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Behaviour of RC beams strengthened with FRP strips under combined action of torsion and bending

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ABSTRACT

Many researchers worldwide have extensively used fibre-reinforced polymer (FRP) strengthening materials to enhance the shear and flexural strengths of reinforced concrete (RC) beams. However, Studies on strengthening of RC beam subjected to combined torsion and bending moment using both spiral and vertical strip configuration of CFRP that explored in this study is rare. This study aims to demonstrate the behaviour of RC beams strengthened with FRP sheets (strips) with different configurations and subjected to combined actions of torsion and bending moment. Eight beams with a dimension of $15 \times 25 \times 200$ cm were cast. One of the beams was not strengthened, but the others were strengthened with carbon FRP. The angle of twist at torque intervals, first cracking torque, ultimate torque and ultimate twist angle of the conventional and strengthened beams during the testing process were compared. Results showed a significant improvement in the torsional performance of RC beams using carbon FRP. The fully wrapped beams performed better than the beams with strip wrapping due to the influence of various wrapping configurations. Amongst the wrapping configurations of FRP fabrics, the 45° spiral strip wrapping configuration was the most effective for RC beam strengthening in terms of torsion resistance.

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KEYWORDS
Reinforced concrete; beam; strengthening; fibre reinforced polymer; torsion

HIGHLIGHTS

- Reinforced concrete (RC) beams strengthened with fiber reinforced polymer composite were tested under combined bending and torsional moment;
- The effect of composite orientation, spacing and number of plies on the torsional response;
- Ultimate torsional moments of RC beams;
- Twist angle of rotation of control and strengthened beams;
- Analytical prediction for CFRP material contributions to the ultimate torsional moment of strengthened RC beam.

Abbreviations: FRP: fibre-reinforced polymer; CFRP: carbon fibre-reinforced polymer; GFRP: glass fibre-reinforced polymer; RC: reinforced concrete

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1. Introduction

Aside from the flexure and shear resistances of reinforced concrete (RC) structural elements, torsion resistance is another crucial factor that must be considered for peripheral beams in multi-storied buildings, ring beams at the base of circular tanks, edge beams of shell roofs and beams supporting overhang slabs and helical staircases.

Strengthening or upgrading of structural elements must be performed after a certain period to increase the service life of these elements (Jariwala et al., 2013; Santhakumar et al., 2007). Several methods of increasing the service life of RC structural elements are available; for example, fibre-reinforced polymer (FRP) strengthening sheets are used to wrap RC structural elements. This technique is inexpensive and can be applied to completely degraded structures. Compared with traditional techniques, repairing concrete structures by using FRP sheets has many advantages. FRP sheets have high tensile strength, extremely low weight, high corrosion resistance and fast installation. Moreover, changing the geometry of the structure is unnecessary when these sheets are used.

The construction sector has extensively used this technique due to its advantages. Several studies (Ghobarah et al., 2002; Jariwala et al., 2013; Patel et al., 2016) have been conducted on this technique because of its multi-functionality in the construction industry. For example, Jariwala et al. (2013) experimentally studied the upgrading of the torsional resistance of RC beams using GFRP. In their experiment, all beams wrapped with GFRP demonstrated higher torsional resistance than the control specimen. Ghobarah et al. (2002) showed that a 45° orientation of fibres is more viable than 0° and 90° configurations in increasing the torsional strength of reinforced beams. Ameli et al. (2007) numerically modelled an FRP-strengthened beam and showed that relative to the use of the carbon FRP (CFRP) wrapping sheet, the ductility of the reinforced beam significantly increased when GFRP wrapping was utilised.

Chalioris (2008) demonstrated the effectiveness of using epoxy-bonded CFRP sheets as external transverse reinforcement for RC beams with rectangular and flanged cross sections subjected to pure torsion. The results showed that FRP fabrics can be effectively used as external torsional reinforcement under the lower part of reinforced concrete beams without the use of transverse steel reinforcement. Mohammadizadeh et al. (2009) evaluated the effect of various steel torsional reinforcement ratios on the torsional behaviour of strengthened beams. They discovered that the effect of CFRP remarkably depends on the total torsional reinforcement ratio. Deifalla and Ghobarah (2010) demonstrated different strengthening techniques by using CFRP for beams under the combined action of shear and torsion. They concluded that the U-jacket is effective and promising in terms of strength and ductility and feasible for strengthening.

Mostofinejad and Talaeitaba (2014) assessed the rehabilitation convenience of a damaged RC beam under the combined shear–torsion effect and determined the beam's shear–torsion capacity by using CFRP rolled strips. Their results revealed that rehabilitating and strengthening of beams by CFRP may not only help recover the original shear–torsion capacity but also increase the ultimate capacity by up to 60%. Kumar et al. (2015) experimentally investigated the upgrading of the torsional resistance of a reinforced concrete beam by using FRP. In their experiments, the beams that were wrapped with GFRP had larger torsional resistance than the control specimen. Patel et al. (2016) experimentally studied the enhancement of the torsional resistance of RC beams using GFRP sheets under pure and combined torsion and bending. Compared with the control specimen, all of the beams that were wrapped with GFRP had larger torsional resistance.

The literature review above indicates that FRP strengthening materials have been extensively used to improve the flexural and shear strength of RC beams (Alam & Jumaat, 2009; Alferjani et al., 2014; Ali et al., 2013; Anil, 2006; Ashour et al., 2004; Barros et al., 2011; Belarbi et al., 2012; Bllkasem Salah Alferjani, 2014; Bonacci & Maalej, 2001; Bousselham & Chaallal, 2008; Dong et al., 2013; El-Ghandour, 2011; Eshwar et al., 2005; Grace, 2001; Issa & AbouJouadeh, 2004; Jayaprakash et al., 2009; Lavorato et al., 2018; Monier et al., 2017; Murad, 2018; Paul & Datta, 2018; Shariatmadar et al., 2013; Sobuz et al., 2011; Sobuz & Ahmed, 2011; Soudki et al., 2007; Zhou et al., 2019). However, studies on torsional strengthening are limited (Ameli et al., 2007; Chalioris, 2008; Deifalla & Ghobarah, 2010; Ghobarah et al., 2002; Jariwala et al., 2013; Kumar et al., 2015; Mohammadizadeh et al., 2009; Mostofinejad & Talaeitaba, 2014; Patel et al., 2016; Santhakumar et al., 2007); and a few number of them simultaneously investigated torsion with bending moment. Therefore, this study aims to demonstrate the behavior of RC beams that strengthened with CFRP sheet under the combined actions of torsion and bending moment.

