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# Improving Torsional Behaviour of Reinforced Concrete Beams Strengthened with Carbon Fibre Reinforced Polymer Composite

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## ABSTRACT

Three groups of rectangular beams, comprising of sixteen specimens with various amounts of torsional steel reinforcement were tested under pure torsion. Evaluating the effects of various steel torsional reinforcement ratios on the torsional behaviour of the strengthened beams was the objective of this investigation. Carbon fibre reinforced polymer (CFRP) sheet wrappings consisted of different configurations including anchored U-wrapping and full and strip wrappings. The total steel ratios, including longitudinal and transverse reinforcements considered in this study were 1.56%, 2.13%, and 3.03%, respectively. This study indicates that the CFRP contributions to the torsional strength of the strengthened beams, having identical volumetric ratio of CFRP reinforcement are quite dependent on the total amount of torsional reinforcements. The above mentioned CFRP contributions will increase as the steel torsional reinforcement is increased. Experimental results show that increasing the steel reinforcement by 37% and 94%, increases the CFRP contribution to torsional strength by up to 54% and 91% for strengthened beams with one CFRP ply; and by up to 60% and 111% for strengthened beams with two CFRP plies, respectively. In this experimental work, the effect of the number of CFRP plies is also investigated. It is found that the increase in CFRP contribution to torsional strength concerning the beams strengthened by one ply and two plies of CFRP sheets is close for various steel reinforcement ratios, when compared to increasing the total amount of steel reinforcement.

**Key Words:**

carbon fibre reinforced polymers (CFRP);
steel reinforcement ratio;
reinforced concrete;
strengthening;
torsional.

## INTRODUCTION

Fibre reinforced polymers (FRPs) are made from a variety of fibres and resins and may be found in different forms such as flexible wraps or fabrics made of thin fibres stitched together as unidirectional strips, thin unidirectional, or bidirectional plates and bars manufactured in different diameters. Fibre reinforced polymers offer high stiffness-to-weight and strength-to-weight ratios [1] as well as corrosion resistance to environmental factors [2-3]. Moreover, these materials when used in the form of flexible wraps show good formability which can be used in a variety of applications, in single layer or multiple layers.

FRPs are used increasingly in various fields such as space and aviation industry, architectural structures, shipbuilding materials, sporting goods, and interior and structural materials of automobiles due to the excellence of mechanical characteristics as well as light weight, heat resistance, and specifi-

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cally designed characteristics.

With the increasing usage of new materials of FRP composites, many research works, on FRPs improvements of processing technology and other different aspects have been performed. There are several polymeric studies on CFRPs in literature [4-13].

As mentioned above, one of the applications in structural engineering is the use of polymeric materials for strengthening the structures. Using FRPs have shown promises in this area, and have been successfully employed in many applications around the world. A good example of these applications is the Westgate Bridge in Melbourne, Australia, which is one of the largest FRP strengthening projects in the world [14]. Research on the use of fibrous polymers is very well developed in flexural and shear strengthening as externally-bonded reinforcement. In contrast, a literature survey conducted by the authors found no experimental data for torsional strengthening published before 2001. Since then, several investigations have been conducted which are as follows.

Zhang et al. tested beams strengthened with carbon fibre reinforced polymer (CFRP) [15]. The strengthening configurations were around the whole cross-section either in strip form or along the entire length. The number of CFRP wrapped layers and the width of strips were varied. This study showed that using carbon fibres for strengthening increased the ductility and ultimate torsional capacities of the beams. Panchacharam et al. performed experimental studies on glass fibre reinforced polymer (GFRP) strengthened reinforced concrete beams of square cross-section [16]. They evaluated the ultimate torque carried by the beams with respect to their specific polymeric strengthening configurations. Ghobarah performed two sets of experiments on CFRP and GFRP strengthened beams using FRPs fully wrapped around the cross-section which were applied in three configurations: (i) along the entire length, (ii) in strips, and (iii) inclined at 45° with respect to the beam axis [17]. Ghobarah extracted torque-twist angle relations for the tested beams from his experimental results and compared the ultimate torsional capacity of beams before and after strengthening. He observed an increase in the ductility after strengthening with fibres polymers and reported that the increase of ductility for the GFRP strengthened beams was greater than that of the CFRP strengthened beams. Ronagh et al., however, in their torsional tests on strengthened beams using glass fibre polymers observed a decrease in the ductility [18]. Ameli et al. performed experiments on beams strengthened using carbon and glass fibre polymers. They investigated the effects of different polymer-made strengthening configurations on torsional behaviour of the test beams. They observed increasing ductility and ultimate torque for the beams [19,20]. Hii et al. tested several beams with hollow and solid cross-sections strengthened with CFRP strips [21-23]. Salom et al. investigated the strengthening effects of carbon fibre reinforced polymer laminates on torsional behaviour of spandrel beams [24]. Mohammadizadeh et al. performed several experiments for finding the effects of strengthening configurations on the behaviour of high-strength concrete using carbon fibre polymers [25,26].

In all previous studies carried out on torsional strengthening, only the effects of different polymeric strengthening configurations on ultimate torque have been investigated. Since in these studies the interaction between torsional steel ratios and polymeric wrap configurations had not been investigated, it was necessary to figure out such interaction. Therefore, the present work has been performed due to this necessity.

