Torsional Behavior of Reinforced Concrete Members Wrapped with CFRP Sheets

Akhrawat Lenwari[1], Siwakorn Soysak[1], and Chanachai Thongchom[2](✉)

[1] Composite Structures Research Unit, Department of Civil Engineering,
Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
[2] Department of Civil Engineering, Thammasat School of Engineering, Thammasat University,
Pathumtani 12120, Thailand
`tchanach@engr.tu.ac.th`

Abstract. This paper presents the torsional behavior of reinforced concrete (RC) members fully wrapped with carbon fiber-reinforced polymer (CFRP) sheets. A total of twelve rectangular RC specimens of identical cross sections were tested under pure torsion (beams) or combined axial compression and torsion (columns). In the case of column specimens, an axial force simulating the service loads was applied before CFRP strengthening and maintained constant during the static test under torsion. The magnitude of axial force was 25% of the nominal compressive strength. Therefore, test variables included the presence of axial force (beam or column), stirrup spacing (75 or 150 mm), hook angle (90 or 135°) of the closed stirrups, and presence of CFRP sheets. Test results showed that the externally bonded CFRP sheets significantly increased the cracking, yielding, and maximum torsional moment capacities of RC beams and columns. The full wrap configuration enhanced the maximum torsional moment capacity by up to 190% and 116% for RC beams and columns, respectively. Also, the use of 135-degree hook for closed-stirrups was more effective than 90-degree hook for both unwrapped and CFRP-wrapped members. Finally, the effective CFRP strain equation by fib14 correlated better with RC beams than columns.

Keywords: Torsion · Fiber-reinforced polymers · Strengthening · Reinforced concrete members · Full wrapping

1 Introduction

Significant torsional effects can be expected for the reinforced concrete (RC) members as a result of the eccentric loading, member geometry, or structural framing. To improve the torsional performance of RC members, the strengthening method is necessary. Although the fiber-reinforced polymer (FRP) materials have been widely adopted for flexural and shear strengthening, their application for torsional strengthening of RC beams and columns has received less popularity due to the limited studies. Ghobarah et al. (2002) conducted an experiment on eleven RC beams with dimensions 150 × 350 × 2440 mm under pure torsion. Both glass FRP (GFRP) and carbon FRP (CFRP) materials were used. The test results showed that the full wrap configuration was more effective on

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enhancing the torsional moment capacity than various strip configurations. In a study by Salom et al. (2004), the main test variables included the fiber orientation and laminate anchoring system. The test results showed that the CFRP sheets increased the torsional moment capacities of RC beams by up to 77%. Hii and Al-Mahaidi (2006) reported that the externally-bonded CFRP strips (50 mm wide) increased both cracking and ultimate torsional moment capacities by up to 40% and 78%, respectively. Such increase was related to the strip spacing and number of CFRP layers. Ameli et al. (2007) conducted an experiment on twelve rectangular RC beams with dimensions 150 × 350 × 1900 mm under pure torsion. The test results showed that the externally bonded CFRP sheets increased the torsional capacity higher than GFRP ones. He et al. (2014) showed that the externally bonded CFRP sheets can be used to restore the torsional performance of severely damaged RC columns. However, previous studies did not emphasize on the effect of axial forces on the torsional performance of RC columns strengthened with CFRP sheets.

This research project investigates the torsional behavior of both RC beams and columns before and after strengthened with CFRP sheets. The full wrap configuration was chosen for the externally bonded CFRP sheets. A total of twelve rectangular RC specimens of identical cross sections were tested under pure torsion (beams) or combined axial compression and torsion (columns). In the case of column specimens, an axial force simulating the service loads was applied before CFRP strengthening and maintained constant during the static test under torsion. The magnitude of axial force was 25% of the nominal compressive strength. Test variables also included the stirrup spacing (75 or 150 mm) and hook angle of the closed stirrups (90 or 135°). The effects of these variables on the torsional moment capacities are emphasized in this paper.

