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Non Destructive Repair of RC Structures Using FRP – Beams under Significant Torsion.

Omar Elmeligy[1], and A. Deifalla [12]

1 The British University in Egypt, El Shorouk City, Egypt
2 Technical University Braunschweig, Braunschweig, Germany

ABSTRACT: Torsion strengthening is a fairly new and complex problem that has been under investigation for over a decade. This study aims to provide a better understanding for the torsional behavior of reinforced concrete (RC) beams externally strengthened using FRP. A brief review for the published experimental testing and analytical studies is presented. The influence of the significant parameters (i.e. FRP reinforcement ratio, cross section shape, strengthening scheme, and failure mode) on the strength of the beams is examined. In addition, a regression formula for calculating the ultimate torsion strength of concrete beams strengthened using externally bonded (EB) FRP is proposed. The formula is developed using an extensive data base that accounts for: (1) various cross section shapes (i.e. rectangular, L-shaped, T-shaped, or H-shaped); (2) various mechanical properties and dimensions of the concrete and the FRP. The ratio between the strength predicted by the proposed formula and that measured during testing was compared to the ratios of the available models from the literature. The formula showed improved agreement and consistency with the experimental results compared to the available models from the literature.

1 INTRODUCTION

In recent years, there have been more reports of structural failures attributed to torsion (Whittle 2013). Whittle (2013) identified several reasons for failures including but not limited to design errors, errors in structural modeling, inappropriate extrapolation of the code of practice or inadequate assessment of critical forces path. In addition, failure could be because of aging and lack of maintenance. Reinforced concrete (RC) members subjected to significant torsion may fail suddenly which could to severe casualties. One such technique for strengthening involves adding external reinforcements in the form of sheets made of advanced materials, which offer the designer a new combination of properties not available from other materials and effective rehabilitation systems. Fiber-reinforced polymers (FRP) is a composite material, which have superior properties over other alternative materials that can be used as external reinforcement for RC beams such as steel plates and concrete jackets. It is Non corrosive and has high strength to weight ratio compared to steel plates. It is easy to handle and install. Externally bonded fiber reinforced polymers (EB-FRP) laminates and fabrics are used for strengthening concrete structures. For the last three decades, most of the research efforts focused on the flexure and shear behavior of RC beams strengthened using EB-FRP. However, for the last two decades, torsion behavior of RC beams strengthened using EB-FRP has recently gained a lot of attention as shown in fig. 1. Over the last few years, several experimental investigations were conducted for studying the torsional behavior of FRP externally reinforced concrete beams. In the case of torsion strengthening, de-bonding failure is most common failure mode, which is usually accompanied by excessive concrete cracking or bond slippage at the FRP and concrete interface.

In addition, available bond models developed based on simple shear testing of FRP sheets bonded to concrete blocks have shown that the FRP ultimate strain most probably will not be reached, regardless, how large the value of the interface length between the FRP and the concrete.

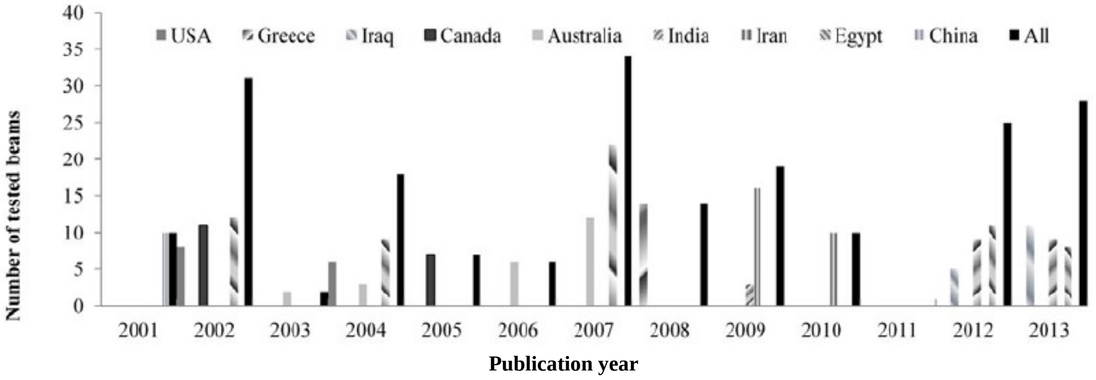


Figure 1. Number of tested beams versus publication year worldwide.