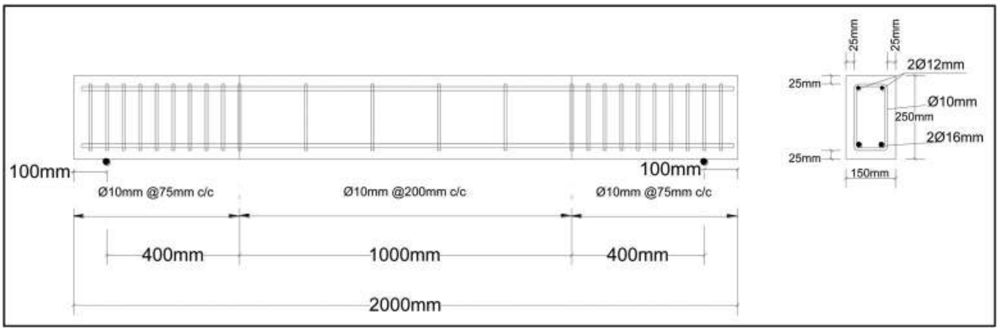


Figure 1. Dimensions and reinforcement details of test beams.

2. Materials and methods

2.1. Concrete mixes

The influence of FRP on the torsion and flexural strength resistance of RC beams was examined by fabricating eight beams, which were prepared using M48 grade ready-mix concrete acquired from a local commercial company. The aim was to identify the effective CFRP wrapping pattern under combined torsion and bending. The size of all beams was 150 mm (width) × 250 mm (height) × 2000 mm (length). Amongst the eight beams, seven were wrapped with CFRP sheets with various configurations, and one beam was not wrapped and considered the control beam.

2.2. Reinforcement and formwork

The main longitudinal reinforcement may withstand the axial force from torsion. When torsional and flexural moments simultaneously occur in a region of an RC beam, the longitudinal torsion reinforcement in the flexural torsion zone is added to the flexural reinforcement in the flexural compression zone. The compression due to the flexural torsion reduces the need for longitudinal torsion reinforcement (Soluit et al., 2007).

To avoid beam failure at torsional and flexural cracking loads, each beam was designed to have a steel reinforcement ratio (ρ) of 2.3% (Equation 1) for each of the longitudinal and transverse reinforcement to the volume of concrete (ACI 318-14, 2014; Ameli et al., 2007; Deifalla & Ghobarah, 2010).

$$\rho = \rho_{sl} + \rho_{st} = \frac{A_{sl}}{A_c} + \frac{A_{st}}{A_c} \cdot \frac{p_t}{s}, \tag{1}$$

where ρ is the total steel reinforcement ratio for each of the longitudinal and transverse reinforcement, ρ_{sl} is the ratio of the longitudinal steel bar, ρ_{st} is the ratio of transverse steel stirrups, A_{sl} is the total area of steel longitudinal bars, A_c is the gross area of the concrete cross section, A_{st} is the area of a steel stirrup, p_t is the perimeter of the steel stirrup and s is the spacing of steel stirrups.

The reinforcement percentage provided in a beam was slightly higher than the minimum requirement (ACI 318-14, 2014) to control the integrity of the beam beyond cracking; moreover, this will reveal the case of a defective beam in terms of reinforcement. All beams were reinforced with the same reinforcement ratio, as shown in Figure 1.

The reinforcement for the specimens included 2Φ16 and 2Φ12 mm diameter steel bars at the bottom and top, respectively. End zones that were 0.4 m long on each end of the beam were reinforced with Φ 10 mm stirrups spaced at 75 mm from centre to centre to force failure in the halfway zone of the tested beam. The test region of (1.0 m) was selected in such a way that at least two complete spiral cracks formed along the length of the region; therefore, Φ 10 mm (f_y = 541 MPa) stirrups spaced at 200 mm on centres were utilised as reinforcement. Furthermore, plywood sheets (1.22 m × 2.44 m × 18 mm) were used to cast the concrete beams (Figure 2).

All of the RC beams used the same concrete mix with a compressive strength ($f\grave{c}$) of 48 MPa. *Lafarge* Concrete Company (local supplier) provided the ready-mix concrete for casting the concrete beams. In addition to the beams, cylinders, cubes and prisms were also cast with the same ready-mix concrete to

Figure 2. Formwork of the concrete beams.

obtain the compressive strength, modulus of elasticity and tension strength of the concrete. The beams, cylinders, cubes and prisms were cured for 28 days.

2.3. FRP material

2.3.1. CFRP material properties

The experiment used carbon fibre fabric SikaWrap®-300 C and epoxy-based saturated resin Sikadur-330. Unidirectional CFRP fabrics (SikaWrap-300C) with a thickness of 0.166 mm per ply were also utilised. The elastic modulus, ultimate tensile strength and elongation at failure of the fibre were 230 GPa, 3900 MPa and 15 mm/m, respectively, according to the manufacturer. The FRP sheets were bonded to concrete by using two pieces of 'rubber-toughened cold-curing-construction epoxy adhesive (Sikadur 330)' with a density, elastic modulus and tensile strength of 1310 kg/m^3, 3800 MPa and 30 MPa, respectively. Tables 1 and 2 list the information related to this system.

2.3.2. Preparing and installing CFRP

The bond between the RC beam and CFRP was given appropriate attention during the strengthening process. When fixing the CFRP to the concrete surface, a handheld grinder was utilised to level the concrete surface disclosing the aggregate. The grinder was used again to arciform the concrete corners to a minimum radius of 13 mm (ACI 440-2R, 2008) and reduce the stress concentration in the fibres at the edges. This stress concentration will lead to rupture failure of CFRP sheets at corner edges before reaching their ultimate strength. Water and compressed air were used to clean the concrete surface from released particles and dirt.

2.3.3. Applying of CFRP sheet

The beams were cleaned by washing with pressurised water and allowed to dry prior to CFRP sheet application. Loose particles and defilements from the specimen's surface were removed by this procedure. The beams were also wire brushed and vacuumed prior to CFRP sheet application. Depending on substrate roughness, the resin (Sikadur-330) was mixed and applied to the prepared concrete surface by using a brush at the amount of approximately 0.75 kg/m^2 to 1.25 kg/m^2. The SikaWrap®-300 C sheet was cut into strips with 100 mm width by scissors for the required length for all the specimens (estimated overlap greater than 150 mm). The SikaWrap®-300 C strip was applied to the resin with a special plastic roller until the resin was squeezed out between the roving. Afterwards, a waiting time of at least 12 h was observed for beams strengthened with two-ply CFRP prior to the application of the next layer. Then, the SikaWrap®-300 C fabric was applied onto the resin coating in the appropriate direction.

