CENTER FOR INFRASTRUCTURE ENGINEERING STUDIES

Torsional Behavior of Reinforced Concrete Beams Strengthened with FRP Composites

by

Saravanan Panchacharam, Graduate Research Assistant
Abdeldjelil Belarbi, Associate Professor

Department of Civil Engineering,
University of Missouri – Rolla, Missouri, USA

University of Missouri-Rolla

CIES
02-27

Disclaimer

The mission of CIES is to provide leadership in research and education for solving society's problems affecting the nation's infrastructure systems. CIES is the primary conduit for communication among those on the UMR campus interested in infrastructure studies and provides coordination for collaborative efforts. CIES activities include interdisciplinary research and development with projects tailored to address needs of federal agencies, state agencies, and private industry as well as technology transfer and continuing/distance education to the engineering community and industry.

Center for Infrastructure Engineering Studies (CIES)
University of Missouri-Rolla
223 Engineering Research Lab
1870 Miner Circle
Rolla, MO 65409-0710
Tel: (573) 341-6223; fax -6215
E-mail: cies@umr.edu
www.cies.umr.edu

Torsional Behavior of Reinforced Concrete Beams Strengthened with FRP Composites

Saravanan Panchacharam, Graduate Research Assistant
Abdeldjelil Belarbi, Associate Professor

Department of Civil Engineering,
University of Missouri – Rolla, Missouri, USA

ABSTRACT

Fiber Reinforced Polymer (FRP) as an external reinforcement is used extensively to address the strength requirements related to flexure and shear in structural systems. But the strengthening of members subjected to torsion is yet to be explored. In this paper, the behavior and performance of reinforced concrete members strengthened with externally bonded Glass FRP (GFRP) sheets subjected to pure torsion is presented. The variables considered in the experimental study include the fiber orientation, the number of beam faces strengthened (three or four), the effect of number of FRP plies used, and the influence of anchors in U-wrapped test beams. Experimental results reveal that externally bonded GFRP sheets can significantly increase both the cracking and the ultimate torsional capacity. Predicted strengths of the test beams using the proposed theoretical models were found to be in good agreement with the experimental results.

Keywords: Composites, Fiber Reinforced Polymer, Reinforced Concrete Beam, Strengthening, Torsional Moments, Twist Deformation.

1 INTRODUCTION

Modern civilization relies upon the continuing performance of its civil engineering infrastructure ranging from industrial buildings to power stations and bridges. For the satisfactory performance of the existing structural system, the need for maintenance and strengthening is inevitable. Commonly encountered engineering challenges such as increases in service loads, changes in use of the structure, design and/or construction errors, degradation problems, changes in design code regulations, and seismic retrofits are some of the causes that led to the need for rehabilitation of existing structures. Complete replacement of an existing structure may not be a cost-effective solution and it is likely to become an increasing financial burden if upgrading is a viable alternative. In such occasions, repair and rehabilitation are the most commonly used solutions. Reinforcement corrosion and structural deterioration in reinforced concrete (RC) structures are common and prompted many researchers to seek alternative materials and rehabilitation techniques. While many solutions have been investigated over the past decades, there is always a demand to search for use of new technologies and materials to upgrade the deficient structures. In this context, strengthening with Fiber Reinforced Polymers (FRP) composite materials in the form of external reinforcement is of great interest to the civil engineering community.

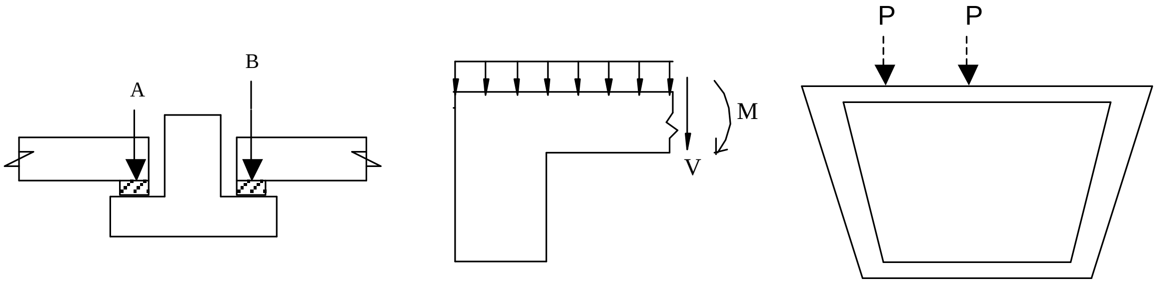
Externally bonded, FRP sheets are currently being studied and applied around the world for the repair and strengthening of structural concrete members [1]. FRP composite materials are of great interest to the civil engineering community because of their superior properties such as high stiffness and strength as well as ease of installation when compared to other repair materials. Also, the non-corrosive and non-magnetic nature of the materials along with its resistance to chemicals made FRP an excellent option for external reinforcement.