The objective of this study is to provide a base for a torsion design provision for EB-FRP concrete beams. A brief review for the experimental studies in the area is being presented and assessed. A simplified regression formula for EB-FRP beams is presented. The formula is developed using an extensive experimental database of over 150 tested beams covering wide range of various parameters including: (1) cross section shape; (2) thickness of each FRP layer; (3) spacing between FRP strips; (4) FRP material properties; (5) concrete cross section properties; (6) number of FRP layers and (7) concrete compression strength. Moreover, the predication of the proposed formula was compared with that of the available models (FIB, 2001; Deifalla and Ghobarah, 2005; ACI, 2008). The proposed model predicted the strength of the beams more accurately than the existing models.

2 PREVIOUS EXPERIMENTAL TESTING

Since 2001, FRP has been studied as an externally reinforcing material for beams under torsion. A review of the previous studies was conducted. For the case of concrete beams strengthened using EB-FRP, the following parameters were investigated: (1) strengthening scheme which varied depending on the practical application (i.e. access to 3 or 4 faces of the beam); (2) type of fibers used (CFRP; GFRP, ...etc.); (3) original loading and condition before strengthening; (4) number of plies; (5) spacing of strips; (6) fiber orientation (parallel and perpendicular to the longitudinal axis of the beam); (7) influence of anchors; and (8) continuous wrap or strips. Table 1 shows a survey of the previous 157 experimental tests conducted on EB-FRP concrete beams under torsion. Various strengthening techniques were implemented, which included the following: a) Full continuous wrapping; b) U-jacket continuous wrapping; c) Full strips wrapping; d) U-jacket strips wrapping; e) Longitudinal strips; f) Longitudinal strips and full strips wrapping; g) inclined one side strips; h) inclined full strips wrapping; i) Full strips wrapping; j) Extended U-jacket strips wrapping with longitudinal strips; k) Extended U-jacket strips wrapping; l) Extended U-jacket continuous wrapping; m) U-jacket continuous wrapping; n) Extended U-jacket continuous wrapping; o) Full continuous wrapping. As shown in figure 2, four distinctive modes of failure were recognized as follows: (i) end de-bonding of the FRP sheet (ED), (ii) intermediate crack induced de-bonding (ID), (iii) diagonal failure due to excessive diagonal cracking or crushing of the diagonal strut (DF), and (iv) FRP rupture (R). Careful examination of the profile of the experimental database showed the following remarks: (1) although beams are usually connected to a flange (i.e. a floor slab or inverted flanged beam) and the cross section shape have a significant effect on the behavior and design, only 21% of the tested beams had a flanged cross section while 77% investigated rectangular beams. T-shaped beams and continuous jackets were studied, even though in many cases continuous jackets can be uneconomic with respect to strips and T-shaped beams are less likely to be subjected to significant torsion compared to L-shaped beams. Only 11% of the tested beams have an L-shaped cross-section; (2) since the usage of anchors significantly increases, the torsional strength, the usage of anchorage systems for beams with EB-FRP under shear and torsion is gaining a lot of attention (Kalfat et al., 2013). However, only 21% of the tested beams examined the usage of anchors; (3) although continuous jackets are more effective than strip jackets, it can be uneconomic in most cases, compared to FRP strip jacket. However, 61% and 37% of tested beams investigated continuous and strip jackets, respectively; (4) Tested beams failing due to DF, ID, ED, R were 46%, 28%, 10%, 16%, respectively, showing that majority of tested beams fail due to DF or debonding, while rupture is limited to only 16%.

(A) (B) (C)

Figure 2. Various failure modes observed: A) DF, B) ED and C) ID.

