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Torsional Behavior of CFRP Strengthening of SCC Box Beams with Web Openings under Repeated Loading

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Abstract

Monotonic and repeated torsional loading frequently occur in many concrete structures. The loading and unloading action of repeated torsion places structures under greater damage and risk of failure than other types of loading. Therefore, keeping old infrastructure maintained, repaired, and upgraded has become an important priority and requirement. In this research, experimental work was done on pre-cracked self-compacted reinforced concrete box beams repaired (strengthened) with CFRP sheets to investigate the effect of web openings and CFRP sheets on the torsional behavior of tested specimens. Two groups of sixteen half-scale CFRP-strengthened RC box beams with different numbers of circular openings in the web, with a diameter of about 30% of the hollow box depth, were investigated. The first group (I), tested under monotonic torsional loading, comprised four unstrengthened RC beams and another four beams strengthened with CFRP strips, whereas the second group (II) consisted of the same details as the first one tested under repeated loading. The range of the repeated loading was about 30% and 60% of the ultimate load of the monotonic tests. The effect of opening and repairing (strengthening) with CFRP on the ultimate and cracking Torques, Torque-Twist Angle, steel strains, and modes of failure were displayed and discussed. Cracking and ultimate torques and the angle of twist of the tested beams were significantly reduced due to openings in the web, accompanied by increased values for the steel strains due to the presence of openings. However, the results showed that using CFRP strengthening techniques increased torsional strength, angle of twist, and decreased steel strain for all the tested beam specimens. Results revealed that repeated loading causes inelastic deformations in proportion to the number of loading cycles, more than static load deformations.

Keywords: Torsion; Repeated Loading; Box Beam; Web Opening; Self-Compacted Concrete; CFRP Strengthening.

1. Introduction

Many concrete buildings are exposed to repeat torsional loading, such as offshore structures, freeways, multi-storey parking garages, etc. Unlike buildings exposed to monotonic torsion, buildings exposed to repeated loading show greater deflection, more cracks, and risk of failure. Today, many rehabilitation and maintenance problems face civil engineering applications in building structures due to increased service loading, aging in buildings, traffic, changes in the use of the building, new seismic rehabilitation methods in some parts of the world, or any update that will affect structural strength. Also, according to new design codes, the old construction buildings are now considered unsafe. Because the reconstruction of some structural members of the old buildings to match the new code requirement in the design will require a lot of money and time, strengthening becomes a more efficient way to rehabilitate these types of buildings. Also, due to environmental degradation or overloading stress R.C. elements need either strengthening or repairing. According to the type of building, the challenge will be to choose the suitable strengthening method that will improve the building's structural strength and serviceability within the appropriate budget [1, 2].

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A lot of researchers have studied and developed knowledge for the effect of CFRP strengthening on the flexural and shear behavior of RC structures, and there is also a guide for the design and construction using the FRP system according to ACI 440 [3]. However, knowledge of the application of CFRP for repeated and pure torsional strengthening is limited and not even mentioned in ACI 440. Allawi [4] studied the behavior of R.C. specimens strengthened with CFRP laminates under pure torsion. He tested twelve R.C. beams, and one reference beam was used for each type (RC solid section, RC hollow section, and plain concrete solid section). It was found that both hollow and solid sections behaved the same, and the strengthening with CFRP increased ultimate torque up to 90% and 84% for R.C. beams with solid and hollow sections, Increasing cracking torque up to 81% and 130% for RC beams with solid and hollow sections, respectively. Also, the stress distribution was non-uniform because CFRP strips are unable to redistribute stresses across them. Hii & Al-Mahaidi [5] studied experimental and numerical work on the torsional strengthening of solid and box-section R.C. beams with CFRP strips. Six medium-scale reinforced concrete beams were tested under pure torsion. Their research showed increases in cracking and ultimate torque for solid and box sections of up to 40% and 78%, respectively; the stress distribution is non-uniform between CFRP strips. Numerical analysis was done by using finite element modeling. There is good agreement with the experimental results of twist angle, CFRP strip behavior, steel reinforcement, and crack patterns of the tested specimens.

Jing et al. [6] conducted an experimental study on the behavior of reinforced concrete box beams under combined loading of bending moment, shear, and cyclic torque, strengthened with CFRP strips. They tested four R.C. rectangular box specimens, one reference beam without strengthening, and the other three beams strengthened schemes in U form. The experimental results showed that using CFRP reduced the ductility of the tested specimens. Also, using CFRP improved the torsional capacity of the tested beams by up to 31.22% and 32.5% when wrapping one and two-layer U-shaped strips, respectively. Ameli et al. [7] conducted an experimental study on R.C. beams strengthened with CFRP and GFRP wraps with different configurations subjected to pure torsion. Twelve R.C. were tested under a pure torsional moment. They concluded that the CFRP strengthening technique increased the ultimate torsional moment more than GFRP; the percentage increase was from 16 to 143% for CFRP and 18 to 110% for GFRP, depending on the strengthening schemes. Using FRP materials increased the ultimate angle of twist. Also, after reaching the peak, the beams that strengthened with CFRP failed immediately, but beams that strengthened with GFRP post-peak responses took some time. Majeed et al. [8] studied the strengthening of multicell-reinforced concrete box girders with CFRP strips under torsional loading. Six R.C. box girders were tested. These specimens were divided into two groups: the first one consisted of three unstrengthened single, double, and triple cell box sections, while the second one was strengthened. The researcher found that using CFRP increased longitudinal elongation by up to 250–360% and increased ultimate strength for specimens by about 22.8%, 6.6%, and 21.7% for specimens with single, double, and triple cells, respectively.

Ma et al. [9] conducted an experimental study on eight reinforced concrete box beams subjected to bending, shear, and torsional loading strengthened by CFRP in different schemes. The beams were divided into two groups according to the (torsional moment, shear) and (torsional moment-to-bending) ratios. Three specimens from each group were strengthened (U-jacket layers and U-jacket layers with or without longitudinal stripes). The researcher found that using U-jacket strips could not enhance the flexural strength of the beams. The ultimate torque of the tested beams was enhanced significantly when using CFRP strips in all scheme types, but the U-jacket with longitudinal stripes was more efficient. The effect of CFRP decreased with an increase in the torsional moment-to-shear ratio, which led to a decrease in beam resistance, angle of twist, and vertical displacement. Tibhe & Rathi [10] conducted an experimental study on the torsional behavior of R.C. beams strengthened with FRP fabric. Thirty-nine rectangular beams were cast and tested under pure torsion. Three were the control beam, and the remaining thirty-six were divided into two groups. One with CFRP fabric wrapping and another with GFRP fabric wrapping. The applied CFRP and GFRP configurations are U-jacketed, vertical strips with spacing, edge strips, and vertical stripes along their entire length. They concluded that strengthening with CFRP is more efficient in increasing torque capacity, angle of twist, and ductility than GFRP fabric, and crack width decreases due to the use of CFRP and GFRP fabric. The strengthening using a fully wrapped U- jacketed Technique in CFRP and GFRP is more efficient than the other schemes used in this research.

Makhlouf [11] studied the torsional behavior of R.C. beam web openings subjected to pure Torsion strengthened with external steel stirrups, steel links, and FRP systems. Six rectangular beams were tested. Two were considered control beams without opening and strengthening; the others were strengthened with CFRP, GFRP, external stirrups, and steel links. The results showed increases in ultimate torsional capacity of about 134%, 100%, 12%, and 386% when using CFRP, GFRP, external stirrups, and steel links, respectively. Also, making an opening in concrete beams decreases cracking and ultimate torque capacity by about 45%. Adheem [12] conducted an experimental study about the torsional strengthening of solid and box-section plain concrete beams using CFRP strips. Also, he compared the efficiency of two strengthening techniques (strengthening with CFPR and the near-surface mounted (NSM) technique). Test results revealed that strengthening with CFRP strips can increase the torque capacity of concrete beams. Concrete beams that were strengthened with the NSM technique increased torsional capacity by about 10% for solid and 14% for box sections compared to CFRP beams.

Al-Bayati et al. [13] studied the behavior of reinforced concrete beams strengthened by using NSM FRP laminates and FRP ropes tested under torsional loading. To evaluate torsional capacity, the researcher used epoxy as an adhesive material for four beams and cement-based adhesive for the other four beams and compared the results. They found that the effectiveness of epoxy in increasing torque capacity was greater than that of cement-based adhesive; using the CFRP rope strengthening technique increased torque capacity more than strengthening with CFRP strips. The steel strain for beams that are strengthened with CFRP rope is smaller than that of beams strengthened with CFRP laminates. Also, beams strengthened with CFRP rope were more ductile than beams strengthened with CFRP strips. Ma et al. [14] studied the prediction of the maximum torque of the CFRP-bonded reinforced concrete box beam. Four reinforced concrete beams with box cross-sections were used in this research program and tested under pure torsion. The beam's best strengthening efficiency was the one that had been enhanced with two-ply U-jackets and longitudinal strips, and the experiment confirmed that the cracking angle mostly waved at 45° to the longitudinal axis of reinforced concrete specimens. Also, they noticed increased stiffness and cracking torsional moments in the tested beams. Al Amli et al. [15] studied the behavior of composite concrete beams cracked by pure torsional loading and then repaired by external strengthening with CFRP. Four composite I-beams were cast with CFRP laminates. Different section types (solid and with opening) were utilized to find the effect of the CFRP strips on the beam's behavior. The test results show that the CFRP affects restoring solid section torsional strength by 89.8 to 91.2% while restoring section with opening by 83.48 to 86.67% of ultimate torque.

Hanoon et al. [16] studied the performance of the CFRP strengthening of the energy absorption of two-span R.C. beams tested under pure torsional loading. Casted beams were divided into two groups: the first group consisted of eight un-strengthened beam specimens, and the second group consisted of eight strengthened beam specimens. The results show that all beams that were strengthened with CFRP strips improved in torsional energy absorption. Under pure torsional loading, the energy absorption may perform as a safety index for the torque capacity of R.C. beams. Gowda et al. [17] studied the use of CFRP laminates by the near-surface mounted (NSM) method to enhance the torsional behavior of R.C. thin-walled tubular components. The study shows that adding NSM-CFRP strips enhanced torque capacity, stiffness, and torsional deformability and stopped crack development. Obaidat et al. [18] studied experimentally and numerically the behavior of RC beams strengthened using near-surface mounted (NSM) carbon fiber-reinforced polymer strips under torsional loading. The test results show that the use of NSM-CFRP strips enhanced the torque capacity of the tested beams and the angle of twist. Also, the numerically estimated torque-angle of twist for all RC beams agrees with the experimental results. Askandar & Mahmood [19] compared the behavior of R.C. beams strengthened with various arrangements of CFRP strips and NSM steel bars with varied spacing tested under combined torsion and bending moments. The test results showed that using CFRP and NSM steel bars enhanced the torsional capacity of the tested specimens; the cracks in the strengthened beams spread more widely throughout the specimen's length; the ultimate torque of test beams was enhanced with CFRP wrapping more than the ultimate torque of test beams with NSM steel bars strengthening. Hekal et al. [20] conducted an experimental program on twenty-one R.C. beams with large openings in the middle of the tested beams strengthened by using CFRP or layers of externally bonded steel in different schemes under pure torsion. They found that making an opening in the R.C. beam decreases the torsional capacity, while using CFRP or steel plates improves the torsional capacity, ductility, and energy absorption. The best strengthening results were obtained from using CFRP, followed by steel plates.