The method of strengthening structures with externally bonded FRP composite materials gained significant attention in the last two decades. The addition of externally bonded FRP sheets to improve the flexural and shear performance of RC beams has been actively pursued during the recent years. Research reveals that strengthening using FRP provides a substantial increase in post-cracking stiffness and ultimate load carrying capacity of the members subjected to flexure and shear [2], [3], [4]. Research related to the strengthening of torsional members with FRP composites is very limited and meager data or design guidelines are available in the literature. The lack of experimental and analytical studies along with the increasing interest in the use of FRP materials in the repair and rehabilitation of concrete structures led to this study on torsional behavior of reinforced concrete beams strengthened with FRP sheets.

The main objectives of this study were to investigate the torsional behavior of RC beams strengthened with externally bonded GFRP sheets and to identify the influence of the design variables considered in the effectiveness of strengthening. The variables considered were (1) fiber orientation (parallel and perpendicular to the longitudinal axis of the beam), (2) access to 3 faces or 4 faces of the beam for strengthening, (3) one ply and two plies orthogonally placed, (4) continuous wrap or strips and (5) influence of anchors in U-wrapped strengthening schemes.

2 EXPERIMENTAL PROGRAM

Structural members curved in plan, members of a space frame, eccentrically loaded beams, curved box girders in bridges, spandrel beams in buildings, and spiral stair-cases are typical examples of the structural elements subjected to torsional moments as shown in Fig. 1 and torsion cannot be neglected while designing such members. Structural members subjected to torsion are of different shapes such as T-shape, inverted L–shape, double T-shapes and box sections. These different configurations make the understanding of torsion in RC members a complex task. In addition, torsion is usually associated with bending moments and shearing forces, and the interaction among these forces is important. In order to improve the level of understanding of the effectiveness of strengthening of RC beams for torsion and to simplify the torsional characteristics, in the current study only square cross sections subjected to pure torsional moment were investigated.



a) Inverted - T beam supporting pre-cast floor slabs

b) Spandrel beam

c) Box girders

Fig. 1 Examples of torsion in structural members

2.1 Test beam details, materials, and strengthening schemes

Details of the reinforcement provided in the beam are explained as follows. In order to avoid the failure of the beams at torsional cracking load, each beam was designed to have a steel reinforcement of 1 % for each of transverse (stirrups) and longitudinal reinforcement, to the volume of the concrete. The percentage of reinforcements provided in the beam was slightly higher than the minimum required to maintain the integrity of the beam beyond cracking. Also this will represent the case of a deficient beam in terms of reinforcement. All beams were 279.4 mm by 279.4 mm square in cross-section and were reinforced with 4 – 12.7 mm and 4 – 9.53 mm bars in the longitudinal direction, (A_l = 800 mm^2) and reinforced with closed stirrups in the transverse direction with 9.53 mm bars spaced at 152.4 mm on center, in the test region. In order to force the failure in the mid zone of the test beam, end zones of 0.914 m long on each end of the beam were reinforced with 9.53 mm stirrups spaced at 38.1 mm on center. The test region of 2.134 m was selected in such a manner that at least two complete spiral cracks would form along the length of the test region. Hence the total length of the specimen was 3.96 m. A constant concrete cover of 25.4 mm was used for all test beams. Fig. 2 shows the details of the test specimen as well as the steel reinforcement provided in the test region as well as in the end regions, based on the above considerations.

In RC torsional members, diagonal cracks are formed due to the same mechanism that is responsible for the formation of shear cracks [5], [6]. Since the diagonal tension cracks are found to be common in both shear and torsion, the strengthening schemes considered in the shear strengthening situations [4] can be considered as possible options for torsional strengthening of RC beams. The main difference between shear cracking and torsional cracking lies in the crack pattern [6]. Spiral-like crack pattern are found in torsional members.

To study the most influential strengthening variable on torsional behavior a total of eight beams were included in this investigation. Out of the eight beams tested seven of them were strengthened with MBrace EGlass FRP sheets and one beam was not strengthened to serve as a reference beam. Schematic representations of the strengthening schemes are shown in Fig. 3. Test beams were identified based on the following naming system. Since test beams were made from three different batches of concrete and reinforcing bar (rebar) properties, the first character in the name (A, B or C) is used to distinguish the batch from which the test beam was made. Second character in the name (0 or 90) is used to specify the fiber orientation with respect to the longitudinal axis of the beam. Third character is used to specify the type of strengthening schemes such as complete wrap (W), strips (S), U-wrap (U) and longitudinal layout of fibers (L). Fourth character was used to specify the number of sides strengthened (three vs. four) along with the information pertained to the use of anchors (Anch).