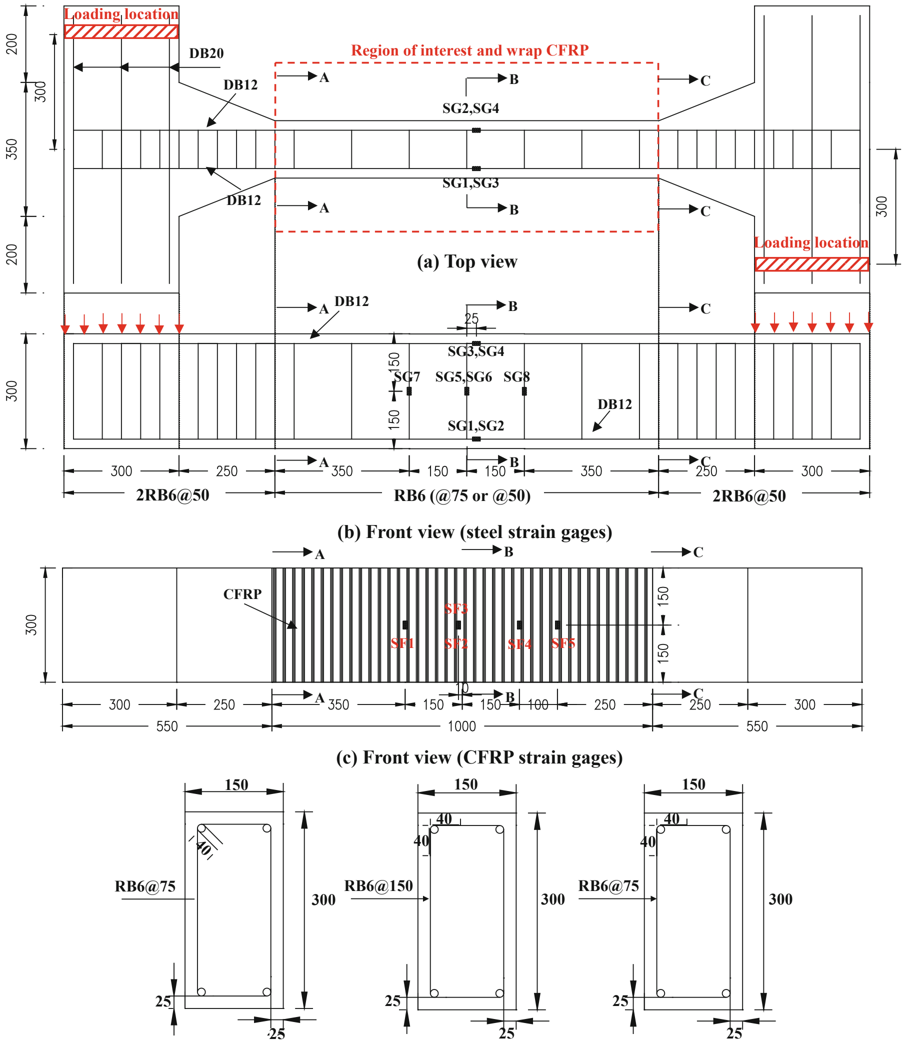
2 Experimental Program

2.1 Material Properties

All RC specimens were cast from the same ready-mixed concrete batch. An average compressive strength from testing three standard Ø150 × 300 mm concrete cylinders at 28 days was 28.5 MPa. The longitudinal steel reinforcements were 12-mm-diameter deformed bars (DB12). The measured elastic modulus, yield strength, and ultimate strength were 195 GPa, 518 MPa, and 582 MPa, respectively. The closed stirrups were 6-mm-diameter round bar (RB6). The measured elastic modulus, yield strength, and ultimate strength were 220 GPa, 283 MPa, and 483 MPa, respectively. The CFRP strengthening system consisted of the CFRP sheet (Sikawrap®-230C) and modified epoxy adhesive (Sikadur®-330). The measured elastic modulus, tensile strength, and ultimate strain were 276 GPa, 3493 MPa, and 1.5%, respectively (ASTM D3039). The curing time of the adhesive was two weeks.