Askandar & Mahmood [21] conducted an experimental study on the behavior of R.C. beams strengthened with CFRP strips in various schemes subjected to combined torsion and bending moment actions. Eight beams were cast, the reference beam was un-strengthened, and the rest beams were strengthened with CFRP in different configurations. The test results show that the fully wrapped specimens performed better than the strip-wrapped ones; the strengthening with a 45-degree spiral strip was the most effective for R.C. beams in torsional resistance among the wrapping schemes of FRP. Also, vertical CFRP strips should not be used at a spacing equal to or greater than the specimen depth. Gowda et al. [22] studied the torsional behavior of thin-walled R.C. beams and analyzed the contribution of various strengthening schemes using the near-surface mounted (NSM) approach. Six beams with different longitudinal and transverse CFRP strip amounts are studied. Digital image correlation (DIC) is utilized to gain knowledge of the NSM CFRP strips' contribution to the fracture mechanism process and the deformation response of the R.C. specimens. The crack mouth opening displacement (CMOD) of the essential crack is compared to the other cracks, and the development of the torsional cracks is compared to the development of strain in the CFRP strips. The results show the NSM-CFRP strengthening technique improved torque capacity, torsional stiffness, and angle of twist by limiting the propagation of crack width. Alrawi & Mohammad [23] conducted an analytical study on the torsional behavior of R.C. beams with close-to-surface steel and CFRP bars. The analytical results show that including NSM reinforcing bars redistributed the stresses and enhanced the concrete beams' ultimate torque, rotational capacity, ductility, and energy absorption. CFRP bars gave a better improvement compared to beams strengthened with NSM steel rebars. The ultimate torque was enhanced by 3.5% and rotation decreased by 4% when the FRP bars were replaced with steel rebars.

Mohammad & Abbas [24] studied the effect of CFRP strengthening on prestressed concrete dapped end beams with openings under monotonic point load. Nine scaled-down prestressed concrete beams were cast. The variables were the position and shape of the openings and the effect of CFRP strengthening around the opening. The test results show that due to the presence of openings, the shear strength decreased by about 20% when the opening was close to the dapped end. The tested beams regained their strength by about 92% when openings were strengthened with CFRP strips.

In the previous study, considerable research was performed on the performance of R.C. members with web openings in the last decades [25]. However, till now, research on the effect of repeated torsional loading and strengthening on RC box beams with openings is still rare and uncommon. This research examines the effect of CFRP strengthening on the ultimate and cracking torques, torque-angle of twist, steel strains, and modes of failure for RC box beams with web openings subjected to static and repeated torsion loads. To achieve the goals intended for this study, sixteen RC box beams with openings in the web were designed and tested up to failure under repeated and static torsional loads to evaluate their structural behavior. The focus on the efficiency of opening strengthening is introduced and highlighted in this study.

2. Experimental Program

Sixteen self-compacting reinforced concrete box beams with web openings were cast and tested under monotonic and repeated loading up to failure. The tested beams were divided into two groups: the first group (I) consisted of eight beams: four beams without strengthening, and the other four strengthened with CFRP strips tested under monotonic torsion loading. The second group (II) also consisted of eight beams: four beams without strengthening and the other four repaired (strengthened) with CFRP strips tested under repeated torsion loading. The experimental program details are listed and given as a flow chart in Figure 1.

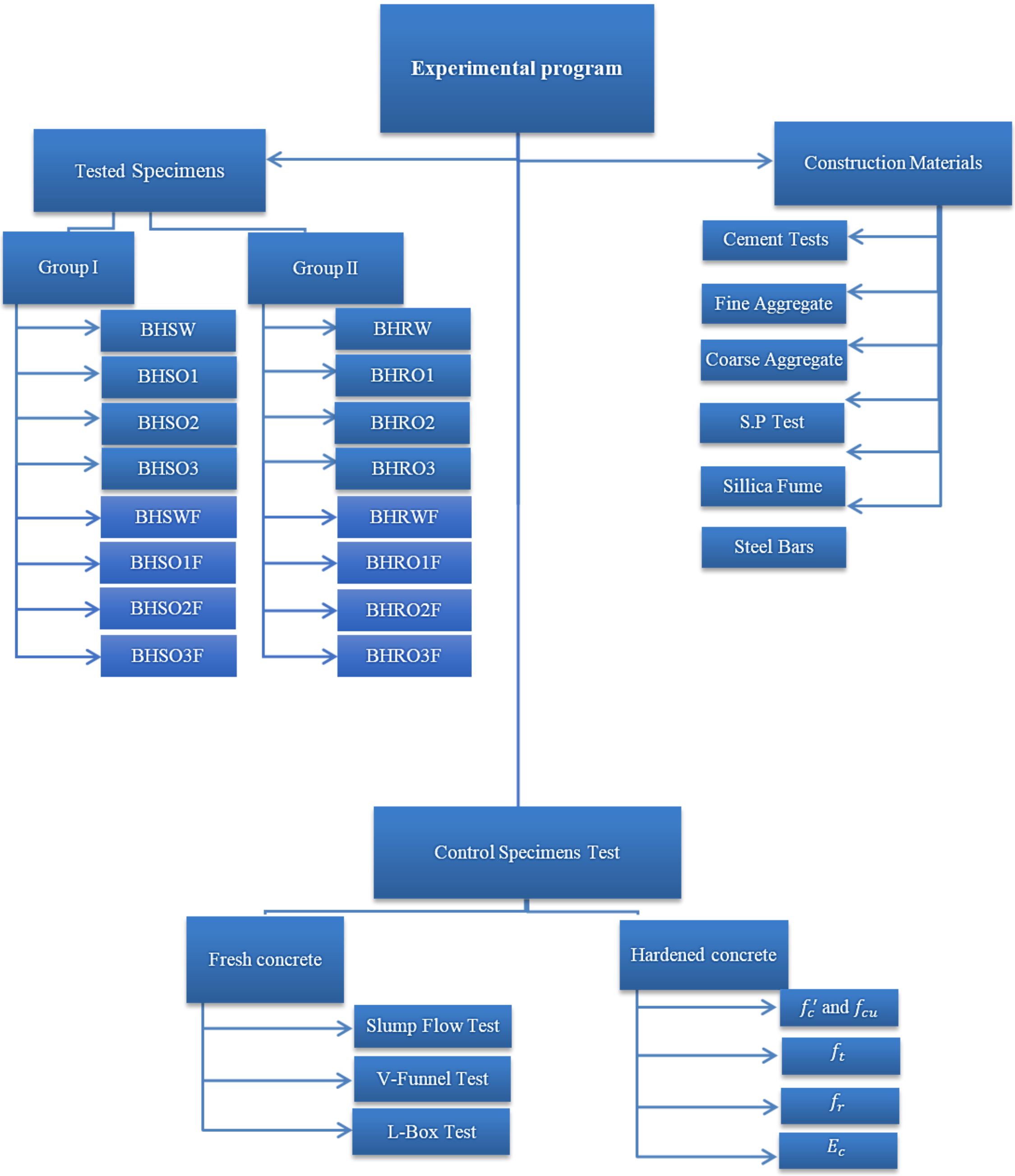


Figure 1. Experimental Program Details

2.1. Tested Specimens Details

The thin-walled tube truss analogy was adopted in this research's design of concrete members according to ACI code 2019 [26]. The design steps were completed according to the code requirements, and the test result was almost the same as the design assumed loads. The beams were tested after completing 28 days of curing. Table 1 shows the parametric of the details of tested beams, explained by the following: **B** = **B**eam, **H** = Hollow, **S** = Static, **R** = **R**epeated, and **W** = **W**ithout openings, **O** = with **O**penings, 1, 2 or 3 = the number of openings and F = Carbon **F**iber. All details are provided in Figure 2.

Table 1. Tested Specimens details

Beam designation	Type of Load	No. of Cycles	No. of Transverse Opening	The presence of CFRP Strips
BHSW	Monotonic	-	None.	-
BHRW	Repeated	7 Cycles	None.	-
BHSO1	Monotonic	-	1	-
BHRO1	Repeated	7 Cycles	1	-
BHSO2	Monotonic	-	2	-
BHRO2	Repeated	7 Cycles	2	-
BHSO3	Monotonic	-	3	-
BHRO3	Repeated	7 Cycles	3	-
BHSWF	Monotonic	-	None	With CFRP
BHRWF	Repeated	7 Cycles	None	With CFRP
BHSO1F	Monotonic	-	1	With CFRP
BHRO1F	Repeated	7 Cycles	1	With CFRP
BHSO2F	Monotonic	-	2	With CFRP
BHRO2F	Repeated	7 Cycles	2	With CFRP
BHSO3F	Monotonic	-	3	With CFRP
BHRO3F	Repeated	7 Cycles	3	With CFRP

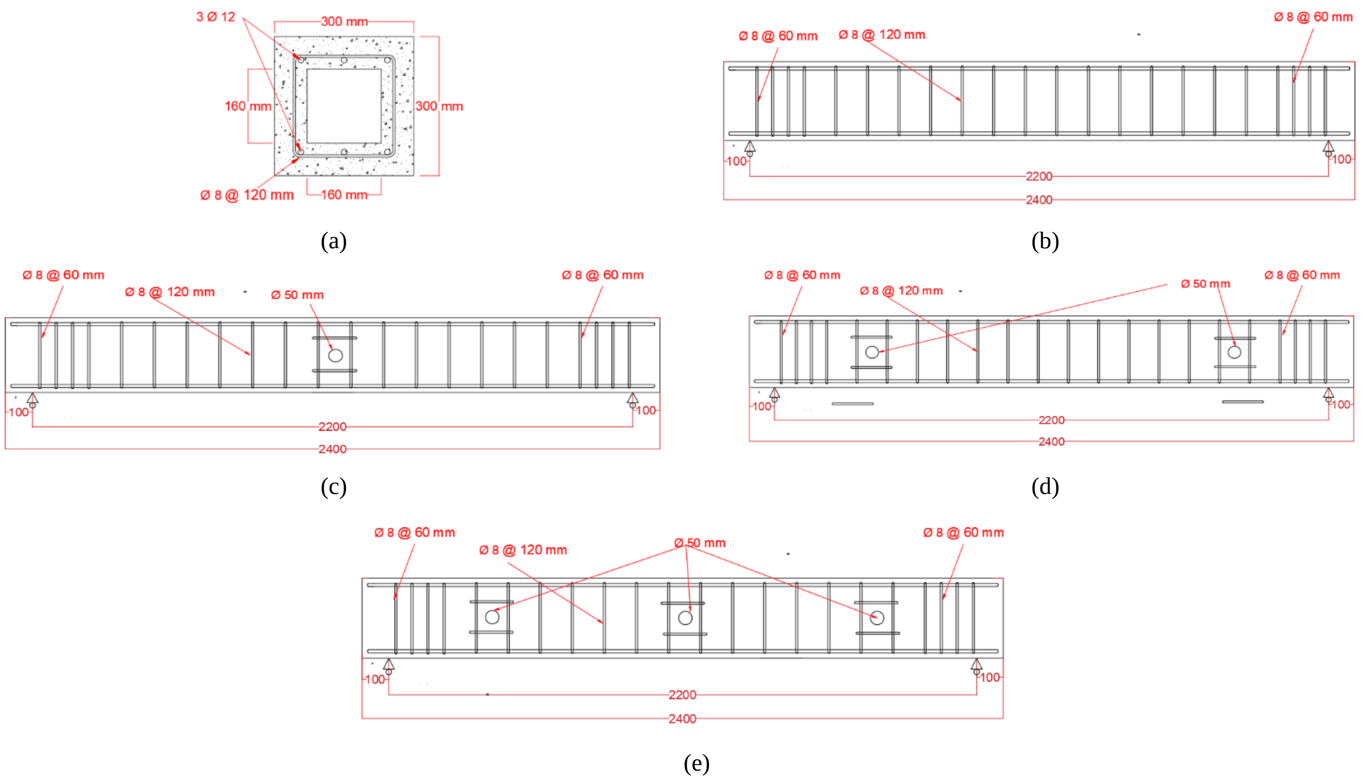


Figure 2. Details of beam specimen (all dimensions in mm): a) beams cross-section, b) (BHSW, BHRW), C) (BHSO1, BHRO1), d) (BHSO2, BHRO2), e) (BHSO3, BHRO3)

2.2. CFRP Strengthening Technique Installation and its Properties

In this research, when the first crack appeared within the acceptance range of 0.3 mm in width, the crack width limit permitted by ACI 318-19 [27], the beam was removed from the testing machine to be strengthened with CFRP strips later and tested again up to failure. Crack widths are measured using a special device of thin stainless-steel plates, as shown in Figure 3.

