Study on the behavior of RC beams strengthened with CFRP laminates under pure torsion using finite element analysis and *fib* Bulletin 14 method

Muhanad Mohammad Majed [1], Mohammadreza Tavakkolizadeh[2]

1 Ph.D. Student, Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
2 Assistant Professor, Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

ABSTRACT

This paper discussed analytical and finite element (FE) studies on behavior of CFRP (Carbon Fiber Reinforced Polymer) strengthened reinforced concrete (RC) beams under pure torsion. Behavior of rectangular reinforced concrete beams strengthened with CFRP laminates under pure torsion was studied using finite element method by ABAQUS. Results were compared with the experimental data collected from previous studies. The finite element ultimate torsional capacity showed good agreement with the experimental results. In addition, the analytical methods suggested by *fib* Bulletin 14 was used to predict value of effective CFRP strain and the torsional moment capacity. The difference between FE capacity of control and strengthened beams was less than 11%. The comparison between the design approaches suggested by *fib* Bulletin 14 with previous experimental results discussed and compared.

1 INTRODUCTION

Very few studies focused on torsion beams strengthening using FRP. The torsion is considered a minor effect in some cases, while it becomes critical in cases such as horizontally curved beams, members of a space frame, eccentrically loaded beams, spandrel beams, and spiral staircases are typical examples of structural elements subjected to major torsional moments and hence torsion cannot be neglected in design of such members. Therefore, it is important to understand the behavior of RC members subjected to twisting about its longitudinal axis, known as torsion.

Testing of FRP-strengthened concrete elements in torsion has been very limited. Some tests have been conducted by Täljsten (1998) who proven that torsional strengthening of beams with rectangular cross sections is viable with CFRP wrapping *fib* (2001). Panchacharam & Belarbi (2002) presented an experimental work to study the behavior and performance of reinforced concrete members strengthened with externally bonded Glass FRP (GFRP) sheets subjected to pure torsion. Six RC spandrel beams were tested by Salom et al (2004). Assuming that the torsional moment capacity is a function of only the amount and spacing of the torsional reinforcement, the nominal torsional capacity of the control specimen can be estimated using the equation given in (ACI318M-02) (2002). Hii & Al-Mahaidi (2006) tested six medium scale RC beams of 500 mm x 350 mm cross section and 2500 mm long; where two specimens were solid sections while the rest were box sections with 50 mm thick walls and flanges. Hii & Al-Mahaidi (2006) performed an experimental and numerical investigation on torsional strengthening of solid and box-section reinforced concrete beams using CFRP laminates. CFRP and GFRP-strengthened RC beams with a rectangular cross-section have been tested by Ameli et al. (2007) and the results then were compared with those obtained from the nonlinear finite element program ANSYS.

Chalioris (2008) used an experimental program includes 14 rectangular and T-shaped beams were tested under pure torsion. Torsion failure is an undesirable brittle form of failure as showed by Deifalla & Ghobarah (2010).

Numerical studies using finite FE have been carried out by many researchers to understand the overall behavior of concrete members with and without FRP strengthening. Chellapandian et al. (2017) Analytical and finite element studies on the behavior of Reinforced Concrete (RC) column elements strengthened using a hybrid Carbon Fiber Reinforced Polymer (CFRP) laminates and externally bonded fabric is explored in this study a numerical model of column elements is developed using a commercial software ABAQUS. Dawood (2013) examined the behavior and performance of solid and box section RC Beams and found that the increase in torsional strength enhances torsional strength when using CFRP composites. For this purpose, that researcher used the ANSYS (FE) program to model the beam. The torsional behavior of RC members strengthened with CFRP laminates presented by Allawi (2006) using two different software DIANA version 9.0 and P3DNFEA. Alabdulhady et al. (2017) described the results of numerical simulation performed using LS-DYNA to investigate the torsional behavior of reinforced concrete beams strengthened with externally bonded fiber reinforced cementitious Matrix (FRCM) composite.