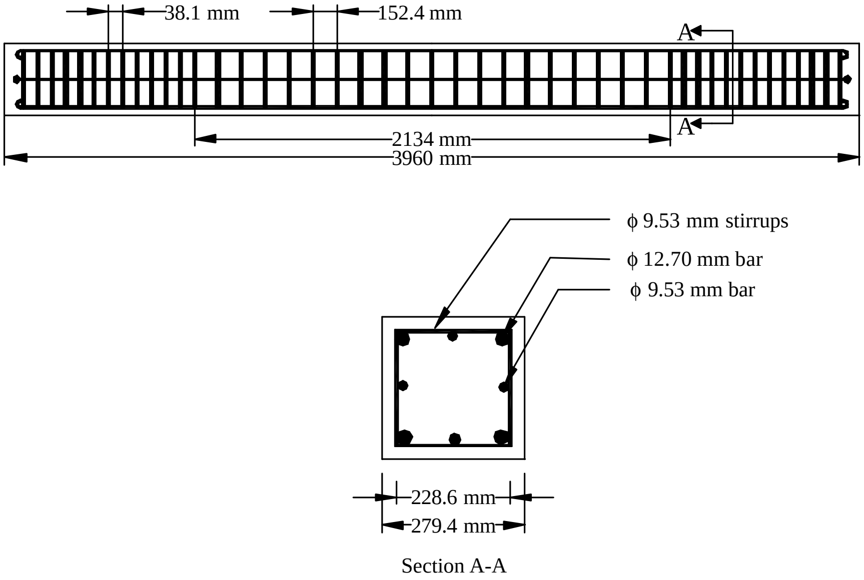
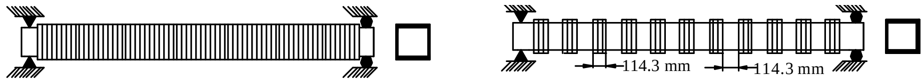
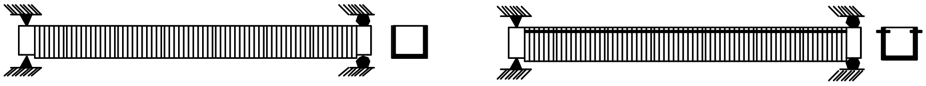


Fig. 2 Details of test beams and reinforcement layout



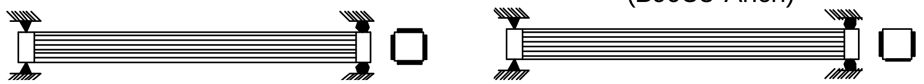
a) 90 degree complete wrap (A90W4)

b) 90 degree strips (A90S4)



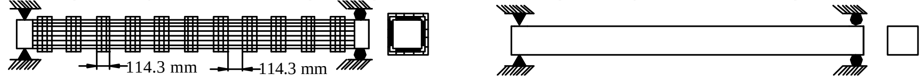
c) 90 degree U- wrap (C90U3)

d) 90 degree U- wrap with anchors (B90U3-Anch)



e) 0 degree, 4 sides (A0L4)

f) 0 degree, 3 sides (A0L3)



g) 0 degree, 4 sides and 90 degree strips (B0L4/90S4)

h) Reference beam (Ref)

Fig. 3 Schematic representation of strengthening schemes

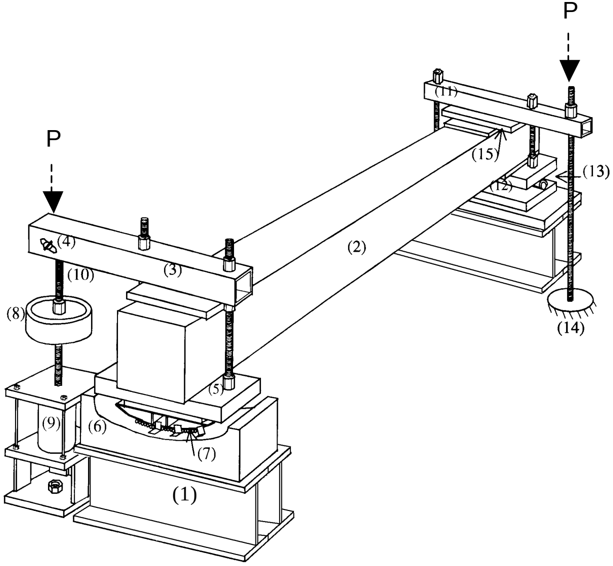
Table 1 provides a summary of the mechanical properties for steel reinforcing bars and concrete used in the manufacturing of the test beams. In the present study, GFRP (MBrace EG 900 E-Glass Fibers) was used to strengthen RC test beams. The design strength and tensile elastic modulus of GFRP sheets used to strengthen the RC beams were 1,520 MPa and 72 GPa, respectively [7].

Table 1 Mechanical properties of steel reinforcement and concrete

Batch	Steel Reinforcement				Concrete
	9.53 mm diameter bars		12.7 mm diameter bars		
	f_y (MPa)	f_u (MPa)	f_y (MPa)	f_u (MPa)	f_c' (MPa)
A	420	700	460	700	34
B	450	620	320	510	26
C	450	620	320	510	31

2.2 Test set-up and instrumentation

All beams were tested under pure torsion using the test setup shown in Fig. 4 [8]. A Hydraulic actuator of 130-kN capacity was used to apply the load on the beam through a loading arm. The loading arm denoted by (3) in Fig. 4. is capable of providing an eccentricity of up to 508 mm normal to the longitudinal axis of the beam. The test setup has a torsional moment capacity of 65 KN-m and 0.3 radians of twist, expandable to 0.7 radians.