Figure 3. Stainless steel thin plates crack width measurement

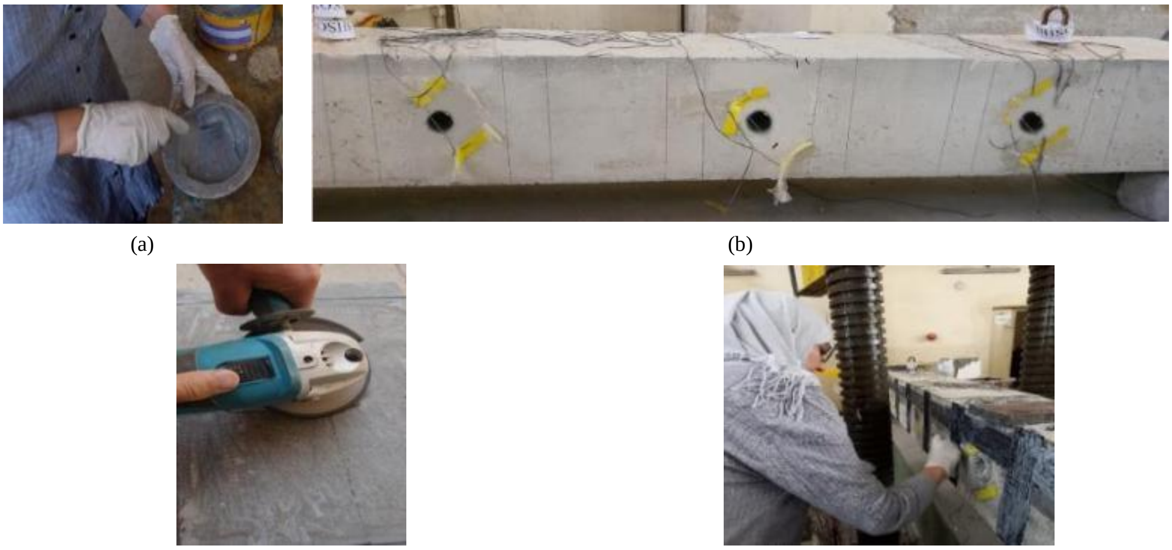
SikaWarp®-300C, a composite material used to repair and strengthen reinforced concrete structures. As a bonding material, Sikadur®-330 is recommended by CFRP manufacturers to bond CFRP to the concrete. Table 2 shows the technical description of CFRP strips and Sikadur®-330. CFRP's strengthening of concrete beams depends on the bonding between CFRP and the concrete surface. The following steps were performed to achieve an effective bond:

- The CFRP fabric was cut to the required length that we needed. The adhesive materials (Compound A and B) were mixed; see Figure 4-a.
- The location and spacing of each CFRP sheet were marked on the beam to sketch where to put the epoxy and CFRP, Smoothing the surface of the concrete using a scraper machine. Use an air blower to remove the dust on the concrete surface, as shown in Figures 4-a, 4-b and 4-c.
- The epoxy was first applied to the concrete surface at a 1 mm thickness. The epoxy was also applied to the carbon fiber strips using the same thickness. The CFRP sheets were applied by hand to the beam surface, pressed until the fabric was saturated, and then rolled with a fluted roller to remove any air pockets, as shown in Figure 4-d.

Table 2. Technical description of (CFRP) and the bonding material (Sikadur®-330)

Properties	Product Data
SikaWarp®-300 C	
Fabric width	600 mm
Dry Fiber Thickness	0.167 mm
Technical Information of SikaWarp®-300 C	
Laminate Tensile Strength	3 500 N/mm^2
Laminate Modulus of Elasticity in Tension	220 KN/mm^2 Average, 210 KN/mm^2 Characteristic
Laminate Elongation at Break in Tension	1.59 %
Tensile Resistance	585 N/mm Average, 534 N/mm Characteristic
Sikadur®-330	
Flexural Strength	8,800 psi (60.6 MPa) (7 days)
Modulus of Elasticity in Flexure	5.06 x 105 psi (3,489 MPa) (7 days)
Tensile Strength	4,900 psi (33.8 MPa) (7 days)
Application Information of Sikadur®-330	
Mixing Ratio	Component 'A': Component 'B' = 4: 1 by weight

For all the tested beams, a schematic of CFRP fabric consists of two horizontal strips from each side and six vertical strips in a U shape. The strips in a U shape were distributed at a constant distance along the beam, as shown in Figure 5.



(a) (b) (c) (d)

Figure 4.Application of CFRP fabric procedure: a) Mixing adhesive material, b) Marketing the location of CFRP sheets Continue, Application of CFRP fabric procedure: c) Grinding of the concrete surface, d) Application of CFRP fabric

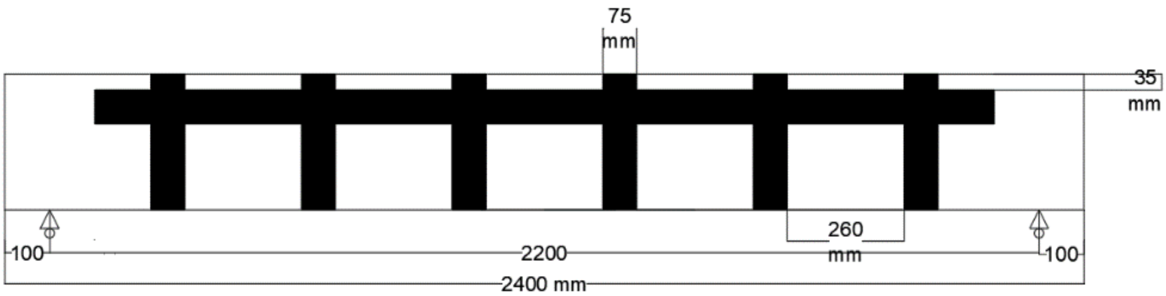


Figure 5. Schematic of CFRP fabric for beam specimens

2.3. Materials

Materials used to construct the self-compacting concrete mix design and steel reinforcement properties are shown in Table 3. The S.C.C. mix was designed according to the requirements of EFNARC [27]. For producing S.C.C., the method, we used was changing the superplasticizer dose while keeping the w/p ratio fixed. Details of the adopted mixture are shown in Table 4.

Table 3. Material properties

Material	Description
Cement	Ordinary Portland Cement (Type-I) (TASLUJA-BAZIAN)
Sand	Natural sand passing from a sieve size of (4.75 mm)
Gravel	Natural crushed gravel Size (14 mm).
Silica Fume	Type Mega Add MS(D) produced by CONMIX company.
Superplasticizer	Glenium 51
Water	Tap water
Reinforcing Bars [28]	(ϕ8 mm) deformed steel bar with a yield strength of (f_{yt}=410 MPa); and (ϕ12 mm) deformed steel bar with a yield strength of (f_{yl}=435 MPa).

Table 4. Trial mix details of self-compacting concrete

Filler%	Glenium 51	Quantities of Mix Ingredients (Kg/m^3)							
		Water (kg)	Powder		W/P ratio	Sand (kg)	Gravel (kg)	Glenium 51 (kg)	Density
			Filler Content (kg)	Cement (kg)					
9.2%	3.82%	179.83	44.00	473.24	0.34	777.1	888.1	19.8	2382.07

2.4. Mechanical Properties of Concrete

2.4.1.Test on Fresh Self Compacting Concrete and Hardened Concrete Properties

Three tests have been conducted as control tests on fresh S.C.C., namely the V-funnel, L-box, and slump flow tests, which gave a good indication of filling ability, passing ability, and segregation resistance. Furthermore, all these tests were compatible with the EFNARC requirements [27]. For each two-beam specimen, three 150×300 mm cylinders and three 150×150×150 mm cubes were used for the compressive strength test according to ASTM C39 [29], three 150×300 mm cylinders for the splitting tensile test according to ASTM C496/C496 [30], three 150×300 mm cylinders for the modulus of elasticity test according to ASTM C469 [31], and three 100×100×500 mm prisms for the flexural according to ASTM C78 [32], were tested to evaluate the mechanical properties of hardened concrete at the age of 28 days as given in Table 5.

Table 5. Mechanical properties of hardened concrete control specimens test's results

Beams Symbols	Properties				
	f'_c MPa	f_{cu} MPa	E_c MPa	f_{ct} MPa	f_r MPa
BHSW, BHSO1	43.62	56.67	24743.408	3.793	5.125
BHSO2, BHSO3	45	57.78	26542.771	3.83	5.2
BHRW, BHRO1	44.71	57	29789.322	3.805	4.212
BHRO2, BHRO3	44.8	56.8	25678.798	3.789	4.205
BHSWF, BHSO1F	44.78	56.44	30567.305	3.786	4.192
BHSO2F, BHSO3F	43.4	55.33	28355.268	3.749	4.15
BHRWF, BHRO1F	45	57.32	30534.551	3.815	4.224
BHRO2F, BHRO3F	44.5	56.8	27561.235	3.798	4.205

f'_c: Cylinder Compressive strength, f_{cu}: Cube Compressive strength, E_c: Modulus of elasticity, f_{ct}: Splitting tensile strength, f_r: Modulus of rupture.

2.5. Test Setup, Instrumentation, and Measurements

All beams have been tested using a universal testing M.F.L. machine model (8551 MFL system) with a 300-ton capacity. With a span of 2200 mm, the beams were set onto free-supported rollers at each end. Supports were designed to rotate about the beam's longitudinal axis, allowing free application of torsion. This was achieved by transferring the load from the universal machine to the two outer points representing the moment arm, which is equal to 500 mm from the applied load on steel arms to the center of the beam. The steel girder of 250 mm in depth and 2500 mm in length was used for load transmission from the universal machine to both arms, as shown in Figure 7. The measurement of the angle of twist was performed by using two dial gauges attached to the bottom of the end of the specimens at a point laid at (230 mm) from the center of the beam (see Figure 6).