## EXPERIMENTAL

### Specimens Details

Sixteen reinforced concrete beam specimens with cross-sections of 150×350 mm and clear concrete cover of 25 mm were fabricated in the structural laboratory. The total length of the beams was 2000 mm. The test region was taken approximately 1600 mm long at the middle of the beams. Heavier reinforcement was provided outside the test region to prevent premature failure. The transverse and longitudinal reinforcements were arranged according to the design provisions of ACI 318-05 [27,28]. Longitudinal reinforcement bars consisted of four bars with 10 mm, 14 mm, and 16 mm diameters in the first, second, and third group, respectively. The bars were located one at each corner of the cross-section. The stirrups in groups A and B had 8 mm diameter and 80 mm spacing, while the stirrups in group C had 10 mm diameter and 80 mm spacing. The total steel ratios, including longitudinal and transverse reinforcements were 1.56%, 2.13%, and 3.03% in the first, second, and third group, respectively. The groups were labelled A, B and C to code the beams representing the first, second and third group, respectively. There were seven beams in group A, six beams in group B and three beams in group C. Two beams in group A, three beams in group B and one beam in group C had no carbon fibre reinforced polymers (CFRP) and were designated as the reference beams. They were called AREF1 and AREF2 in the first group, BREF1, BREF2, and BREF3 in the second group and CREF in the third group. The rest of the beams strengthened by carbon fibre (Mbrace CF 240) in different configurations. Figures 1a and 1b show a roll of carbon fibres (CF 240) which is in the form of flexible wraps and a closer view of the carbon fibres (CF 240), respectively.

The wrapping configurations were identical in the three groups. U-wrapping and strip wrapping configurations were not used in group C. In all the strengthened beams, CFRP was employed vertically with respect to the longitudinal beam axis. One beam in each group was wrapped with one layer of CFRP, around the perimeter of the section and along the entire beam. These beams were labelled ACW1, BCW1 and CCW1. The beams labelled ACW2, BCW2 and CCW2 were wrapped with two layers of CFRP. The beams labelled ACUJ-anc. and BCUJ-anc. were wrapped with CFRP on two sides, and also on the bottom as a U-jacket along the entire beam. The free edges of CFRPs on two sides were fastened to the top of the beam. Applying the CFRP to just two sides plus the bottom of the beams was considered in order to represent the case where the top of the beams would be inaccessible. The beams labelled ACS1 and BCS1 were wrapped with one-layer strip of CFRP, having 100 mm width and 100 mm spacing around the perimeter of the section. Table 1 gives the specimen beams characteristics.

## Carbon Fibre Reinforced Polymer

A fiber-reinforced-polymer (FRP) is an advanced composite. It is defined as a solid material composed of two or more substances having different physical characteristics where each substance retains its identity while contributing desirable properties to the whole. In such a structural material made of plastic within which a fibrous material is embedded the components remain physically identifiable exhibiting an interface between one another. FRP composites exhibit anisotropic behaviour and are often composed of brittle constituents. The successful physical performance of these composites is, therefore, inherently dependent upon the individual properties of the materials of which they are made.

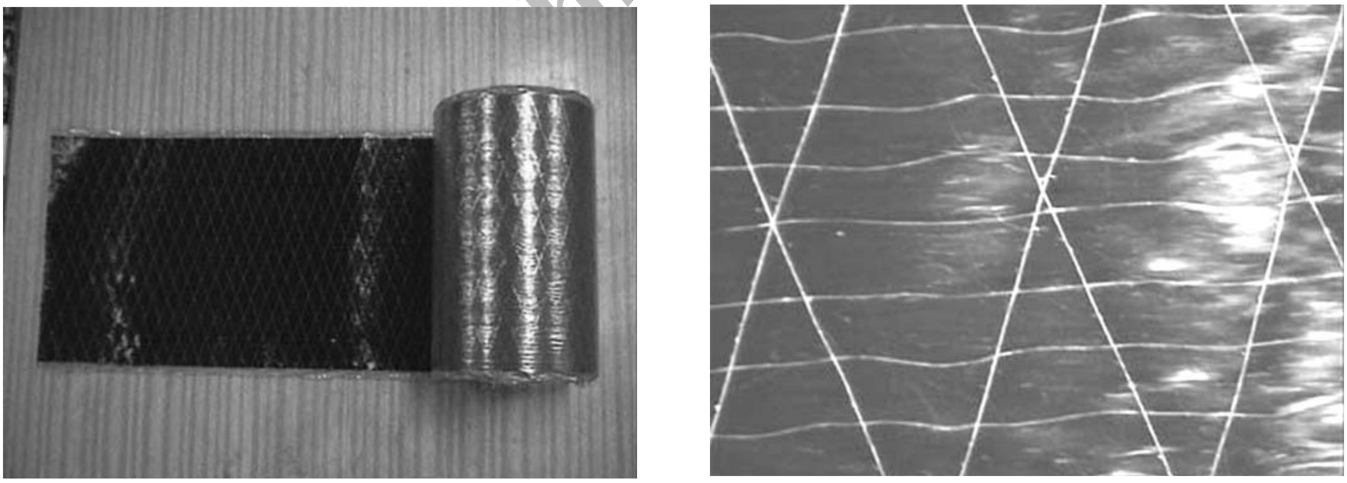

(a)
(b)

**Figure 1.** Fibres in the form of flexible wraps: (a) a roll of the fibres and (b) closer view of the fibres.

**Table 1.** The characteristics of the specimens.

| Specimen | Composite sheets | No. of layers | Anchor used | Concrete compressive strength, (MPa) |
|---|---|---|---|---|
| AREF1 | Reference beam | None | - | 78.12 |
| AREF2 | Reference beam | None | - | 80.89 |
| ACS1 | Full Strip | 1 | No | 74.39 |
| ACUJ-anc. | U-jacket | 1 | Yes | 72.67 |
| ACW1 | Full wrap | 1 | No | 73.18 |
| ACW2 | Full wrap | 2 | No | 73.24 |
| BREF1 | Reference beam | None | - | 76.94 |
| BREF2 | Reference beam | None | - | 77.82 |
| BREF3 | Reference beam | None | - | 79.34 |
| BCS1 | Full Strip | 1 | No | 78.52 |
| BCUJ-anc. | U-jacket | 1 | Yes | 80.56 |
| BCW1 | Full wrap | 1 | No | 78.12 |
| BCW2 | Full wrap | 2 | No | 74.95 |
| CREF | Reference beam | None | - | 74.55 |
| CCW1 | Full wrap | 1 | No | 73.33 |
| CCW2 | Full wrap | 2 | No | 74.43 |
| Standard deviation | | | | 2.78 |

*Different Types of Fibres*
There are three more well-known types of fibres used for strengthening of structural members. The first type is carbon fibre, usually manufactured in two categories of high modulus and high strength. The second type of fibres is glass fibre which is produced in two varieties of E-glass and S-glass. S-glass fibres are stronger and stiffer than E-glass [29]. The third type of fibres is Aramid which has a much higher creep rate than glass or carbon fibres [30]. Glass, carbon, and Aramid are the most commonly employed organic and inorganic substances available for the fibrous load-bearing constituents.