After allowing the composite to cure for at least 15 days, the apparent surface of the concrete beams was painted with specific white colour to easily detect crack propagation.

2.3.4. Wrapping configurations

CFRP composite wrap spacing and ply numbers were the main parameters investigated. One specimen was stored without strengthening and referred to as the control specimen. Meanwhile, the CFRP sheet composite was used to strengthen the remaining specimens. A full-wrap CFRP composite was employed

Table 1. SikaWrap®-300 C (woven carbon fibre fabric for structural strengthening).

Characteristics	Note
Fibre type	Mid-strength carbon fibres
Fibre orientation	0° (unidirectional)
Areal weight	300 ± 15 g/m^2
Fabric design thickness	0.166 mm (based on fibre content)
Tensile strength of fibres	3,900 N/mm^2 (nominal)
Thickness	1.3 mm per layer (impregnated with Sikadur®-330) 1.0 mm per layer (impregnated with Sikadur®-300)
Tensile E-modulus	2,30,000 N/mm^2
Elongation at break	1.5% (nominal)

Table 2. Sikadur-330 (two-part epoxy impregnation resin).

Appearance and colours	Resin part A: white (paste); Hardener part B: grey (paste)
Density	1.31 kg/l (mixed)
Mixing ratio	A : B = 4 : 1 by weight
Open time	30 min (at + 35 °C)
Viscosity	Pasty, not flowable
Service temperature	−40 °C to +50 °C
Tensile strength	30 MPa (cured seven days at +23 °C)
Flexural E-modulus	3800 MPa (cured seven days at +23 °C)

to strengthen specimen 100C100. By contrast, a 100 mm width CFRP composite was used to strengthen four other beam specimens, and all-around wraps were placed at a spacing of 150 and 200 mm c/c using one and two layers of the CFRP composites, respectively. Beams SC1 and SC2 were wrapped with CFRP spirally at a 45° angle with a development length of 150 mm for all specimens. All beam specimens were tested under combined torsion and bending. Figure 3 shows the wrapping arrangement, and Table 3 presents the test specimen design.

2.3.5. FRP ratio as transverse reinforcement

Figure 4 presents the FRP ratios for the strengthened beams. Equation 2 was used to calculate the volumetric ratios of CFRP reinforcement, ρ_f

$$\rho_f = \frac{n_f t_{fd} b_f P_f}{A_c s_f}, \tag{2}$$

where n_f is the number of plies of CFRP sheets, t_{fd} is the fabric design thickness, b_f is the width of the CFRP strips, P_f is the perimeter of the strengthened beam cross section using CFRP, A_c is the gross area of the concrete cross section and s_f is the c/c spacing of CFRP strips (for beams with a continuous jacket along the beam, the terms b_f and s_f have identical values).

2.4. Test setup and instrumentation

Figure 5 shows the details of the test setup. The load at the active support was applied using a 200 t hydraulic jack. The periodical applied load was measured using a compression load cell with 100 t capacity. The hydraulic jack had a movable length of 250 mm, thus providing a 57.3° twist capacity for the beam. The reaction arm had 500 mm eccentricity from the centroidal axis of the beam. The beam elongated longitudinally after cracking and was allowed to slide and elongate freely to avoid any longitudinal restriction and consequent compression. This feature was obtained by supporting the beam ends on rollers at the unresisting support. The twist angle of the free end (the point of applying torque) was measured by a dial gauge with the aid of the downward distance of the lever arm at that point.

Load application on the beam specimens to be tested under the combined action of torsion and bending utilised a fabricated loading frame from the Civil Engineering Laboratory. Rotation around the longitudinal beam axis was arranged via a special support condition, and lever arms were attached to the specimen to provide torsional moment, as shown in Figure 5.

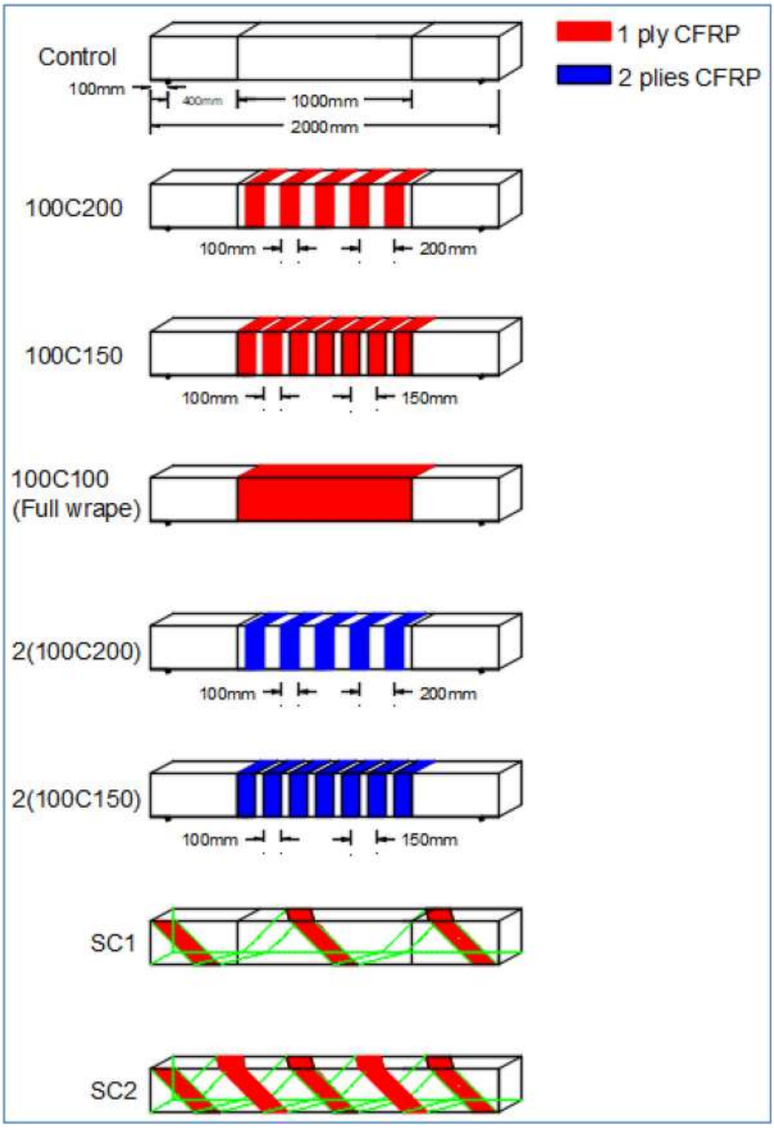


Figure 3. Strengthening details of the tested beams.