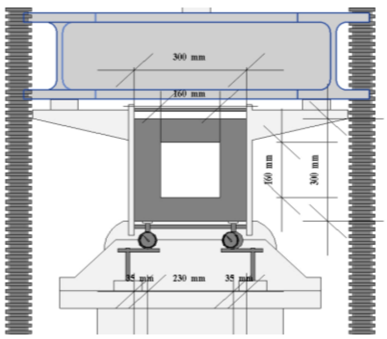


Figure 6. Dial gage location in beams

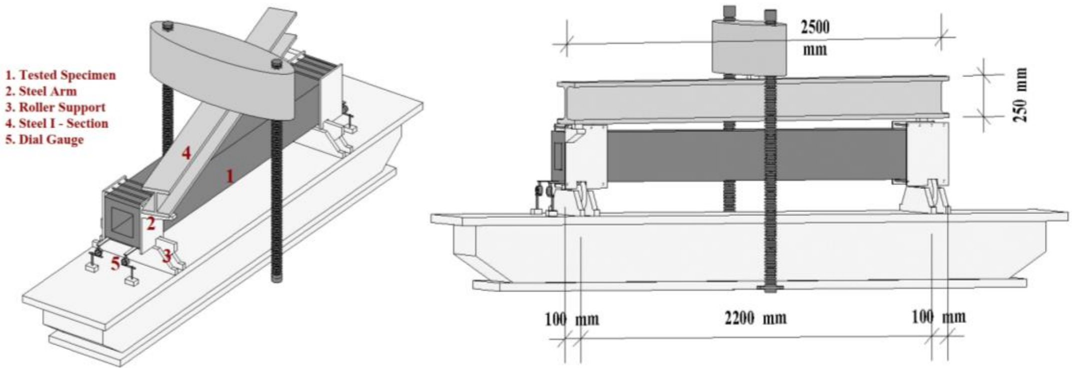


Figure 7. Schematic diagram of the test setup and the applied loading

Figure 8 shows the test setup. For the monotonic test in the first group (I), all beams were tested under an increasing 5 K.N. torque increment up to failure. For the repeated loading test, in the second group (II), 30% of the ultimate torsion of the beams failed under the monotonic loading for three cycles, and then after three cycles, 60% of the ultimate torsion load of specimens that failed under the monotonic load was repeated for seven cycles until failure.

Figure 8. Test setup

3. Results and Discussion

3.1. Cracking and Ultimate Torsional Moments and Modes of Failure

Table 6 shows the experimental work results. The ultimate torque is defined as the maximum torque at which the beam will fail, and the cracking torque is the torque when the first crack appears. For unstrengthened beams, after starting the test, cracks will appear on the surface of the concrete if the principal tensile stress reaches the tensile strength of the concrete. As shown in Figure 9, the crack had an inclination of about 45 degrees from all sides until failure and connected from all sides of the tested specimens. For the repeated loading test, 30% of the ultimate torsion load of the other beams that failed under the monotonic loading was applied for the first three cycles, followed by three cycles with 60% of the ultimate torsion load of the other beams that failed under the monotonic loading. The loading process was continued for the 7th cycle until failure. No cracks appeared in the first three cycles; in the second three cycles, as shown in Figure 9, the crack pattern refers to the cracks that appeared in the 4th and 5th cycles. The green color refers to the cracks that appeared in the 6th cycle, whereas the red color refers to the cracks that appeared in the 7th cycle.

Table 6. Cracking and Ultimate Torque for the tested Beams

Beam designation	Type of Load	Cracking Torque, T_{cr} (kN.m)		Ultimate Torque, T_u (kN.m)
BHSW	Monotonic	9.375	-	20.63
BHSO1		6.75	-	12.25
BHSO2		8.375	-	14.88
BHSO3		5	-	10.25
BHRW	Repeated	8.75	-	17.5
BHRO1		5.625	-	9.25
BHRO2		7.75	-	11.25
BHRO3		4	-	7.5
		Cracking Torque, T_{cr} (kN.m) before strengthening	**Cracking Torque, T_{cr} (kN.m) after strengthening**	
BHSWF	Monotonic	8.75	10	29.375
BHSO1F		6.5	7.875	21.875
BHSO2F		7.875	9.375	24.375
BHSO3F		5.5	6.875	20.375
BHRWF	Repeated	8.25	9.5	26.875
BHRO1F		5.625	6.25	18
BHRO2F		7.5	8.75	20
BHRO3F		4.5	5.75	16.75

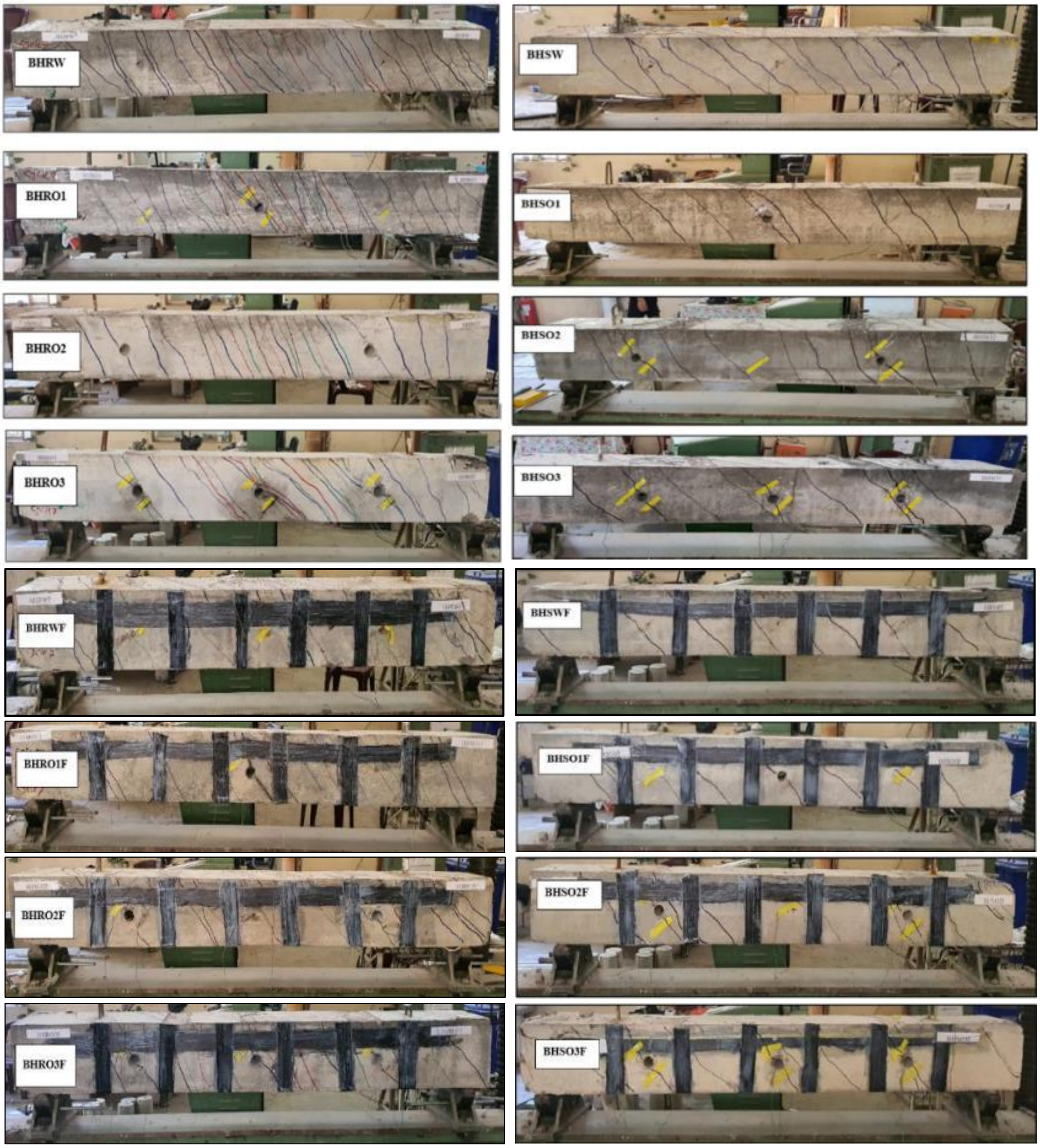
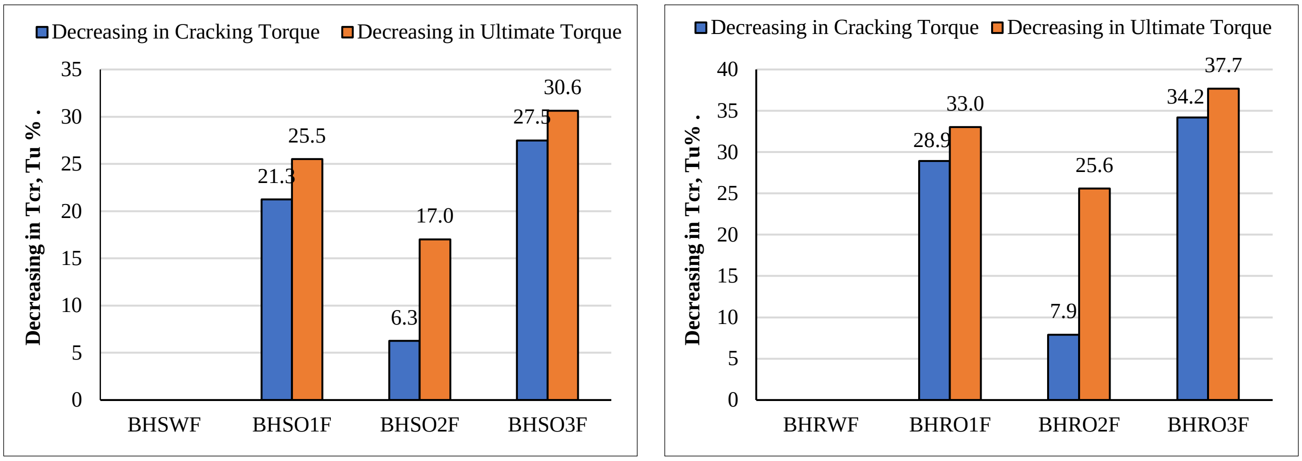


Figure 9. Cracks Pattern after Failure for Monotonic and Repeated Loading Test

For strengthened beams, the same test procedure for unstrengthened beams was done for monotonic and repeated tests. As mentioned before, when the first crack appeared within the acceptance range (0.3 mm in width), the beam was removed from the testing machine to be strengthened with CFRP later and tested again up to failure. So there is a cracking torque before and after strengthening; therefore, the cracking torque value will be different before and after strengthening, as mentioned in Table 6. The pattern of cracking and the mode of failure for the monotonic and repeated loading tests are shown in Figure 9. The stiffness of all strengthened beams gradually decreased with increased torque until failure, and it was generally higher than the stiffness of the beams without strengthening, which can be referred to as the CFRP strip's contribution in bearing the additional torque. In general, the beams that are strengthened with CFRP strips gain higher torsional strength than the beams without strengthening. We can also notice from Figure 9 that the number of cracks in strengthened beams is less than that in beams without strengthening, as well as the difference in distribution and density of the cracks along the specimens after using CFRP fabric.

3.1.1. Effect of Opening on Cracking and Ultimate Torsional Strength of the Strengthened Beams

For the monotonic loading test, the cracking and ultimate torques were reduced and decreased, respectively, due to openings compared with the beam BHSWF (beam without opening). The percentage decrease is shown in Figure 9. Moreover, the results also indicated a reduction in the cracking and ultimate torque capacities for the repeated loading test-strengthened specimens compared to the beam without opening too. Figure 10 also shows that the ultimate torque strength is more affected by the presence of the web opening as compared with the cracking torsion strength. For the monotonic and repeated loading tests, a maximum reduction in the ultimate torque moments was approximately 30.6% and 37.7%, respectively.