In order to compare the general behaviour of different FRPs with each other and with conventional steel under tensile stresses, their typical stress-strain relations are shown in Figure 2 [29]. As shown in this figure, CFRP's (carbon FRP) stiffness is higher than those of GFRP (glass FRP) and AFRP (Aramid FRP).

From the three main types of FRPs used in the form of flexible wraps, CFRP and GFRP have been used in higher quantities in structures particularly in reinforced concrete strengthening applications. Some typical properties of carbon, glass, and Aramid fibres materials are shown in Table 2.

Three natural resources supply the production of structural carbon fibres: pitch; a byproduct of petroleum distillation, PAN; polyacrylonitrile, and rayon. High modulus and high strength are the two types of carbon fibres available. In general, carbon fibres tend to exhibit high stiffness and good resistance to chemical attack, but have low toughness and impact resistance. Carbon fibres may often exhibit a slightly negative coefficient of thermal expansion, meaning they contract upon heating, increasing in negativity with higher modulus fibres. Carbon fibres may also be

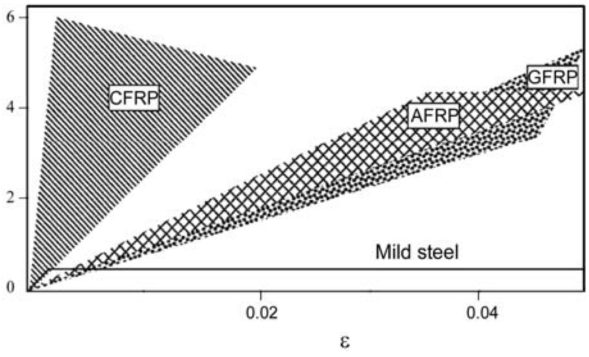


**Figure 2.** Typical stress-strain relations for different FRPs and normal steel (CFRP = carbon FRP, GFRP = glass FRP, and AFRP = Aramid FRP).

**Table 2.** Some typical properties of carbon, glass, and Aramid fibres.

| Type of fibre | Thickness (mm) | Ultimate tensile strength (MPa) | Elastic modulus (GPa) | Ultimate tensile elongation (%) |
|---|---|---|---|---|
| Carbon | 0.10 - 0.25 | 2100 - 6000 | 215 - 700 | 0.2 - 2.3 |
| Glass | 0.06 - 0.30 | 1900 - 4800 | 70 - 90 | 3.0 - 5.5 |
| Aramid | 0.10 - 0.30 | 2900 - 4100 | 70 - 130 | 2.5 - 5.0 |

referred to as graphite. In graphite fibres, the carbon has been graphitized and has a carbon content of greater than 99%.

*Matrix Polymers*

Polymers are plastics whose molecular structure consists of a chain of one or more repeating units of atoms. The two classifications of polymer matrices are: thermoplastic and thermosetting. While molecules remain linear, thermoplastic polymers can be repeatedly softened at high temperatures. Thermoset plastics are used for structural purposes for their ability to undergo a chemical reaction when cured. Molecules of these polymers become highly cross-linked at high temperatures and the matrix turns into an infusible and insoluble material.

By affecting the mechanical, chemical, and thermal properties of FRP composites, the thermoset matrix resin serves a variety of purposes. It protects the fibres from environmental degradation, provides lateral support against compression buckling, and allows the transfer of stresses from the bar surface to the interior fibres. Although strong, the reinforcing fibres can be brittle and not all fibres may be capable of resisting the applied stresses. The matrix helps redistribute the load and can absorb energy by deforming under stress. Besides stiffness, the matrix polymer also allows the composite good thermal stability and chemical resistance. To enhance structural and aesthetic characteristics, the polymer matrix resin is combined with filler, catalyst, and additives (ultraviolet inhibitors, dies, release agents, etc.). Still, for structural applications, the resin matrix makes up only a small portion of the total volume of the FRP composite. Some common thermosetting matrix resins include epoxy, polyester (*ortho/iso*), and vinyl ester.

*Manufacturing Processes*

Design and manufacturing processes have significant influences on resulting composite properties. When investigating FRP as reinforcing material, it needs to be emphasized that there are two factors influencing experimental results. The thermo-mechanical properties of the composite material can rely on both its chemical composition as well as the process by which the composite is produced. Quality control during manufacture plays a critical role in developing the product's final characteristics.

Material type, fibre, and matrix volume fractions and manufacturing processes all have effects on the elastic properties of FRPs. Investigations on the manufacturing of a more ductile hybrid composite can help to increase its strength and low elastic modulus. One area to consider FRP is those of properties such as tensile strength and elastic modulus which are dependent upon the direction of measurement in relation to the direction of the fibres. These mechanical properties are proportional to the amount of fibre by volume oriented in the direction of measurement. Although anisotropic, the preferential directional strengthening of the fibres during this manufacturing procedure provides FRP composites a design being advantageous over steel [31]. The properties of the fibres used are stated in Table 3 [32].