(1) Supporting beam, (2) Test test beam (3) Loading arm, (4) Inclined cut, (5) Spherical bearing seat (6) Concrete pedestal, (7) Steel rollers, (8) Load cell, (9) Hydraulic Jack, (10) 25-mm diameter threaded rod, (11) Reaction arm, (12) Bearing plate, (13) 25-mm diameter steel roller, (14) Reaction floor, (15) Steel plates with rollers

Fig. 4 Schematic diagram of the torsion test set-up

The reaction end of the beam was allowed to slide freely in the longitudinal direction to avoid any axial restraints on the beam. After cracking, the beam is expected to elongate. Therefore, to allow for this longitudinal elongation, the reaction end of the beam was supported on rollers. A rotational variable differential transformer (RVDT) was used to measure the twist of the beam. Relative twist of the beam was also determined by measuring vertical displacements using two linear variable differential transformers (LVDTs) placed at both ends of the test region with one on each opposite side of the beam. Three other LVDT's were used to measure the surface strain in concrete, which were oriented in the form of rosette. Additional strain gages were placed on the steel rebars and on FRP sheets in the directions parallel and perpendicular to the fiber orientation for a more comprehensive data collection to be used for further analysis and future studies [9].

3 TEST RESULTS AND DISCUSSIONS

The beams were made in three different batches and hence the strength of the concrete was slightly different from one batch to another as given in Table 1. Also, one beam was slightly larger in dimension compared to other beams, due to manufacturing defect. To take into account the variation of concrete strength and cross sectional variation of the tested test beams, the test results were adjusted using $\sqrt{f_c^{'}}$ and A_{cp}^2/P_{cp}, as correcting parameters deduced from the design equations of ACI-318-99 design code [10]. For the purpose of comparing the test results of all test beams, the reference dimension of the test beam was taken as 279.4 mm by 279.4 mm and the concrete strength was taken as 30 MPa, which is an average of concrete strength obtained from 3 batches (see Table 1). In this study, eight beams were tested to investigate the parameters that potentially influence the behavior of RC beams strengthened with FRP sheets. Table 2. Provides the summary of the parameters studied and the corresponding test beams used for comparison and discussions.

Table 2 Summary of investigated parameters and corresponding test beams

Parameters Investigated	Test-beams
Fiber orientation	A90W4, A0L4, Ref
Complete wrap vs. strips	A90W4, A90S4, Ref
Three vs. four sides longitudinally strengthened	A0L4, A0L3, Ref
Complete wrap vs. U-wrap	A90W4, B90U3-Anch, C90U3, Ref
Strengthening in longitudinal and transverse directions	A90S4, A0L4, B0L4/90S4, Ref

Table 3 provides a summary of cracking and ultimate torsional moments of all test beams along with their relative increase in cracking and ultimate torsional moments with respect to reference beam. Even though the cracking strength is increased in all the strengthened beams, the Test-beam A0L4 with 0-degree fiber orientation exhibited a maximum (53 %) increase in cracking torque among all the test beams as shown in Table 3. However the increase in ultimate strength is the largest (149 %) for the Test-beam A90W4 strengthened with fibers in 90-degree direction.

Table 3 Test results for cracking and ultimate torsional moments

Test-beams	Cracking torque (kN-m)	% of increase in cracking torque	Ultimate torque (kN-m)	% of increase in ultimate torque
A90W4	22	29	45	149
A90S4	21	25	34	90
A0L4	26	53	29	62
A0L3	25	47	26	43
B0L4/90S4	22	29	35	96
B90U3-Anch	21	24	25	39
C90U3	20	20	24	35
Ref	17	-----	18	-----

3.1 Effect of fiber orientation

Fig. 5 shows the influence of fiber orientation on the torsional behavior of the RC beams strengthened with GFRP sheets. Cracking strength of the RC beam was increased significantly when it was strengthened with 0-degree GFRP fibers. Whereas the ultimate strength of the RC beam was increased significantly when it was strengthened with 90-degree GFRP fibers. The beam strengthened with 0-degree GFRP fibers provides considerably higher energy absorption capacity when compared to the un-strengthened beam. Also, 0-degree fibers provide considerably higher ductility when compared to the beam strengthened with fibers in 90-degree orientation. Post-cracking stiffness of the beam with fibers in 90-degree orientation is much higher than the beam with fibers oriented in the 0-degree direction. In Test-beam A90W4, failure mode of the test beam at ultimate was controlled by FRP rupture. Whereas, in the test beam A0L4, the diagonal tensile stresses induced in the beam causes the GFRP sheet to tear off along the fiber direction (separation in bundles of fibers). Overall, the 90-degree complete wrapping scheme provided an efficient confinement and in turn a significant increase in ultimate strength was observed, and 0-degree fibers provided a higher cracking capacity, larger post-cracking twist, and deformation-softening.