2.2 RC Specimens

In the experimental program, a total of twelve RC specimens were tested, as shown in Table 1. The test variables included the presence of axial force (beam or column),



(a) Top view

(b) Front view (steel strain gages)

(c) Front view (CFRP strain gages)

(d) Closed stirrups using 90° or 135° standard hook

Fig. 1. Details of tested RC specimens (Dimensions in mm).

stirrup spacing (75 or 150 mm), and standard hook angle (135 or 90°). All specimens had identical rectangular cross section dimensions (150 mm × 300 mm) and longitudinal steel reinforcements, as shown in Fig. 1. Strain gages were installed at longitudinal steel reinforcements, closed stirrups, and CFRP sheets (only for strengthened specimens).

Figure 2 shows the full wrap configuration details for single-layer CFRP sheet. The overlap length was 300 mm in the longitudinal fiber direction. Before CFRP sheets were bonded to the RC specimens, a manual grinding was conducted on the concrete substrate to remove the localized out-of-plane variations. All corners were also rounded to 25-mm radius to reduce stress concentrations (ACI 440.2R-17). In the case of RC column specimens, an axial compression force of 270 kN was applied with four external steel rods before the CFRP wrapping process. This load level, which is 25% of the nominal compressive strength calculated from RC section properties (ACI 318–19), was chosen to simulate the columns under service loads. The axial compression force was maintained constant until the end of torsion test.

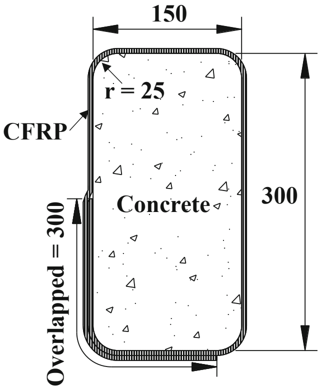


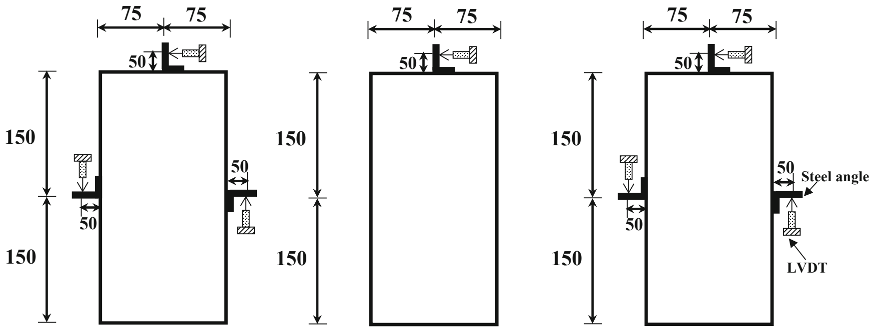
Fig. 2. Full wrap configuration (Dimensions in mm).

2.3 Static Torsion Test

Figure 3 shows the torsion test setup for both RC beam and column specimens. All specimens were simply supported by two steel rollers. Two rotatable steel caps were used at both ends of the specimens to minimize the friction, i.e., allow free rotation, during the torsion test. The torsional moment was applied by the vertical hydraulic jack via a steel spreader beam. In the case of column specimens, the external steel rods were replaced with the horizontal hydraulic jack at the beginning of the torsion test. In the replacement process, the tension forces in the external steel rods were relieved as the compression force of the hydraulic jack increased. During the torsion test, the rate of vertical loading was controlled at 10 kN/min, while the horizontal axial compression was maintained constant by the horizontal hydraulic jack. Figure 4 shows the setup of displacement transducers for measuring the angle of twist.

a) b)

Fig. 3. Torsion test setup a) constant axial compression from horizontal hydraulic jack, b) increasing torsional moment from vertical hydraulic jack.



(a) Section A-A **(b) Section B-B** **(c) Section C-C**

Fig. 4. LVDT setup for angle of twist (Dimensions in mm).