**Table 3.** Properties of the fibres used.

| Type of fibre | Thickness (mm) | Modulus of elasticity (MPa) | Ultimate tensile strength (MPa) | Ultimate tensile elongation |
|---|---|---|---|---|
| CF 240 | 0.176 | 240.000 | 3800 | 1.55% |

**Table 4.** Steel reinforcement properties.

| Type of bars | Reinforcement properties | | | |
|---|---|---|---|---|
| | Area ($mm^2$) | Young's modulus (MPa) $\times 10^4$ | Yield Strength (MPa) | Ultimate strength (MPa) |
| Stirrups (Φ 8 mm) | 50.27 | 23.98 | 480 | 695 |
| Longitudinal (Φ 10 mm) | 78.54 | 17.60 | 352 | 568 |
| Longitudinal (Φ 14 mm) | 153.94 | 19.83 | 397 | 610 |
| Longitudinal (Φ 16 mm) | 201.06 | 20.20 | 404 | 620 |

*Concrete*

High strength concrete, designed for 28-day cylinder compressive strength of 75 MPa was supplied by a local ready-mix plant.

*Steel Bars*

The yield strengths of the transverse and longitudinal reinforcements were obtained from tensile tests listed in Table 4.

### Test Set-up and Instrumentation

Details of the test set-up are shown in Figure 3. A 2 MN hydraulic jack was used to apply the load at the active support. The load had a 400 mm lever arm from the centroidal axis of the beam. A 2 MN compression load cell was used to measure the applied load. The hydraulic jack had a stroke length of 150 mm providing a 35-degree twist capacity for the beam. A reaction arm was used at the passive support to balance the applied load by attaching the arm to the laboratory strong floor. The reaction arm also had a 400 mm eccentricity from the centroidal axis of the beam. After cracking, the beam elongated longitudinally. To avoid any longitudinal restraint and subsequent compression, the beam was allowed to slide and elongate freely. This was achieved by supporting the end of the beam on rollers at the passive support. The twist angle of the free end, (the point of applying the torque) was measured by a clinometer.

In each beam, 12 electrical resistance strain gauges were used to measure strains on the reinforcing bars. Three strain gauges were mounted on three stirrups within the test region, one stirrup located at mid-span and two of them located symmetrically at 400 mm from the mid-span. Each stirrup was instrumented with one strain gauge, mounted at the mid-point of the long leg (side face; Figure 4). Nine strain gauges were mounted on longitudinal bars at three different sections of the test regions. One set of three gauges was located in the middle, and the other two sets were

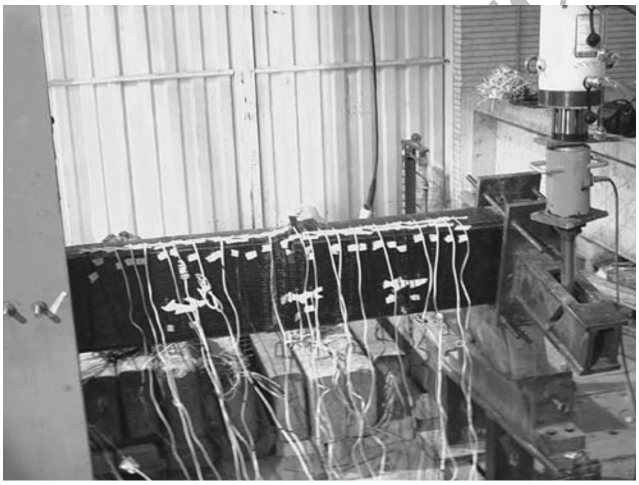


**Figure 3.** Test set-up.

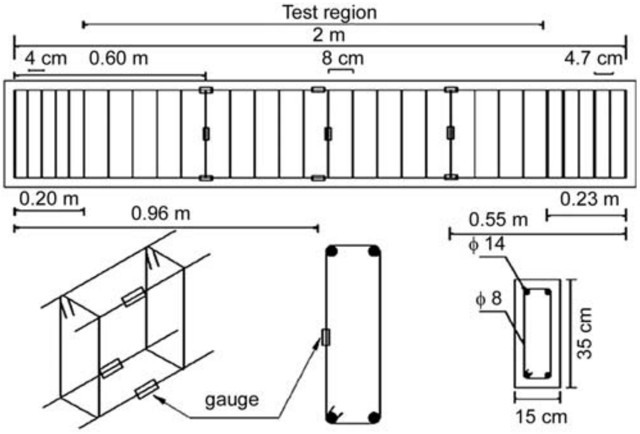


**Figure 4.** Location of strain gauges along the beam, strain gauges on stirrups, and strain gauges on longitudinal bars.

symmetrically located at 400 mm from the middle, on each side of the test beam. At each section, two gauges were mounted on the bottom corner bars and one gauge on the upper corner bar.

For each strengthened beam, in addition to the instruments provided as for the reference beams, at least 32 strain gauges were also attached to the CFRP sheets on the middle part of one side along the principal fibre direction with a spacing of 50 mm. Thirty-two gauges were located with a spacing of 50 mm along the entire beam. The first gauge was located 25 cm from the beam's starting point and the last one was located 25 cm before its ending point. Needless to say, the first 20 cm of the beam's length was occupied by the passive support, and the final 20 cm of its length was occupied by the active support.

