Advances in Research
8(3): 1-10, 2016; Article no.AIR.30247
ISSN: 2348-0394, NLM ID: 101666096

SCIENCEDOMAIN ***international***
www.sciencedomain.org

Torsional Behavior of RC Beams with Opening Using (CFRP - GFRP - Steel) Stirrups

M. H. Makhlouf[1*]

[1]Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt.

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/AIR/2016/30247
Editor(s):
(1) Akash Dixit, Department of Mechanical Engineering, Oakland University, USA.
Reviewers:
(1) Natt Makul, Pranakhon Rajabhat University, Thailand.
(2) S. Suppiah, Veltech Dr. RR & Dr. SR University, India.
(3) Muhammad Mukhlesur Rahman, RMIT University, Australia.
(4) Suraya Hani Adnan, University Tun Hussein Onn Malaysia (Uthm), Malaysia.
Complete Peer review History: http://www.sciencedomain.org/review-history/17364

Original Research Article

Received 27th October 2016
Accepted 24th December 2016
Published 28th December 2016

ABSTRACT

This paper presents the torsional behavior of R.C. beams strengthened with externally steel stirrups, steel links and Fiber Reinforced Polymers (FRP) systems, R.C beams with web opening subjected to pure torsion. A total six rectangular beams were tested. Two un-strengthened specimens without and with web opening, which considered as control specimen, the rest four beams with web opening which one specimens strengthened with external steel stirrups, one specimen strengthened with steel links, one specimen strengthened with external stirrups made from Glass Fiber Reinforced Polymer (GFRP), and one specimen strengthened with external stirrups made from Carbon Fiber Reinforced Polymer (CFRP). All the beams were subjected to pure torsion till failure. The type of strengthening material and system is the basic parameter in this study. The experimental results showed a noticeable increase in torsion resistance for the strengthened specimens compared to control specimen. In comparison with control beam, the ultimate torsional moment increased up to 287% for beam strengthened with steel links, up to 134 % for beam strengthened with CFRP and increase capacity of beams with, and up to 100% for beam strengthened with GFRP stirrups.

An analytical model was proposed and applied to predict the torsional strength of the tested RC beams, the predicted strengths were found to be in good agreement with the experimental results.

**Corresponding author: E-mail: Mohamed.makhlouf@bhit.bu.edu.eg, mohamedmakhlouf83@yahoo.com;*

Keywords: Fiber reinforced polymer; steel links; pure torsion; web opening.

1. INTRODUCTION

In recent decades, Transverse opening in reinforced concrete beams has become one of civil engineering challenges. Especially, in high rise buildings in where the height of the floor is not sufficient to place their utility under the soffit of the beam. Transverse opening in reinforced concrete beams are often provided for the passage of utility ducts and pipes. Ducts are necessary in order to accommodate essential service such as water supply, electricity, and telephone and computer network especially in the construction of multistory buildings. However, providing an opening in the beams cause cracks around the opening thus reduce the beam stiffness which lead to the need of strengthening for beams. Recently, strengthening of reinforced concrete (RC) beams subjected to torsion is receiving increased attention; torsion is considered one of the main factors affecting the stability of structural elements. Structural elements subjected to torsion experience diagonal tension and compression and fails in a brittle manner which may result in a progressive collapse of the building. Strengthening and repair the RC structures with externally FRP Composite materials gained significant attention around the world during the last two decades, widely used as externally strengthening because of their superior properties such as high stiffness and strength, ease of installation and non - corrosive. The flexural strengthening of beams with FRP was studied by several researchers. Studies on torsional strengthening of RC beams by composite materials are relatively limited [1,2]. The behavior of a beam containing a small opening is not significantly different from the solid beam and the failure of such a beam is due to bending about skew axis, [3,4,5,6,7,8], but when the opening dimension is increased, the beam strength -decreases, [9,10], and the mechanism of failure changes from skew-bending type to one resembles the failure of a grid frame [11]. Mansur and Hasnat 1979 considered that the accurate classification for opening to be small or large depends on opening is small enough to maintain the same behavior of the beam in case of with and without opening, and the usual beam theory can be applied, otherwise it becomes a large opening. Recent studies [1,12] has concluded that the web opening affects significantly on the capacity of the beam and the web opening height has a pronounced effect on the capacity than the opening width. This research differs from earlier research using the relay-technique stirrups instead of strips.