3 Experimental Results and Discussion

Table 1 summarizes the static torsion test results of all tested RC specimens including the cracking torsional moment, (T_{cr}), yielding torsional moment ($T_{yield,s}$ from strain gages at steel stirrups and $T_{yield,l}$ from strain gages at longitudinal steel), maximum torsional moment (T_{max}), and maximum CFRP strain values.

Figure 5 shows typical failure characteristics of unwrapped and CFRP-wrapped RC specimens. The fiber rupture was observed at the round corner of the section of CFRP-wrapped specimens. No debonding was observed. This implies that the overlap length was sufficient.

Table 1. Static torsion test results of RC specimens

Specimen	Standard hook angle (deg)	Stirrup spacing (mm)	Torsional moment (kN.m)				Maximum measured CFRP strain (microstrain)
			T_{cr}	$T_{yield,s}$	$T_{yield,l}$	T_{max}	
Beams							
B-90–150	90	150	3.17	3.66	4.73	5.64	
B-90–75	90	75	4.33	5.76	-[b]	6.39	
B-135–75	135	75	5.52	8.52	-[b]	8.74	
BF-90-150[a]	90	150	8.28	13.92	12.76	16.34	5924
BF-90–75	90	75	8.31	11.54	13.82	17.60	6154
BF-135-75[a]	135	135	8.70	14.86	13.46	17.28	-[c]
Columns							
C-90–150	90	150	4.89	9.49	-[b]	11.08	
C-90–75	90	75	4.92	11.26	-[b]	11.42	
C-135–75	135	75	5.56	-[b]	-[b]	11.89	
CF-90–150	90	150	13.42	14.75	-[b]	23.05	11968
CF-90–75	90	75	11.92	15.94	23.02	23.19	8634
CF-135–75	135	75	13.29	18.04	-[b]	25.70	4391

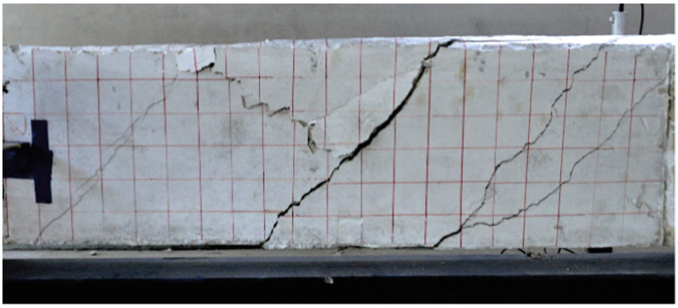
Remark [a] = retested after concrete cracking had occurred; [b] = no yielding before the maximum load; [c] = sensor problem.

Figure 6 shows the torsion-twist angle relationship of the representative CFRP-wrapped beam specimen. The measured steel and CFRP strains are also shown. Obviously, both longitudinal reinforcements and closed stirrups had yielded before the maximum load was attained. In addition, the CFRP strains at the measured locations (strain gage no. SF 1 to 5 in Fig. 1) were less than the fiber rupture strain.

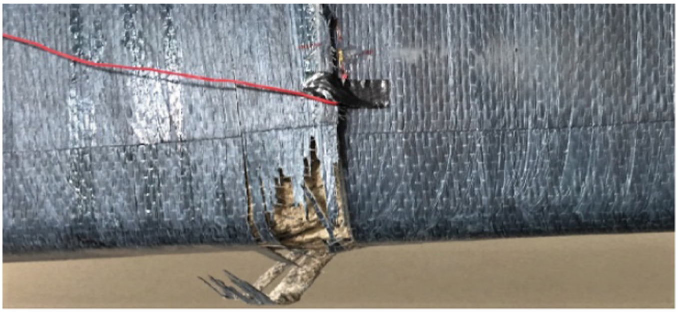
Figures 7, 8, 9 show the torsion-twist angle relationships of the representative CFRP-strengthened column specimens CF-90–150, CF-90–75, and CF-135–75, respectively. For these specimens, the closed stirrups had yielded before the maximum load was attained. Similar to the CFRP-strengthened beam specimen, the CFRP strains in the column specimens were less than the fiber rupture strain.