### Test Procedure

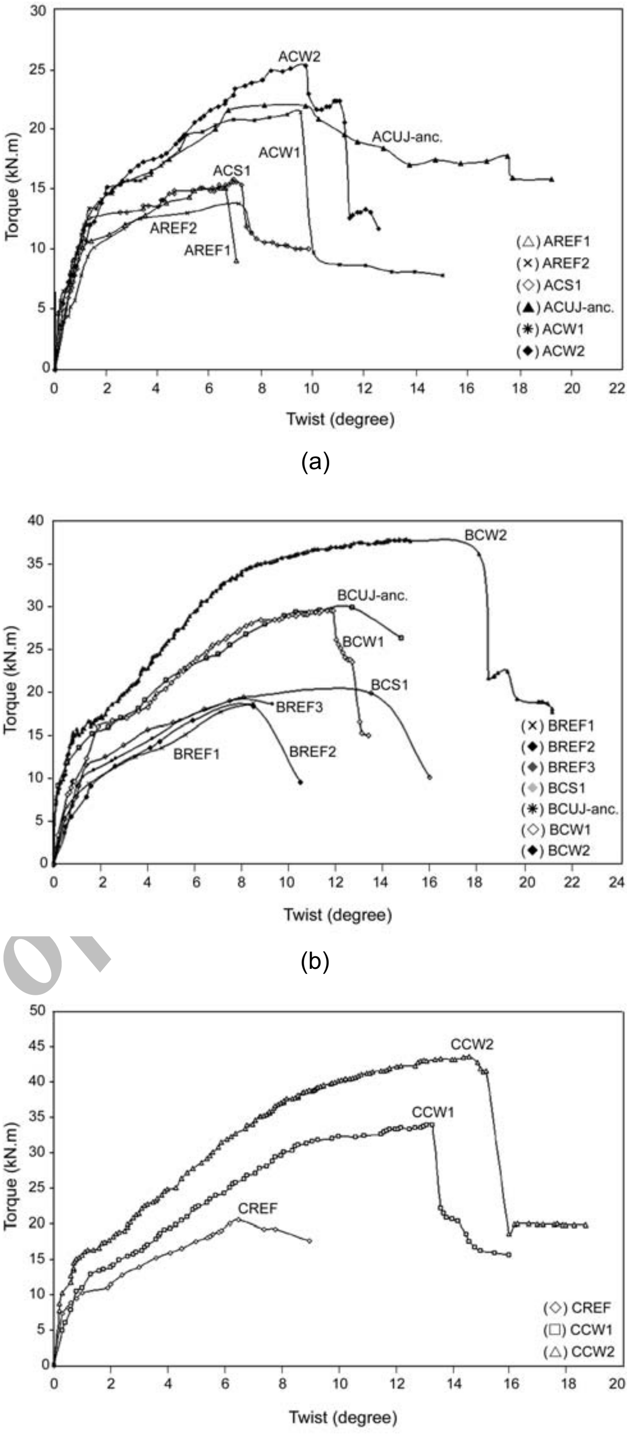
Measurements of loads and strains were recorded through a computer-driven data acquisition system. Before testing, the cracking and ultimate strengths of the beam specimens were estimated using the available analytical models. Prior to the failure of the beam, data were recorded at a prescribed load increment. Smaller increments were applied closer to the cracking state, in order to accurately measure the value closest to actual cracking torque. For the reference beams, at every load stage after cracking, the load was held constant for several minutes before recording data, after which the crack pattern was marked and the crack width and spacing were measured.

## RESULTS AND DISCUSSION

Figures 5a, 5b, and 5c represent the torque-twist curves for all the beams of groups A, B, and C, respectively.

In Figure 5b, the difference observed in the initial stiffness of the beams can be attributed to a less-than-perfect fixed condition achieved in the setup. We believe that such difference does not substantially affect the result of the torsional retrofitting of the specimens.

A major dislocation along the crack in the strengthened beam CCW2 caused an ultimate twist angle at approximately 14.6º. This is less than the expected value in comparison with the peak twist angle of beam BCW2. By comparing torque-twist curves of beams BCW2 and CCW2, it can be seen



(a)

(b)

(c)

**Figure 5.** The torque-twist curves of: (a) beams of group A, (b) beams of group B, and (c) beams of group C.

that this behavioural dislocation is distinctive.

In Figures 5a-5c, three different zones can be observed on each curve. The first zone represents the torsional stiffness of un-cracked beam, the second zone represents the stiffness of the cracked beam and the last zone corresponds to the damaged cross-section with wide cracks, with yielding torsional reinforcement and ruptured CFRP sheets.

As shown in Figures 5a-5c, the torque-twist curves for all the beams of three groups A, B, and C were linear up until cracking. After cracking, the torsional stiffness decreased significantly while affected by the volumetric ratio of CFRP reinforcement.

Table 5 provides a summary of cracking and yield torques of all test beams together with their relative percentage increase in cracking and yield torques in comparison with the reference beams.

From Table 5, it is clearly seen that increasing the volumetric ratio of CFRP reinforcement would increase the cracking and yield torques of the strengthened beams in each group. Of course, the wrapping configuration is effective as well.

Table 5 also presents the ratio of cracking and yield torques of all the beams of groups A, B, and C to the cracking and yield torque of the corresponding beams in group A. It reveals that for beams strengthened with the same volumetric ratio of CFRP reinforcement, the beams with a higher amount of total torsional reinforcement had higher cracking and yield torques. In other words, increasing the amount of total torsional reinforcement increased the effect of CFRP reinforcement in increasing the cracking and yield torque capacity.

It is obvious that for the strengthened beams with the same volumetric ratios of CFRP reinforcement, the torsional stiffness after cracking is increased as the amount of total steel reinforcement increases.

Figure 5 indicates that for a given twist angle, the beams with a higher amount of total torsional reinforcement have higher torsional capacity. This is due to the fact that a higher amount of total torsional reinforcement increases the post-cracking stiffness (the second zone of the curves) which results in a higher ultimate twist angle of the beams. Hence, based upon the results obtained, it can be concluded that the cracking and yield torque capacity of the strengthened beams is dependent on both volumetric ratios of steel and CFRP reinforcement.