3.2 Effect of continuous wrapping versus strips

Fig. 6 shows that Test-beam A90W4, strengthened continuously with GFRP fibers in 90-degree orientation provided higher ultimate strength compared to Test-beam A90S4, strengthened with strips of 114.3 mm width, and spaced at 228.6 mm on center. Test-beam A90W4 exhibits a higher post-cracking stiffness compared to that of Test-beam A90S4. This is due to the effect of effective confinement in Test-beam A90W4. Also, the post cracking stiffness of Test-beam A90S4 is affected by the spacing of the strips. As the spacing of the strips becomes larger, the post-cracking stiffness will decrease due to the ineffectiveness of confinement of the test beam. Hence, one may infer that the effect of confinement, which is governed by both the strip width and spacing, affects the post cracking behavior of the test beams strengthened with fibers in 90-degree orientation. Post-cracking deformation and energy absorption capacity of the test beam strengthened with strips is much higher than the continuously wrapped beam, as shown in Fig. 6**.** Cracking strength was almost same for both Test-beams A90W4 and A90S4, but was considerably higher when compared to that of reference beam (see Fig. 6 and Table 3).

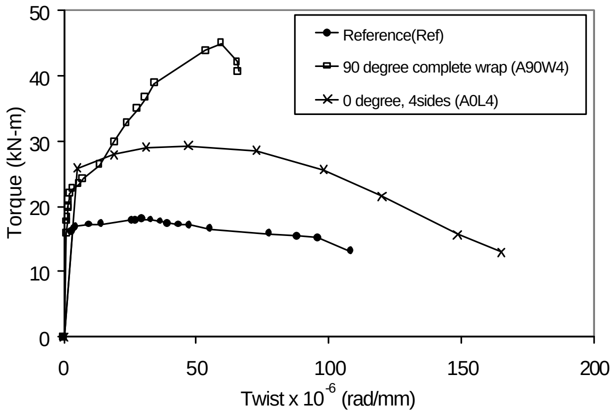


Fig. 5 Effect of fiber orientation

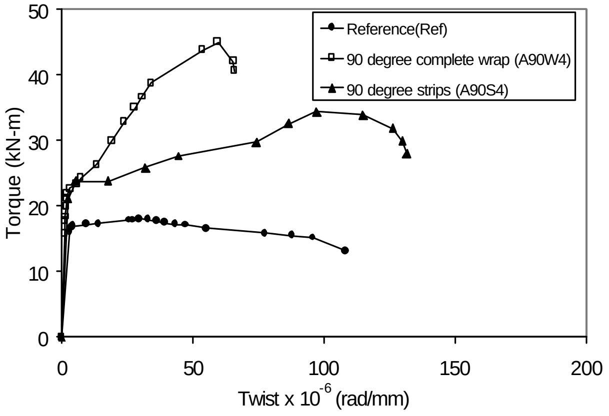


Fig. 6 Effect of 90-degree complete wrap vs. strips

3.3 Effect of three versus four sides strengthened longitudinally

In most practical situations, only 3 sides of the beam may be accessible for strengthening. The effect of strengthening on 4 sides versus 3 sides with fibers oriented in longitudinal direction is discussed herein. The beams strengthened on 4 sides and 3 sides with fibers oriented in longitudinal direction of the beam exhibited a similar behavior. Although the increase in cracking strength for both test beams was almost equal (Fig. 7), the increase in ultimate strength was proportionally related to the ratio of FRP used. In Test-beam A0L4, a total increase of 11KN-m in ultimate torque was observed when compared to the reference test beam. In Test-beam A0L3, the increase in ultimate torque with respect to reference was about 8KN-m, which is approximately three-fourth of the increase in ultimate strength obtained in Test-beam A0L4. It was also observed that Test-beam A0L3 reaches its ultimate strength at a relatively smaller twist angle when compared to Test-beam A0L4. This is due to the fact that Test-beam A0L3 had one un-strengthened side of the beam. As the load increases, the stiffness of Test-beam A0L3 reduces rapidly due to crushing of concrete in the un-strengthened face of the beam. When comparing the twist deformation of Test-beam A0L3 at ultimate, with that of reference beam the magnitude of both twists were almost identical to each other. Even though Test-beam A0L3 was strengthened with sheets on 3 sides the ultimate twist was controlled by the un-strengthened face similar to that of reference beam.

