Information Sciences Letters
An International Journal

http://dx.doi.org/10.18576/isl/120136

Improving the Torsional Strength of Reinforced Concrete Hollow Beams Strengthened with Externally Bonded Reinforcement CFRP Stripe Subjected to Monotonic and Repeated Loads

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Received: 12 Jun. 2022, Revised: 16 Aug. 2022, Accepted: 17 Sep. 2022.
Published online: 1 Jan. 2023

Abstract: The loading on bridges, ports, multi-story parking garages, airport facilities, and many other structures is often repeated and usually built with reinforced concrete beams. The behavior of concrete under repeated loads differs from that of static loads. Due to the loading and unloading process, repeated loads cause crushing in some concrete sections. The war and other events damaged numerous concrete structures and bridges in Iraq. Therefore, maintenance and rehabilitation of these structural parts are already required. This study aims to illustrate the behaviour of reinforced concrete hollow beams strengthened with a strip of carbon fiber reinforced polymer (CFRP) in various configurations using the externally bonded reinforcement (EBR) method when exposed to monotonic and repeated torsion. Eight beams of 250 x 350 x 3000 mm were cast and tested up to failure under pure torsion. Two of these beams were unreinforced. Other beams were strengthened with varied configurations of CFRP strips. The tested specimens were divided into two groups. For each investigation condition, the beam was examined under monotonic torsion and utilized as a control for those examined under repeated torsion after seven cycles of 60% of the control samples' ultimate loads. Using the CFRP stripe, the torsional performance of the reinforced concrete beams was greatly enhanced. Test beams reinforced with two continuous CFRP stripes demonstrated a more significant increase in the ultimate torsional moment than beams strengthened with other CFRP stripe configurations. Beams tested under repeated torsion show less degradation in torsional strength than beams tested under monotonic torsion moment.

Keywords: Externally-bonded reinforcement (EBR), CFRP stripes, Repeated loads, Crack width, Energy Absorption, Ductility.

1 Introduction

Despite the availability of numerous classic rehabilitation procedures like epoxy repair or steel jacketing, there is always a demand for new technologies and materials to update weak buildings. In this context, external reinforcement of reinforced concrete structures employing FRP composite materials offers unique designer benefits not available with traditional strengthening techniques. Because of its superior features, such as high stiffness and strength, as well as ease of installation compared to other repair materials, externally bonded FRP sheets are now being explored and implemented for the repair and strengthening of concrete structural components all over the world. The materials' non-corrosive and nonmagnetic properties and their chemical resistance made FRP a suitable choice for external reinforcement [1].

Externally bonded FRP composite materials to reinforce structures have gotten much attention in the last two decades. Externally bonded FRP sheets have been intensively pursued to improve reinforced concrete beams' flexural and shear performance. According to research, FRP strengthening significantly increases the post-cracking stiffness and ultimate load-carrying capability of flexure and shear elements [2,3,4,5,6,7].

The meager data or design guidelines available in the literature reveal that the FRP composite is a promising material for strengthening and repairing RC members subjected to torque [8, 9, 10]. Ghobarah [11] found that FRP torsional strengthening has improved the ductility and strength of RC beams. Hii and Al-Mahaidi [12] conducted experiments on torsional strengthening and discovered a 40% increase in cracking torque and angle of twist for ultimate torque strength. Deifalla et al. [13] examine the torsion behaviour of FRP externally strengthened flanged beams. Researchers concluded that the extended vertical U-jacket strip works better than the vertical U-jacket strip. Shraddha and Rathi [14] looked into how fibre-reinforced polymer fabric bonded with epoxy could be used to make reinforced concrete beams stronger in a twisting direction. Researchers find that fully wrapped U-jacketed beams of both CFRP and GFRP have greater torque strength. So, we can say cracks are less wide when CFRP and GFRP fabrics are used. A.N. Hanoon et al**.** [15]

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found that the energy absorption capacity of reinforced specimens reinforced with CFRP with concrete strength of 55 MPa was increased by (18.36%–29.14%) compared to un-strengthened beams with the same concrete grade. Askandar and Mahmood [16] describe the behavior of reinforced concrete beams strengthened with FRP sheets (strips) in various configurations. Due to the impact of different wrapping configurations, the fully wrapped beams performed better than the strip-wrapped beams.

They were loading on offshore construction, motorways, multistory parking garages, and other structures. For a long time, extensive theoretical and experimental research on reinforced concrete beams has yielded fundamental approaches to serviceability design under static stresses. However, the consequences of repeated loading on reinforced concrete beams for cracking and deflection are still uncommon and poorly understood. Unlike static loading, concrete structures subjected to repeated loads undergo more deflection. There are a lot of permanent sets in this deflection, and permanent deflections rise in proportion to the number of load cycles. Many researchers have seen this behavior, yet there is currently a scarcity of relevant experimental data [17].

We conclude from the above that there is a progressive increase in strengthening concrete structures, particularly bridges, by using FRP composite strengthening techniques. Recently, an externally bonded reinforcement carbon fiber polymer was demonstrated to be a powerful strengthening technique. However, this technique has not been examined under repeated torsion loading conditions like traffic loads on bridge girders. The main objective of this study is to look at how hollow concrete beams with externally bonded carbon fiber reinforced polymer (CFRP) stripes behave when subjected to monotonic and repeated torsional loads.

2. Experimental Program

2.1 Specimen Details

In the experimental program, eight concrete beam specimens with a rectangular hollow cross-section (350) mm in depth, (250) mm in width, and (3000) mm in length, and a circular hollow in the center of the concrete samples with a diameter of 100 mm, were cast using ready-mixed concrete and tested under pure torsion up to failure.

All beams were reinforced with (4 φ 12 mm) and (2φ 8 mm) longitudinal bars around the perimeter. The beams were designed intentionally to display torsion failure at their central parts. End zones of 0.4 m on each end of the beam were reinforced with (8 mm) stirrups spaced at 60 mm on the center to force failure in the mid-zone of the tested beam. The 2.2 m test region was chosen so that at least three complete spiral cracks at an angle of 45° would form along its length, so it was reinforced with (8 mm) stirrups spaced at 120 mm on the center. Reinforcements in both transverse and longitudinal directions are given for torsion specifications to prevent the collapse of the beam at cracking. The steel reinforcement details and the beam cross-section dimensions used for each beam are shown in **figure1**. The yield strength of the (φ 8 mm and φ 12 mm) was tested experimentally and determined to be (475 and 410) Mpa, respectively.

Reinforced concrete specimens of identical dimensions and reinforcement have been cast using a concrete mix that was designed to achieve an average compressive concrete strength cylinder (300 mm and diameter is 150 mm) strength of (30 MPa) at (28) days (normal strength concrete), and the slump was approximately 100 mm. **Figure 2** depicts the specifics of the employed moulds and reinforcing steel.