Table 3. Design of the concrete beams.

Beams	Strengthening technique	Transverse strip No. of layers	Transverse strip Width mm	Transverse strip Spacing mm	Spiral strip No. of layers	Spiral strip Width mm	Spiral strip Spacing mm
Control				Un-strengthened			
100C100 (full wrap)	CFRP sheet	1	Full		–	–	–
100C150		1	100	150	–	–	–
100C200		1	100	200	–	–	–
2(100C150)		2	100	150	–	–	–
2(100C200)		2	100	200	–	–	–
SC1		–	–	–	1	100	566
SC2		–	–	–	1	100	283

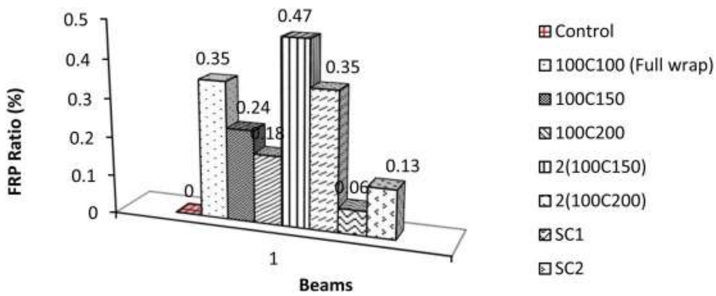


Figure 4. FRP ratios for the strengthened beams.

- Two dial gauges were used for measuring displacements were positioned under the lever arm.
- A distance of 400 mm was maintained between the centre of the support and lever arm to achieve bending and torsion.
- The load of the hydraulic jack was transferred to specimen through a spreader beam resting on the end of a lever arm attached to the specimen. Thus, half of the applied load acted at the end of each lever arm.
- The length of the specimen between supports was 1.8 m, with 0.1 m projection outside the support. The central 1.0 m length of the specimen was subjected to combined bending and torsion, whereas 0.4 m length of the beam near each support was subjected to bending moment and shear force. The torque in the middle part of the specimen was the product of the load at the end of each lever arm (half the total of applied load) multiplied by the length of the lever arm from the centre of the specimen. The twist angle at each lever arm was achieved from a vertical displacement of a lever arm end point and length of the lever arm. The overall twist angle in the middle part of the specimen was equal to the sum of twist angles at the couple of the lever arm.

2.5. Test procedure

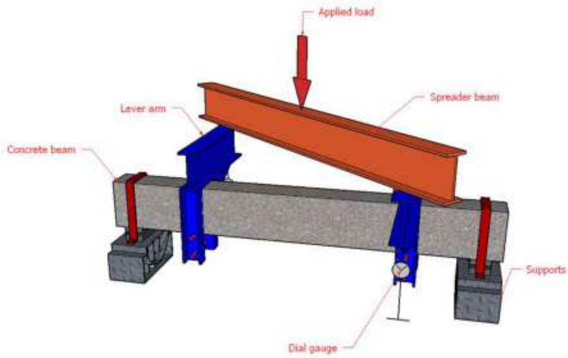
The circular rotation of the supports around the longitudinal axis of the beam and the transmission of applied load from the centre of the machine to the two points that express the moment arm must be adjusted and checked during the experimental test. Figures 5 and 6 show the particular clamping loading frame used in this study. This frame consisted of an I-section (200 mm × 80 mm × 8 mm) attached to two steel channels (100 mm × 50 mm × 8 mm) by welding. After insertion around the beam cross section by long bolts, these steel channels connect from the bottom, and each arm utilises two bolts. Attached steel clamps work as lever arms for applied torque with separated faces to connect them over the sample. The final shape is similar to a bracket. These lever arms are suitable for providing the required eccentricity of 500 mm with respect to the longitudinal axis. Increment readings at each load were acquired through recorded camera videos and cracks were recorded in accordance with their occurrence.

2.6. Angle of twist measurements

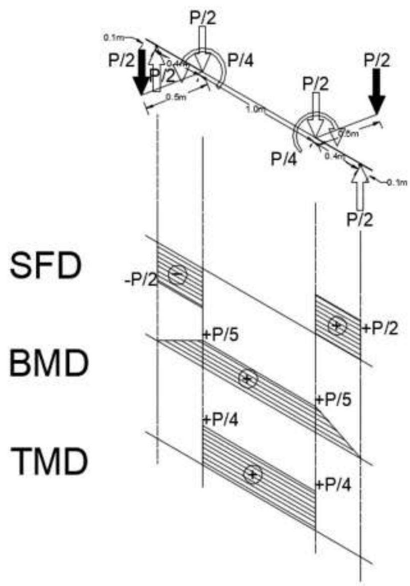
As shown in Figure 7, a dial gauge connected to the bottom of a lever arm at a point (500 mm) from the centre of the longitudinal axis of the beam was used to evaluate the angle of twist. The downward value of the lever arm was recorded by the dial gauge to determine the twist angle in radians.

3. Results and discussion

Table 4 shows a summary of the cracking torque (T_{cr}), ultimate torque (T_u) and ultimate twist angle (θ_u) of the concrete beams. The type of beam failure is also shown in the table. Overall, the results demonstrate the significant improvement of T_{cr}, T_u and θ_u of the concrete beams with the use of FRP sheets.



a-schematic of test the setup for applying combined torsion and bending



b- Internal force diagrams and dimensions for specimen under combined torsion and bending moment

Figure 5. (a) Schematic of test the setup for applying combined torsion and bending; (b) Internal force diagrams and dimensions for specimen under combined torsion and bending moment.

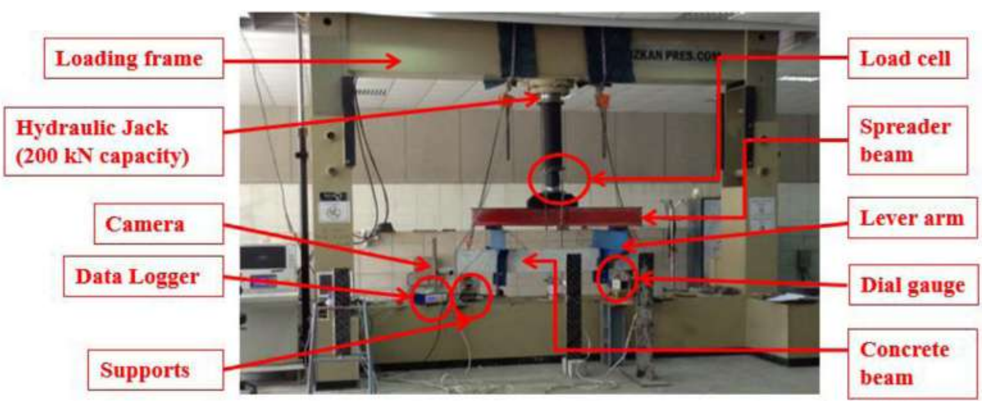


Figure 6. Test setup with the loading frame.