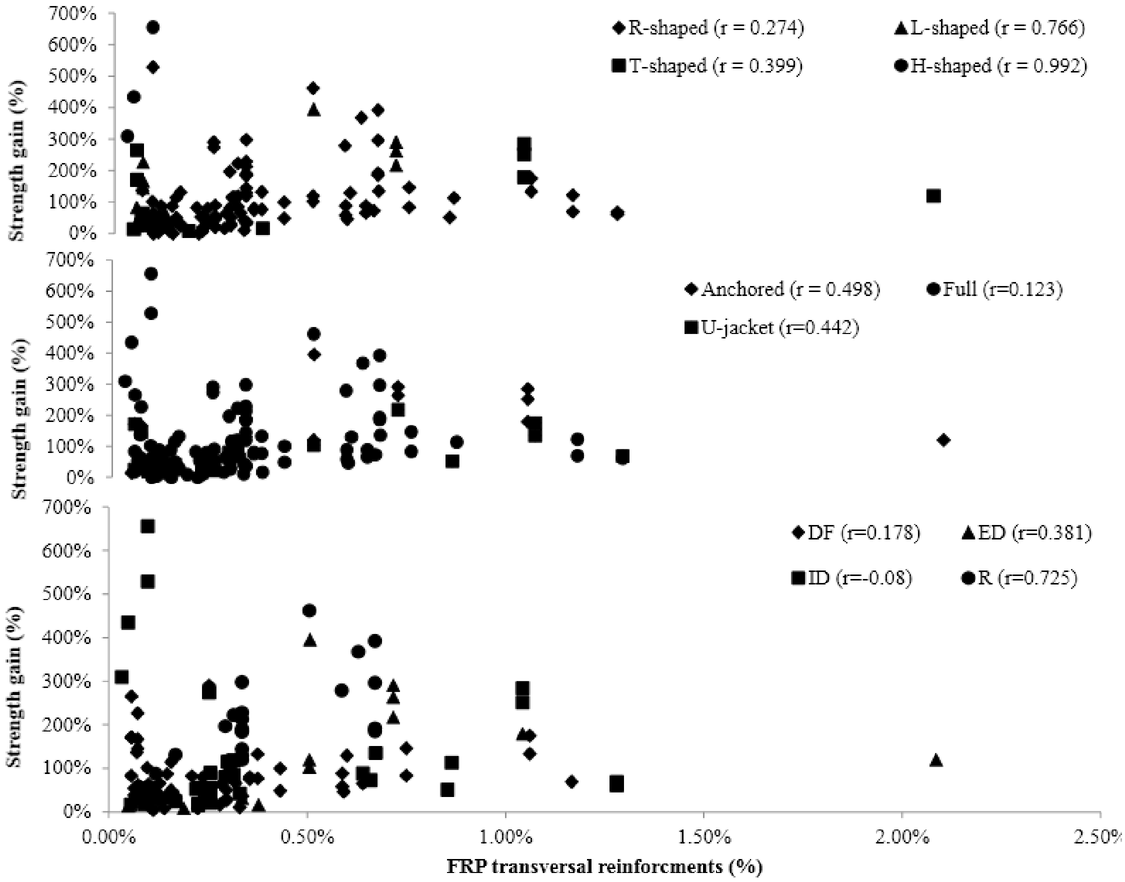


Figure 3.Strength gain versus FRP reinforcement ratio

Table (1) previous experimental studies

Study	No. of beams	Rectangle	T-shaped	L-shaped	Hollow	h ≤ 400 mm	Full	U-jacket	Strips	Continuous	Inclined	Using Anchors	Spacing	Preloading	Number of plies	Size effect
Zhang et al. (2001)	9	9				9	7		7				■	■	■	
Biddah et al. (2002)	4	4				4	4			4				■	■	
Ghobarah et al. (2002)	8	8				8	8		5	2	2		■			
Panchacharam (2002)	7	7				7	4	3	4	3		■			■	
Sharobim and Moktar (2002)	7	7				7	5	2	5	2			■	■		
Ronagh and Dux (2003)	1	1				1	1			1						■
Salom et al. (2004)	4			4		4		4		4	1	■				
Sayed Mandour (2004)	6	6				6	2		6						■	
HE et al. (2004)	6	6				6	6		3	3						
Hii and Al-Mahaidi (2004)	2	2				2	2		2							
Deifalla and Ghobarah (2010)	4		4			4	2	2		4	4	■			■	
Hii and Al-Mahaidi (2006)	4	1			3	4	4		4				■		■	
Ameli et al. (2007)	10	10				10	6	4	4	6					■	
Genidi (2007)	16	10	3	3		16	8	8	14	2	2			■		
Chalioris (2008)	8	6	2			8	6	2	3	5					■	■
Mohammedizadeh et al. (2009)	10	10				10	8	2	2	8		■			■	
Natarajan and Kumar (2009)	2	2				2		2	2							
Mohammedizadeh et al. (2010)	7	7				7	6	1	2	5		■			■	
Mahmood and Mahmood (2011)	8	8				8	6	2	3	5			■			
Abduljalil and Sarsam (2012)	4		4			3		4	4		1					
Chhabirani (2012)	8	8				8	8		6	2	2		■			
Deifalla et al. (2013b)	8	2	2	4		8	3	5	8		3	■	■			
El-kateb et al. 2013	7			7		7	2	5	7				■			■
Khanna and Patra (2013)	1	1				1	1		1							■
Jariwala et al. (2013)	6	6				6	6		4	2	2	■	■			
Number of tested beams	157	121	15	18	3	156	105	46	96	58	17	7	9	4	12	2
Percentage (%)		77	10	11	2	99	67	29	61	37	11	28	36	16	48	8

2.1 *Effect of various parameters on the strength gain*

Figures 3.a, 3.b, and 3.c shows the strength gain versus the FRP reinforcement ratio categorized based on the cross section shape, the strengthening scheme, or the failure mode, respectively. In addition, the Pearson correlation coefficients calculated for each category as shown in fig. 3.