The current study is aimed to explore more information about RC beams strengthened with externally bonded CFRP and subjected to pure torsion numerically with different strengthening schemes. The simulation is performed with software program ABAQUS/CAE 2016. Torsional strength, torque and angle of twist per unit length response are evaluated and compared with experimental results to validate the model and determine its accuracy. *fib* Bulletin 14 (2001) described here and compared with experimental data. The model is capable of predicting failure for concrete materials. Both cracking and crushing failure modes but in this study, failure criteria for CFRP strengthened beams were not considered. They are needed to define a failure surface for the concrete. The results of FE were plotted until the beams readied failure in the experimental study.

2 VALIDATION OF FE AND *fib* BULLETIN 14 METHOD

For FEA validation the specimens tested is taken from other researchers previously published by Chalioris (2008). The beams selected for the purpose of the numerical simulation in this paper were Ra-Fs150 (2) and Ra-S5.5/75 for group Ra, Rb-F (1) and Rb-S5.5/160 for group Rb. The datails of tested beams are summarized in Table 1.

Table 1. Details of the test beams used for validation.(Chalioris, 2008)

Beam	Flexural reinforcement	Shear reinforcement	Type of strengthening	n_f mm ()	A_f/S_f (mm)	ρ_{sl} %	ρ_{st} %	ρ_{ft} %
Ra-Fs150(2)	4Ø8	-	Wrapping with 150 mm width strips spaced 300mm apart	2	0.11	1.01	-	0.33
Ra-s5.5/75	4Ø8	Ø 5.5/75	-	-	-	1.01	0.67	-
Rb-F(1)	4Ø8	-	Full wrapping	1	0.11	0.45	-	0.22
Rb-s 5.5/160	4Ø8	Ø 5.5/160	-	-	-	0.45	0.22	-

For fib Bulletin 14 method validation, five beams strengthened with CFRP (Ra and Rb) were considered. Details of these beams are listed in Table 2 and their experimental test setup is shown in Figure 1. Additional information of the experimental work and setups may be found in references (Chalioris, 2008).

3 FINITE ELEMENT ANALYSIS FOR EXPERIMENTAL RESULTS

To study more thoroughly the torsional behavior of reinforced concrete beams strengthened with CFRP, a nonlinear finite element analysis has been carried out to analyze experimentally tested beams. The analysis was performed by using the FE using software program ABAQUS. A nonlinear finite element model is proposed in this study to Simulate the torsional behavior of FRP strengthened RC beams for various parameters using ABAQUS. Modelling details are discussed in the following sections. The verification is done in order to check the validity and accuracy of the finite element procedure. The accuracy of the finite element models was determined by ensuring that the ultimate torque was reasonably predicted with the experimental results, and the torque - twist and torque are close to the experimental curves.

Table 2. Details of strengthening and testing beams.(Chalioris, 2008)

Beam	b , h mm	ε_{fu} x 10^{-2}	f'_c MPa	t_f mm	E_{fu} GPa	θ Deg	β Deg	Experimental values Ultimate Torque kN.m	Ultimate Torque Refrence kN.m	Ultimate torque ($T_{f,CFRP}$) kN.m
Ra-F(1)	100,200	1.5	27.5	0.11	230	45	90	4.86	2.389	2.479
Ra-F(2)	100,200	1.5	27.5	0.22	230	45	90	6.65	2.389	4.261
Ra-Fs150(2)	100,200	1.5	27.5	0.11	230	45	90	3.018	2.389	0.629
Rb-Fs200(1)	150,300	1.5	28.5	0.05	230	45	90	9.315	6.951	2.364
Rb-Fs300(1)	150,300	1.5	28.5	0.05	230	45	90	7.52	6.951	0.569

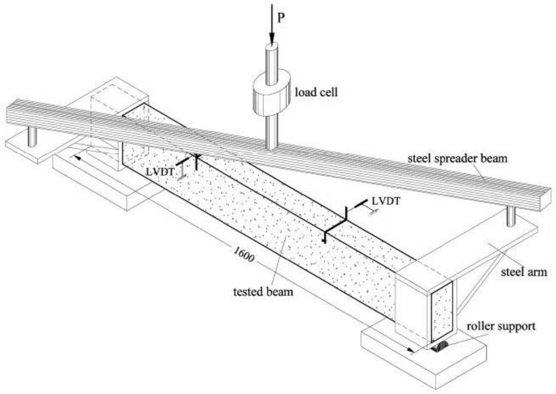


Figure 1. Experimental test setup for RC beam under torsion Chalioris (2008)