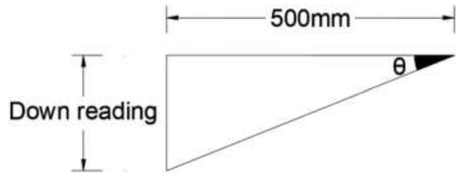


Figure 7. Angle of twist measurements.

Table 4. Experimental results of the tested beams.

Beam Code	Str. Tech.	f′c MPa	T_{cr} kN.m	%Incr.T_{cr}	T_u kN.m	%Incr.T_u	θ_u deg./m	%Inc. θ_u	Modes of Failure
Control	Un-str.	48	4.81	–	11.06	0	4.77	0	Con. Cr.
100C100 (Full wrap)	CFRP Sheet		9.10	–	25.46	130	10.49	120	Con.Cr.+ FRP R.
100C150			8.06	68	22.06	99	10.39	118	Con.Cr.+ FRP R.
100C200			7.31	52	20.19	83	9.17	92	Con.Cr.+ FRP R.
2(100C150)			8.75	82	26.09	136	8.20	72	Con. Cr.
2(100C200)			7.06	47	20.29	83	7.64	60	Con. Cr.
SC1			7.06	47	13.81	25	5.68	19	Con. Cr.
SC2			8.31	73	19.11	73	5.86	23	Con. Cr.

Str. Tech.: Strengthening Technique; f′c: Concrete Compressive Strength; T_{cr}: Cracking Torque; %Incr.T_{cr}: Increase of Cracking Torque in percentage; T_u: Ultimate Torque; %Incr.T_u: Increase of Ultimate Torque in percentage; θ_u: Ultimate Twist Angle; %Incr. θ_u: Increase of Ultimate Twist Angle in percentage; Un-str.: Un-strengthened; Con. Cr.: Concrete Crush; FRP R.: FRP Rupture.

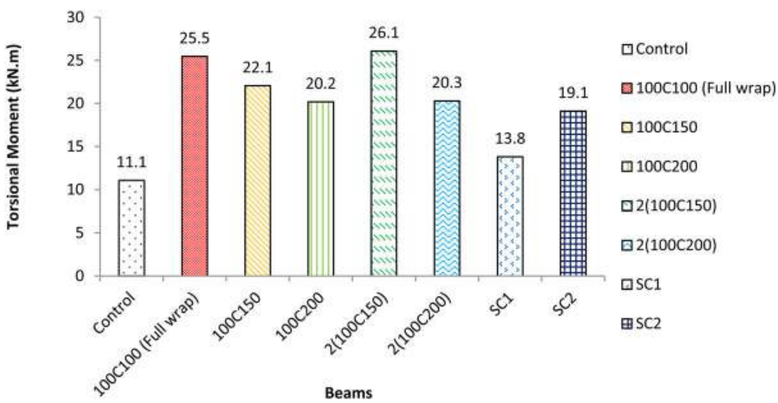


Figure 8. Ultimate torsional moment carrying capacity.

3.1. Ultimate torsional moment carrying capacity

The ultimate torsional moment carrying capacity of the control and strengthened beams are shown in Figure 8. Nonlinear improvement of the ultimate torsional moment carrying capacity of the strengthened beams in relation to the control beam was also observed. The configuration of the FRP system mainly influenced the improvement. For example, the maximum ultimate torsional moment (26.9 kN.m) was demonstrated by beam 2(100C150), and beam SC1 showed the minimum torsional moment (13.81 kN.m). The values for the other strengthened beams were between those of the two beams.

Figure 9 shows the FRP ratios for strengthened beams and the enhancement percentage of their ultimate torsional moment (T_u) with respect to the control beam. The maximum (0.47%) and minimum (0.06%) FRP ratios were exhibited by beams 2(100C150) and SC1, respectively. The ratios of the other strengthened beams were between those of the two beams.

However, applying of CFRP sheet along the test region of the strengthened beam serves to arrest the concrete cracks and obstructing them from widening. Moreover, CFRP strip width and spacing affects the confinement provided to the concrete, which influences the post-cracking behavior and consequently delaying failure of RC strengthened beams.

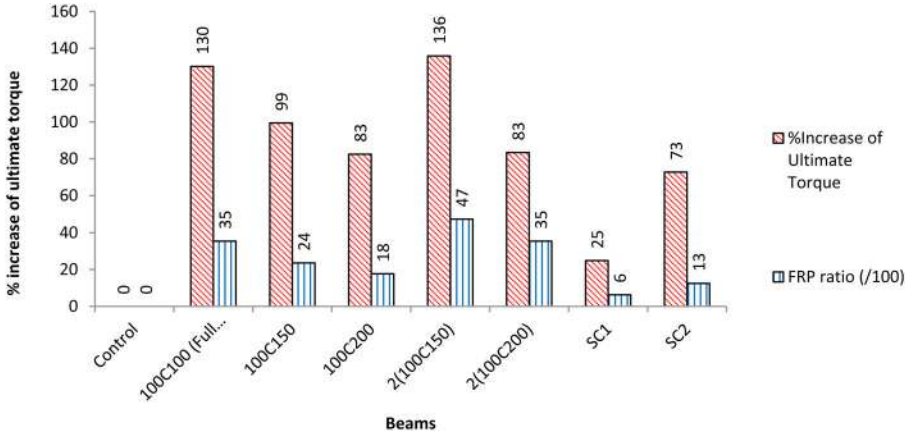


Figure 9. FRP ratios and increase in ultimate torsional moment in percentage.

3.2. Influence of FRP fabrics on torsional strength

Effect of FRP ratio, c/c spacing of FRP strips, number of plies and angle of FRP configuration on torsional strength will be illustrated in this section.

3.2.1. Influence of FRP ratio on torsional strength

Figure 10 shows the influence of FRP ratio on the torsional strength of the strengthened beams and the percentage of their increase in the ultimate torsional moment (T_u) with respect to the control beam. The maximum (0.47%) and minimum (0.06%) FRP ratios were demonstrated by beams 2(100C150) and SC1, respectively. The values for the other strengthened beams were between those of the two beams. The same FRP ratios (0.35%) were observed for beams 100C100 (full wrap) and 2(100C200), but they exhibited different enhancement percentages in the ultimate torsional moment (T_u) (130% and 83%, respectively). From the Figure 10 it's concluded that percentage increase of ultimate torsional moment (T_u) doesn't change linearly with FRP ratio; there many other factors that affect this relation such as FRP number of plies and angle of FRP configuration.