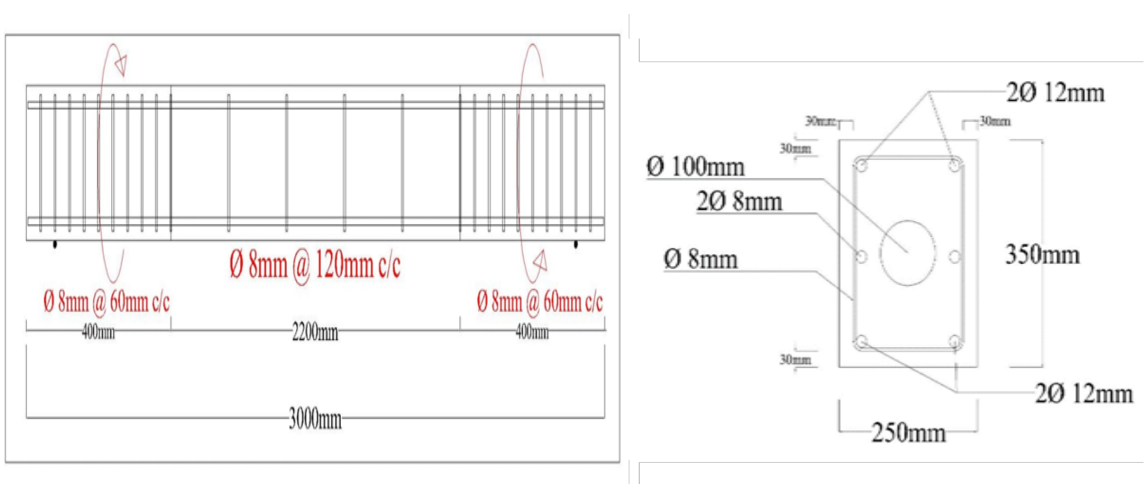


Fig. 1. Dimensions and reinforcement details of the tested beams

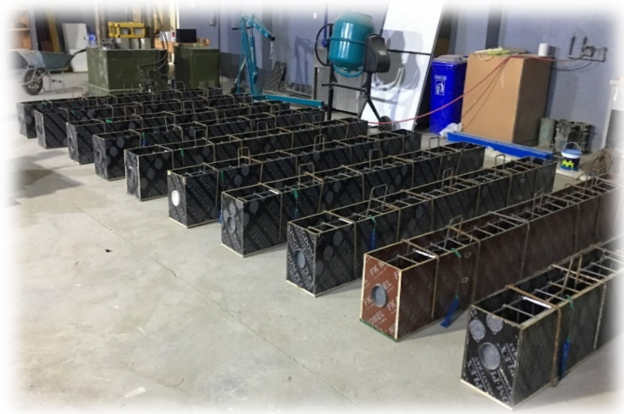


Fig. 2. Molds and reinforcement steel used for casting sample.

2.2 Torsion strengthening configurations

The strengthening system is chosen carefully according to some considerations, mainly the crack pattern around the specimen and the most effective and economical application in practice. In addition to the mechanism by which the rotation of the concrete section is restricted, a total of eight beams were used in this analysis to determine the most important strengthening variables for torsional behaviour. Two of these beams did not have any extra material added to be used as "control beams".

The strengthening samples included six beams strengthened with CFRP stripe materials with EBR methods in different schemes and tested up to failure. The first two beams are strengthened by using one continuous fabric wrapped at an equal width (7 cm) at each face around the sample at an angle of 45° and continuing through the total length of the sample. The other samples have been strengthened by doubling the stripe wrapped around the same width. Other techniques for wrapping the fabric were used in this study for the last two beams, which were strengthened by using a stripe that takes a spiral path around the sample. The difference between this technique and the previous technique used in this study is that the path taken by the tape in this technique parallels the supposed crack line on the other side of the beam, in contrast to the previous method, in which the tape was following a path perpendicular to the assumed crack line, and the purpose of that is to show the extent to which the direction of the strengthened CFRP fabric affects the threshold properties.

It is noticeable that they have two beams for each state of study, one tested under monotonic load and the other for repeated load with seven cycles of service load taken at 60% of the monotonic load. Also, they use the same cross-section area of materials for each type of scheme to compare them. **Table 1** shows the description of all tested beams in this study, and **figures 3** show the strengthening scheme of the tested beams.

Table 1: The designation and description of all tested beams in this study.

Beam designation	Type of Load	No of Cycles	Details of Strengthening
C-H-M	Monotonic	-	Un-strengthened
C-H-R	Repeated	7 Cycles	
S-H-M-EC-1C	Monotonic	-	One continuous stripe of 7 cm wide around the sample at an angle of 45° and continuing through the total length of the sample, the horizontal spacing between the stripes equals 50 cm.
S-H-R-EC-1C	Repeated	7 Cycles	
S-H-M-EC-2C	Monotonic	-	Two continuous stripes of 7 cm wide around the sample at an angle of 45° and continuing through the total length of the sample, the horizontal spacing between the stripes equals 25 cm.
S-H-R-EC-2C	Repeated	7 Cycles	
S-H-M-EC-1S	Monotonic	-	A spiral stripe of 7 cm wide is drawn around the sample at an angle of 45°. The stripe goes around the sample for the entire sample length, and the horizontal spacing between the stripes is 25 cm. This method's path of the stripe is parallel to the supposed crack line on the other side of the beam.
S-H-R-EC-1S	Repeated	7 Cycles	

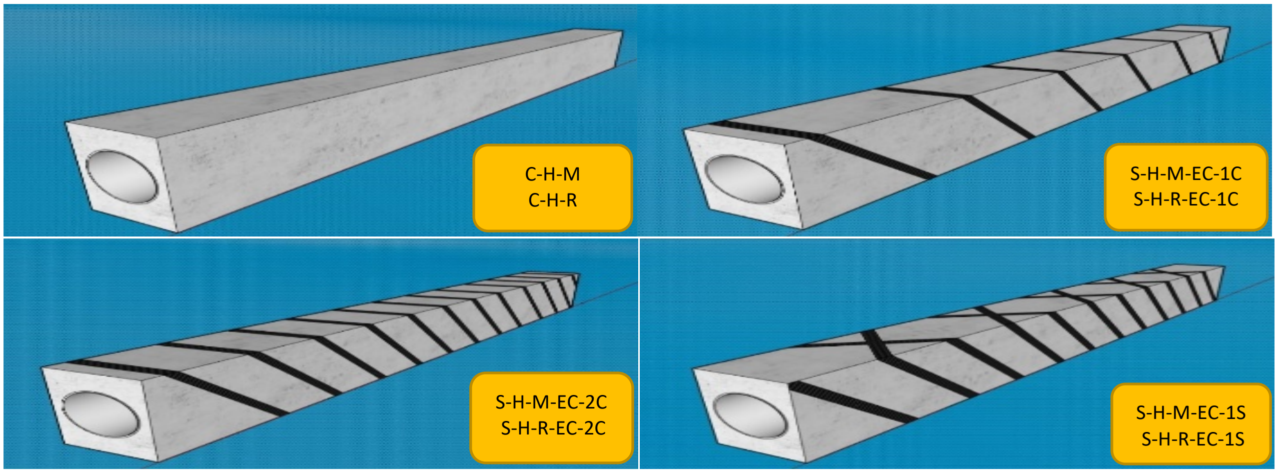


Fig. 3. strengthening scheme of the tested beams.

2.3 FRP Material properties

Sika Warp-300C carbon fiber fabric and Sikadur-330 epoxy-based saturated resin were employed in the experiment. Unidirectional CFRP fabric with 0.17 mm per ply (SikaWrap-300C) was used. According to the manufacturer, the elastic modulus, ultimate tensile strength, and elongation at failure of the fiber were 230 Gpa, 3900 Mpa, and 15 mm/m, respectively. The bonding adhesive supplied by the same company has a trading name of "Sikadur-330" and is used as a bonding agent for the dry application of CFRP fabric. According to the manufacturer, epoxy resin has two components (A and B). The mixing proportion of those components is 4:1 with an open time of 30 min. with density, elastic modulus, and tensile strength of 1310 kg/m3, 3800 Mpa, and 30 Mpa, respectively, were used to connect the CFRP fabric to concrete.

2.4 CFRP Composite System Application to Existing Reinforced Concrete Element

The procedure used in applying the CFRP composite system is summarized below. These steps were followed according to the recommendation of the CFRP manufacturer.

The bond between the reinforced concrete beams and the CFRP was given special attention during the strengthening process. A handheld grinder was used to grind the concrete surface at the place of glueing the CFRP to the concrete to remove the soft surface before attaching the CFRP to the concrete. Again, the grinder was used to arciform the concrete corners to a minimum radius of 13 mm [1] and reduce stress concentration in the fibers at the edges. CFRP sheets will rupture at the corner edges due to this stress concentration before reaching their ultimate strength.