According to Table 1, the cracking, yielding, and maximum torsional moment capacities of RC members tended to increase as the spacing of closed stirrups decreased. Also, the hook angle influenced both cracking and maximum torsional moment capacities. The use of 135° hook was superior to 90° hook. Figure 10a and 10b show the deformations of closed stirrups using 90° and 135° hooks after the torsion test. Obviously, the 90° hook exhibited more slips and openings than the 135° hook.

The cracking and maximum torsional moment capacities of unstrengthened RC members tended to increase as the spacing of the closed stirrups decreased. The increase in cracking, yield, and maximum torsional moment capacities of RC members ranged



a) unwrapped RC members (specimen B-90-75)



b) CFRP-wrapped RC members (specimen CF-90-150)

Fig. 5. Typical failure characteristics.

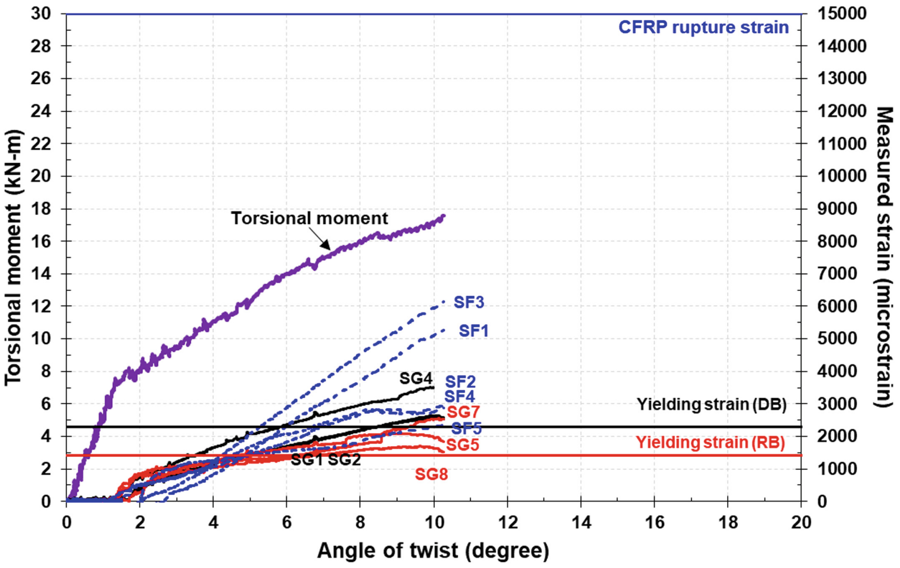


Fig. 6. Torsion-twist angle relationship of CFRP-strengthened beam specimen BF-90–75.

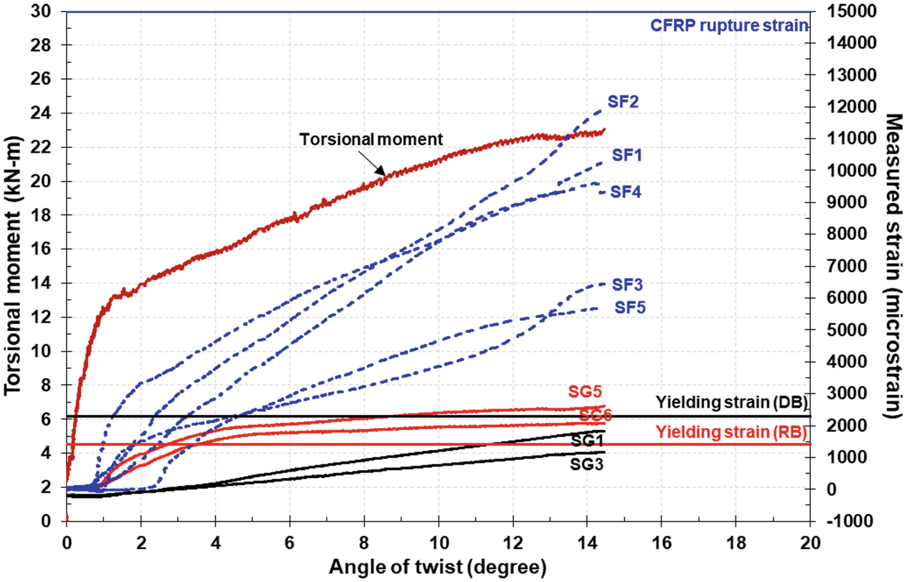


Fig. 7. Torsion-twist angle relationship of CFRP-strengthened column specimen CF-90–150.