The main objectives of the present study were to evaluate the effectiveness of the use of external transverse stirrups for strengthening of rectangular R.C beams with opening. The variables considered in this study were: (1) strengthening system (links – stirrups), (2) strengthening material (mild steel – GFRP – CFRP).

2. EXPERIMENTAL INVESTIGATION

2.1 Details of Test Specimens

Six beam specimens were tested under pure torsion. The beam shown in Fig. 1. had a rectangular cross section of 150*250 mm, a total length of 900 mm is divided in three parts, the middle part 700 mm was the testing strengthening zone. The end parts have a "Z" shape with right angles at both joints. The bottom beam reinforcement consisted of two bars of diameter 10 mm, whereas the top beam reinforcement consisted of two bars of diameter 10 mm. 6 mm steel stirrups were placed at 150 mm centers. The two cantilevers were reinforced with 3 stirrups of diameter 12 mm in longitudinal and 4 stirrups of diameter 8 mm in transverse direction. The two cantilever parts were loaded at their ends with two equal concentrated loads in order to produce the torsional moment. Tables (1) summarize the characteristics of the tested beams. Different strengthening system and material were investigated. Two Solid beam without and with web opening was tested without strengthening and considered as a control beam while the rest beams with web opening were strengthened and then tested.

2.2 Material Properties

The specimens were cast using normal strength concrete of 25 MPa characteristic strength. The concrete mix was prepared in the concrete Lab of Benha faculty of Engineering, The cubic meter of concrete mix constitutes of: 1240 kg of crushed stone (dolomite) of 10 mm maximum aggregate size, 620 kg of siliceous sand, 350 kg of ordinary Portland cement, 175 liters of water. High tensile steel (36/52) of 3980 Mpa proof stress was used for longitudinal

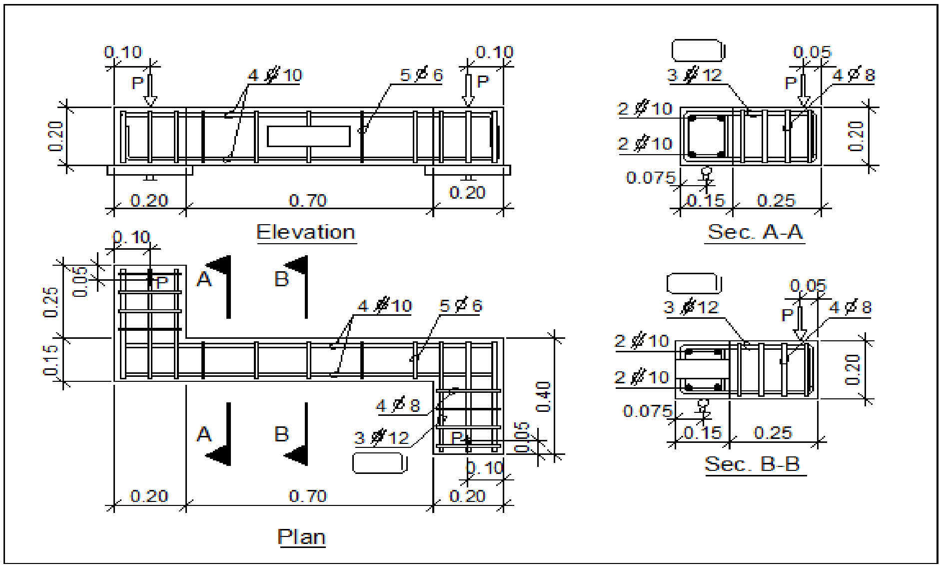

Fig. 1. Details of tested R.C. specimens

Table 1. Characteristic of test specimens

Specimens	Dimension of opening		Retrofit scheme
	Depth (mm)	Width (mm)	
B-1	-	-	Control
B-2	60	230	Control
B-3	60	230	Strengthening with steel stirrups
B-4	60	230	Strengthening with steel links
B-5	60	230	Strengthening with GFRP stirrups
B-6	60	230	Strengthening with CFRP stirrups

Table 2. Mechanical properties of GFRP and CFRP wraps

Property	Glass fiber woven roving wraps (WR)	CFRP (Sika Wrap Hex-230C)
Fabric thickness, mm	0.17	0.12
Tensile strength, MPa	284	4020
Modulus of elasticity, MPa	74000	225000
Elongation at failure , %	2.0	1.7

reinforcement and normal mild steel of 280 Mpa yield stress was used for stirrups. Table (2) gives the properties of the GFRP wraps and CFRP wraps used in this work, given by the manufacturer.