The application of CFRP to the concrete substrate was made in stages. Before using the CFRP sheet, the beams were wire brushed and vacuumed. The resin (Sikadur-330) was mixed and applied to the prepared concrete surface using a brush at roughly 0.8 kg/m2 to 1.2 kg/m2, depending on substrate roughness. For all specimens, the SikaWrap®-300C fabric was cut into 70 mm wide strips with scissors for the required length (choosing the width of the strip according to the requirements of comparison with studies conducted with other strengthening materials of the same cross-sectional area). With a unique plastic roller, the SikaWrap®-300C strip was applied to the resin until the resin was squeezed out between the roving. The SikaWrap®-300C cloth was applied to the resin coating in the correct direction. In this case, **Figure 4** shows applying the CFRP system to the concrete element.

Fig. 4. Applying the CFRP system to the concrete beams.

2.5 Instrumentation and Testing

In the university's structural laboratory, all beams are tested in pure torsion until they fail. Two external arms attached at both ends were used to apply torque to various eccentricities. The load was applied at the ends of the beam using a 2000 kN hydraulic jack through a diagonal (I) section steel girder with a (300) mm depth and a (4000) mm length. Under the jack, load cells were fixed to measure the applied load. These arms could achieve a maximum eccentricity of 500 mm concerning the beam's longitudinal axis. The utilized supports allowed rotation around the longitudinal axis to achieve pure torsion. Two LVDT sensors were attached to the bottom of each end of the beam. The sensors recorded the uplift and down values so that the twist angle at each end of the beam could be found.

The first cracks and the crack width of concrete were measured using a micro crack meter with (0.02 mm) accuracy. The ultimate torsion capacity and the twist angle were determined as the load was applied gradually. Readings were obtained using the data logger connected to the device's computer, which transmits the data on the loads and displacements from the load cell and LVDT sensors. Torque gradually increased up to the failure of the beams. Failure is defined by dropping the loading capacity and increasing the rotation of the beam. To measure the elongation of the beam, dial gages were fixed in the center of each beam's one end. **Figure 5** shows the test setup with the loading frame and specific clamping loading structure on each end of the beam employed in this study.

Fig. 5. Testing setup with the loading frame.

3. Results and discussion

In order to understand the behavior of reinforced concrete specimens and CFRP strengthened specimens under monotonic and repeated torsion loads, the twist of the specimen is measured at regular intervals of torque up to failure. Also, all specimens' torque at the first crack and ultimate torque is observed. The failure mechanism of each specimen is observed to understand the role of CFRP in torsional strengthening subjected to different load types. Table 2 summarizes the concrete beams' cracking torque (**T_{cr}**), ultimate torque (**T_u**), and ultimate twist angle (**θ_u**).

Table 2: The Experimental results of the tested beams.

Beam designation	Tcr (kN. m)	% increase of Tcr	Tu (kN. m)	% increase of Tu	θu deg./m	% increase of θu
C-H-M	7.09	-	15.39	-	2.72	-
S-H-M-EC-1C	11.04	55.7	25.79	67.6	4.03	48.2
S-H-M-EC-2C	12.03	69.7	28.856	87.5	4.754	74.8
S-H-M-EC-1S	11.9	67.8	28.5	85.2	4.666	71.5
C-H-R	6.99	-	12.62	-	2.338	-
S-H-R-EC-1C	11	58.3	20.645	63.6	3.57	52.7
S-H-R-EC-2C	11.907	71.3	22.83	80.9	4.096	75.2
S-H-R-EC-1S	11.766	69.3	22.43	77.7	3.98	70.4

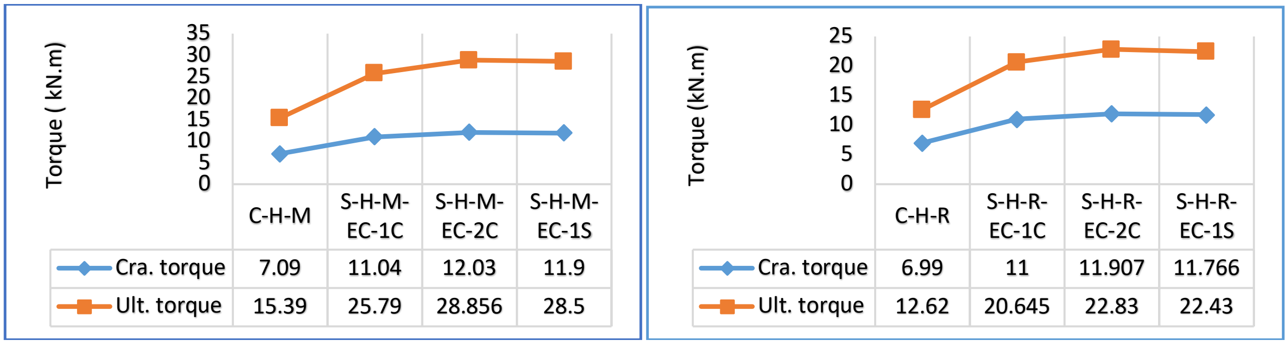
3.1 Cracking and Ultimate Torque Comparison

The cracking torsional moment (**T_{cr}**) is the torque at which cracking appears and shows that the section's tension strength's applied stress has been exceeded. However, the ultimate torsional moment (**T_u**) reflects the load-carrying capacity of the tested beam, and the beam rapidly deforms after that drop in machine reading.

3.1.1 Influence of techniques used for strengthening on cracking and Ultimate torsional moment carrying capacity.

The first crack of all specimens appeared approximately at apposition, between the support and mid-span of the tested beams. The first crack torque and ultimate torsional moment carrying capacity of the control and strengthened beams by CFRP under the influence of monotonic and repeated loads are shown in **figure 6**. Nonlinear improvement of the crack and ultimate torsional moment carrying capacity of the strengthened beams to the control beam, significantly for beams strengthened using double fabric CFRP around them.

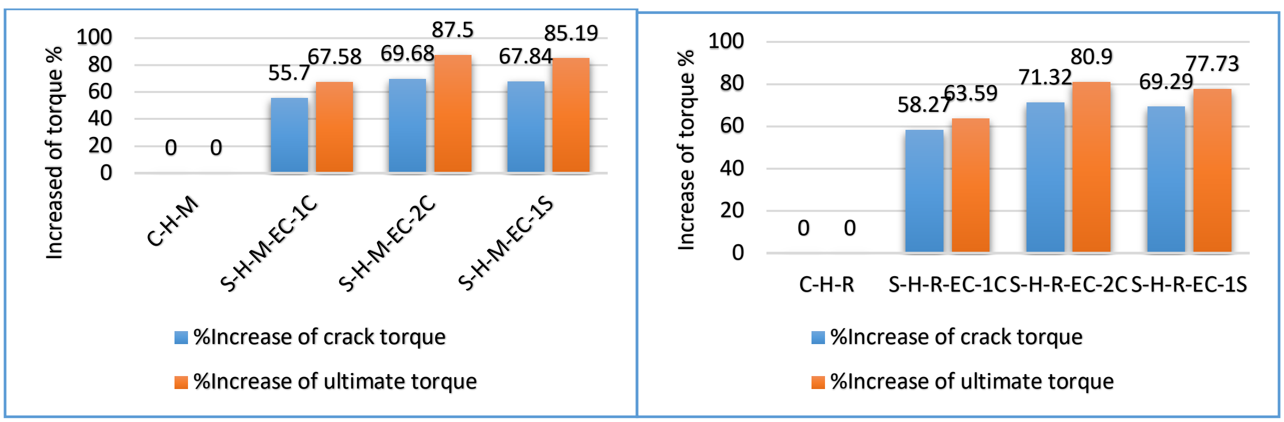
The crack and ultimate torsional moment of the sample (**S-H-M-EC-2C**) tested under monotonic load were 12.03 & 28.856 kN.m, respectively, while the torsional moment of the control beam was 7.09 & 15.39 kN.m. The value of the examined beam was under the influence of repeated loads compared with the control beams tested under the same loading conditions. The beams (**S-H-R-EC-2C**) had the crack and ultimate torsional moment of 11.907 & 22.83 kN.m, while the value of the crack and ultimate torsional moment of the control beam was 6.99 &12.62 kN.m. The strengthening method was mainly responsible for the improvement rather than the control beams.