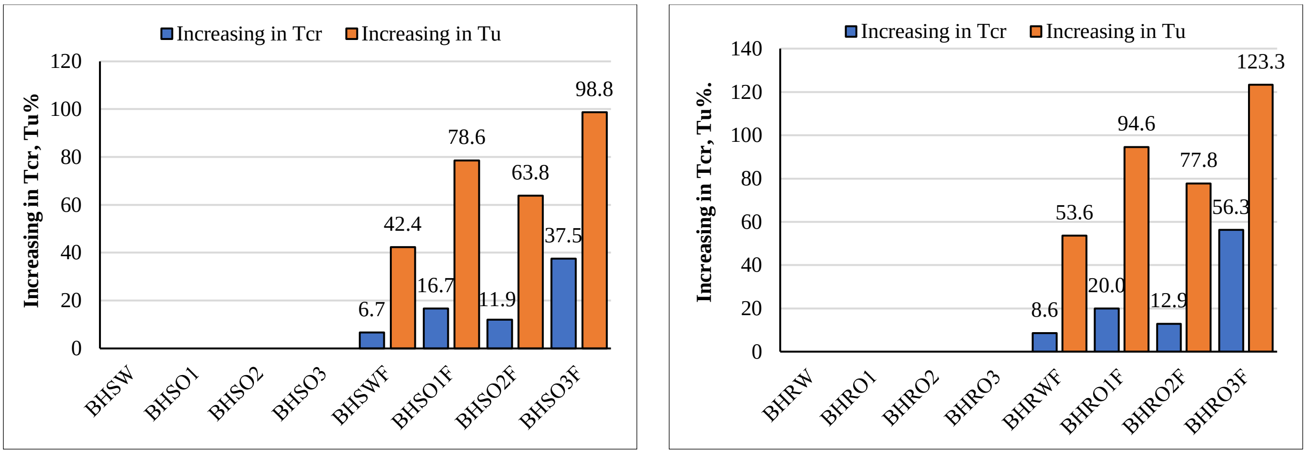
(a) (b)

Figure 10. Percentage of decrease in the Cracking and Ultimate Torques due to the presence of opening for strengthened beams tested under (a) Monotonic load and (b) repeated load

3.1.2. Effect of CFRP Strengthening on Cracking and Ultimate Torsional Strength

Table 6 shows the values of the cracking and ultimate torques of the tested beams. For the monotonic loading test, the cracking and ultimate torques were improved and enhanced due to using the CFRP strengthening technique compared with the specimens without strengthening. The percentage increase is shown in Figure 11. Moreover, the results presented also indicated an improvement in the cracking and ultimate torque capacities for the repeated loading test specimens compared to the beam without strengthening. Results presented in Figure 11 showed that the ultimate torque strength is more affected by the use of the CFRP strengthening technique as compared with the cracking torsion strength. For the monotonic and repeated loading tests, a maximum reduction in the ultimate torque moments of approximately 98.8% and 123.3%, respectively, are noted.

On the other hand, Figure 11 compares the effect of repeated loading to the monotonic loading of the strengthened beams. Results indicated that the cracking and ultimate torque capacities for the repeated loading specimens decreased compared to the monotonic loading test. The results presented in Figure 12 also showed that the ultimate torque strength is more affected by the repeated load's action than the cracking torsion strength. A maximum reduction in the ultimate torque moments of about 17.8% is recorded compared with a 16.4% reduction in the cracking torque moments when the repeated loading effect is compared with monotonic loading for the strengthened box beam samples with and without openings.



(a) (b)

Figure 11. Percentage of increase in the Cracking and Ultimate Torques due to CFRP strengthening technique for beams tested under (a) Monotonic and (b) repeated load

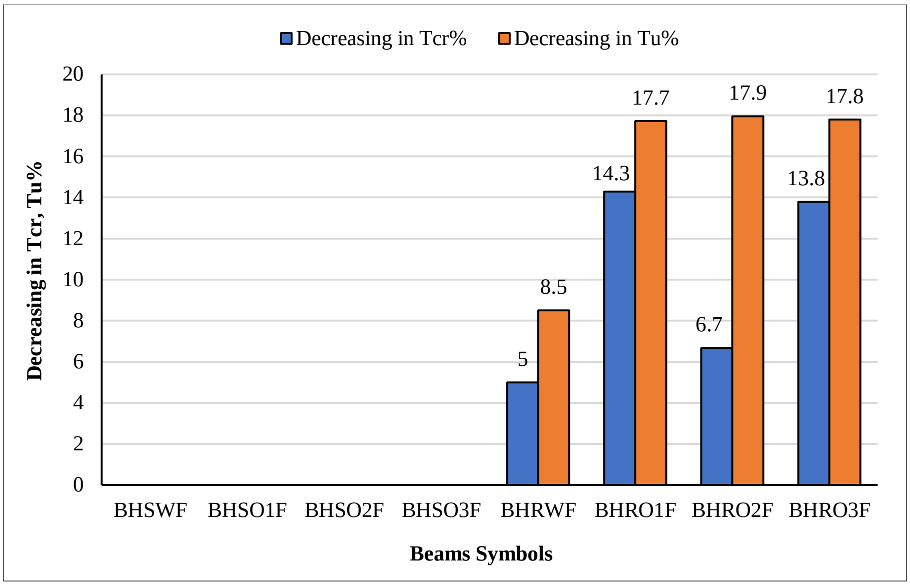


Figure 12. Comparison of the Cracking and Ultimate torque capacities for the repeated and Monotonic loading strengthened specimens

3.2. Torsion-angle of Twist

The angle of twist is defined as a two-dimensional torsional moment deformation. Table 7 shows the results of the twist angle of all the tested beams, and Figure 13 shows the torsional moment graphed against the average of two twist angles for each tested beam separately for strengthened and unstrengthened specimens under monotonic and repeated loading. The effect of openings and CFRP strengthening on the cracking and the ultimate angle of the twist of the strengthened beams will be displayed and discussed in the next paragraphs.

Table 7. Experimental results for the angle of twist

Beam designation	**Type of Load**	**Cracking Torque, T_{cr} (kN.m)**		**Cracking Angle of Twist ϕ_{cr} (Rad.)**		**Ultimate Torque, T_u (kN.m)**	**Ultimate Angle of Twist ϕ_u (Rad.)**
BHSW	Monotonic	9.375	-	0.00161		20.63	0.01565
BHSO1		6.75	-	0.00083		12.25	0.00761
BHSO2		8.375	-	0.00090		14.88	0.00858
BHSO3		5	-	0.00070		10.25	0.00687
BHRW	Repeated	8.75	-	0.00103		17.5	0.00880
BHRO1		5.625	-	0.00042		9.25	0.00410
BHRO2		7.75	-	0.00056		11.25	0.00490
BHRO3		4	-	0.00032		7.5	0.00342
		Cracking Torque, T_{cr} (kN.m) before strengthening	Cracking Torque, T_{cr} (kN.m) after strengthening	Cracking Angle of Twist ϕ_{cr} (Rad.) before strengthening	Cracking Angle of Twist ϕ_{cr} (Rad.) after strengthening		
BHSWF	Monotonic	8.75	10	0.00147	4.3478E-05	29.375	0.02943
BHSO1F		6.5	7.875	0.00069	3.2609E-05	21.875	0.01271
BHSO2F		7.875	9.375	0.00075	3.7826E-05	24.375	0.01507
BHSO3F		5.5	6.875	0.00064	2.6957E-05	20.375	0.01109
BHRWF	Repeated	8.25	9.5	0.00119	3.8478E-05	26.875	0.02028
BHRO1F		5.625	6.25	0.00041	2.2609E-05	18	0.00781
BHRO2F		7.5	8.75	0.00052	2.7826E-05	20	0.01097
BHRO3F		4.5	5.75	0.00027	1.6957E-05	16.75	0.00648

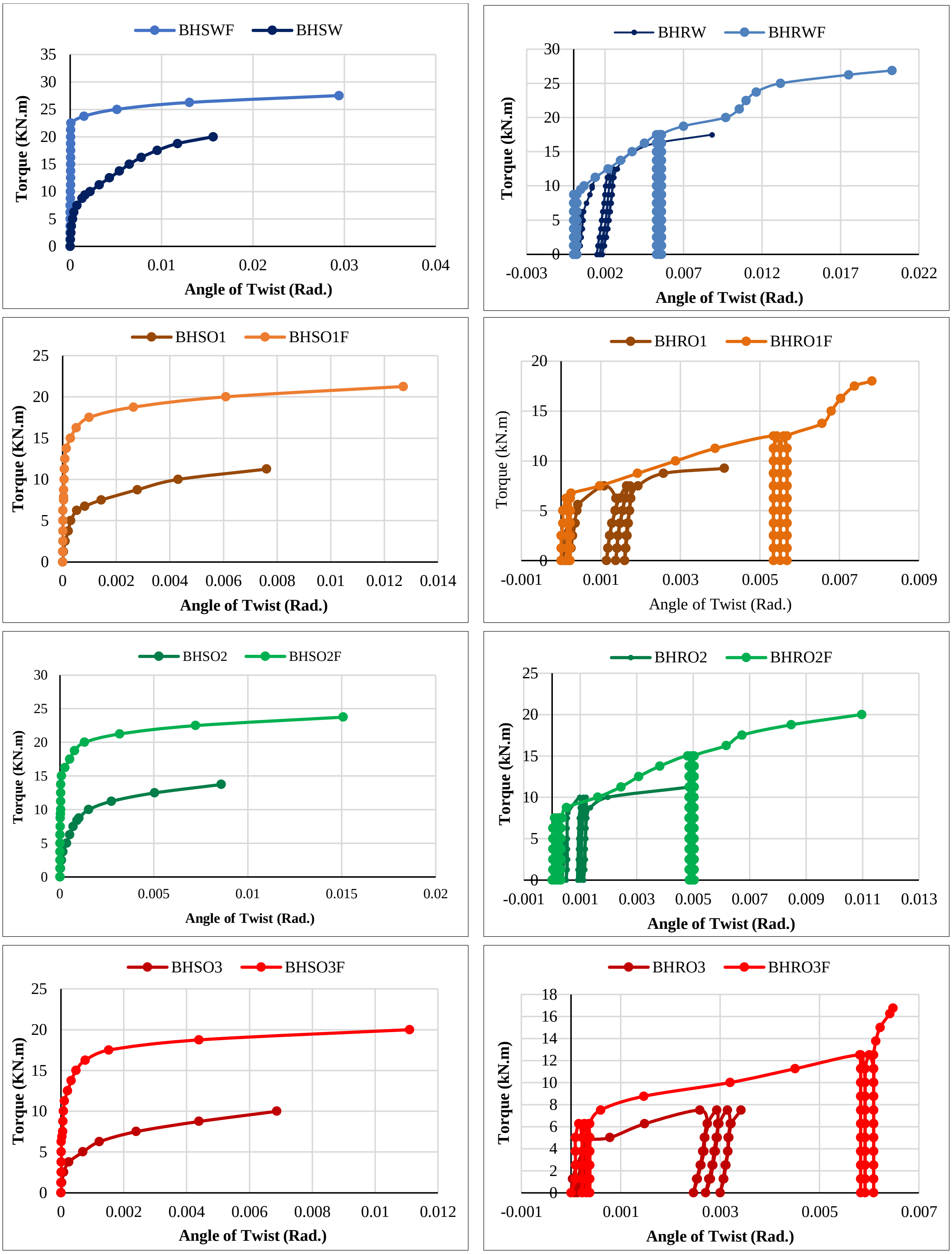
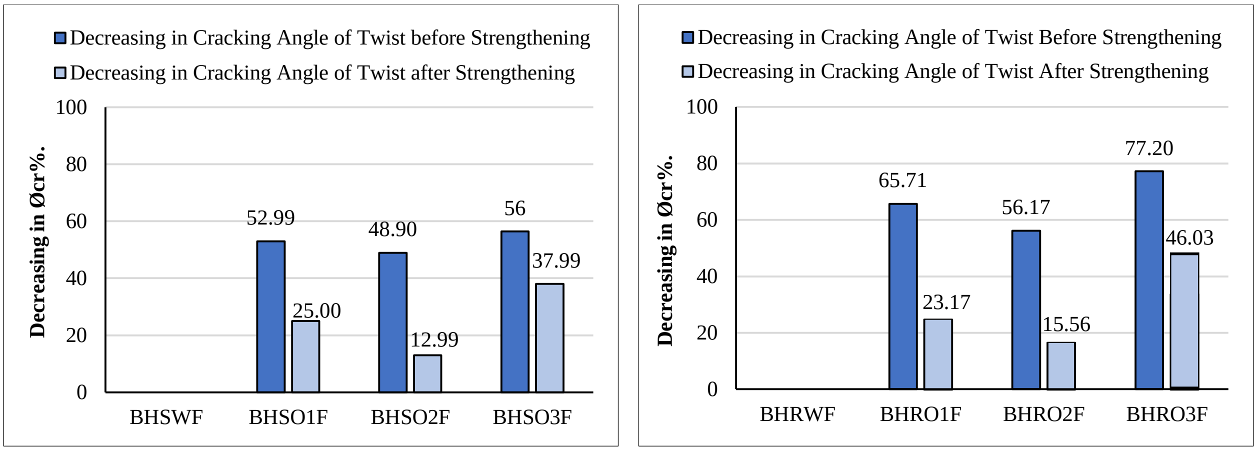


