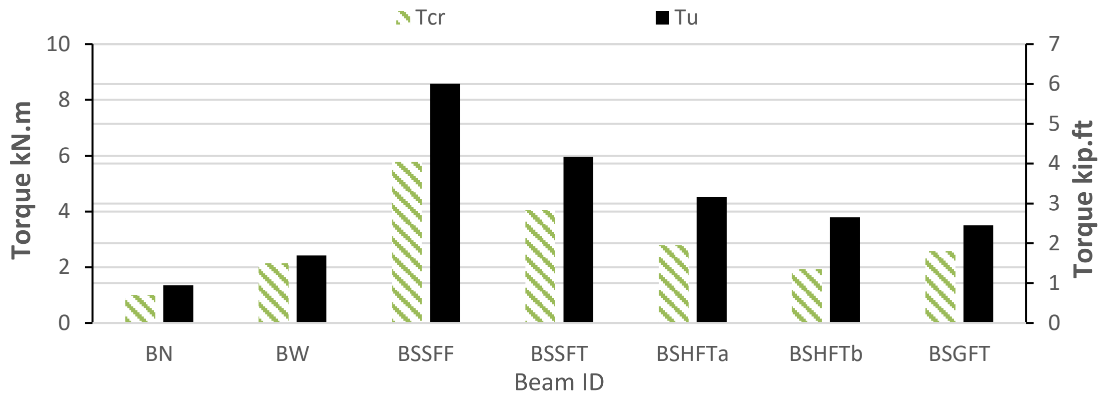


Fig. 5 Cracking and Ultimate Torque

Roughly, the cracking torque rises (125%) for the (BW) beam, while the full side jacket strengthens beam (BSSFF) showed an increase of about (504%) and 184%) over (BN and BW), respectively. When compared (BSSFT) with references beam (BN and BW), there is increasing in cracking torque by about (324 and 99%) respectively. Full jacket strengthening has been more effective in cracking torque. When compared (BSHFTa) with references beam (BN and BW), there is an increase in cracking torque of about (192 and 37%). When compared (BSHFTb) with references beam (BN and BW), there is an increase in cracking torque of about (103 and -5%). When comparing (BSGFT) with reference beams (BN and BW), there is an increase in cracking torque of about (170 and 27%) see Fig. 6. The type of (steel, hybrid, and glass) fiber has an effective influence on cracking torque. Also, the ultimate torque has been improved. For reference beams (BW), when compared with (BN), the reach of the ultimate torque is increasing to (80%). The beam strengthened with a fully side jacket (BSSFF) is the best beam, and has ultimate torque of about (537, 254%) over (BN, BW). The strengthened beam with three sides and has (5%) steel fiber (BSSFT) the ultimate torque reached (543, 257%) compared with (BN, and BW) respectively. The ultimate torque increased in beams (BSHFTa, BSHFTb) than (BN), also compared with (BW) by about (236, 87)%, (181, 56%) respectively. (BSGFT) have an increase in ultimate torque reach to (160, and 45%) when compared with (BN, and BW) respectively. So, it can be observed the effect of the type of fiber used on ultimate torque has been more effective in ultimate torque, as shown in Fig. 7. The cracking torque (Tcr) increase is less than the ultimate torque (Tu) increase. This might be because at the start of loading, the concrete only resists the subjected stress, and the first crack starts in the mid-span. After that, reinforcing steel starts to contribute to the applied load's resistance. In SIFCON, fiber will mostly resist the subjected load during later loading periods. Put another way, the amount of concrete that contributes to the applied load's resistance determines the (Tcr) value, while the contributions of concrete determine the (Tu) value, of steel fiber with steel reinforcement. Consequently, it is feasible to draw the conclusion that adding SIFCON to strengthening results in a notable improvement in torsional capacity. In addition, a theoretical study was conducted using the Abaqus program, which can be viewed within the thesis [26].