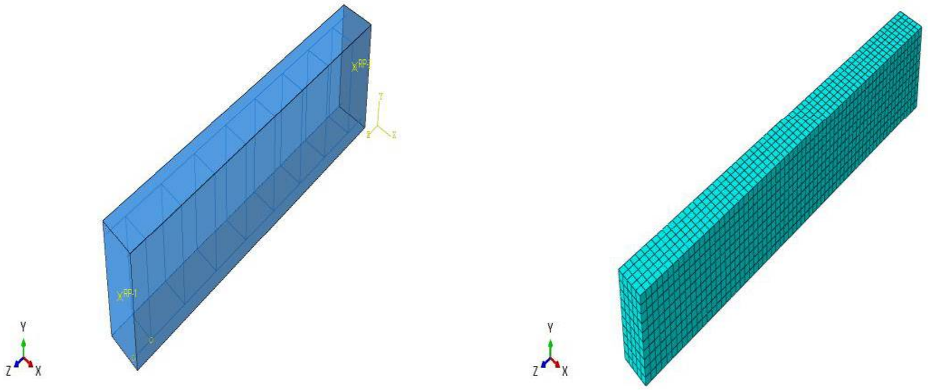
3.1 Model geometry

3.1.1 Concrete idealization

The modelled beam in ABAQUS is shown in Figure *2*. Concrete damaged plasticity available in ABAQUS/STANDARD. Concrete is modelled using three dimensional eight node solid brick elements with three Translational degrees of freedom at each node (C3D8R), Behavior of concrete in compression and tension are different, and the damage plasticity approach is adopted to model the concrete. Isotropic and linear elastic behavior of concrete both in compression and tension are defined Using Young's modulus and Poisson's ratio, nonlinear behavior is defined in terms of inelastic Strain and corresponding yield stress, parabolic model is used to define the compressive stress strain curve, Failure ratios for concrete used in the model are reported in Table *3*.

Table 3. Parameters for FE Modelling

Dilation angle	Eccentricity	Bi-axial to uni-axial compressive strength ratio	K	Viscosity parameter
36	0.1	1.16	0.67	0



(a) Concrete and steel section.

(b) Mesh of the Model

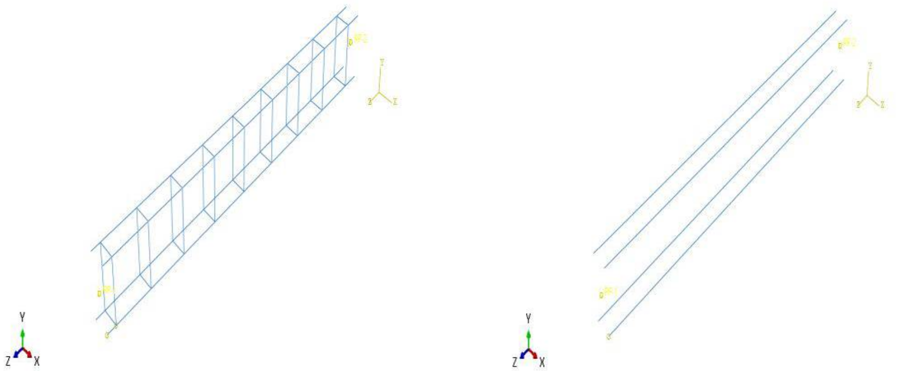
Figure 2. Finite element discretization of different components

3.1.2 Reinforcing bar idealization

The modeled of the longitudinal and stirrups rebars in ABAQUS is shown in Figure 3. The embedded element technique is used to specify that steel reinforcement element are embedded in host concrete elements. Steel reinforcing bars were modeled using material model type plastic. The parameters needed are the modulus of elasticity E, Poisson's ratio and yield stress. The modulus of elasticity and yield strength are listed in Table *4*. Longitudinal and transverse reinforcements are modeled with three dimensional; two nodded truss elements (T2D3), elastic perfectly plastic stress strain relationship is assumed for steel under both compression and tension, Steel being an isotropic material; linear elastic behavior is defined by elastic modulus and Poisson's ratio. Perfectly plastic behavior is defined using any two points on the yield line in terms of inelastic strain and yield stress.