Table 6 indicates the results of the tests in terms of the ultimate torque, the corresponding torque percentage increase, CFRP contribution to ultimate torque, and failure modes for all beams of groups A, B and C,

**Table 5.** Cracking and yield torques obtained from experiments, corresponding percentage increase, cracking, and yield torques ratios for beams of groups A, B, and C.

| Specimen | Cracking torque (kN m) | Yield torque (kN m) | Cracking torque increasing (%) | Yield torque increasing (%) | $\frac{(T_{CR})_{A\ or\ B\ or\ C}}{(T_{CR})_A}$ | $\frac{(T_Y)_{A\ or\ B\ or\ C}}{(T_Y)_A}$ |
|---|---|---|---|---|---|---|
| $AREF_{ave}^a$ | 10.20 | 13.32 | - | - | 1.00 | 1.00 |
| ACS1 | 12.55 | 13.56 | 23.04 | 1.80 | 1.00 | 1.00 |
| ACUJ-anc. | 13.50 | 17.31 | 32.48 | 29.95 | 1.00 | 1.00 |
| ACW1 | 13.33 | 17.46 | 30.69 | 31.08 | 1.00 | 1.00 |
| ACW2 | 15.15 | 17.63 | 48.53 | 32.36 | 1.00 | 1.00 |
| $BREF_{ave}^b$ | 9.13 | 15.73 | - | - | 0.90 | 1.18 |
| BCS1 | 12.25 | 16.70 | 34.17 | 6.14 | 0.98 | 1.23 |
| BCUJ-anc. | 16.12 | 23.00 | 76.56 | 46.19 | 1.19 | 1.33 |
| BCW1 | 16.46 | 22.50 | 80.28 | 43.01 | 1.23 | 1.29 |
| BCW2 | 16.60 | 24.31 | 81.82 | 54.51 | 1.07 | 1.38 |
| CREF | 11.75 | 16.90 | - | - | 1.15 | 1.27 |
| CCW1 | 16.56 | 28.00 | 40.94 | 65.68 | 1.62 | 2.10 |
| CCW2 | 17.25 | 30.76 | 46.81 | 82.01 | 1.69 | 2.31 |

(a) Average cracking and yield torques of the reference beams in group A. (b) Average cracking and yield torques of the reference beams in group B.

**Table 6.** Ultimate torques obtained from the tests, corresponding percentage increase, ultimate torques ratios, CFRP contribution to ultimate torque, CFRP contribution to ultimate torque ratios, and failure modes for beams of groups A, B, and C, individually.

| Specimen | Ultimate torque ($T_{U_{max}}$) | Ultimate torque increasing (%) | $\frac{(T_{U_{max}})_{A\ or\ B\ or\ C}}{(T_{U_{max}})_A}$ | CFRP Contribution to ultimate torque ($T_{U_{FRP}}$) | $\frac{(T_{U_{FRP}})_{A\ or\ B\ or\ C}}{(T_{U_{FRP}})_A}$ | Mode of failure |
|---|---|---|---|---|---|---|
| $AREF_{ave}$[a] | 14.41 | - | 1.00 | - | - | Yield & Crushing |
| ACS1 | 15.83 | 9.88 | 1.00 | 1.42 | 1.00 | Yield & Debonding |
| ACUJ-anc. | 22.00 | 52.69 | 1.00 | 7.59 | 1.00 | Yield & Rupture |
| ACW1 | 21.41 | 48.54 | 1.00 | 7.00 | 1.00 | Yield & Rupture |
| ACW2 | 25.26 | 75.29 | 1.00 | 10.85 | 1.00 | Yield & Rupture |
| $BREF_{ave}$[b] | 18.71 | - | 1.30 | - | - | Yield & Crushing |
| BCS1 | 20.50 | 9.57 | 1.25 | 1.79 | 1.26 | Yield & Rupture |
| BCUJ-anc. | 29.85 | 59.54 | 1.36 | 11.14 | 1.47 | Yield & Rupture |
| BCW1 | 29.48 | 57.56 | 1.38 | 10.77 | 1.54 | Yield & Rupture |
| BCW2 | 36.04 | 92.62 | 1.43 | 17.33 | 1.60 | Yield & Rupture |
| CREF | 20.52 | - | 1.42 | - | - | Yield & Crushing |
| CCW1 | 33.87 | 65.06 | 1.58 | 13.35 | 1.91 | Yield & Rupture |
| CCW2 | 43.46 | 111.79 | 1.72 | 22.94 | 2.11 | Yield & Rupture |

(a) Average ultimate torques of the reference beams in group A. (b) Average ultimate torques of the reference beams in group B.

individually.

Table 6 also presents the effect of the amount of total steel reinforcement on the ultimate torsional strength and the CFRP contribution to ultimate strength for the beams with the same volumetric ratios of CFRP reinforcement.

The experimental CFRP contribution to the torsional strength, $T_{U_{FRP}}$ , is determined by subtracting the ultimate torques of the reference beams, $T_{U_{REF}}$ , from, $T_{U_{Str}}$ , the ultimate torques of strengthened specimens: ($T_{U_{FRP}} = T_{U_{Str}} - T_{U_{REF}}$ ). The CFRP contribution to torsional capacities of all the strengthened beams of the three groups (A, B, and C) is listed in the fourth column of Table 6. The test results reveal that CFRP contributions to torsional strength were greater for those strengthened beams which have the same volumetric ratio of CFRP reinforcement and higher amount of total steel reinforcements. This increase can be attributed to the strain levels of steel torsional reinforcement in the beams which is lower than those of the beams with a lower amount of steel torsional reinforcements. In other words, in the beams with a higher amount of total torsional reinforcements, failure occurred at higher strain levels and ultimate torque. Further details in this regard are explained in the following sections.

The least and highest CFRP contributions to torsional strength, corresponding to beams BCS1 and CCW2, exceeded those of the beams ACS1 and ACW2 up to 26% and 111%, respectively. The least CFRP contribution to torsional strength, relating to beam BCS1 occurred because of using strip wrap configuration which does not provide full confinement for preventing the propagation of cracks between the strip wrap.

Figure 6 shows the experimental results in terms of the torque versus maximum CFRP reinforcement strain. In this figure, the torque-strain curves for several strengthened beams are plotted typically.

By qualitative study of Figure 6, it can be seen that similar to strain levels at the steel reinforcement, for a given torque, CFRP reinforcement strain levels corresponding to beams BCW1 and BCW2 are less than those of the beams ACW1 and ACW2, respectively. Similarly, strain levels of CFRP reinforcement corresponding to beams CCW1 and CCW2 are lower compared to beams BCW1 and BCW2, respectively.