From figure 3, the following can be shown: (1) although the torsion gain of beams with various cross section shapes is dependent on the FRP reinforcement ratio; however, the degree of correlation ranges between 27% to 99%; (2) For the full wrapping scheme, the torsion gain is not dependent on the FRP reinforcement ratio, while for the anchored and U-jacket scheme, the torsion gain is highly dependent on the FRP reinforcement ratio; (3) For beams failing due to DF or ID, the torsion gain is not dependent on the FRP reinforcement ratio, while for beams failing due to ED or R, the torsion gain is dependent on the FRP reinforcement ratio.

3 PREVIOUS ANALYTICAL MODELS

3.1 FIB (2001)

The model assumed that there is no interaction between the steel and FRP contribution to the torsion resistance of the section. The contribution of the FRP to the torsion capacity of the beam (T_f) was computed as:

$$T_f = \frac{2E_f \varepsilon_f t_f w_f bh \cot(\theta)}{s_f} \text{ For full wrapping,} \qquad T_f = \frac{E_f \varepsilon_f t_f w_f bh \cot(\theta)}{s_f} \text{ For U-wrapping} \tag{1}$$

Where E_f is Young's Modulus of the FRP, t_f is the thickness of the FRP, b and h is the width and depth of the concrete section, respectively, w_f is the width of the FRP strip, s_f is the spacing between strips, θ is the angle of inclination of the diagonal cracks to the longitudinal axis of the beam. The effective FRP strain ε_f is calculated such that: and using the formulas:

$$\varepsilon_f = 0.17\left(\frac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.3} \varepsilon_{fu} \text{ For CFRP,} \qquad \varepsilon_f = 0.048\left(\frac{f_{cm}^{2/3}}{E_{fu}\rho_f}\right)^{0.47} \varepsilon_{fu} \text{ For GFRP} \tag{2}$$

where ε_{fu} is the ultimate strain in the FRP and ρ_f is FRP reinforcement ratio with respect to concrete calculated as $\rho_f = \frac{2t_f w_f}{bs_f}$