Figure 13. Torsional moment vs. angle of twist for beams under Monotonic and Repeated loading

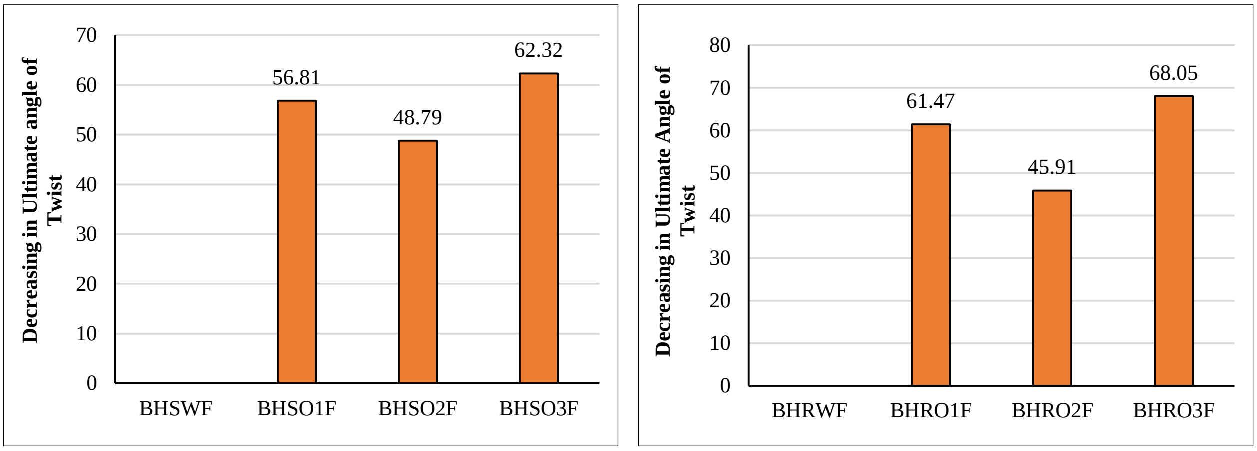
3.2.1. The Effect of Opening on Cracking and Ultimate Angle of Twist for the Strengthened Beams

As mentioned before, when the first crack appears within the acceptance range (0.3 mm in width) (the crack width limit permitted by ACI 318-19 [18] is 0.3 mm), the beam is removed from the testing machine to be strengthened with CFRP later and tested again up to failure, so there are two angles of twist (before and after strengthening). For strengthened specimens, The curves for strengthened and non-strengthened beams show a linear behavior until the first cracking load, then the curves show inelastic behavior until failure due to differences in torsional stiffness for the tested concrete beams. The results presented for the monotonic and repeated loading tests indicated that the area under the curve becomes smaller for all the tested beams with openings. This result shows that the beam samples with openings have less torsional stiffness and will decrease in cracking and ultimate angle of twist. Figures 14 and 15 display the percentage decrease for each tested beam. The results also show that the ultimate angle of twist is more affected by the presence of the web openings compared to the cracking angle of twist.



(a) (b)

Figure 14. Percentage of Decrease in the Cracking Angle of Twist before and After Strengthening due to the presence of Opening for Beams Tested under (a) Monotonic and (b) Repeated Loading



(a) (b)

Figure 15. Percentage of Decrease in the Ultimate Angle of Twist due to the Presence of Opening for Strengthened Beams Tested under (a) Monotonic and (b) Repeated Loading

Generally, a reduction in the cracking angle of the twist before and after strengthening of about 13% to 78% and, about 46% to 70% in the ultimate angle of the twist are observed due to different numbers of openings under monotonic or repeated loading compared with box beam samples without openings.

3.2.2. Effect of CFRP Strengthening on Cracking and Ultimate Angle of Twist

From the results obtained from the test, using the CFRP strengthening technique will lead to a decrease in the cracking angle after strengthening and an increase in the Ultimate Angle of Twist for (strengthened beams with CFRP) compared to the reference beams (without strengthening), as shown in Figure 16. Results presented in Figure 16 showed that the decrease in the cracking angle (after strengthening) of the twist ϕ_{cr} For both Monotonic and repeated loading is almost the same, but for the ultimate angle of twist ϕ_u In the repeated loading, the percentage of increase is more than the ultimate angle of the twist in the monotonic loading test. For the Monotonic loading test, the percentage increased from about 60% to 88% in the ultimate angle of the twist ϕ_u. For the Repeated loading test the percentage increased from about 89% to 130% in the ultimate angle of the twist ϕ_u.

On the other hand, Figures 17 and 18 compare the effect of repeated loading as compared with monotonic loading for strengthened beams. Results indicated that the cracking and ultimate angle of the twist for the repeated loading specimens decreased compared to the monotonic loading test. The results presented in Figure 17 also showed that the cracking angle of the twist before strengthening is more affected by the repeated load's action than the cracking torque after strengthening the torsion strength. A maximum reduction in the cracking torque moments after strengthening of about 37% is recorded compared with a 57.6% reduction in the cracking angle of the twist before strengthening when the repeated loading effect is compared with monotonic loading for the box beam samples with and without openings. Also, Figure 18 shows that the ultimate angle of the twist is affected by the repeated load's action. The maximum reduction is for BHRO3 by about 41.6% when the repeated loading effect is compared with monotonic loading for the box beam samples with and without openings.

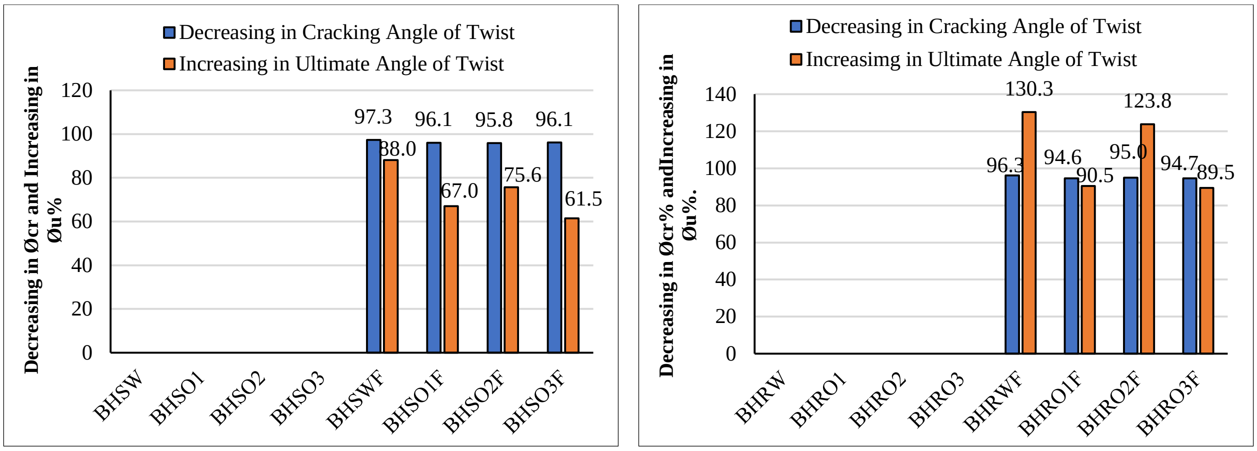


Figure 16. Percentage of variation in the Cracking and Ultimate Angle of Twist for Strengthened Beams Tested under (a) Monotonic and (b) Repeated Loading

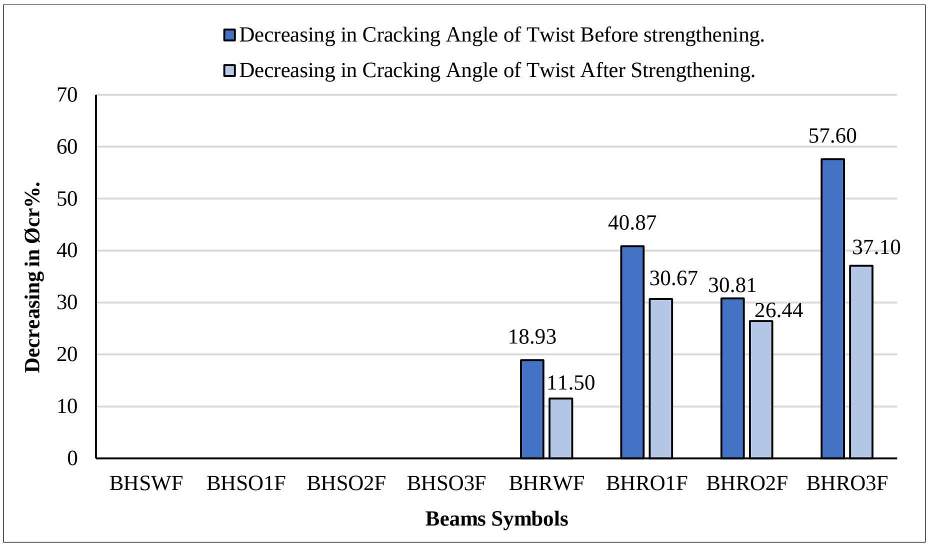


Figure 17. Percentage of Decrease in Cracking Angle of Twist Before and After Strengthening for strengthened Beams compared to Monotonic Loading Test