3. TEST PROCEDURE

All beams were tested under pure torsion on the middle part, the beam was load by applying two downwards concentrated loads at the ends of the cantilevers parts, and using two hinged supports at both joints of the Z-shape as shown in Fig. 2a and 2b. Both hinged supports are capable of rotation and inclination in vertical plane in order to pure torsional moment in transferred from both cantilever parts to the middle part of the tested beam specimen. In order to determine the twisting angle, Deflections were measured using Linear Variable Deformation Transducers (LVDT) located at the center and under the two points load. All specimens were loaded incrementally every 2.5 KN till failure. All deflections and strains were recorded for every load increment. Also, cracks initiation and propagation were monitored.

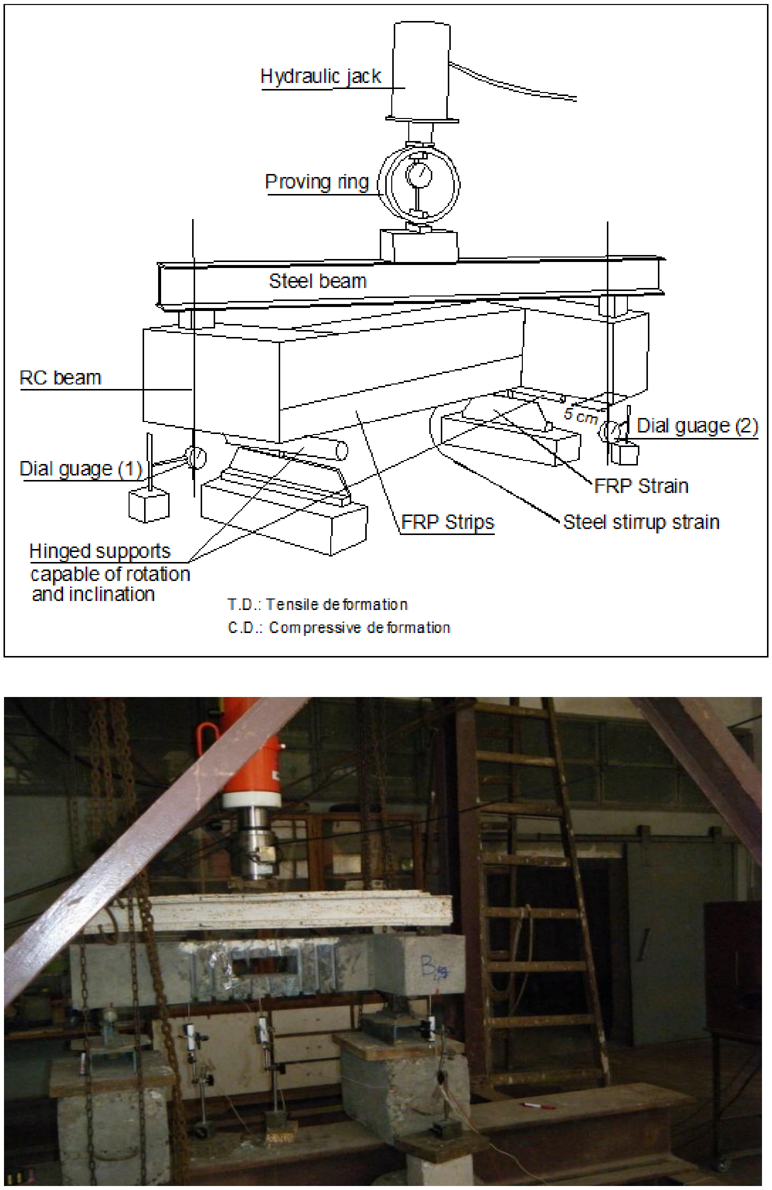

Fig. (2a and 2b.). Test setup and instrumentations

4. PREPARATION OF TEST SPECIMENS

Different strengthening systems are shown in Fig. 3 as follow:

4.1 Using Steel Stirrups

The proposed conventional strengthening system consisted of steel stirrups of 6 mm diameter. Steel stirrups were installed through the groove. The clearance between steel stirrups groove was filled by polyester to ensure good bond between concrete and steel stirrups.