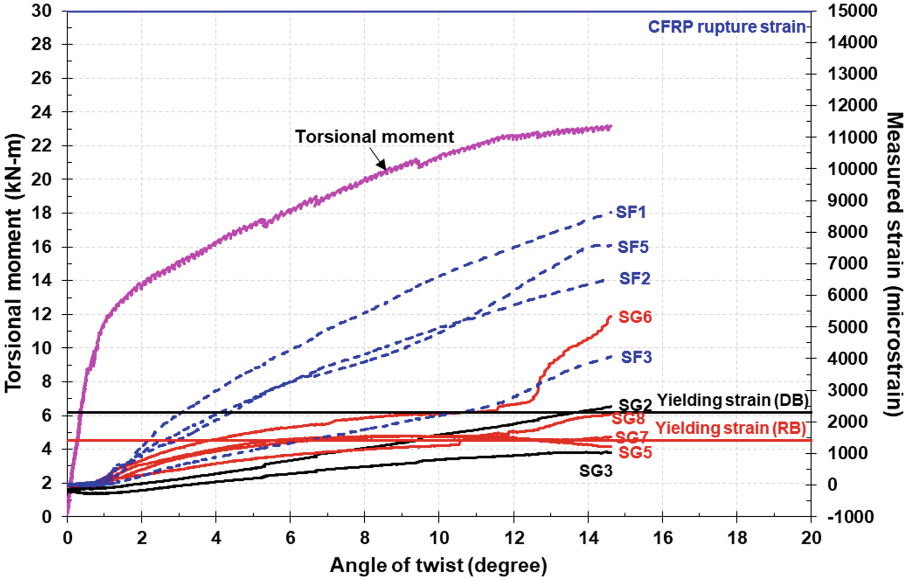


Fig. 8. Torsion-twist angle relationship of CFRP-strengthened column specimen CF-90–75.

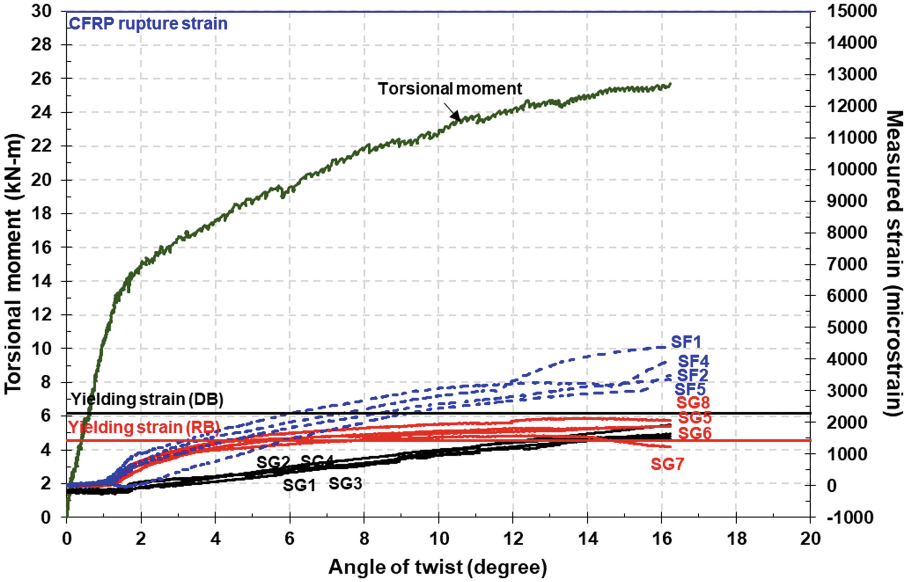


Fig. 9. Torsion-twist angle relationship of CFRP-strengthened column specimen CF-135–75.

from 1 to 37%, 19 to 58%, and 3 to 13%, respectively. An application of the constant axial force at 25% of the nominal compressive strength influenced more on the maximum torsional capacity than cracking one. The increases in cracking, yielding, and maximum torsional moment capacities ranged from 1 to 54%, from 95 to 160%, and from 36 to 96%, respectively.