(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 6. Ultimate torque and cracking for the tested beams.

As shown in **figure 7,** The percentage of enhancement in cracking and ultimate torsional moments for the tested beams with different CFRP strengthening techniques (**S-H-M-EC-1C, S-H-M-EC-2C, S-H-M-EC-1S**) compared to the control specimen (**C-H-M**) tested under monotonic load is (55.7%,69.7%,67.8%) in crack torsional and (67.6%,87.5%,85.2%) in the ultimate torsional moment, respectively. The percentage of enhancement in the cracking and ultimate torsional moment for the specimens (**S-H-R-EC-1C, S-H-R-EC-2C, S-H-R-EC-1S**) subjected to repeated loads is (58.3%,71.3%,69.3%) in crack torsional and (63.15%,80.9%,77.7%) in the ultimate torsional moment, compared to the control specimen (**C-H-R**).



(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 7. Percentage improvements in the torque of the beams tested.

3.1.2 The effect of the repeated load on cracking and Ultimate torsional moment.

Under monotonic loading, all the tested beams behaved elastically during the applied load and at the low load level, and the rotation at the ends of the beam specimens was slight in proportion to the applied loads. When the load is increased, the first crack occurs, and several cracks are observed in the region of the pure torsion moment. When beam specimens are subjected to repeated loading, similar cracks in the monotonic test were observed in the first cycle. In the subsequent cycles, the same cracks observed in the first cycle during the loading phase were gradually widened and propagated diagonally along the beams, at the last cycle, beams loaded up to failure.

For this reason, repeated loads do not affect the crack torsion moment characteristics of the strengthened and un-strengthened beams compared with the beams tested under the influence of monotonous loads, while the effect of repeated loading resulting from cycles of loading and unloading is to reduce the value of the ultimate torsional moments of the reference and reinforced beams when they are compared with beams similar to those tested under the influence of monotonous loads.

As shown in **figure 8**, The percentage of decrease in the ultimate torsional moment carrying capacity of the strengthened and un-strengthened beams (**C-H-R, S-H-R-EC-1C, S-H-R-EC-2C, S-H-R-EC-1S**) under the influence of repeated loads resulting from cycles compared with the control beams is (17.99%,19.9%,20.8%,21.3%), respectively.

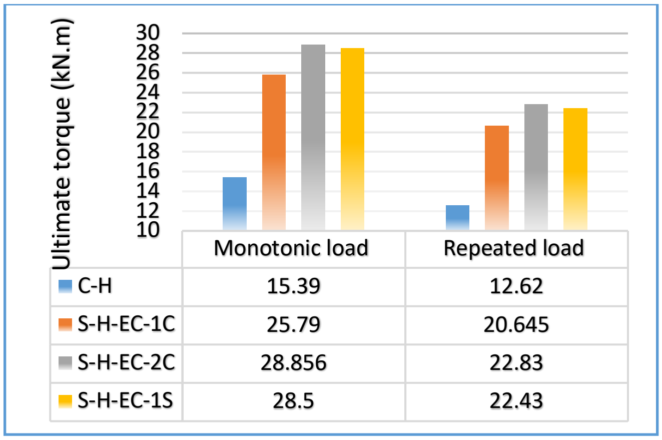
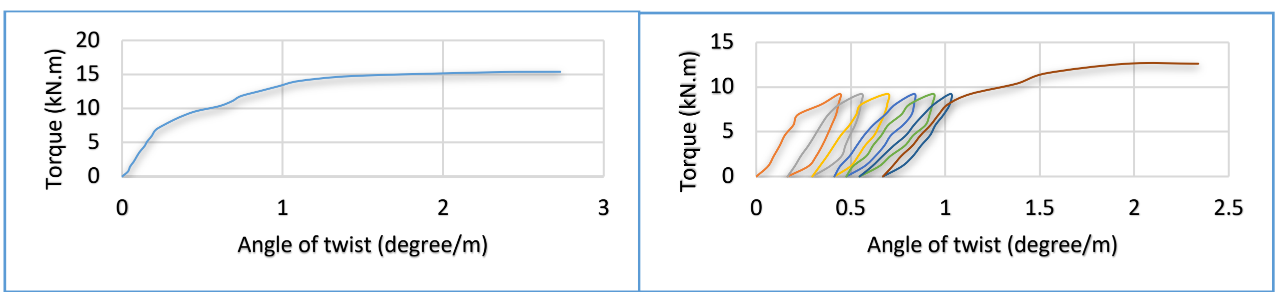


Fig. 8. Ultimate torque value of tested beams under monotonic and repeated loads.

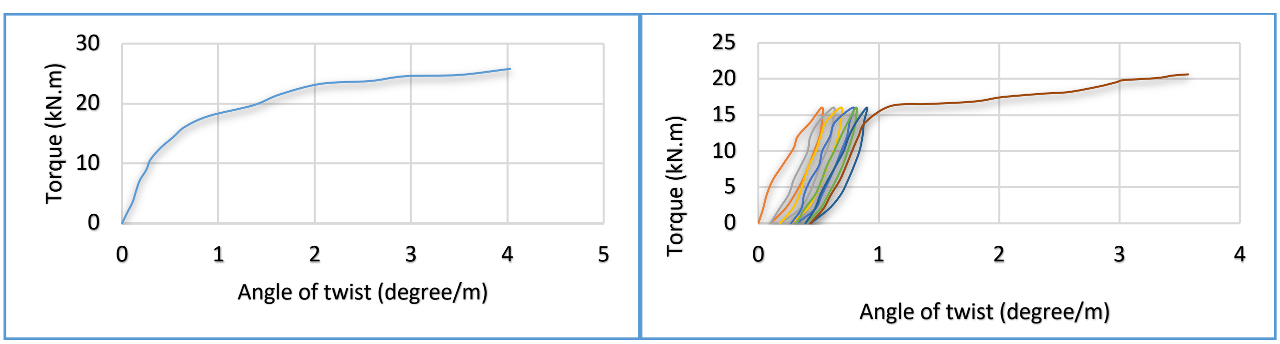
3.2 Torque–twist behaviour comparison

The torque-twist relationships for tested beams (strengthened and un-strengthened) under monotonic static loading and counterpart specimens after seven repeated loading cycles are shown in **figures 9-12**. In general, linear elastic behaviour was observed in all beams first, followed by a considerable increase in twist angle and a gradual increase in torque until failure. The crack and ultimate torques for each beam were calculated using the torsion-twist curves, with the ultimate torque being the maximum torque beyond which the beam will fail and the crack torque being the torque at which the first diagonal crack appears. The torque vs angle of the twist curve revealed the first cracking, with the torque dropping suddenly at the point of first cracking, followed by a change in the slope of the torque-twist curve. The effect of external CFRP strengthening and the type of loading applied to the beams were discussed in the previous paragraphs.