4.2 Using Steel Links

The proposed conventional strengthening system consisted of steel links which were locally fabricated using normal tensile steel bars of 6 mm diameter fixed at both ends by two steel plates of 5 mm thickness and 25 mm width. Steel links were installed through the groove. The clearance between steel links groove was filled by polyester to ensure good bond between concrete and steel links.

4.3 Using FRP Stirrups

Specimens were strengthened by using intertwined FRP rods which were manually manufactured from fiber wraps of 6 mm diameter stirrups which prepared from 4 cm. The FRP wraps were saturated with polyester for GFRP and epoxy resin (Sikadur-330) for CFRP, and then the intertwined rods were formed and stitched through holes along the depth of the beam. 24 hours later, the clearance between GFRP or CFRP stirrups and groove was filled by polyester or Sikadur-330, respectively, to ensure good bond between FRP stirrups and concrete.

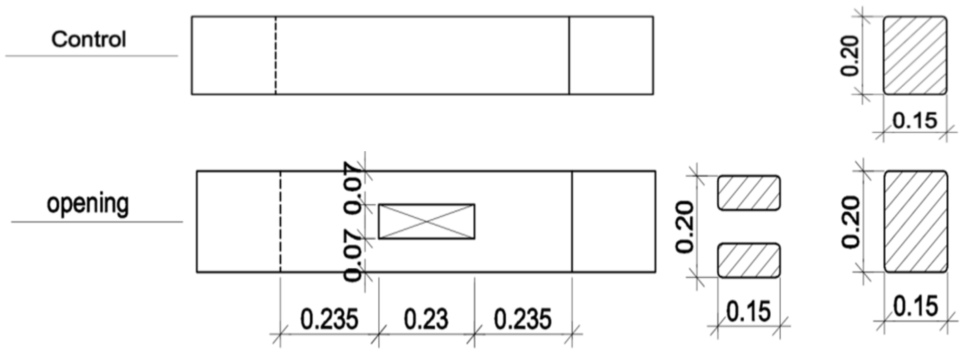

Fig. 3a. Control specimen

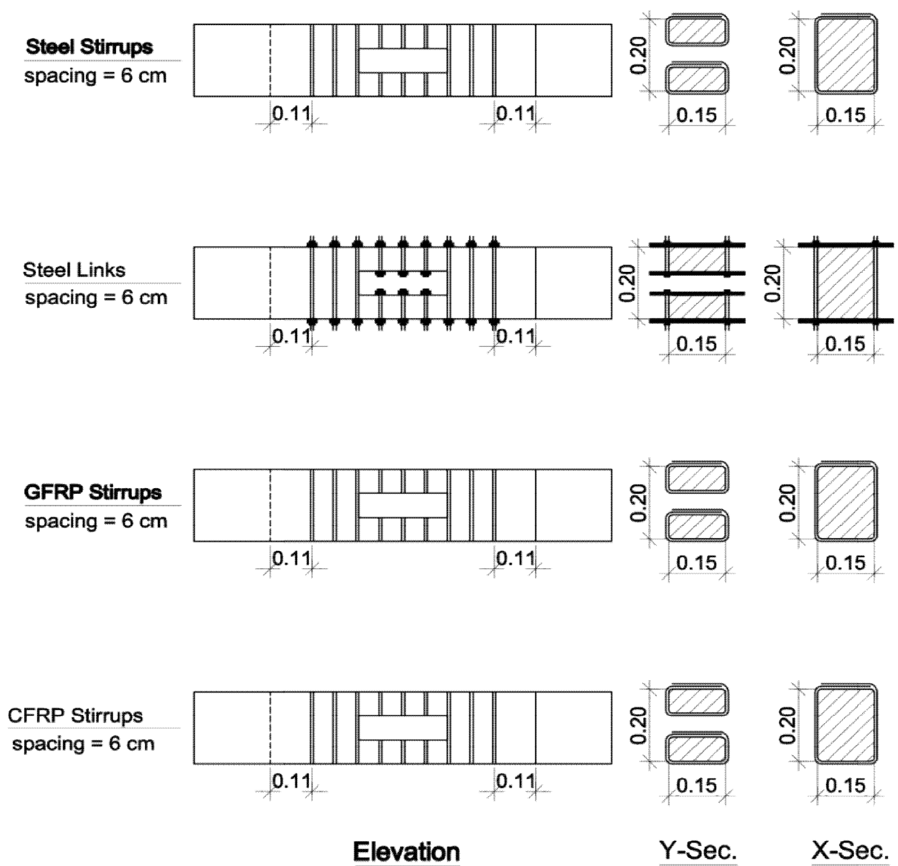

Fig. 3b. The different configurations of strengthening systems

5. EXPERIMENTAL RESULTS AND DISCUSSION

Table 3 provides a summary of cracking torsional moments, ultimate torsional moments, cracking twisting angle and ultimate twist angle of all tested RC beams along with their relative increase in cracking and ultimate torsional moments with respect to control beam. The presence of openings seems to be effective in decreasing the crack torque and torsional capacity because the opening decreased the section rigidity. Hence it became the weakness position through the whole beam. In a comparison with the control beam (B-1), the cracking torque and torsional capacity of specimens (B-2) are decreased by 0.00% and 0.45% respectively.