Table 4. Reinforcement material properties

Rebar diameter (mm)	Yield Stress (MPa)	Modulus of Elasticity (GPa)
8	560	200
5.5	350	200



(a) Transverse Reinforcement (b) Longitudinal Reinforcement

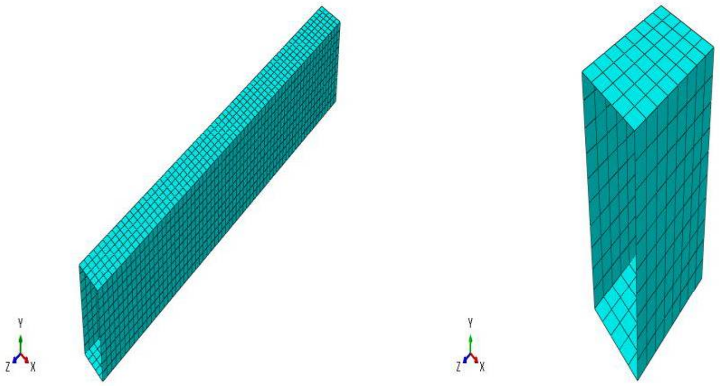
Figure 3. Finite element discretization of different components

3.1.3 CFRP idealization

The modeled of full wrapping and wrapping with strips in ABAQUS is shown in Figure 4. FRP (S4R) is modelled using three dimensional shell element. The main parameters needed in this model are E and shear modulus G in three orthogonal directions, and fiber direction is defined by a vector. The properties of fibers are listed in Table 5.

Table 5. Properties of the CFRP used in the present study

Properties	CFRP (SikaWrap-200c)
Thickness (mm)	0.11
Tensile strength (MPa)	3900
Modulus of Elasticity (GPa)	230



(a) Mesh of full wrapping (b) Mesh of wrapping with strip

Figure 4. Finite element discretization of different components

3.1.4 Interaction: Concrete

Concrete - steel interaction is modelled using embedded region constraint which is a built-in interaction in ABAQUS. Steel interaction is modelled using embedded region constraint which is a built-in interaction in ABAQUS. Perfect bond is also assumed to define the interaction between Concrete and FRP for simplification using a tie constraint. Table 6. summarizes the type of element and material behavior used for all specimens.

Table 6. Element type and Idealized stress strain curve of materials

Material	Element type	Idealized curve
Concrete	Solid-C3D8R	Parabolic
Steel	Truss-T3D3	Elastic –perfectly plastic
FRP	Shell-S4R	Elastic

4 RESULTS

4.1 *Ultimate torque*

Finite element and experimental results for overall torsional moment behavior are compared for the tested beams. Analytical predictions are validated with the experimental results taken from previous study and a good agreement was found. The values of ultimate torsion (kN.m) and ultimate angle of twist per length (rad/m) of tested beams obtained from the theoretical study (ABAQUS/CAE.2016) and experimental tests are reported in Table *7*. Results obtained from FE show that the model was able to predict the ultimate torque with difference in the range of 1-11%. Considering the bond properties of FRP and concrete my yield improved results. The influence of FRP is less significant before cracking of the concrete and this led to accurate prediction of the cracking torque and corresponding twist. However, the ultimate torque and corresponding twist were reasonably captured. The boundary condition plays very important role in the calculations of FE analysis.