3.4 Effect of complete wrap versus U-wrap

Torsion is well resisted by closed-form of reinforcement, due to the circulatory nature of the torsion-induced shear flow stresses in a beam. Therefore, it will be more efficient to have strengthening schemes, which are wrapped in closed form around the cross section. But strengthening with U- wrap (three sides) is more practical because of the inaccessibility of the entire cross section due to extension of flanges in monolithic beam-slab construction. Since in the case of U-wrap, shear flow is not in the form of a closed loop, it was expected that the strengthening scheme might not be efficient in improving the ultimate torsional strength as shown in Fig. 8. Failure was governed by splitting (spalling) of concrete cover at the corner of the beam after GFRP sheets peeled of prematurely. One way to improve the performance of this scheme is to anchor the ends of the wrap to the beam. By the use of anchors the premature failure mode and hence the drastic reduction in post-cracking twist, observed in beam C90U3, was prevented Fig. 8. Rather than peeling of FRP sheets, crushing of concrete and lateral separation of anchor bars along with FRP sheets was observed in Test-beam B90U3-Anch. But the increase in ultimate strength of both test beams U-wrapped with anchors and without anchors was almost the same. Fig. 8 shows that the presence of anchors increases the post-cracking twist and absorption capacity when compared to U-wrapped test beam without anchors. Strengthening with complete wrap increases the ultimate strength of the beam considerably when compared to beams strengthened with U-wrap with and without anchors. However, the cracking strength was the same for all test beams of this group as shown in Fig. 8.

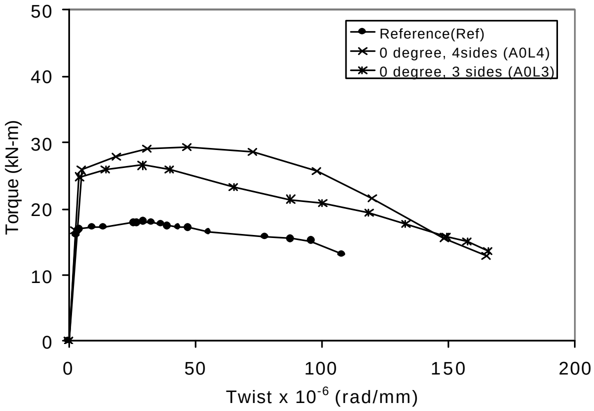


Fig. 7 Effect of number of sides strengthened longitudinally

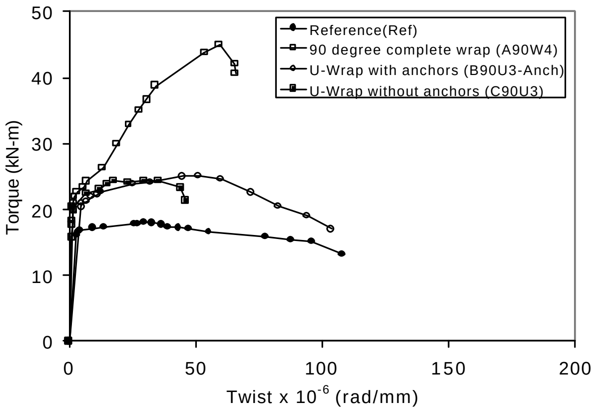


Fig. 8 Effect of complete wrap and U-wrap (with and without anchors)

3.5 Effect of strengthening in both longitudinal and transverse directions

Test-beam B0L4/90S4 was strenthened with longitudinal sheets on all four sides and with wrapped strips similar to Test-beam A90S4. In a sense, this beam combines the strengthening schemes of Test-beams A90S4 and A0L4. To understand the individual contribution of the 0-degree and 90-degree layers in Test-beam B0L4/90S4, torque-twist curves of Test-beams A0L4 and A90S4 are provided along with that of Test-beam B0L4/90S4 and reference beam, as shown in Fig. 9. The Post-cracking strength and Stiffness of test beam B0L4/90S4 was almost similar to that of Test-beam A90S4, except in the post-peak region, Test-beam B0L4/90S4 showed continuing gain in strength. Hence, Test-beam B0L4/90S4 inherits both strength and ductility from its constituent layers and provided a considerable strength increase and energy absorption capacity, over all the other strengthened beams. Post-cracking stiffness of this beam was controlled mainly by the presence of GFRP reinforcement in the form of strips with fibers in 90-degree orientation since experimental observations on beams strengthened with GFRP in 0-degree direction shows that fibers in 0-degree would not contribute to post cracking stiffness. Therefore, test results reveals that strengthening using FRP sheets arranged longitudinally and

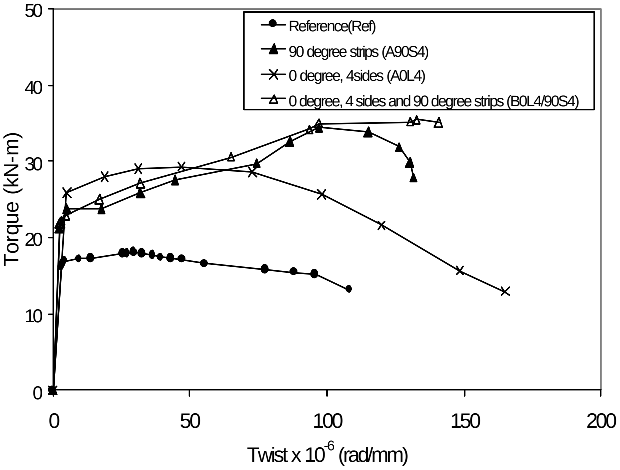


Fig. 9 Effect of strengthening in both directions

wrapped with transverse FRP strips will not enhance the cracking strength but will increase both the ultimate strength and post-cracking torsional twist and ductility of the beam.