3.2.2. Influence of c/c spacing of FRP strips on torsional strength

Figure 11 shows the effect of the c/c spacing of FRP strips on the enhancement of the ultimate torsional moment (T_u) of the strengthened beams. The ultimate torsional moment (T_u) increased with the decrease in c/c spacing of strips.

3.2.3. Influence of FRP number of plies on torsional strength

Figure 12 shows the effect of FRP number of plies on the torsional strength of the strengthened beams. A significant change in the ultimate torsional moment (T_u) was observed when the number of FRP plies was increased, especially when FRP strip spacing was small (beam 100C150); however, when the FRP strip spacing was large (beam 100C200), it has insignificant effect on enhancement of ultimate torsional strength.

Although some enhancement in torsional strength transpired by increasing the number of layers of CFRP sheet, the effectiveness of the strengthening system appears to be reduced when spacing between strips became greater or equal to the beam depth. In other words, the enhancement in torsional strength may not be proportional to the number of CFRP composites layers.

3.2.4. Influence of angle of FRP configuration on torsional strength

Figure 13 shows the effect of the angle of FRP configuration on the torsional strength of the strengthened beams. The enhancement in the ultimate torsional moment (Tu) was large when the FRP alignment

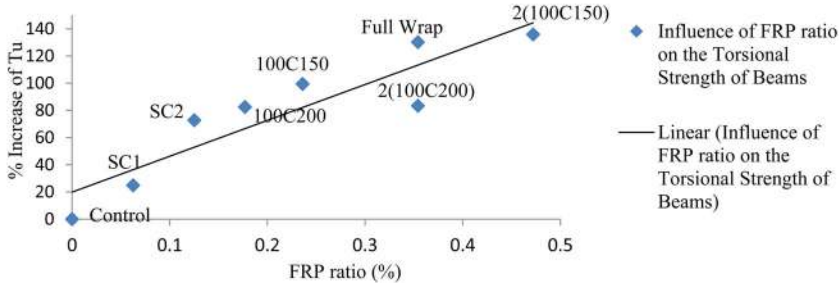


Figure 10. Influence of ratio of FRP fabrics on the torsional strength of the concrete beams.

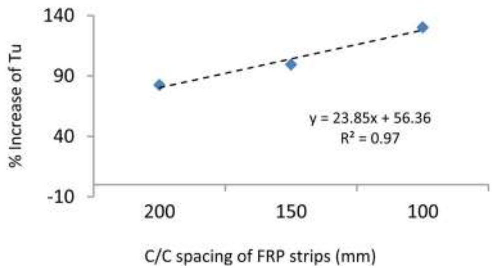


Figure 11. Influence of c/c spacing of FRP strips on torsional strength.

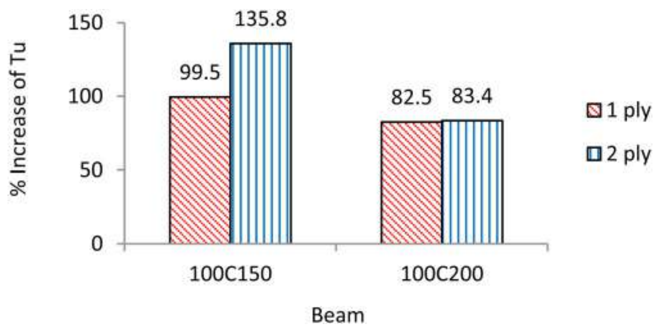


Figure 12. Influence of FRP number of plies on torsional strength.

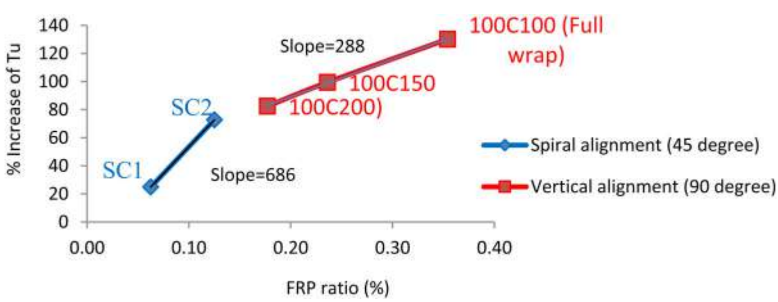


Figure 13. Influence of angle of FRP configuration on torsional strength.

was spiral (45°). For example, the T_u of beams SC2 and SC1 with FRP ratios of 0.13 and 0.06 increased by 73% and 25%, respectively. However, the enhancement in Tu for the vertical (90°) FRP alignment was not as large as that for the spiral alignment (45°). It is demonstrated in this study that fibre direction and angle of FRP configuration have a significant influence on the torsional strength and rotational capacity of a strengthened RC beam.

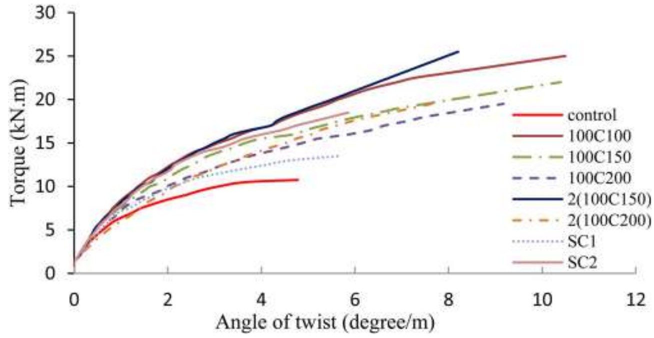


Figure 14. Torque versus angle of twist at each concrete beam.

3.2.5. Torque–twist comparison

Figure 14 shows the torque–twist behaviour of the control and strengthened beams. It's illustrated that; the control beam had a smaller torque carrying capacity and higher twist angle values for the same load compared with the strengthened beams. Amongst all of the strengthened beams, 2(100C150) and 100C100 (full wrap) exhibited the best ductility. up to concrete cracking; all beams have the same angle of twist. Owing to the stirrup or external CFRP strips that exhibited torque resistance in the post-cracking stage, all curves showed a reliable slope to reach the ultimate torque of beams. Therefore, an increase in torsional rigidity of the beams was observed, and the loading stopped after reaching the ultimate torque.