3.2 Deifalla and Ghobarah (2005)

Deifalla and Ghobarah (2005) developed a simple method for calculating the torsion contribution of the FRP contribution (T_f) such that:

$$T_f = \frac{2A_{of} f_f n_f t_f w[\cot(\beta_f) + \cot(\theta)]\sin(\beta_f)}{S_f} \tag{3}$$

where A_{of} is area enclosed inside the critical shear flow path due to the strengthening, f_f is the stress in the FRP sheets at failure, β_f is angle of orientation of the fiber direction to the longitudinal axis of the beam and s_f is the spacing between the centreline of the FRP strips, n_f is the number of FRP layers and w_f is the width of the FRP strips. The FRP effective strain is taken such that:

$$\varepsilon_f = \min mum\ of\left(\frac{0.33}{L_e}\frac{w_f}{s_f}, \frac{0.2\alpha_f}{L_e}, 0.1(E_{fu}\rho_{ft})^{-0.86}\varepsilon_{fu}\right) \tag{4}$$

where the development length(L_e) is calculated using $L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_c^`}}}$, α_f is a constant to take into account the difference in the stress distribution between the continuous FRP sheets and the strips which is calculated as $\alpha_f = \sqrt{\frac{(2 - \frac{w_f}{s_f \sin\beta_f})}{(1 + \frac{w_f}{s_f \sin\beta_f})}}$ and ρ_{tf} is the FRP reinforcement ratio and calculated as: $\rho_{ft} = \frac{A_f}{t_c s_f}$, where t_c is the thickness of the equivalent hollow tube section taken as A_{of} / p_f.

3.3 ACI (2008)

The effective strain for FRP strips in shear is being adapted for the purpose of this study such that:

$$\varepsilon_{f\max} = \begin{cases} 0.004 \le 0.75\varepsilon_{ult} \cdots\cdots\cdots\cdots\cdots\cdots \text{for full wrapping} \\ \frac{K_1 K_2 L_e}{11{,}900\varepsilon_{fu}}\varepsilon_{ult} \le 0.75\varepsilon_{ult} \le 0.004 \cdots \text{for U or side jacket} \end{cases} \tag{5}$$

Where, $K_1 = \left(\frac{f_c^`}{27}\right)^{2/3}$, $K_2 = \begin{cases} \frac{d_{fv} - L_e}{d_{fv}} \cdots \text{for U} - \text{jacket} \\ \frac{d_{fv} - 2L_e}{d_{fv}} \cdots \text{for Side} - \text{jacket} \end{cases}$, and $L_e = \frac{23{,}300}{\left(n_f t_f E_f\right)^{0.58}}$

4 PROPOSED MODEL

While examining the available models, it was noticed that all of them drop down to a power equation in terms of the mechanical properties and dimensions of the concrete beam and FRP strips. A Multivariable regression analysis in search for finding the best fit for the extensive data was carried out. The outcome of this was the simple model for calculating the torsion strength of concrete beams strengthened with EB-FRP such that:

$$T_f = 0.09\frac{f_c^{`0.82} A_c^{1.22} n_f^{0.92}\left(w_f / s_f\right)^{0.37}}{P_c^{0.95} t_f^{0.2} E_f^{1.1} \varepsilon_{ult}^{0.27}} \tag{6}$$

In order to measure the strength of the relationship between the torsion strength and the dependent variables using the proposed model, Multiple R was calculated as 0.87, which indicated good correlation. In addition, an F test was conducted in order to determine whether the proposed model represents a good fit and can be generalized to the population represented by the experimental database. It showed the proposed model is, in fact, a good fit with a level of significance less than 0.05. Moreover, a t-test was used to evaluate the individual relationship between each of the parameters included in the model and the ultimate torsion strength, which showed that there is a statistically significant relationship between each of the parameters and the ultimate strength with a level of significance less than 0.05. It is worth noting that the model is different from the well-known theoretical models for torsion, where the increase in the strength is always directly proportional with the maximum strain and young's modulus of the FRP. However, this could be due to the following reasons: (1) with the exception of beams failing in rupture, which are less than 16% of the total tested beams, the strength gain is not dependent on the FRP strength; (2) models assume uniform distribution for the shear flow, wall thickness, shear stresses, and stirrup strain, which was shown to be in accurate by many researchers. In addition, further investigations into proposing a conservative design provision based on the proposed formula, with simpler power constants, is under going (Deifalla, 2015).