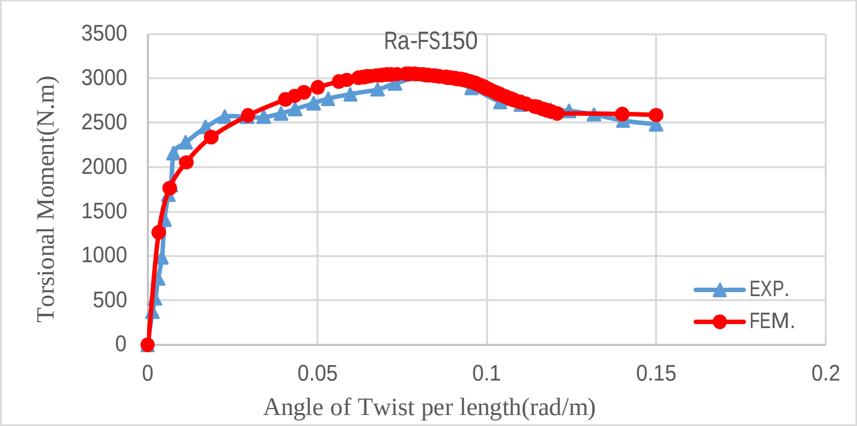
Table 7. Experimental and theoretical ABAQUS ultimate torque results for the control and strengthened beams

Specimen	Cracking torque (k N-m)		Cracking twist (rad/m)		Peak torque T_u (k N-m)		Peak twist θ_u (rad/m)		$\frac{T_{u,EXP.}}{T_{u,FEM.}}$	$\frac{\theta_{u,EXP.}}{\theta_{u,FEM.}}$
	EXP.	FEM.	EXP.	FEM.	EXP.	FEM.	EXP.	FEM.		

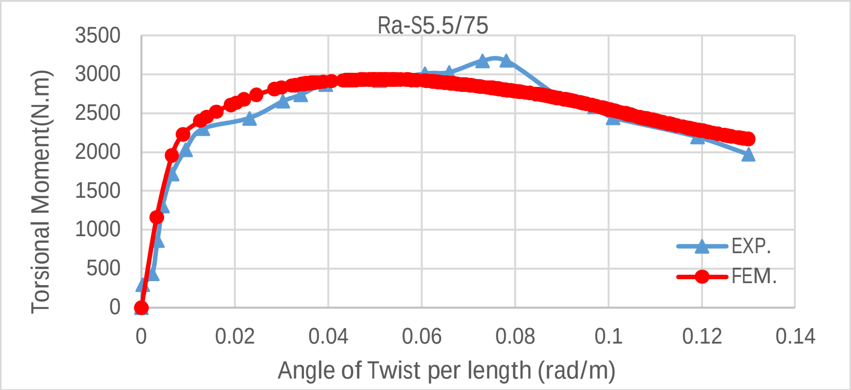
Ra-Fs150(2)	2.219	1.762	0.009	0.0065	3.018	3.049	0.088	0.076	1.01	1.15
Ra-S5.5/75	2.250	2.230	0.013	0.0089	3.156	2.940	0.078	0.052	1.07	1.5
Rb-F(1)	8.794	8.779	0.009	0.0077	10.050	10.27	0.071	0.027	1.021	0.37
Rb-S5.5/160	6.924	7.660	0.009	0.0088	6.924	7.7	0.009	0.0075	1.11	1.2

4.2 Torque – Twist behavior

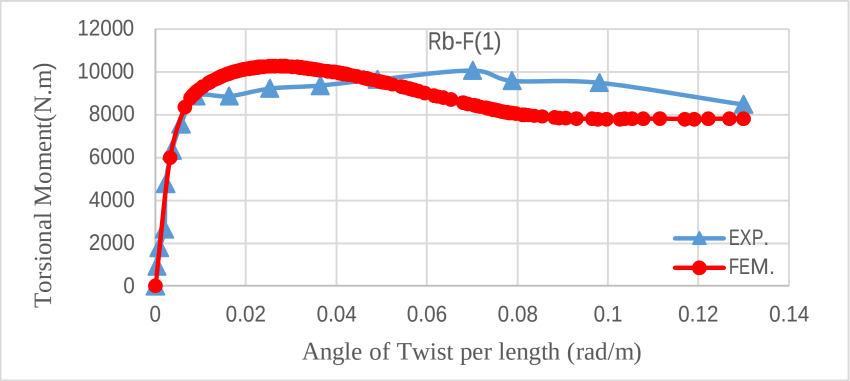
Torque-twist behavior of the all specimens predicted by model is offered in Figure 5 shows the comparison between experimental and FE results of overall torque - twist behavior of all tested beams. In general, it can be noted from the torque - twist curve that the finite element analysis are agree well with the experimental results during the full range of behavior. The FE models accurately predicted the cracking torque and cracking twist peak values of torque and peak twist were also captured reasonably well.