4 ANALYTICAL PREDICTION

The increase in cracking torsional moments of the strengthened test beams was modeled as reinforced concrete beams subjected to prestress. The strain in the FRP is gradually varying due to the tensile stresses in surface of the beam. The resistance of FRP to the tensile stresses and strains at the surface of the beam can be considered as applying a passive prestressing force acting in the direction of fibers on the RC beams. Due to the gradual variation of strain in the FRP, the effective prestress is determined based on average strain in the FRP sheets at the instant of cracking as given in Equation (1). The calculation of strain in FRP is based on the Mohr's circle of strains as detailed in [6] and [9].

$$effective\ prestress = \frac{e_f E_f}{2} \tag{1}$$

Cracking torque can be determined using the effective prestress as given in Equation (2). Detailed discussion on Equation (2) is provided in Reference [6].

$$T_{cr} = c_1 b^2 h f_t \sqrt{1 + \frac{effective\ prestress}{f_t}} \tag{2}$$

where c_1 is St. Venant's constant, which is based on elastic theories, b and h are the dimensions of the beam as shown in Fig. 10, e_f and E_f are the tensile strain and tensile elastic modulus of the FRP sheets, respectively, and f_t is the tensile strength of concrete at rupture.

Ultimate torque calculations are based on the fiber orientation and the mode of failure. When the failure of the test beam is controlled by FRP rupture and the fibers are oriented in the 90-degree direction, the contribution of FRP sheets to ultimate strength is determined by using the effective strain in the fibers. The effective strain in the fibers is determined by using the empirical equations proposed in FIB (CEB-FIP) Technical Report [11]. If the rupture of fibers does not govern the failure mode, design approach based on effective bond length is used to calculate the ultimate strength [12]. When the fibers are oriented in 0-degree direction, the ultimate strength was not much greater than its cracking strength. Hence, the cracking torque calculated is taken as the predicted ultimate torque.

For Complete wrap and strips,

$$T_{u,frp} = 2e_{ke,f} E_{fu} \frac{t_f b_f}{s_f} bh\cot(a) \tag{3}$$

For U-wrap with anchors

$$T_{u,frp} = e_{ke,f} E_{fu} \frac{t_f b_f}{s_f} bh\cot(a) \tag{4}$$

where $e_{ke,f}$ is the characteristic value of effective FRP strain (corresponding equation to calculate the effective strain in FRP is available in Reference [11]), E_{fu} is the elastic modulus of FRP in the principal fiber orientation, t_f is the thickness of the FRP sheet, s_f is the center-to-center spacing of FRP strips, b_f is the minimum width of the cross section over the effective depth of the cross section, b and h are the cross sectional dimensions of the beam as shown in Fig. 10, and a is the angle of diagonal crack with respect to the member axis, assumed equal to 45° based on the reinforcement of the test beams.

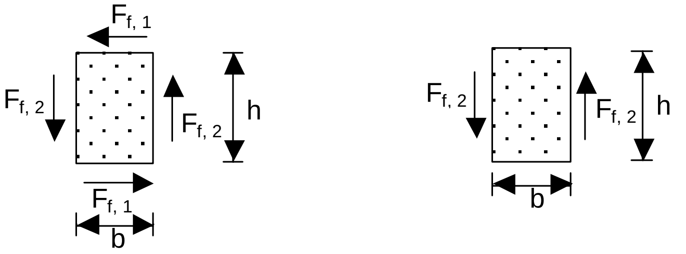
The design equations to calculate the ultimate torsional strength of a reinforced concrete beam, recommended by ACI 318-99 [10] is

$$T_{u,RC} = \frac{2A_0 A_t f_{yv}}{s} \cot(a) \tag{5}$$

where, A_0 is the cross sectional area bounded by the center line of the shear flow, A_t is the area of the transverse steel reinforcement (stirrups) provided, f_{yv} is the yield strength of transverse steel reinforcement, s is the spacing of stirrups, and a is the angle of diagonal crack with respect to member axis. Hence, the ultimate torsional strength for the FRP strengthened test beams can be obtained by adding the contribution due to fibers and due to reinforced concrete beam as follows:

$$T_u = T_{u,RC} + T_{u,frp} \qquad (6)$$

The cracking and ultimate torsional moments predicted using the analytical model are presented in Table 4. The analytical models used to calculate the cracking and ultimate torsional moments are explained in detail in Reference [9].