3.3. Crack pattern and failure modes

Figure 15 shows the failure modes of the un-strengthened (control) and CFRP-strengthened RC beams under combined bending and torsion. The torsional moment resulted in the failure of all the tested beams. The number of cracks in the strengthened beams was larger than that in the control beam; thus, the strengthened beams had higher tensile stress. The emergence of flexural cracks was observed in the control beam at the mid-length of one or both of the beam vertical faces. Tension cracks generated and propagated in a spiral form. The cracks gradually widened as the load increased, with the two lever arms rotating relative to one another around the RC beam centroidal axis along with bending. Most of the concrete cracks in the strengthened beams were dispersed through the concrete surfaces between the FRP strips. In addition, fibre failure in specimen 100C100 was observed from the edge of the central portion of the beam specimen, and sudden failure of the RC beam occurred after the emergence of the first fibre crack.

The FRP sheets ruptured after concrete cracking in specimens 100C150 and 100C200, but beam failure suddenly occurred in specimen 2(100C150) due to simultaneous FRP rupture and concrete crushing and high FRP ratio. Although specimen 2(100C200) had a high FRP ratio and due to the high FRP strip spacing of this beam, failure of the beam occurred due to concrete crushing without FRP rupture or debonding. Specimen (SC1) had a low FRP ratio and large spacing between FRP sheet strips, and beam failure can be attributed to concrete crushing without FRP rupture or debonding. By contrast, specimen (SC2) had a medium FRP ratio and good alignment (spiral 45°) of FRP strips. The sudden occurrence of beam failure can be attributed to simultaneous FRP rupture and concrete crushing.

4. Analytical analysis

The full torsional strength of CFRP-strengthened RC beams can be analyzed by the design codes using the principle of superposition from both the CFRP and steel reinforcement.

The ultimate torsional strength for the FRP strengthened tested beams, T_u, can be achieved by adding the contribution due to fibers and due to steel reinforcement in concrete beams as follows in equation 3:

$$T_u = T_{u,RC} + T_{u,FRP}, \quad (3)$$

where T_u - nominal torsional capacity of the FRP strengthened beam, $T_{u,RC}$ - the ultimate torsional capacity from steel reinforcement, $T_{u,FRP}$ is the ultimate torsional capacity from FRP reinforcement.

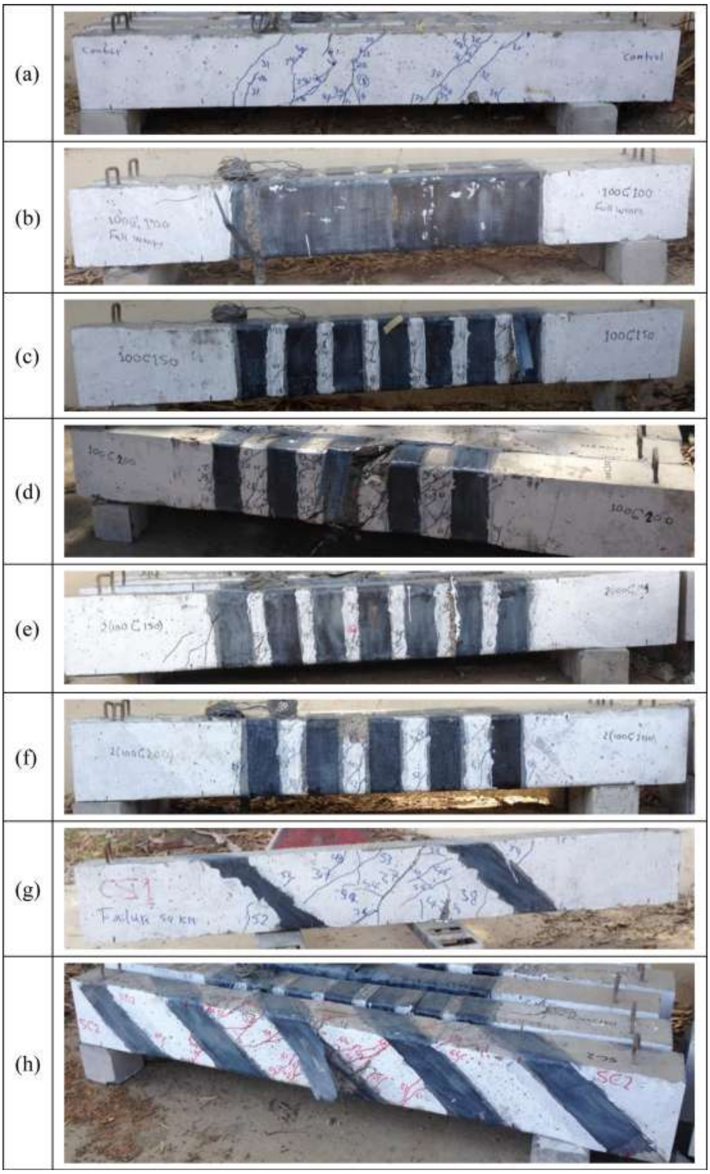


Figure 15. Mode of failure for specimens tested under combined torsion and bending. (a) Control specimen, (b) full transverse wrapping (100C100), (c) 100C150, (d) 100C200, (e) 2(100C150), (f) 2(100C200), (g) SC1 and (h) SC2.

The design equation to calculate the ultimate torsional strength of a reinforced concrete beam, $T_{u,RC}$, recommended by ACI 318-14 is as in Equation 4:

$$T_{u,RC} = \frac{2(0.85).A_{\circ}.A_t.f_{yv}}{S}, \tag{4}$$

where, A_o - is the cross-sectional area bounded by the center line of the shear flow according to ACI 318-14, A_t - is the area of the transversal steel reinforcement (stirrups), f_{yv} - is the yield stress of transversal steel reinforcement and S - is the spacing of stirrups.

FIB Bulletin-14, 2001 design model (Fib (CEB-FIP), 2001) states that an externally bonded FRP laminate will grant contribution to the torsional capacity only if full wrapping around the beam's cross section is applied, so that the tensile forces carried by the FRP on each side of the cross section may create a continuous loop. The technical document also provides for the possibility of using inclined FRP strips as a

Table 5. Comparison between experimental and analytical ultimate torsional moments.

Beam code	Ultimate torsional moment T_u (KN.m) Experimental	Analytical	$T_{u,Exp.}$ / $T_{u,An.}$
Control	10.8	6.18	1.74
100C100 (Full wrap)	25.2	19.68	1.28
100C150	21.9	16.34	1.34
100C200	19.9	14.49	1.37
2(100C150)	25.8	22.69	1.14
2(100C200)	20.0	19.68	1.02
SC1	13.6	13.82	0.98
SC2	18.8	18.59	1.01

$T_{u,Exp.}$: Experimental ultimate torsional moment; $T_{u,An.}$: Analytical ultimate torsional moment.