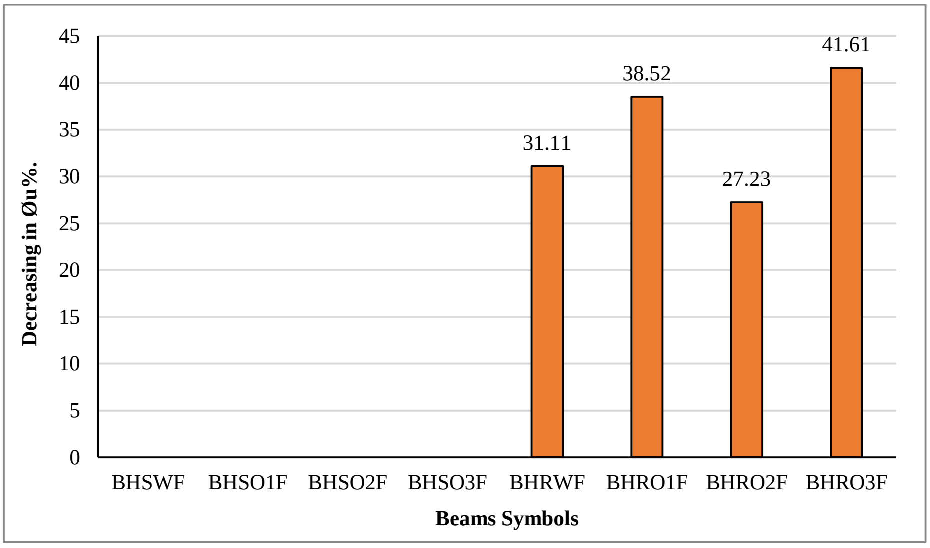


Figure 18. Percentage of Decrease in Ultimate Angle of Twist for strengthened Beams compared to Monotonic Loading Test

3.3. Reinforcing Steel Bar Strains

The location of steel strain gages for each tested beam is shown in Figure 19. Table 8 shows steel strain values at the ultimate stage for all tested beams. Figure 20 also shows torque-steel strain relationships for the tested beams separately for strengthened and unstrengthened specimens under monotonic and repeated loading. All the steel strain values for the tested specimens are positive (tension) at the ultimate loading of the test. All the strain values of the tested specimens do not exceed the yield strain value of the steel reinforcement (ε_y=2245× 10^{-6}), which shows that the specimens' steel can carry additional torsional moments higher than the recorded maximum strain. The effect of openings and CFRP strengthening on the ultimate steel strain for the strengthened beams is displayed and discussed in the next paragraphs.

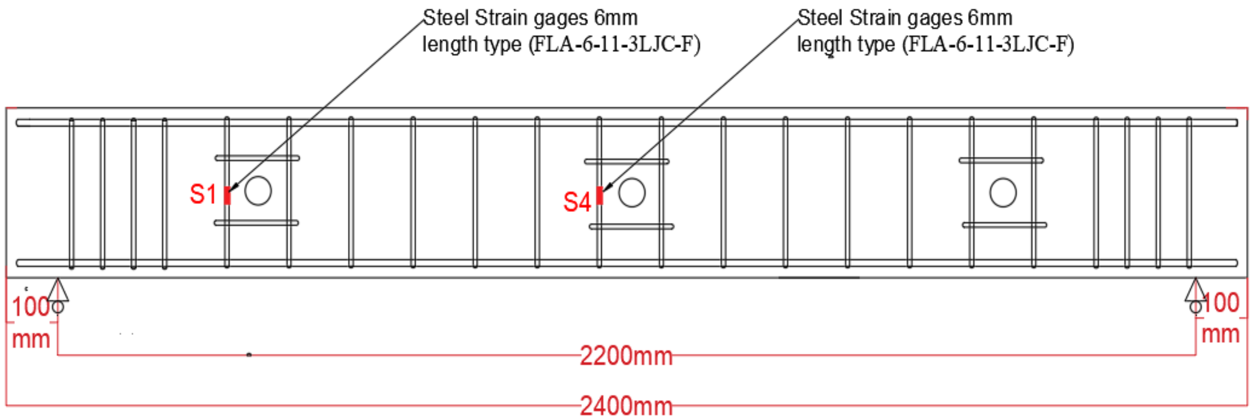
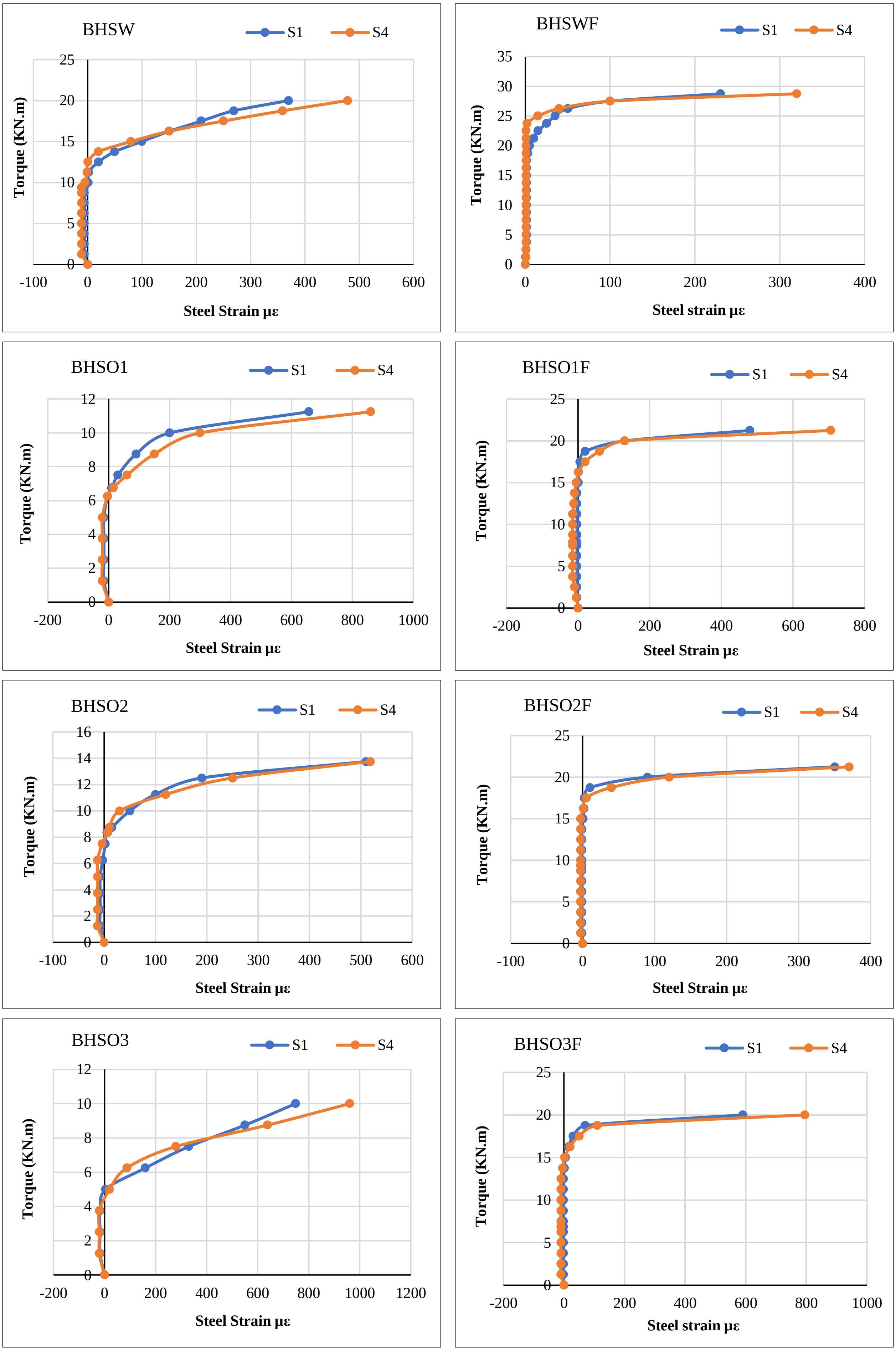


Figure 19. Location of Steel strain gages of the tested beams

Table 8. Steel strain at the Ultimate stage for strengthened beams tested under Monotonic and Repeated Loading

Beam Designation	Type of Load	Steel Strain× 10^{-6} at ultimate loading	
		S1	S4
BHSW	Monotonic	370	479
BHSO1		657	880
BHSO2		510	519
BHSO3		748	960
BHRW	Repeated	470	590
BHRO1		950	1320
BHRO2		690	660
BHRO3		1150	1520
BHSWF	Monotonic	230	320
BHSO1F		480	705
BHSO2F		350	370
BHSO3F		590	795
BHRWF	Repeated	355	440
BHRO1F		770	1090
BHRO2F		550	505
BHRO3F		980	1270


BHSW
S1
S4
Torque (KN.m)
Steel Strain με
BHSWF
Steel strain με
BHSO1
BHSO1F
BHSO2
BHSO2F
BHSO3
BHSO3F