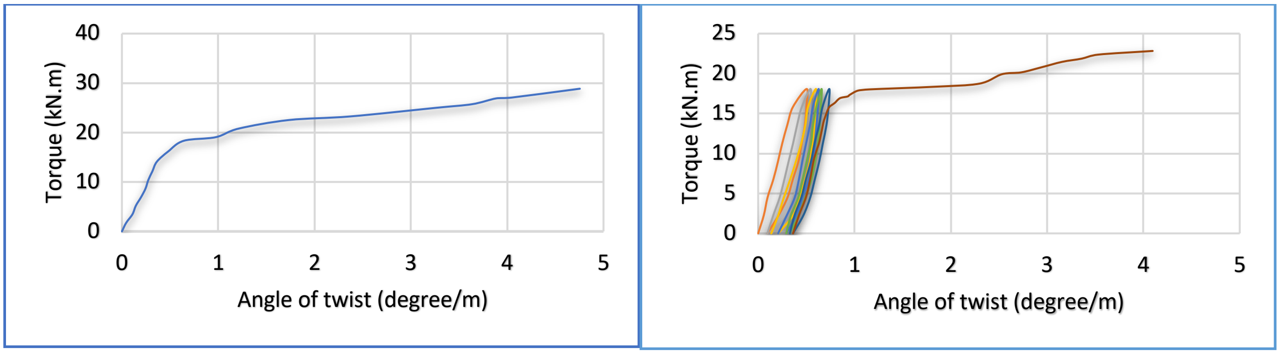
(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 9. Torque - twist angle relationship of tested beams ((**C-H-M**) &(**C-H-R**)) under Monotonic and repeated loads.



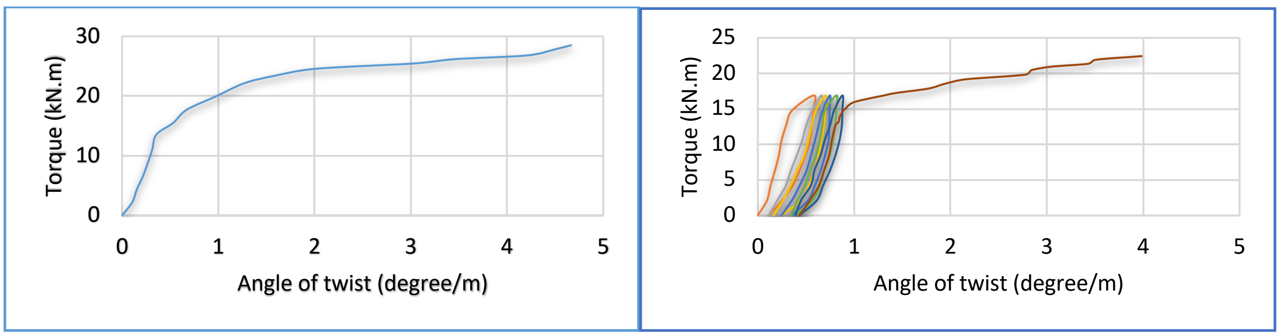
(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 10. Torque - twist angle relationship of tested beams ((**S-H-M-EC-1C**) &(**S-H-R-EC-1C**)) under Monotonic and repeated loads.



(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 11. Torque - twist angle relationship of tested beams ((**S-H-M-EC-2C**) & (**S-H-R-EC-2C**)) under Monotonic and repeated loads.



(a) Beams tested under Monotonic loads. **(b)** Beams tested under Repeated loads.

Fig. 12. Torque - twist angle relationship of tested beams ((**S-H-M-EC-1S**) & (**S-H-R-EC-1S**)) under Monotonic and repeated loads.

3.3 Angles of twist

The angle at which a beam's free end rotates concerning the fixed end. When a body is twisted by force, one end or section of a longitudinal axis rotates in one direction while the other is turned opposite. Two LVDTs were attached to the steel plate at the end of the beams to measure the twist angle. Figures 9-12 show that each tested beam's average of two twist angles is plotted against the torsional moment. As the ultimate torsional moment value increases, the beam's maximum twisting angle increases. As a result, as the beams are strengthened, the area under the curve increases gradually. The increase in value of twist at ultimate torque of beams strengthened with different CFRP strengthening techniques (**SHMEC1C, SHMEC2C, SHMEC1S**) compared to the control specimen (**CHM**) tested under monotonic load is (48.16 %,74.78 %,71.54%) and (52.69%,75.19%,70.39%) for beam specimens tested under repeated load effect.

In this regard, the angle of twist for the identical beams tested under the effect of repeated loads is less than the angle of twist for the identical beams tested under monotonic load at their twist angle at the ultimate torsion moment.

3.4 Longitudinal elongation response

Because of the formation and widening of concrete cracks, all beams elongated longitudinally once they reached the cracking torsional moment. We recorded the elongation values for each load during the test until the torsional moment reached its peak.

Control beams **C-H-M** and **C-H-R** (2.16 and 2.056) mm had the highest elongation at peak torsional moment. The supporting members may constrain this elongation in functional structures, especially monolithic concrete construction. However, the effect of this elongation (or its restriction) may require more consideration. The beams strengthened with external CFRP stripe using various strengthening techniques reduced longitudinal elongation values by (18.8%,28.77%, and 30.55%) for beams tested under monotonic load and (22.18%, 28.01%, and 28.4%) for beams tested under repeated load when compared to un-strengthened samples tested under the same condition tested. That means the CFRP restraint of cracks from propagation and widening.

Figure 13 shows the torque-longitudinal elongation relationships for the beams tested under monotonic load. It can be seen that beam elongations at the center of the supported end had started in the early stages after cracking. **Figure 14**

shows the effect of repeated loads on the longitudinal elongation values of the tested beams compared with their counterparts tested under the influence of monotonous loads.

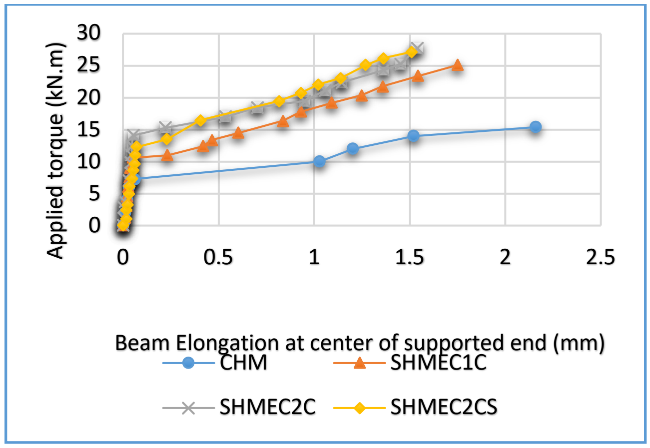


Fig. 13. Beam longitudinal elongation tested under monotonic loads.

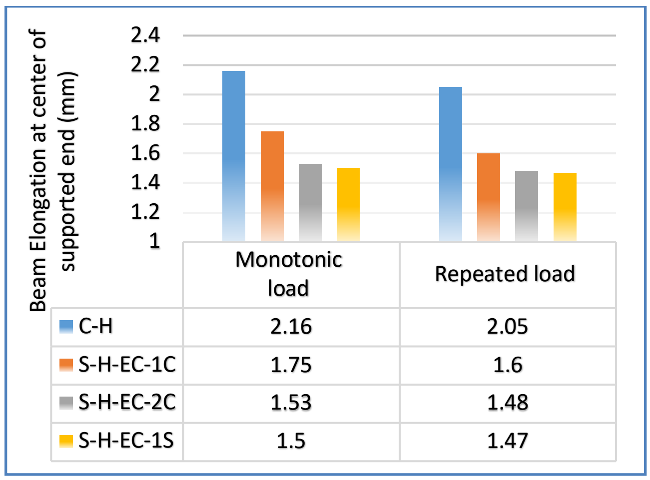


Fig. 14. longitudinal elongation value of tested beams under monotonic and repeated loads.