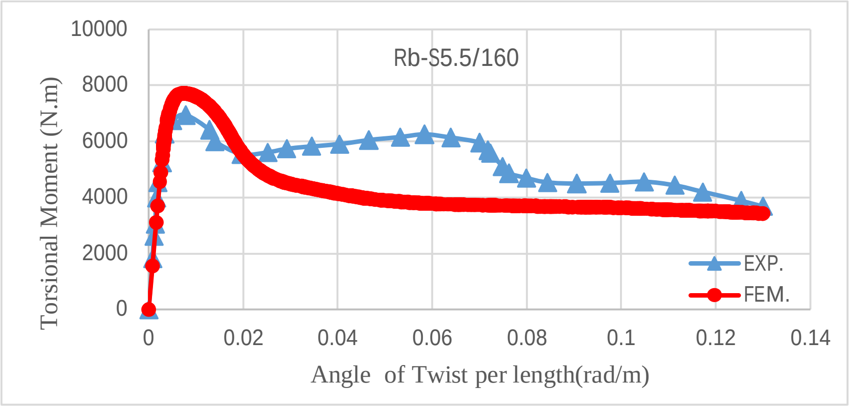
(a) Ra-Fs150 (2)



(b) Ra-S5.5/75



(c) Rb F (1)



(d) Rb-S5.5/160

Figure 5. Comparison of FEM results and experimental data for beams

5 ANALYTICAL METHODS (*FIB*-14 GUIDELINE METHOD (FIB,2001)

Ghobarah et al. (2002) and (Salom et al., 2004) have proposed a simple limiting FRP strain value.

$$\varepsilon_{fe} = \frac{T_f\, S}{2A_0 A_f E_f(\cos\alpha+\sin\alpha)} \qquad (5.1)$$

Ameli et al.(2003), Panchacharam & Belarbi (2002) and Hii & Al-Mahaidi (2007) adopted *fib*-14 guideline method of predicting the effective CFRP strain. These analytical methods can be discussed below and compared to a data base compiled from the previous study data.

$$T_{n,FRP} = 2\varepsilon_{fde}E_{fu}\,A_f S_f^{-1} A_c(\cot\theta+\cot\alpha)\sin\alpha \qquad (5.2)$$

$$\varepsilon_{f,calc} = \frac{T_{f,exp}}{2\,E_{fu}A_f S_f^{-1}A_c(cot\,\theta+cot\,\alpha)\,sin\,\alpha} \qquad (5.3)$$

$$\varepsilon_{fk,e} = K\varepsilon_{f,e} \leq \varepsilon_{max} \qquad (5.4)$$

$$\varepsilon_{fd,e} = \frac{\varepsilon_{fk,e}}{\gamma_f} \qquad (5.5)$$

where $(A_f = b_f t_f)$ is the area of fiber strip/wrap; $(b_f)$is the width of FRP strips; $(K = 0.8)$ is used to define the characteristic effective FRP strain$(\varepsilon_{fk,e})$; $(S_f)$is center to center spacing of FRP strips; $(t_f)$is the thickness of fiber laminate; $(\alpha)$is the angle between principal fiber orientation and longitudinal axis of member; $(\varepsilon_{fd,e})$is the design value of effective fiber strain; $\varepsilon_{max} = 5000$ micro-strain for shear case as stated by (*fib*, 2001) while ,the (ACI Committee 400 , 2002) suggest limited value of 0.004 ; $(\gamma_t)$is the material safety factor for the FRP (range 1.2 - 1.5 in *fib* bulletin 14*);* and (θ) is the angle of crack to longitudinal axis.