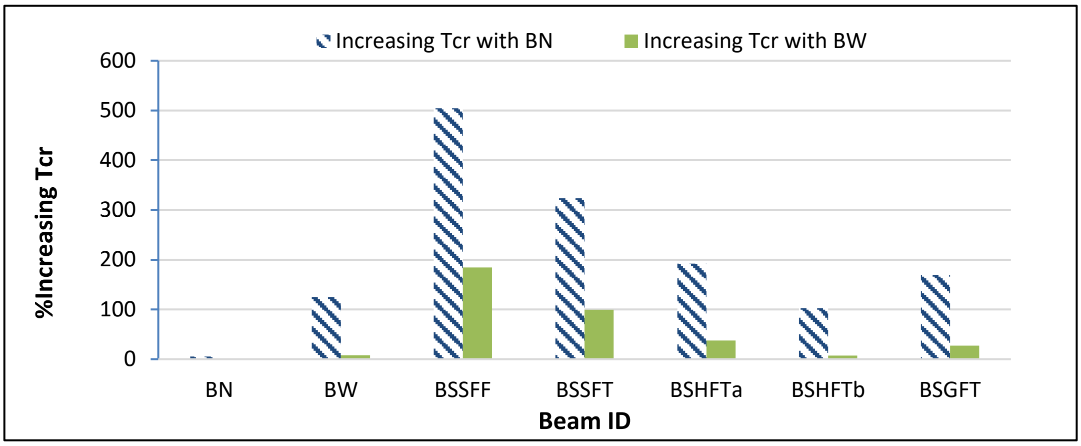


Fig. 6: Increasing in Cracking Torque

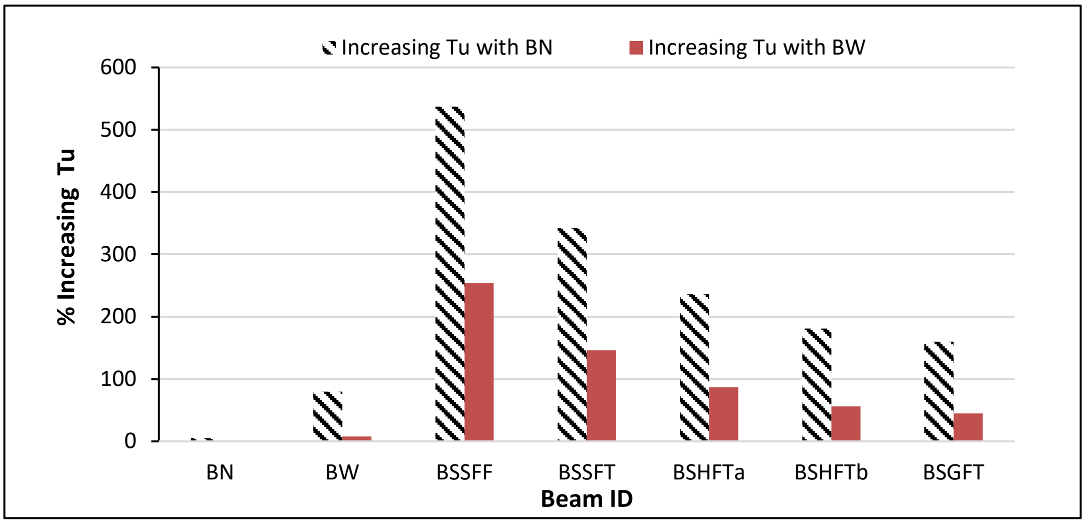


Fig. 7: Increasing in Ultimate Torque

4.2 Ttorque-Twist of Angle Behavior

Two LVDT gauges have been used to calculate the angle of twist are measured, as shown in Fig. 8 to Fig. 11. The ultimate angle of twist for beams (BN, BW, BSSFF, BSSFT, BSHFTa, BSHFTb, BSGFT) is (0.071, 0.064, 0.145, 0.10, 0.11, 0.08, 0.0909) rad.