3.5 Crack width response

The effect of the strengthened CFRP stripe and type of load on the width of the cracks generated on the surface of the models was one of the most important things that were noticed when examining all of the models. A micro concrete crack width meter was used to measure and record the crack widths at each load increment during the test, as illustrated in **figure 15**. Compared to controlled beams, strengthening beams (**SHMEC1C, SHMEC2C, SHMEC1S**) and (**SHREC1C, SHREC2C, SHREC1S**) resulted in a decrease in the crack width value at ultimate torque. The strengthening has reduced crack width in the center regions, according to the results. In other words, the crack behavior was improved.

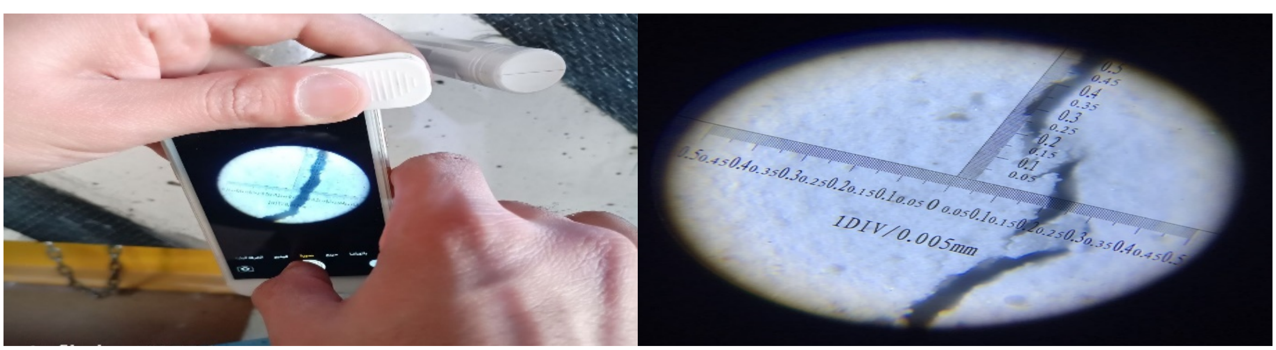


Fig. 15. measure and record the crack widths during the test.

The torque-crack width relationships for the beams tested under monotonic load are shown in **figure 16.** There will be a comparison of specimens tested under monotonic static loading and specimens subjected to repeated loading. This comparison aims to see how repeated loading influences crack width. **Figure 17** compares maximum crack width for specimens subjected to monotonic static loading and counterpart specimens subjected to restricted repeated loading cycles. The decrease in crack width for beams under repeated load compared to beams tested under monotonic load is due mainly to new large cracks that developed due to the applied cycles of repeating load and the reduction in ultimate load.

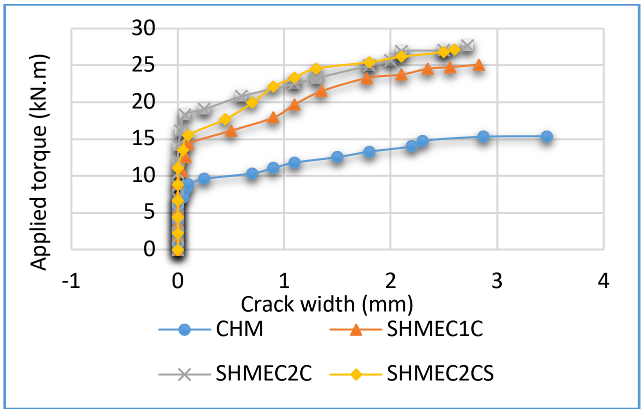


Fig. 16. Crack width behavior of beams tested under monotonic loads.

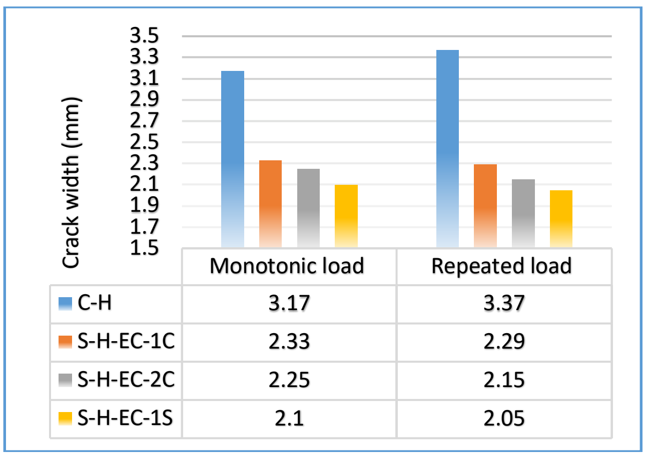


Fig. 17. Crack width value of tested beams under monotonic and repeated loads.

3.6 Torsional Stiffness

Stiffness is a property that can be used to describe the rigidity of a material. Thus, torsional stiffness is the amount of resistance a member provides for each degree of twist. Torsional stiffness before cracking is defined as stiffness previous to cracking (Kpre). It can be calculated from the torque-twist curve as the pre-cracking tangent slope of this curve, as in equation (1), whereas stiffness after cracking is defined as a post-cracking stiffness (Kpost) significantly less than that of the pre-cracking stiffness. As in equation (2), it represents the tangent slope of the torque-twist curve following cracking [18]. In the current study, this method was used to calculate stiffness, figures **18 and 19** show the effect of parameters on the pre and post-stiffness values, respectively.

$$k_{pre}{-}\mathbf{cracking} = T_{cr}/\Theta_{cr} \quad \ldots\ldots\ldots\ldots \tag{1}$$

$$k_{post}{-}\mathbf{cracking} = (T_{max}-T_{cr}) \,/\, (\Theta_{max}-\Theta_{cr}) \quad \ldots\ldots\ldots\ldots \tag{2}$$

The torsional stiffness of strengthened beams is greater than that of un-strengthened beams (monotonic and repeated loads). This is because the CFRP stripe adds stiffness and increases the torsional capacity, particularly at the model's linear relationship between twisting angle and torque stage.

Under repeated load effects, the torsional stiffness of beams is lower than under monotonic load effects because the loading and unloading process makes the ultimate torsional capacity of the beams less than before.

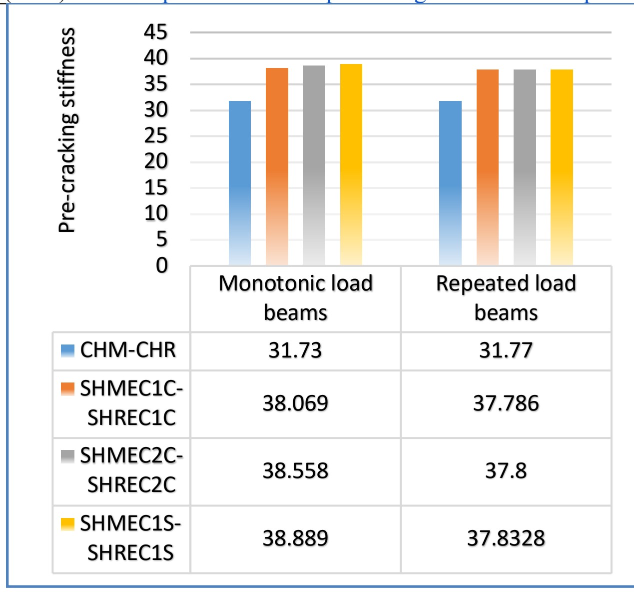


Fig. 18. Effect variables on pre-cracking stiffness value.