Although the apparent discrepancy in values of the

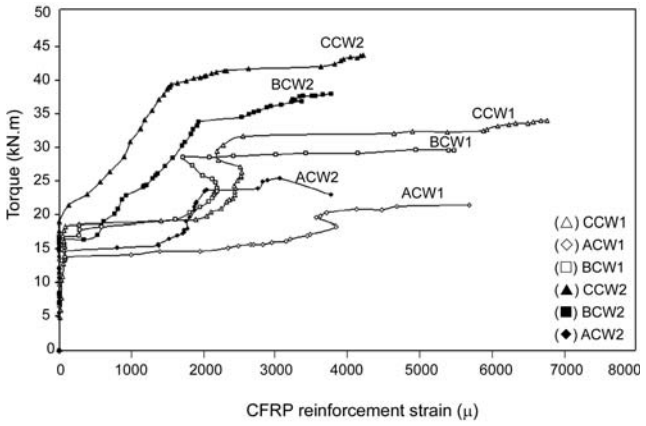


**Figure 6.** The torque vs. maximum CFRP reinforcement strain for the strengthened beams ACW1, BCW1, CCW1, ACW2, BCW2 and CCW2.

strain levels can be observed throughout the torque-CFRP reinforcement strain curves, the maximum values of CFRP reinforcement strains for beams ACW1 and BCW1 or beams ACW2 and BCW2 are almost identical. It must be also noted that for the strengthened beams of group C, which have a volumetric ratio of steel reinforcement almost twice of that of similar beams in group A, their maximum values of CFRP reinforcement strains are not increased significantly.

Test results show that the CFRP contribution to torsional strength of the strengthened beams with a higher amount of total steel torsional reinforcement is not increased significantly with an increase in the number of plies of CFRP sheets. For example, the ultimate torque due to CFRP reinforcement for beam BCW1 with only one ply of CFRP has been increased by 54%, compared to beam ACW1, while beam BCW2 which was strengthened with two plies of CFRP sheets in the same wrap configuration, has an increase in ultimate torque capacity due to CFRP sheets by 60%. Similarly, comparing beam CCW1 to beam ACW1, and beam CCW2 to beam ACW2, the increases of ultimate torque capacity due to CFRP reinforcement are 91% and 111%, respectively.

Hence, it can be concluded that the increase of CFRP contribution to torsional strength corresponding to the beams strengthened by either one ply or two plies of CFRP sheets (around the perimeter of the section and along the entire beam) for various steel reinforcement ratios would not be very significant. No doubt, for more accuracy, further experiments are required.

By comparing the results in Table 6, it can be seen that the percentage increase in ultimate strength due to CFRP reinforcement depends not only on the amount of total steel reinforcement but also on the volumetric ratio of CFRP reinforcement.

In contrast to beams of group A, the percentage increases of CFRP contribution for beams BCS1, BCUJ-anc., BCW1 and BCW2 having higher steel reinforcement (the 37% increase in steel reinforcement) were 26, 47, 54, and 60, respectively. These different percentage increases are attributed to different strengthening configurations.

In addition, it can be observed in Table 6 that the torsional strength capacities of beams CCW1 and CCW2 due to CFRP reinforcement were 1.91 and 2.11 times those of beams ACW1 and ACW2, respectively, while the amount of steel reinforcement was increased from 1.56% in group A to 3.03% in group C.

The different percentage increases in the similar strengthened beams of groups B and C occurred because of different volumetric ratio of steel reinforcement.

The volumetric ratio of steel reinforcement, $\rho_s$, is calculated by the following formula,

$$\rho_s = \frac{A_{sl}}{A_c} + \frac{A_{st}P_{st}}{A_c s} \tag{1}$$

where,

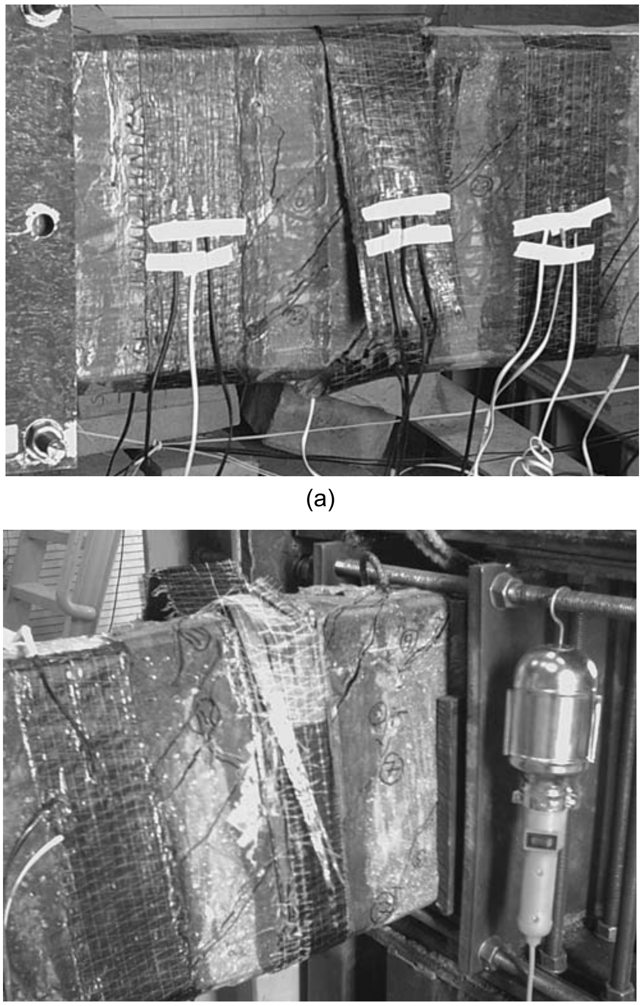
$A_{sl}$ : Total area of steel longitudinal bars,
$A_{st}$ : Area of one leg of a steel stirrup,
$A_c$ : Gross area of the concrete section,
$P_{st}$ : Perimeter of the steel stirrup,
s : Spacing of steel stirrups.