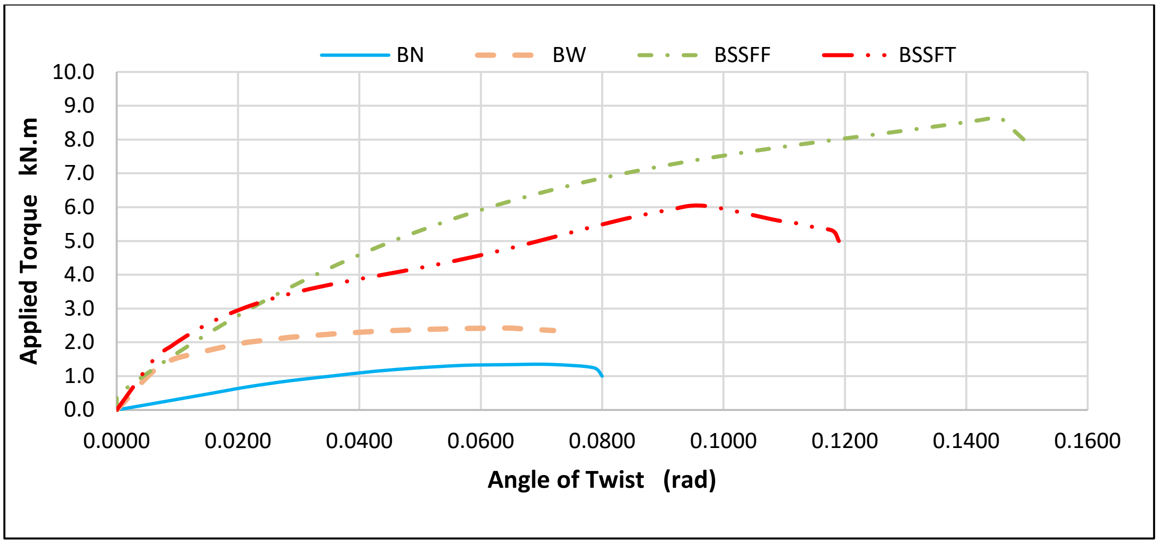


Fig. 8: Effect of Number of Strengthening Side Jacketing

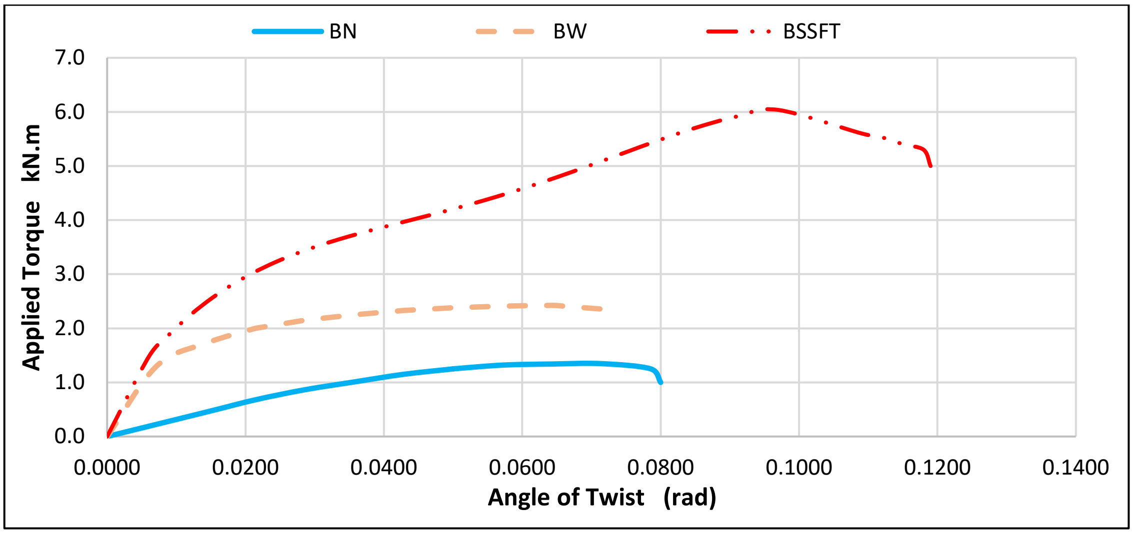


Fig. 9: Effect of use of Steel Fiber Strengthening Side Jacketing

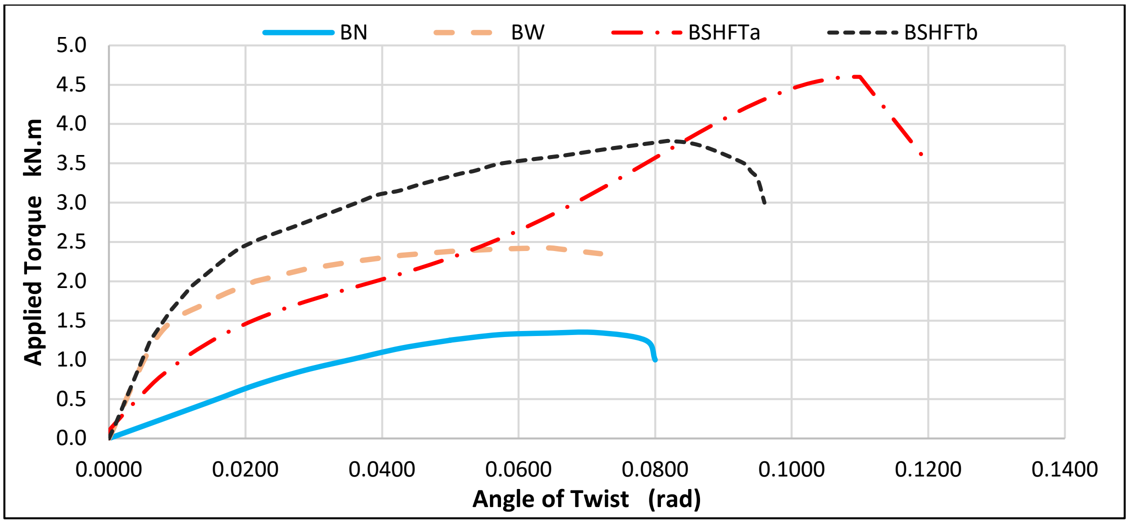


Fig. 10: Effect of Use of Hybrid Fiber Strengthening Side Jacketing

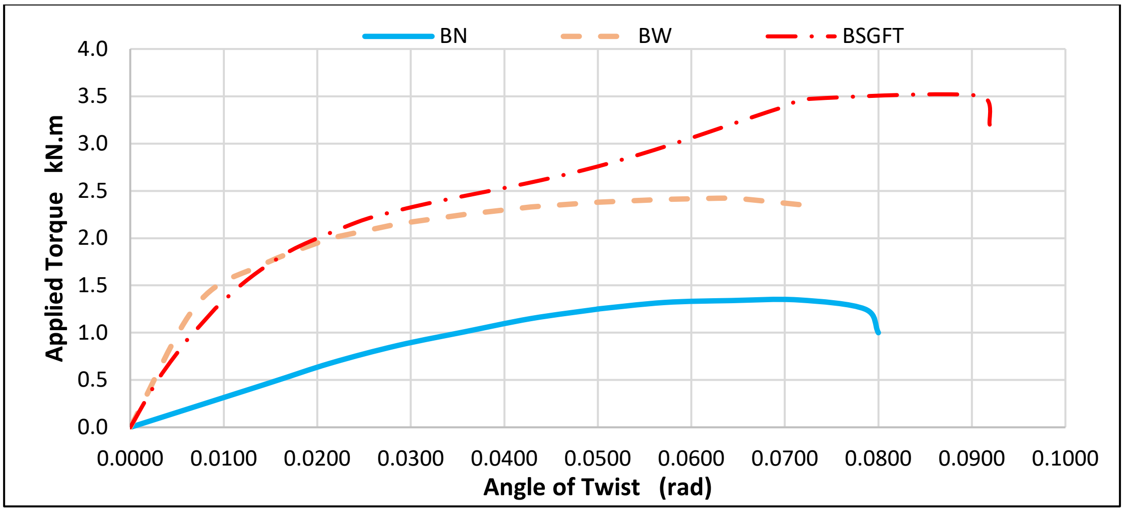


Fig. 11: Effect of use of Steel Fiber Strengthening Side Jacketing

4.3 Energy Absorption (Toughness) Torsional Stiffness (k)

All tested beams' toughness measurements are listed in Table 7. It is possible to use toughness as a predictor of ductility. Toughness was assessed for each beam using the area under the curve of the torque-angle twist [27]. The region below the torque-angle twist was found in this investigation using the Microsoft Excel program.

The capacity of a body to withstand deformations in response to all applied loading is known as **Torsional stiffness** [23, **24]**. As shown in Table 7 Structural members may have a torsional stiffness calculated from the;

$$k = \frac{T\ (kN.m)}{\theta\ (rad)} \quad (1)$$

where:

k = Torsional Stiffness (kN.m/rad)

T = Ultimate Torque (kN.m)

Θ = Angle of twist corresponding to ultimate torque (rad)

Table 7 Toughness and Torsional Stiffness of Tested Beam.