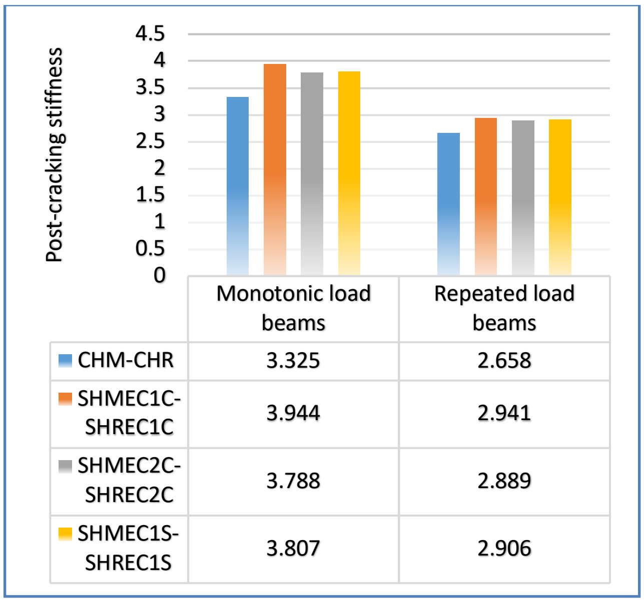


Fig. 19. Effect variables on post-cracking stiffness value.

3.7 The Energy Absorption and The Ductility

Mechanical energy is converted into internal potential energy by reinforced concrete members, and this is due to those members' inherent ductility and energy absorption. In addition, concrete members have to deal with many complicated processes, like the fracture mechanics of concrete cracking and the deformations caused by elastic and plastic forces [15].

Many studies have shown that the ductility of reinforced concrete members is related to how much energy they can take in. This study computed the areas under energy absorption curves for all beams tested. With this note, the energy absorbed at each cycle of the torque-twist curves of beams subjected to repeated loads is calculated, and the cumulative absorbed energy for each girder is then calculated.

The ductility ratio is usually defined as the ratio of the angle of twist corresponding to ultimate torque to the angle of the twist that corresponds to the yield torque. As shown in **figure 20**, Strengthened beams with CFRP stripes with different technics decreased the ductility factor of the beams by (4.18%, 13.58%, and 12.238%) compared with controlled beams tested under monotonic loads and (4.87%, 17.916%, and 18.7%) for beams tested under repeated loads. This is due to the CFRP's brittle nature, which affects the ductility of the overall strengthened beams.

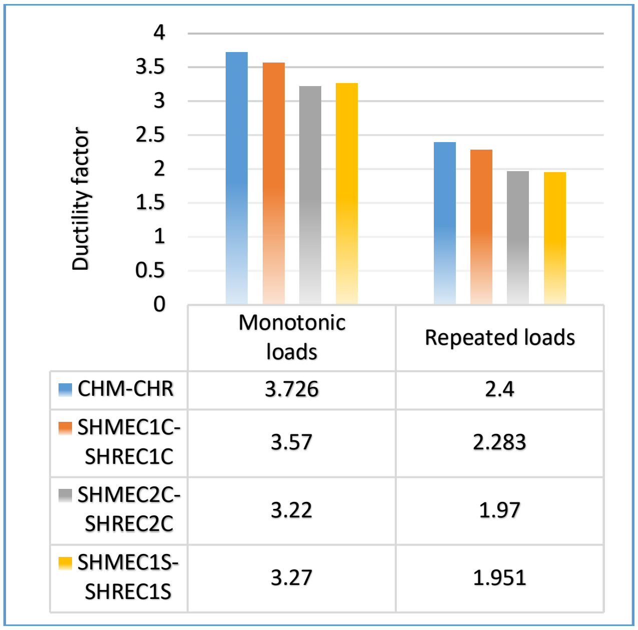


Fig. 20. Effect variables on ductility factor.

The ductility factor of tested beams under monotonic load is greater than the values of the ductility factor of tested beams under repeated loads after a cycle of loads because of the loss in the stiffness of the beams when they are subjected to repeated loads, especially in the last five or six cycles of the loading and unloading process.

Generally, the energy absorption capacity of CFRP reinforced beams was much larger than that of unreinforced beams. This was attributed to the CFRP fabrics' capacity to limit crack propagation. Repeated loading was seen to have a detrimental effect on the rise in cracking and ultimate loads. In pure torsion, the maximum increase in cracking loads was noted. CFRP strips showed more significant post-cracking energy deformation and energy absorption capacities than reference beams.

The experimental result shows that the energy absorption capacity of reinforced concrete beams externally bonded with CFRP stripe is more than that of un-strengthened beams, as illustrated in **figure 21** and **figure 22**. However, the predominant mode of failure was CFRP strip debonding. Additionally, CFRP strips provided greater post-cracking rigidity and confinement, which increased ultimate torque.

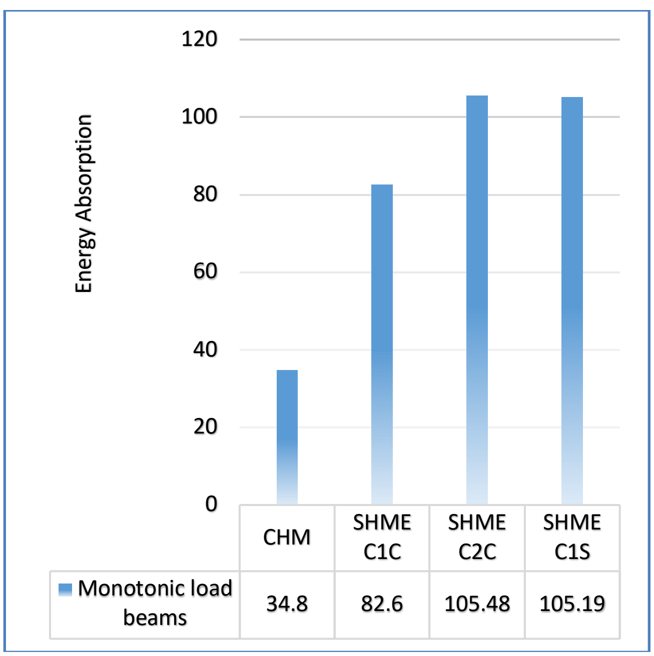


Fig. 21. Energy absorption capacity of beams tested under monotonic load.

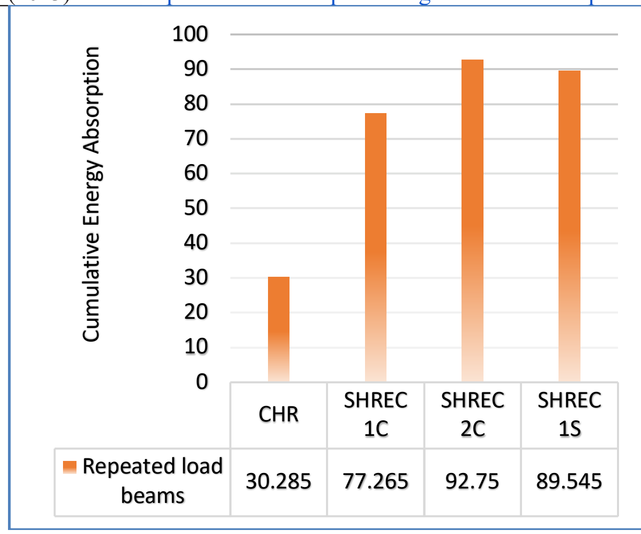


Fig. 22. Cumulative Energy absorption capacity of beams tested under repeated load.

3.8 Failure Mechanism

All reinforced concrete beams subjected to testing failed due to torsional moments. We found typically reinforced beam cracking in both control and strengthened beams, and diagonal cracks developed in a spiral pattern on all four sides of the testing span.

As the applied loading rose, the cracks grew larger at both ends and around the reinforced concrete beam's centroidal axis. Upgraded beams with CFRP strips failed at a slower rate than control beams. Additionally, the failure of CFRP was shown by the debonding of CFRP fabrics and the concrete crash. Compared to the control beam, the strengthened beam had more cracks due to the rising tensile stress. The photograph shown in **figure 23** demonstrates that most cracks in the reinforced beams were dispersed and contained inside the concrete surfaces between the CFRP strips.

Fig. 23. Failure modes of beams tested under monotonic and repeated loads.