a) Complete wrap and strips b) U-wrap with anchors

Fig. 10 Forces in FRP sheets in torsional cross-section

Table 4 Comparison of experimental and analytical cracking and ultimate torsional moments

Test-beams	Cracking Torque (kN-m)			Ultimate Torque (kN-m)		
	Experimental (Ex)	Analytical (An)	Ex/An	Experimental (Ex)	Analytical (An)	Ex/An
Reference	17.1	15.7	1.09	18.2	16.9	1.07
A90W4	22.9	20.8	1.10	47.1	45.4	1.04
A90S4	22.1	17.7	1.25	36.0	36.4	0.99
A0L4	27.0	29.9	0.90	30.7	29.9	1.03
A0L3	26.3	28.8	0.91	27.8	28.8	0.97
B0L4/90S4	20.1	24.4	0.82	32.6	35.9	0.91
B90U3-Anch	22.0	18.2	1.20	26.3	28.1	0.94
C90U3	20.6	19.1	1.08	24.6	26.4	0.93
		Mean	1.04		Mean	0.98
		COV	0.14		COV	0.06

5 CONCLUSIONS

The conclusions drawn from the experimental and analytical program are summarized below:

- Torsional reinforced concrete beams strengthened with GFRP sheets exhibited significant increase in their cracking and ultimate strength as well as ultimate twist deformations.
- Strengthening schemes with complete wraps in 90-degree fiber orientation with respect to beam axis provided an effective confinement and therefore resulted in a significant increase (about 150%) in the ultimate torsional strength.
- Substantial increase in cracking strength was observed when RC beams were strengthened with FRP sheets oriented in the longitudinal direction of the beam, where the FRP provided passive prestress forces.
- Strengthening with FRP sheets in the longitudinal direction of the beam on three faces or four faces of the cross-section provided similar behavior.

- U-wrapped strengthening showed the least twist capacity due to peeling of FRP sheets along the side of the beam. However, anchoring the wraps to concrete enhanced the twist capacity and failure was mainly due to crushing of concrete and lateral separation of anchor bars along with FRP sheets.
- When combining FRP sheets in the longitudinal direction of the beam followed by all-around wrapped strips, the results showed that there was an increase in both the ultimate strength and post-cracking torsional twist and ductility of the beam.
- The proposed design equations for both cracking and ultimate torsional moments seemed to predict very closely the experimental results.

REFERENCES

[1] Meier, U. : Post-strengthening by continuous fiber sheets in Europe. Proceedings of Third International Symposium, Non-Metallic (FRP) Reinforcement for Concrete Structures, Vol. 1, Japan Concrete Institute, Tokyo, pp. 41–56, 1997.

[2] Triantafillou, T.C. and Plevris, N. : Strengthening of RC Beams with Epoxy-Bonded Fibre-Composite Materials, Materials and Structures, Vol. 25, pp. 201-211, 1992.

[3] Chajes, M. J., Januska, T.F., Mertz, D.R., Thomson, T.A., and Finch, W.W. : Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics. Structural Journal of the American Concrete Institute, Vol. 92, No. 3, pp. 295-303, 1995.

[4] Khalifa, A., Belarbi, A., and Nanni, A. : Shear Performance of RC Members Strengthened with Externally Bonded FRP Wraps. Proceedings (CD-ROM) of Twelfth World Conference on Earthquake, Auckland, New Zealand, January 30 - February 4, 8 pages, 2000.

[5] Mitchell, D. and Collins, M.P. : Diagonal Compression Field Theory – A Rational Model for Structural Concrete in Pure Torsion. Structural Journal of the American Concrete Institute, Vol. 71, No. 8, pp. 396-408, 1974.

[6] Hsu, T.T.C. : Torsion of Reinforced Concrete. Van Nostrand Reinhold, Inc., New York, N.Y., 516 pages, 1984.

[7] Master Builders Technologies : MBrace Composite Strengthening System-Engineering Design Guidelines. Second Ed., Cleveland, OH, 140 Pages, 1998.

[8] Koutchoukali N. and Belarbi, A. : Torsion of High-Strength Reinforced Concrete Beams and Minimum Reinforcement Requirements. Structural Journal of the American Concrete Institute, Vol. 98, No. 4, pp. 462-469, 2001.

[9] Panchacharam, S. : Torsional Behavior of Reinforced Concrete Beams Strengthened with GFRP Laminates. M.S. Thesis, Department of Civil Engineering, The University of Missouri – Rolla, 123 Pages, 2002.

[10] ACI 318-99 : Building Code Requirements for Structural Concrete (318-99) and Commentary (318R-99). American Concrete Institute, Farmington Hills, MI., 391 pages, 1999.

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

[12] Khalifa, A., Gold, W.J., Nanni, A. and Aziz, A. : Contribution of Externally Bonded FRP to Shear Capacity of Flexural Members. ASCE Journal of Composites for Construction, Vol. 2, No. 4, pp. 195-203, 1998.