Beams	Energy Absorption(Toughness) [kN.m. rad] $*10^{-4}$	Torsional Stiffness (k) [kN.m/rad]
BN	597	18.86
BW	1245	37.70
BSSFF	8557	59.03
BSSFT	4617	54.64
BSHFTa	2856	43.73
BSHFTb	2485	42.68
BSGFT	2303	38.99

4.4 The Mechanism of the Failure

The development of the crack provided important details on the test beam failure process. The tested beams all experienced torsion failure. Any specimen had a firstly crack that started in the weaker area and finally expanded in size. As the torque moment mounted, cracks started to appear on both sides, finally taking the form of a helix. The failure modes for the tested beams are shown from Fig. 13 to Fig. 18. Significant diagonal concrete cracking (torsional spiral fractures) caused all beam specimens to fail [25, 26**]**. Before loading, the beams (BN and BW) were twisted without developing cracks. The first crack (tensile limit) forms when the loading approaches the cracking load in the middle of the beams. Cracks spread around both sides of beams as a result of increased loading, creating a continuous spiral structure. The mid-span fractures that formed in the beams caused them to break. The strengthening was made to resist twisting brought on by subjected loads to strengthen beams. These beams' cracking, which occurred in the strengthened sides and beam core, indicates that the strengthening was done successfully. Demonstrating that the strengthening was carried out correctly. Also, as can be seen in the beam (BSSFF), these cracks were bigger and more common in beams with lower sides strengthened. Additionally, this shows the efficiency of the SIFCON strengthening approach because the SIFCON layer employed for strengthening did not split from the beam during the subjected load.

Fig. 12: Cracks Pattern in Beam BN

Fig. 13 Cracks Pattern in Beam BW

Fig. 14 Cracks Pattern in Beam BSSFF a) left side, b) right side

Fig. 15 Cracks Pattern in Beam BSSFT a) left side, b) right side

Fig. 16 Cracks Pattern in Beam BSHFTa

Fig. 17 Cracks Pattern in Beam BSHFTb a) before loading, b) after loading

Fig. 18 Cracks Pattern in Beam BSGFT

5 Conclusions

The following conclusions may be drawn from the experimental data given in this work:

1) Using SIFCON with different types of fiber as a strengthened material is perfect for improving the behavior of reinforced concrete beams for torsion.

2) For every beam, the first crack emerged at different applied torques. There was a range of 63% to 88% for the cracking torque relative to the ultimate torque. The maximum cracking torque found in the beam with full-side SIFCON strengthening (BSSFF), exceeded the BN and BW beams by 250% and 548%, respectively. This proves the efficacy of the full-side strengthening method using SIFCON.

3) The ultimate torsional for tested beams was determined by measuring their ultimate torque. The ultimate torque of the beam with torsion steel reinforcement (BW) was about 80% greater than that of the beam without torsion reinforcement (BN).

4) The ultimate torque of the full-side SIFCON strengthened beam (BSSFF) was more than the (BN) and (BW) beams by 254% and 537%, respectively, among all tested beams.

5) The efficiency of SIFCON strengthening was demonstrated by the beams with three sides of SIFCON strengthening (BSSFT, BSHFTa, BSHFTb, BSGFT), which had greater ultimate torques than the BN and BW beams.

6) The reinforced concrete beam strengthening with the SIFCON three-sided with hybrid fiber (BSHFTa) appears the highest increase in peak torque among the hybrid fiber-reinforced beams.

7) Higher energy absorption and torsional stiffness were observed in beams strengthened with SIFCON in comparison to reference beams.

8) In comparison to the reference beams and other SIFCON-strengthened beams, the hybrid fiber reinforced beams (BSHFTa, BSHFTb) demonstrated respectable gains in energy absorption and torsional stiffness.

9) The glass fiber improves the ultimate torsional capacity (160%).

10) The study's overall results demonstrated that SIFCON strengthening was successful in greatly increasing the beams' ultimate and cracking torque capability, particularly when three-sided reinforcement with a steel, hybrid, and glass fibers combination was used.

11) All specimens of tested beams failed due to a grave diagonal concrete crack (torsional spiral cracks). For beams with or without strengthening, the failure occurred at a mid-span due to the increase in the number of cracks after speared at the length of beams.

12) Cracks spread in the strengthening layers and inside the beams for strengthening beams. The increase in the number of cracks in the mid-span caused the failure. When compared to other full jacket strengthening beams, the cracks are larger and wider than the beam strengthened by utilizing 5% steel fibers three side jacket. Cracks appeared on the SIFCON layer that was used in the strengthening beam and the core of beams during the loading stage, and this indicates the effectiveness of the SIFCON strengthening technique.

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