4.1 *Proposed Model Verification*

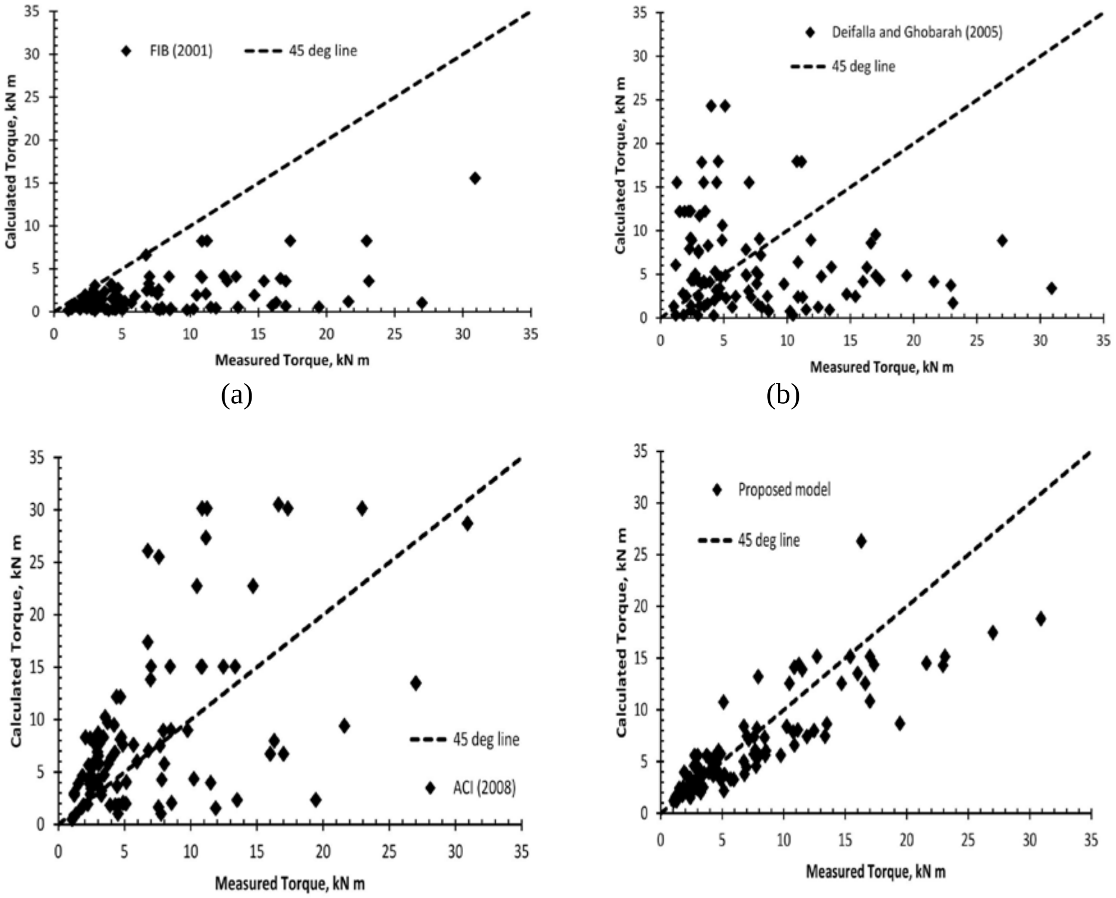
The strength was calculated using the available and proposed models. Angle Θ was taken 45 degrees to simplify the analysis for the purpose of this study. The ratios between the calculated strength, using the four different models, and the measured strength were graphed as shown in figs. 4(a-d). In addition, Table 2 shows the overall average, standard deviation, maximum, minimum, and 95% confidence interval. The proposed model showed a better agreement with the experimental results compared to the other models. Although the ACI (2008) had a comparable average with the proposed model, the proposed model predictions were remarkably consistent, having significantly lower standard deviation, compared to the ACI (2008) and the other models.

Table 2 – Comparing the ratio of the measured and predicted strength from various models.