Finally, the externally bonded CFRP sheets with the full wrap configuration significantly improved the torsional performance of RC beams and columns. For RC beams, the CFRP wraps enhanced the cracking, yielding, and maximum torsional moment capacities from 58 to 161%, from 58 to 249%, and from 98 to 190%, respectively. For RC columns, the CFRP wraps enhanced the cracking, yielding, and maximum torsional moment capacities from 139 to 174%, from 42 to 55%, and from 103 to 116%, respectively.

a) b)

Fig. 10. Deformations of stirrups after removal of concrete covering a) 90° hooks [specimen B-90–150], b) and 135° hooks [specimen C-135–75].

4 Assessment on Fib14 Effective Strain

fib14 (2001) provides an equation to calculate the effective FRP strain (ε_{fe}) in the principal material direction for the case of fully wrapped FRP as follows,

$$\varepsilon_{fe} = 0.17\left(\frac{f_c^{\prime 2/3}}{E_f \rho_f}\right)^{0.30} \varepsilon_{fu} \tag{1}$$

where $f_c^{\prime}$ is the concrete compressive strength (MPa); E_f is the elastic modulus of FRP (GPa); ε_{fu} is the ultimate strain of FRP; and ρ_f is FRP reinforcement ratio. Using Eq. (1), the predicted effective CFRP strain was 5788 μm/m.

In the experiments, the maximum CFRP strains measured in beam specimens BF-90–150 and BF-90–75 were 5924 (39% of rupture CFRP strain) and 6454 (41%) μm/m, respectively, while ones in column specimens CF-90–150, CF-90–75, and CF-135–75 were 11968 (80%), 8634 (58%), and 4391 (29%) μm/m, respectively. Therefore, the ratios between measured CFRP strains to prediction were 1.02, 1.06, 2.07, 1.49, and 0.76 for specimens BF-90–150, BF-90–75, CF-90–150, CF-90–75, and CF-90–135, respectively. Therefore, Eq. (1) correlated better with the maximum CFRP strains in RC beams than columns.

5 Conclusions

In this paper, the experimental program that investigated the strengthening effects of one-layer CFRP full wrapping on the RC members under torsion is described. Effects of test variables including the constant axial compression, internal stirrup spacing, and standard hook type of the closed stirrups on the torsional moment capacities are emphasized. Based on the experimental results, the following conclusions can be drawn:

1. The cracking, yielding, and maximum torsional moment capacities of RC members tended to increase as the spacing of closed stirrups decreased. The cracking, yielding,

and maximum torsional moment capacities of RC members increased up to 37%, 58%, and 13%, respectively.
2. The use of 135° hook was more effective than 90° hook. The cracking, yielding, and maximum torsional moment capacities of RC members increased up to 27%, 48%, and 48%, respectively.
3. An application of the constant axial force (25% of the nominal compressive strength) increased the cracking, yielding, and maximum torsional moments by up to 54%, 160%, and 96%, respectively.
4. The fiber rupture was observed in all RC members fully wrapped with CFRP sheets.
5. The CFRP wrapping enhanced the cracking, yielding, and maximum torsional moment capacities of RC beams from 58 to 161%, from 58 to 249%, and from 98 to 190%, respectively.
6. The CFRP wrapping enhanced the cracking, yielding, and maximum torsional moment capacities of RC columns from 139 to 174%, from 42 to 55%, and from 103 to 116%, respectively.
7. The effective CFRP strain predicted by fib14 equation correlated better with RC beams than RC columns.

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