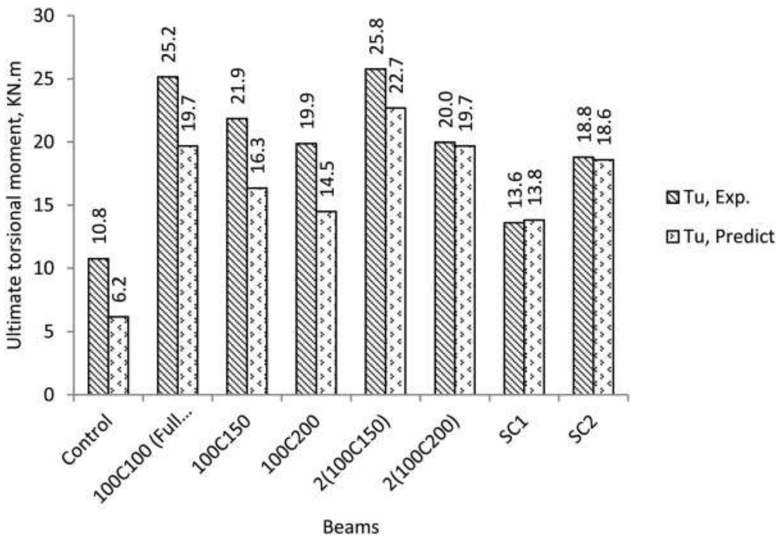


Figure 16. Experimental versus analytical ultimate torsional moment at each concrete beam.

strengthening solution. Based on the assumption of the validity of the truss mechanism, the following Equations 5–7 were provided to predict the FRP contribution to strength $T_{u,FRP}$:

$$T_{u,FRP} = 2\varepsilon_{fk,e} E_{fu} \frac{t_f b_f}{S_f} bh.\cot\theta, \tag{5}$$

$$\varepsilon_{fk,e} = 0.8\varepsilon_{fe}, \tag{6}$$

$$\varepsilon_{fe} = 0.17\left(\frac{f'^{\frac{2}{3}}_c}{E_{fu}\rho_f}\right)^{0.3} \varepsilon_{fu}, \tag{7}$$

where $T_{u,FRP}$ - design value of torsional moment resisted by the FRP, $\varepsilon_{fk,e}$ - characteristic value of effective FRP strain, t_f - thickness of fiber laminate, b_f -width of FRP strips, S_f - center-to-center spacing of FRP strips, b * h: cross section dimensions of beam, f'_c: mean value of the concrete compressive strength, ε_{fe} - effective FRP strain, θ angle of diagonal crack with respect to the member axis, E_{fu} - modulus of elasticity of FRP at ultimate, ε_{fu} - ultimate FRP strain.

Equation 2 was used to calculate the volumetric ratios of CFRP reinforcement, ρ_f (Chalioris, 2008; Mohammadizadeh et al., 2009).

Table 5 and Figure 16 presents the comparison of the experimental and the predicted analytical results of the total torsional capacity using ACI 318-14 M and FIB Bulletin-14, 2001 design model equations. It was observed that the total torsional capacity (Torsion strength from reinforced concrete plus those from CFRP sheet) was under-estimated by 74% for the control beam. This was due to the model being established upon the space truss theory which neglects the contribution from inside the core of the concrete section to the torsional capacity. Moreover, the existence of the aggregate interlock for RC beams has an additive effect on the torsional capacity which was neglected in the model.

For strengthened RC beams 2(100C150), 2(100C200), SC1 and SC2, the predicted values of ultimate torsional moment are in good agreement with the experimental results. However, for strengthened beams 100C100, 100C150 and 100C200, the predicted values are obviously lower than the experimental values. Larger difference in results refers to Space Truss Analogy theory that use to assess torsional strength of RC beams; effect of concrete core and aggregate interlock is neglected in this theory.

5. Conclusions

The following conclusions were obtained from the experimental work.

- Regardless the wrapping configurations, higher torsional resistance than that of the control beam was observed for all strengthened beams wrapped with CFRP.
- Amongst the investigated wrapping configurations of CFRP fabrics, the 45° spiral strip wrapping configuration was the most effective in strengthening RC beams in terms of torsion resistance.
- The test beam with two-ply transverse strip wrapping (number of layers is two, width is 100 mm and spacing is 150 mm; 2(100C150)) showed the maximum (136%) increment in ultimate torque, and the beam with one-ply spiral strip wrapping (number of layers is one, width is 100 mm and spacing is 566 mm; SC1) presented the minimum (25%) increment in ultimate torque in comparison with the control beam.
- The test beam with two-ply strip transverse wrapping (2(100C150)) showed the maximum (82%) increment in cracking torque, and the beams with one-ply spiral strip wrapping (SC1) and two-ply strip wrapping (2(100C200)) showed the minimum (47%) increment in cracking torque compared with the control beam.
- The ductility of all the strengthened beams increased, and the increment was significant for several FRP configurations.
- The enhancement percentage of the ultimate torsional moment (Tu) proportionally increased with increasing of FRP ratio.
- Cracks in the strengthened beams spread more extensively along their length compared with the singular cracks that formed in the control beam.
- Failure in the concrete beams was delayed when CFRP strips were used to strengthen the beams. However, this failure unavoidably occurred in the unwrapped space between strips.
- The ultimate torsional moment was improved when the spacing between FRP strips (increasing the FRP ratio) was reduced, instead of increasing the number of FRP plies.
- Vertical strips of CFRP should not be used when these strips are arranged at a similar or larger spacing than that of beam depth because they may be ineffective for carrying torsional moment, as in other strengthening techniques. In particular, beams 100C200 and 2(100C200) showed an increase of approximately 83% in ultimate torque.
- For strengthened RC beams by 2plies of CFRP laminates and spirally strengthened RC beams the predicted values of ultimate torsional moment are in good agreement with the experimental results. However, for strengthened beams by 1ply of CFRP laminates, the predicted values are obviously lower than the experimental values.

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Disclosure statement

The authors declare no conflict of interest. The sponsors had no role in the design of the study, in the collection, analyses or interpretation of data, in the writing of the manuscript and in the decision to publish the results.

Author contributions

Both authors conceived and designed the experiments. Nasih Askandar analysed the data and wrote the paper, and Abdulkareem Mahmood made necessary revisions.

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