Models	FIB (2001)	Deifalla and Ghobarah (2005)	ACI (2008)	Proposed formula
Average	8.50	2.31	1.22	1.11
St. Deviation	9.48	3.58	1.53	0.40
Maximum	42.29	22.62	8.25	2.32
Minimum	0.89	0.21	0.07	0.23
Lower 95%	6.47	1.55	0.89	1.02
Upper 95%	10.52	3.08	1.54	1.20

5 SUMMARY AND CONCLUSIONS

A comprehensive literature review for the experimental research on torsion strengthening was presented. The effectiveness of the repair was not only dependent on the ratio of the FRP reinforcement but it is affected by many parameters including but not limited to: (1) the mechanical properties and dimensions of the concrete and the FRP; (2) the cross section shape; and (3) the implemented strengthening technique. In addition, a formula for predicting the torsion strength of concrete beams strengthened using EB-FRP was presented, which was found to provide better accuracy compared with previous models.



(a) (b)

(c) (d)

Figure 4 – Measured torque versus calculated using a) FIB (2001), b) Deifalla and Ghobarah (2005), c) ACI (2008), d) Proposed formula.

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7 REFERENCES

Abduljalil, B., S. and Sarsam, K., F., 2012, Torsional Behavior of Reinforced Concrete T Beams Strengthened with CFRP Strips. Eng, & Tech. Journal, 30(9): 1462-1482.

Ameli, M. Ronagh, H., R. Dux, P., F. 2007, Behavior of FRP strengthened concrete beams under torsion. ASCE, J Compos Constr, 11(2): 192–200.

American Concrete Institute, ACI., 2008, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. ACI 440.2R-08, Farmington Hills, MI.

Biddah A, El-Behairy S and Hussien S., 2002, Repair and strengthening of bridge concrete beams subjected to shear and torsion using FRP. Proceedings, 6th international conference on short and medium span bridges, Vancouver, Canada.

Chakraborty, D. and Mehrolia, A., 2011, Torsional Behavior of RC Beams Wrapped With Fibre Reinforced Polymer (FRP). BTech thesis.

Chalioris, C., E., 2008, Torsional strengthening of rectangular and flanged beams using carbon fiber-reinforced-polymers - Experimental study. Construction & Building Materials, 22(1): 21-29.

Chhabirani, T., 2012, Study of Torsional Behavior of Rectangular Reinforced Concrete Beams Wrapped with GFRP. Thesis submitted in partial fulfillment of the requirements of the master of technology in civil Engineering, National Inst. Of Tech., India, 90 pp.

Deifalla A, Awad A, El-Garhy M., 2013, Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion: an experimental study. Eng Struct, Elsevier, 56: 2065–75.

Deifalla, A. and Ghobarah, A., 2010, Strengthening RC T-Beams Subjected to Combined Torsion and Shear Using FRP Fabrics: Experimental Study. J. Compos. Constr, ASCE, 14(1), 301-312.

Deifalla, A., 2015, Proposed torsion design provisions for concrete beams strengthened using EB-FRP. On progress.

Deifalla, A., Ghobarah, A., 2005, Simplified Analysis of RC Beams Torsionaly strengthened Using FRP. Proceedings of International Symposium on Bond Behavior of FRP in Structures (BBFS 2005), Hong Kong, China, 381-386.

El-Kateb, M., M., Abdel Rahman, A., Hassan, T. K., 2013, Torsional Strengthening of Reinforced Concrete Beams Using CFRP Sheets. Civil engineering Research Magazine CERM, Al-Azhar University, 35 (2): 10.

FIB, 2001, Externally Bonded FRP Reinforcement for RC Structures. (CEB-FIP) Technical Report, 14: 59-68.

Genidi, M., 2007, Strengthening of reinforced concrete beams in shear and torsion using composite materials. Thesis submitted in partial fulfillment of PhD degree, Faculty of Engineering, Helwan University.

Ghobarah, A, Ghorbel, M, Chidiac, S., 2002, Upgrading torsional resistance of RC beams using FRP. J Compos Constr, ASCE, 6(4): 257–63.

HE , H., Kiyomiya, O., and Masuda, A. 2004, Experimental Study on Torsion Behaviour of PC Beams Strengthened with Carbon Fiber Sheets. Composite， 26 (2): 4 -8.