The failure mechanism for each specimen exposed to repeated loading was similar to that of its counterpart subjected to monotonic static loading on the specimen.

4. Conclusions

The following points highlight the major conclusions drawn from the results of this study based on the obtained experimental data:

1. Despite the different CFRP stripe patterns and load types, all strengthened beams exhibited more excellent torsional resistance than the control beam.

2. The percentage of improvement in cracking and ultimate torsional moments and value of twist at ultimate torque for the tested beams with various CFRP strengthening techniques (**S-H-M-EC-1C, S-H-M-EC-2C, S-H-M-EC-1S**) compared with the control specimen (C-H-M) tested under monotonic load is (55.7%, 69.7%, 67.8%) in crack torsional and (67.6%,87.5%,85.2%) in the ultimate torsional moment and (48.2%, 74.8%, and 71.5%) in twist angle value, respectively.

3. When compared to the control beam (**C-H-R**), the percentage of improvement in cracking and ultimate torsional moments and value of twist at ultimate torque for the tested beams (**S-H-R-EC-1C, S-H-R-EC-2C, S-H-R-EC-1S**) subjected to repeated loads is (58.3%, 71.3%, 69.3%) and (63.15%, 80.9%, 77.7%) and (52.7%, 75.2%, 70.4%), respectively.

4. Repeated loads do not change the crack torsion moment characteristics of the strengthened and un-strengthened beams compared to those tested under monotonous loads. However, repeated loading from cycles of loading and unloading does lower the value of the ultimate torsional moments of the reference and strengthened beams when compared to beams tested under monotonous loads.

5. When compared to un-strengthened beams, longitudinal elongation and crack width values were reduced by (18.8%, 28.77%, 30.55%) and (26.5%, 29.02%, 33.75%) for beams tested under monotonic load and by (22.18 %, 28.01%, 28.4%) and (33.23%, 36.20%, 39.17%) for beams tested under repeated load. This indicates that the CFRP restricts the propagation and growth of cracks.

6. Under repeated loading, the crack width is smaller than when beams are tested under monotonic load. This is mostly because the applied cycles of repeating load and the lower ultimate load caused new large cracks to form.

7. The torsional stiffness of strengthened beams exceeds that of un-strengthened beams (monotonic and repeated loads). The CFRP stripe increases stiffness and torsional capacity, especially at the model's linear relationship between twisting angle and torque stage.

8. The energy absorption ability of beams strengthened with CFRP was much greater than those without strengthening. This was ascribed to the ability of CFRP fabrics to prevent crack growth. Repeated loading was shown to have a deleterious impact on the increase in cracking and ultimate loads. The most significant increase in cracking loads was seen in pure torsion. CFRP strips' post-cracking energy deformation and energy absorption capabilities were much more significant than reference beams.

9. The failure rate of upgraded beams with CFRP strips was lower than that of control beams. Additionally, the debonding of CFRP fabrics and the concrete crash. The failure mechanism for each specimen exposed to repeated loading was similar to that of its counterpart subjected to monotonic static loading on the specimen.

Conflict of interest

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

References

[1] American Concrete Institute, ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, American Concrete In stitute, Farmington Hills, MI, USA, 2008.

[2] On Anil, "Improving shear capacity of RC T-beams using ¨ CFRP composites subjected to cyclic load," Cement and Concrete Composites, vol. 28, no. 7, pp. 638–649, 2006.

[3] D. Paul and A. Kumar Datta, "A Study on flexural strengthening of RC beam using FRP," in Proceedings of the International Conference on Advances in Construction Ma terials and Structures, pp. 1–9, IIT Roorkee, Uttarakhand, India, 2018.

[4] Y. Murad, "An experimental study on flexural strengthening of RC beams using CFRP sheets", International Journal of Engineering & Technology,vol. 7, no. 4, pp. 2075–2080, 2018.

http://dx.doi.org/10.14419/ijet.v7i4.16546

[5] D. Lavorato, C. Nuti, and S. Silvia, "Experimental in vestigation of the shear strength of RC beams extracted from an old structure and strengthened by carbon FRP U-strips," Applied Sciences, vol. 8, no. 7, Article ID 1182, 2018.

[6] N. Zhuang, H. Dong, D. Chen, and Y. Ma, "Experimental study of aged and Seriously damaged RC beams strengthened using CFRP composites," Advances in Materials Science and Engineering, vol. 2018, Article ID 6260724, 9 pages, 2018.

[7] Y. Zhou, M. Guo, L. Sui et al., "Shear strength components of adjustable hybrid bonded CFRP shear-strengthened RC beams," Composites Part B: Engineering, vol. 163, pp. 36–51,2019.

[8] Meyyada Y. Alabdulhady, Lesley H. Sneed and Christian Carloni. " Torsional behavior of RC beams strengthened with PBO-FRCM composite - An experimental study" ELSEVIER, Engineering Structures 136, 393 – 405, (2017). http://dx.doi.org/10.1016/j.engstruct.2017.01.044.

[9] Ali Sabah Ahmed Al Amli, Nadhir Al-Ansari and Yaarub G. Abtan. " Behavior of Repairing Composite I-Section Beams with Opening under Ultimate Torque" Scientific Research Publishing, Engineering, 10, 202-214 (2018). https://doi.org/10.4236/eng.2018.104014

[10] Khaled Fawzy and Mohamed A. Farouk " Torsion Strengthening of RC Beams with External Lateral Pressure Using Steel Plates" Springer, Journal of Science and Technology, Transactions of Civil Engineering, 1413–1425 (2020). https://doi.org/10.1007/s40996-020-00536-0

[11] Ghobarah, A., "FRP Composites in Civil Engineering", Edited by Teng, J.G., Published by Elsevier Science, Vol. I, pp. 705-712, (2001).

[12] Hii, Adrian K. Y., and Al-Mahaidi, Riadh. “Experimental Investigation on Torsional Behavior of Solid and Box-Section RC Beams Strengthened with CFRP Using Photogrammetry.” Journal of Composites for Construction 10, no. 4, 321–329, (August 2006). doi:10.1061/(asce)1090-0268(2006)10:4(321).

[13] Deifalla, A. Awad and M. Elgarhy. " Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion: An experimental study" ELSEVIER, Engineering Structures 56,2065–2075, (2013). http://dx.doi.org/10.1016/j.engstruct.2013.08.027

[14] Shraddha B. Tibhe and Vijaykumar R. Rathi. " Comparative Experimental Study on Torsional Behavior of RC beam using CFRP and GFRP Fabric Wrapping" ELSEVIER, ScienceDirect, Procedia Technology 24 ,140 – 147, (2016). doi: 10.1016/j.protcy.2016.05.020

[15] A.N.Hanoon, Ali A.Abdulhameed, Haider A.A., and Saad K .Mohaisen. “Energy Absorption Evaluation of CFRP-Strengthened Two Spans Reinforced Concrete Beams under Pure Torsion.” Civil Engineering Journal , Vol 5, No 9 ,(September 2019). https://doi.org/10.28991/cej-2019-03091389

[16] Nasih Habeeb Askandar and Abdulkareem Darweesh Mahmood and Rawaz Kurda. " Behaviour of RC beams strengthened with FRP strips under combined action of torsion and bending" European Journal of Environmental and Civil Engineering, Volume 26, Issue 9, 2022. https://doi.org/10.1080/19648189.2020.1847690

[17] Oukaili, Nazar K., and Mohammed M. Khattab. "Serviceability and ductility of partially prestressed concrete beams under limited cycles of repeated loading." GEOMATE Journal 17.60, 9-15, (2019).

[18] Peng, X. N., & Wong, Y. L. , Behavior of reinforced concrete walls subjected tomonotonic pure torsion-An experimental study. Engineering structures, 33(9), 2495-2508, (2011).