The volumetric ratios of CFRP reinforcement, $\rho_f$, are calculated by the following formula,

$$\rho_f = \frac{n_f t_f b_f P_f}{A_c s_f} \tag{2}$$

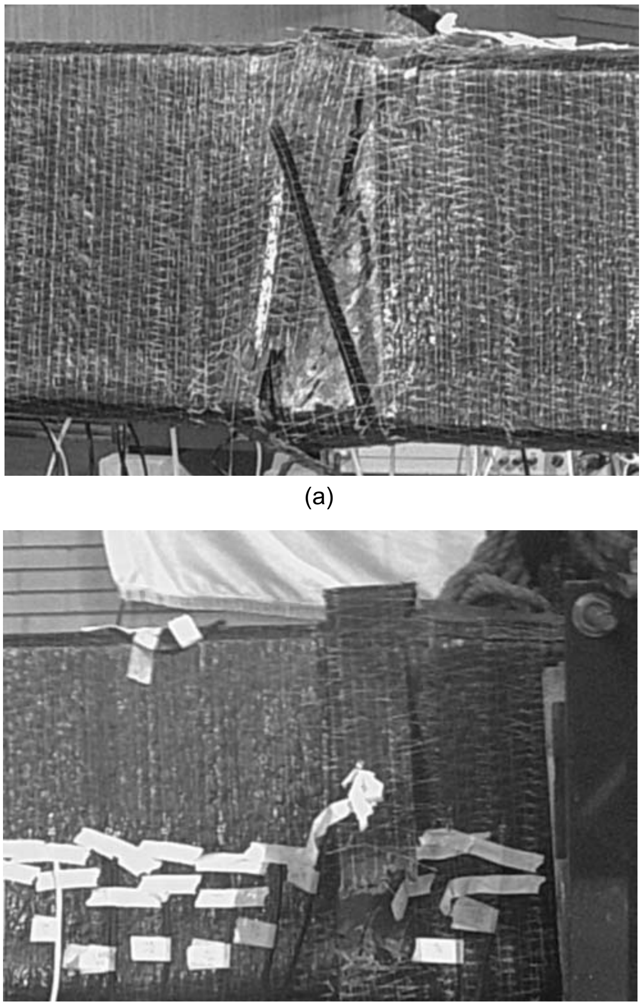
in which,

$n_f$ : Number of plies of CFRP sheets,
$t_f$ : Thickness of one ply of CFRP sheet,
$b_f$ : Width of the CFRP strips,


(a)

(b)

**Figure 7.** The failure modes of: (a) beam ACS1 and (b) beam BCS1.


(a)

(b)

**Figure 8.** The failure modes of the strengthened beams: (a) beam CCW1 and (b) beam CCW2.

$s_f$ : Centre-to-centre spacing of CFRP strips (for beams with continuous jacket along the beam, the terms $b_f$ and $s_f$ have identical values),

$P_f$ : Perimeter of the strengthened beam cross-section using CFRP.

The failure of the wrapped beams with CFRP strips was delayed in respect to the failure of the corresponding referenced beams. It can be observed in Table 6 that the ultimate torques of beam specimens ACS1 and BCS1 are very close to those of the corresponding referenced beams. For beams of ACS1 and BCS1, diagonal torsional cracks occurred and widened in the unwrapped concrete part of the beams between strips, and eventually failures followed through CFRP rupture and debonding, respectively. The failure modes for beams ACS1 and BCS1 are presented in Figure 7.

The strengthened beams with CFRP sheets around the perimeter of the section and along the entire beam length (for instance beams ACW1 and ACW2 of group A, beams BCW1 and BCW2 of group B, and beams CCW1 and CCW2 of group C) exhibited better behaviour than the strengthened beams with CFRP strips since fibres inhibited the cracks propagation. This is the reason that the fully wrapped beams presented higher values of cracking torque in respect to the other beams of their group (Table 5). The failure in these beams was followed by the rupture of that part of the CFRP sheets intersected by the main torsional crack. The failure modes for the strengthened beams CCW1 and CCW2 are typically displayed in Figure 8.

## CONCLUSION

An experimental investigation was carried out to evaluate the effect of various steel torsional reinforcement ratios on the behaviour of strengthened beams with the same volumetric ratios of CFRP reinforcement. From test results of 16 beams, the following conclusions are drawn.

- The least and highest CFRP contributions to torsional strength correspond to beams BCS1 and CCW2, for which the torsional strengths are exceeded by those of beams ACS1 and ACW2 by up to 26% and 111%, respectively. The least CFRP contribution to torsional strength, relating to beam BCS1, is due to the use of strip wrap configuration which does not provide full confinement in preventing the propagation of cracks between CFRP strips.

- The increased CFRP contribution to torsional strength corresponding to the beams strengthened by either one ply or two plies of CFRP sheets for various steel reinforcement ratios would not be very significant. Quantitatively, beam BCW2 has 6% more torsional strength than beam BCW1, while both have 37% more steel reinforcement with respect to the beams of group A. Beam CCW2 has 20% more torsional strength than beam CCW1, while both have 94% more steel reinforcement with respect to the beams of group A. No doubt, for more accuracy, further experiments are required.

- It can be clearly seen that for beams CCW1 and CCW2, the torsional strength capacities due to CFRP reinforcement are 1.91 and 2.11 times those of the beams ACW1 and ACW2, respectively, while the amount of steel reinforcement had been increased from 1.56% to 3.03%.

- It is observed that for beams CCW1 and CCW2 the strain levels to the peak torque are 1.26 and 1.22 times those of the beams BCW1 and BCW2, respectively, while the amount of steel reinforcement is increased from 2.13% to 3.03%. Thus, the increase in strain levels is not as great as the increase of steel reinforcement.

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