The effective fiber strain (ε_{fe}) is:

For completely wrapped sample

$$\varepsilon_{fe} = 0.17\left(\frac{fcm^{2/3}}{E_f\rho_f}\right)^{0.3}\varepsilon_{fu} \tag{5.6}$$

And for samples strengthened with strips:

$$\varepsilon_{fe} = \min 0.8\left[0.65\,\left(\frac{fcm^{2/3}}{E_f\rho_f}\right)^{0.56} x10^{-3}, 0.17\left(\frac{fcm^{2/3}}{E_f\rho_f}\right)^{0.3}\varepsilon_{fu}\right] \tag{5.7}$$

Where $f_{cm}$is the compressive strength of concrete in MPa, $E_f$is in GPa and. ρ_f is the CFRP reinforcement ratio.

Table 8. Comparison between experimental and calculated CFRP torsional contribution predicted by *fib*-14 Method

Beam	$T_{f.CFRP}$ KN.m (Test)	$T_{f.CFRP}$ KN.m (*fib*-14)	$T_{f.CFRP}$ KN.m ($\varepsilon_{f.CFRP=0.004}$)	$\frac{T_{f,CFRP,EXP}}{T_{f,CFRP(FIB-14)}}$	$\frac{T_{f,CFRP,EXP}}{T_{f,CFRP(\varepsilon_{f,CFRP=0.004})}}$	CFRP Strain Level	
						Analytical CFRP Stain	
						ε_{fe} Calculate $x10^{-3}$ Ghobarah & Salom et al.	ε_{fe} *fib*-14 Calculate $x\,10^{-3}$
Ra-F(1)	2.479	3.477	2.522	1.40	1.017	2.449	5.376
Ra-F(2)	4.261	5.648	5.044	1.32	1.18	2.105	4.366
Ra-Fs150 (2)	0.629	0.676	0.646	1.07	1.027	0.621	2.092
Rb-Fs200 (1)	2.364	2.3194	2.181	0.98	0.922	2.076	3.923
Rb-Fs300 (1)	0.569	1.427	0.727	2.5	1.277	0.499	3.923

The determination of effective CFRP strain (ε_{fe}) is based on partial safety factor (γ_f) equals to 1.3 and k = 0.8 CFRP torsional contribution based *fib*-14 expression for effective strain is compared with experimental results in Table 8. It can be seen the results are in good agreement with the test result and in encouraging when used maximum allowable value for effective CFRP strain of 0.004 according to the recommended ACI Committee 440 (2000) while the torsional contribution of CFRP predicted by *f*ib-14 (2001) is generally un conservative in defining the effective CFRP strain (ε_{fe}) when associated to the experimental results. That is because of limited available data on the behavior of reinforced concrete members strengthened with CFRP subjected to torsion at that time and the suggested torsion model by *fib*-14 (2001) is based on similar cracking mechanism of shear.

6 CONCLUSIONS

Numerical and analytical studies were carried out on strengthened beams elements under pure torsion. A non-linear finite element model was developed using ABAQUS and was calibrated with the test results. From the results and observation the following major conclusions can be drawn presented in this study:

1. The finite element simulation shows good agreement with the experimental results. Maximum difference in ultimate strength was (1-11%) for the strengthened and control beams.
2. The slight difference between the results from finite element models and experimental results indicate that the assumption of full interaction between CFRP composite and concrete is reasonable.
3. The nonlinear finite element model was able to capture the behavior of RC beams with and without FRP strengthening techniques under pure torsion.
4. The only torsional design method for reinforced concrete members strengthened with CFRP recommended by *fib*-14 was found to be generally un conservative. Therefore, future improvement is needed for *fib*- 14 guideline to make it suitable as a design method for torsional strengthening.
5. A value of 0.004 for the characteristic effective CFRP strain (ε_{fke}) suggested by ACI Committee 440 is shown to be an optimum value for design purposes.

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