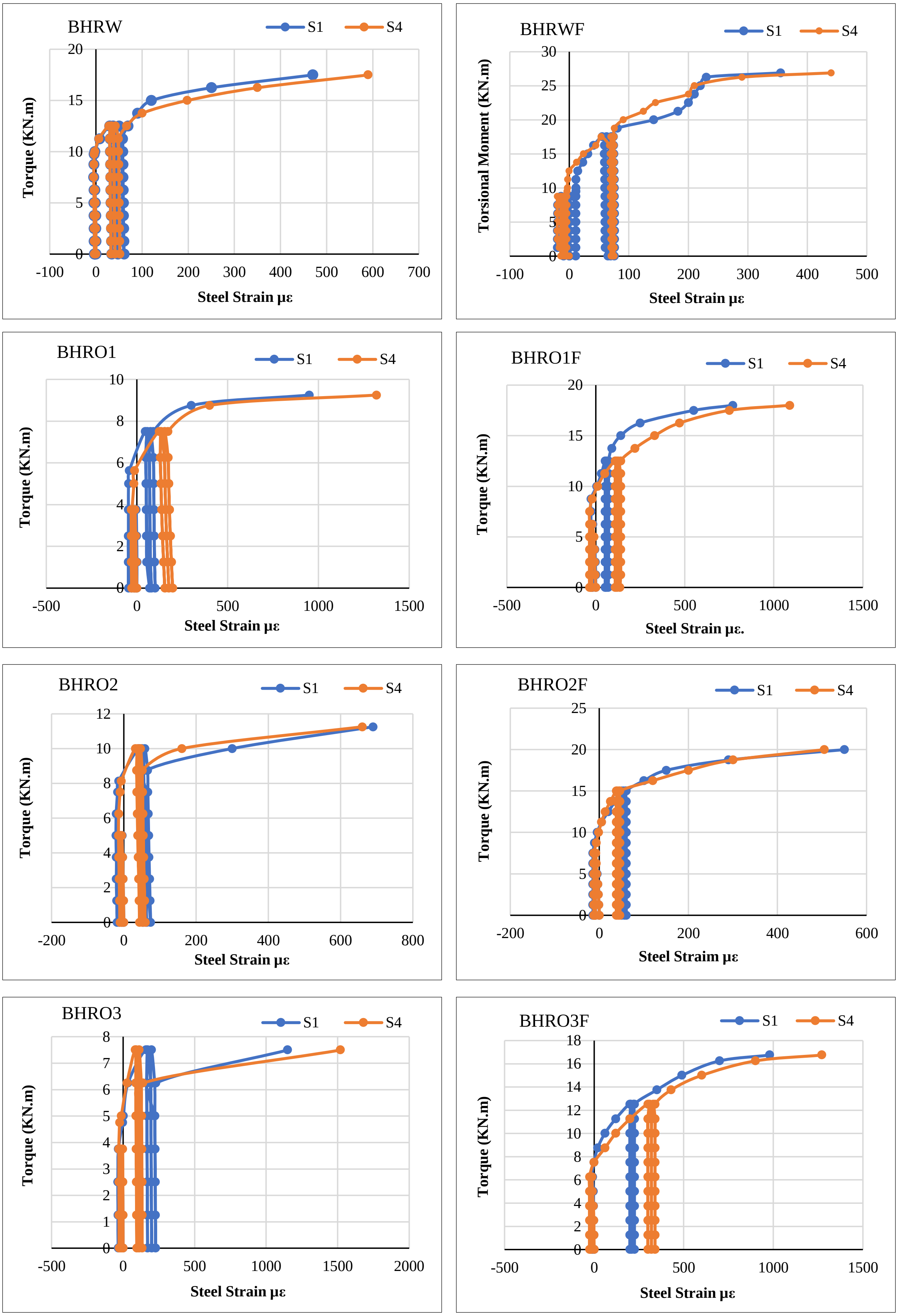
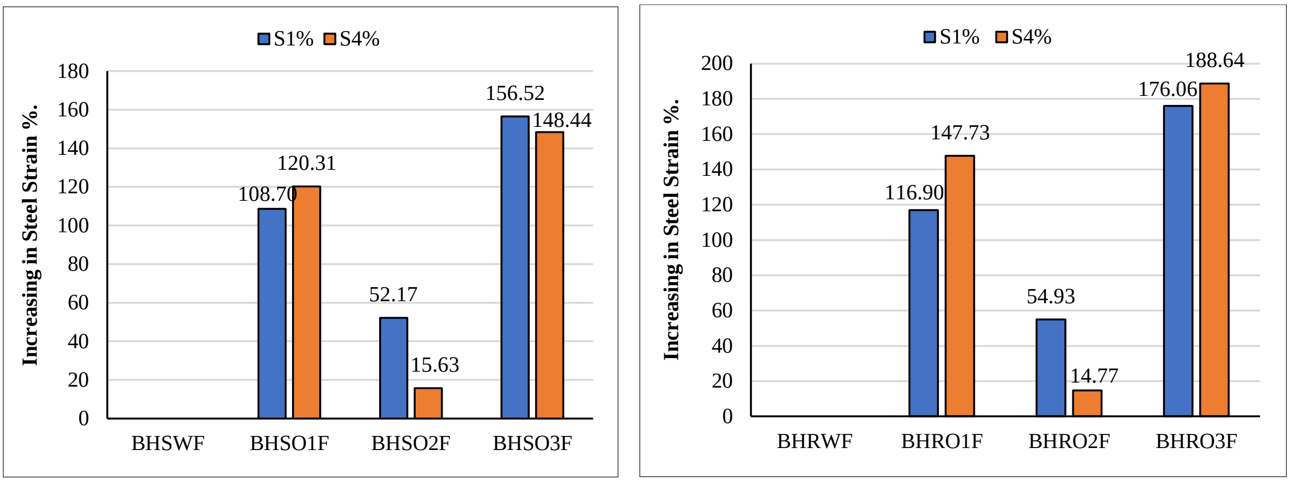


Figure 20. Torque–steel Strain relationships for the tested Specimens under Monotonic and Repeated Loading

3.3.1.The Effect of Opening on Ultimate Steel Strain of the Strengthened Beams

The ultimate steel strain values show an increase with the presence of openings as compared to the reference beams (BHSWF and BHRWF, beam without opening); this may be due to a decrease in the stiffness of the tested beam. Figure 21 shows the increasing steel strain percentage due to the presence of openings. Moreover, the results also indicated an increase in the ultimate steel strain for the repeated loading test-strengthened specimens compared to the beam without opening too. Generally, the increase in the ultimate steel strain due to opening under monotonic loading is about 50% to 160% for S1 and about 15% to 150% for S4 for the tested steel strain values for the specimens. For the repeated loading test, the ultimate steel strain increased by about 55% to 177% for S1 and by about 15% to 189% for S4 for the tested steel strain values for the specimens.

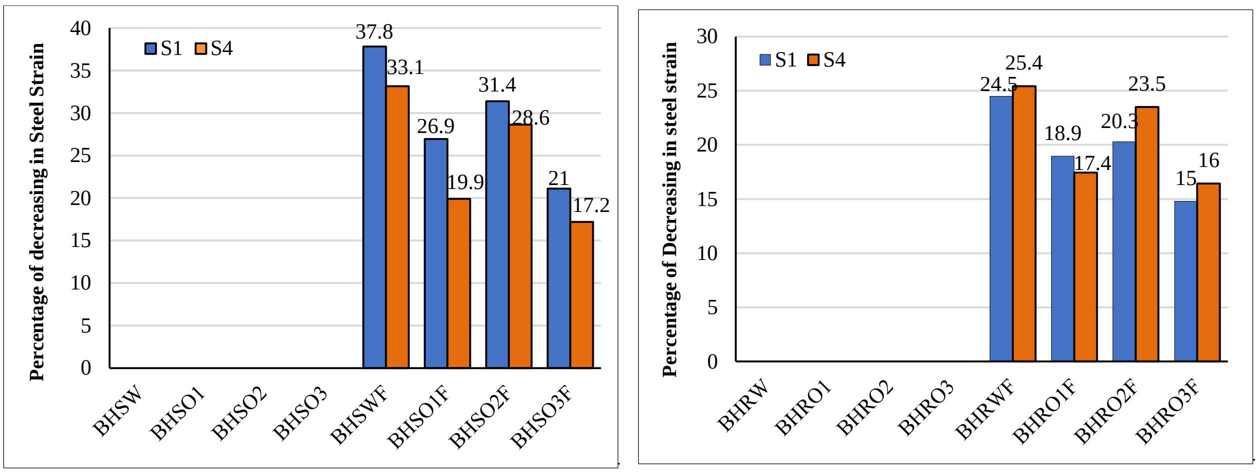


(a) (b)

Figure 21. Percentage of variation in the steel strain for Strengthened Beams Tested under (a) Monotonic and (b) Repeated Loading

3.3.2.Effect of CFRP Strengthening on Ultimate Steel Strain

From the results obtained from the test, using the CFRP strengthening technique will lead to a decrease in the steel strain value for strengthened beams with CFRP compared to the reference beams without strengthening, as shown in Figure 22. Generally, the decrease in the ultimate steel strain due to CFRP for beams tested under monotonic loading is about 20% to 38% for S1 and about 17% to 33% for S4 for the tested steel strain values for the specimens. For the repeated loading test, the decrease in the ultimate steel strain was about 15% to 25% for S1 and about 16% to 26% for S4 for the tested steel strain values for the specimens.



(a) (b)

Figure 22. Percentage of decrease in Steel stain value for strengthened beams due to applying CFRP tested under (a) Monotonic and (b) Repeated Loading

On the other hand, Figure 23 shows the comparison of the effect of Repeated loading as compared with Monotonic loading for strengthened beams. Results indicated that the ultimate steel strain capacities for the repeated loading specimens were increased compared to the Monotonic loading test. Results presented in Figure 23 also showed that the ultimate steel strain in BHRO3F is more affected by the repeated load's action than the other specimens.

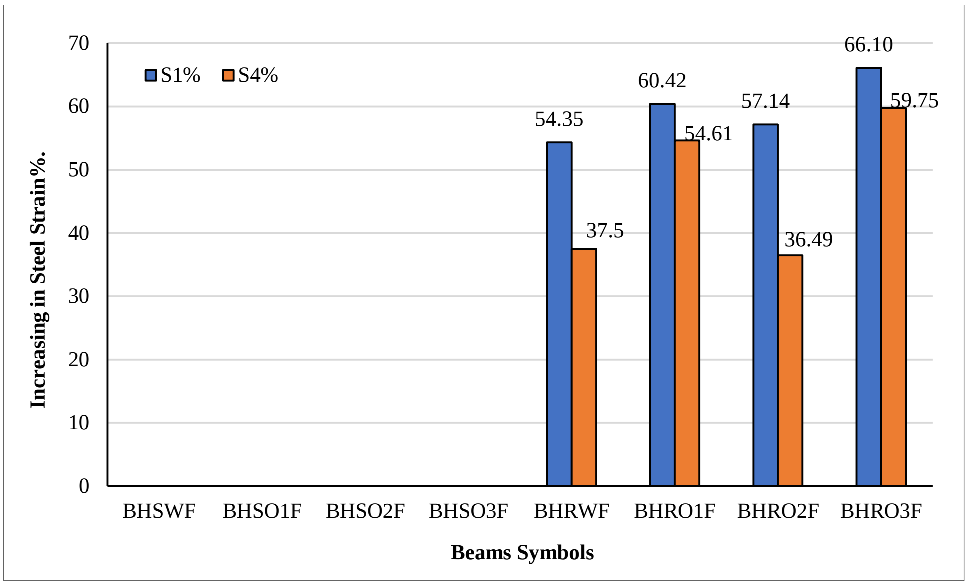


Figure 23. Percentage of Increase in Steel stain value for Unstrengthen beams compared to Monotonic Loading Test

4. Conclusions

After studying the experiment findings, the conclusions listed below have been made:

- All tested specimens under monotonic and repeated loading that were strengthened with CFRP strips had greater torsional resistance than the specimens without strengthening.
- The cracking and ultimate torque for the strengthened beams tested under monotonic loading are greater than for specimens without strengthening. The cracking torsional moment has increased by about 6.7% to 37.5%, whereas the ultimate torsional strength has increased by approximately 42.4% to 98.8%.
- For the repeated loading test, the cracking and ultimate torque for the strengthened beams are greater than for specimens without strengthening. The cracking torsional moment has increased by about 8.6% to 56.3%, whereas the ultimate torsional strength has increased by approximately 53.6% to 123.3%.
- Results indicated that the cracking and ultimate torque capacities for strengthened specimens under repeated loading tests are lower than their counterparts tested under monotonic loading by about 5% to 14.3% for the cracking torsional moment, whereas the ultimate torsional strength decreased also by approximately 8.5% to 17.9%.
- Regarding the angle of twist, test results show that beam samples with openings became less in torsional stiffness and revealed a decrease in the cracking angle of twist before and after strengthening, and, generally, strengthening significantly enhances torsional stiffness, especially for beam samples under repeated loading.
- Results indicate that steel reinforcement for the strengthened specimens has greater ultimate strain values due to the presence of openings as compared to the beam without openings. The repeated loading test case has recorded a greater increase in the steel strain values compared to the monotonic loading test.
- Using the CFRP strengthening technique leads to a decrease in the ultimate steel strain values compared to the reference beam (without strengthening).
- Results indicated that the ultimate steel strains for the strengthened specimens under repeated loading have greater values compared to the monotonic loading test.

Further work is suggested to study the effect of other types of strengthening techniques on the behavior of concrete box beams with openings (like near surface-mounted NSM bars and internal steel reinforcement) or the effect of other strengthening configurations on R.C. box beams with openings.

5. Declarations

5.1. Author Contributions

Conceptualization, H.M.; methodology, H.M.; validation, H.M.; formal analysis, H.M. and R.M.; investigation, H.M.; resources, H.M.; data curation, H.M.; writing—original draft preparation, H.M.; writing—review and editing, H.M. and R.M.; project administration, H.M.; funding acquisition, H.M. 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 in the article.

5.3. Funding

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

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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