Higazy, E. and El-Kateb, M., 2011, Strengthening of reinforced concrete beams under torsion using CFRP sheets. 36th Conference on Our World in Concrete & Structures Singapore, August 14-16.

Hii A. and Al-Mahaidi R., 2006, An Experimental and numerical investigation on torsional strengthening of solid and box-section RC beams using CFRP laminates. Composite Structures, 75: 213–221.

Hii, A., K. Y., and Al-Mahaidi, R., 2004, Torsional strengthening of reinforced concrete beams using CFRP composites. 2nd Int. Conf. on FRP Composites in Civil Engineering, CICE2004, Adelaide, Australia: 551–559.

Jariwala, V. H., Patel, P. V., Purohit, S. P., 2013, Strengthening of RC beams subjected to combined torsion and bending with GFRP composites. Procedia Engineering, 51: 282-289.

Jing M, Raongjant W., Li Z., 2007, Torsional strengthening of reinforced concrete box beams using carbon fiber reinforced polymer. Composite Structures, 78 (2): 264-270.

Kalfat R, Al-Mahaidi R, Smith ST., 2013, Anchorage devices used to improve the performance of reinforced concrete beams retrofitted with FRP composites: state-of-the-art review. J Compos Constr, ASCE,17(1): 14–33.

Khanna, S. and Patra, K.C., 2013, Torsional Strengthening of R.C. Beams Using Glass Fibre Reinforced Polymers (GFRP). IJERT, 2(8): 1873-1878.

Mahmood, M. N. and Mahmood, A. Sh., 2011, Torsional behavior of pre-stressed concrete beam strengthened with CFRP sheets. 16th International Conference on Composite Structures, ICCS 16.

Mohammadizadeh M.R., Fadeel M.J. and Ronagh, H. R., 2009, Improving Torsional behavior of reinforced concrete beams strengthened with carbon fibre reinforced polymer composite. Iranian Polymer Journal, 18(4): 315-327.

Mohammadizadeh, M.R., Fadeel M.J., 2010, Experimental investigation on torsional strengthening of high strength concrete beams using CFRP sheets. Kuwait J. Sci. Eng. 37(1B): 1-19.

Natarajan, C. and Kumar, P. A., 2009, Experimental investigation of torsional behaviour of glass fibre wrapped reinforced concrete beam. International Journal of Earth Science and Engineering, 2(1): 63-67.

Panchacharam S, Belarbi A., 2002. Torsional behavior of reinforced concrete beams strengthened with FRP composites. Proceedings, 1st FIB congress on concrete structures, Osaka, Japan; 10 pp.

Ronagh, H. R., and Dux, P. F., 2003, Full-scale torsion testing of concrete beams strengthened with CFRP. 1st Int. Conf. on the Performance of Construction Materials in the New Millennium, Cairo, Egypt: 735–743.

Salom PR, Gergely JM, Young, D.T., 2004, Torsional strengthening of spandrel beams with fiber-reinforced polymer laminates. J Composite for Construction, ASCE, 8(2), 157–162.

Sayed M., 2004, Strengthening of reinforced concrete beams in torsion. Master thesis, Faculty of Engineering, El zag-zig University, Egypt.

Sharobim K, Mokhtar H., 2002, Behavior of retrofitted concrete beams using carbon fiber reinforced plastics under torsion. In: Structural composites for infrastructure application, Aswan, Egypt; December 17–20: 10 pp.

SURE, N., 2013, Experimental and analytical study on torsional behavior of RC flanged beams strengthened with glass fiber. Submitted in partial fulfillment of the requirements for the Master of Technology Degree in Civil Engineering, Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha, India

Whittle, R., 2013, Failures in Concrete Structures - Case Studies in Reinforced and Prestressed Concrete, CRC Press Taylor & Francis Group, FL 33487-2742: 140.

Zhang JW, Lu TZ, Zhu H. 2001, Experimental study on the behavior of RC torsional members externally bonded with CFRP. Proceeding of FRP composites in civil engineering conference, vol. I. Elsevier Science Ltd.: 713–22.