The results illustrate that using of external steel links system is more effective in improving cracking and ultimate torsion moment. Using stirrups strengthening system increase the capacity of beam with opening by 12%, using steel links strengthening system increase the capacity of the beam with opening by 287%, Using GFRP stirrups strengthening system increase the capacity of the beam with opening by 100%, Using CFRP stirrups strengthening system increase the capacity of the beam with opening by 134%.

For all specimens, test results illustrate that web opening have effect on the rotation. For two control beams, the opening increases the twisting angle by 23% because the weakness results from opening.

5.1 Effect of Steel Stirrups

Fig. 4 Shows the influence of external stirrups on the behavior of the tested beams which lead to increase the ultimate torsional moment by 12%.

5.2 Effect of Steel Links

Fig. 5 Shows the influence of external steel links on the torsional behavior of the tested beams which lead to increase the ultimate torsional moment by 287%.

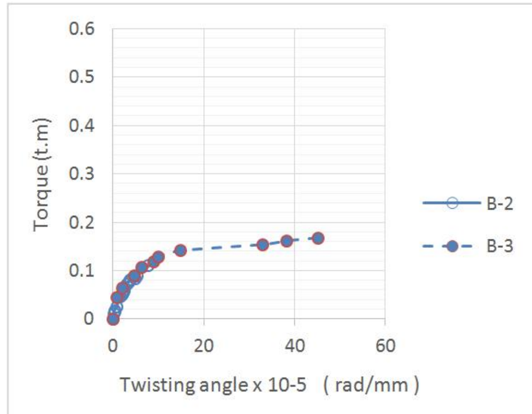

Fig. 4. Torque –twisting angle curve B-2 & B-3

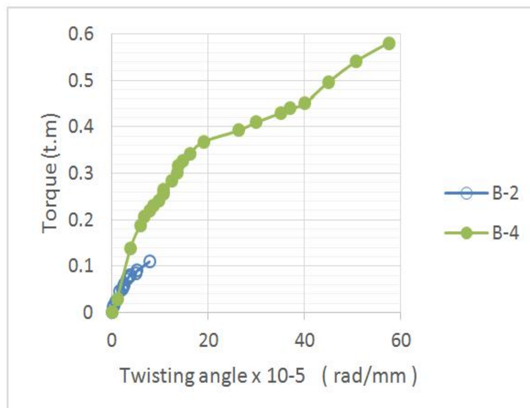

Fig. 5. Torque –twisting angle curve between opening control beam and beam strengthening with external steel links

5.3 Effect of GFRP Stirrups

Fig. 6 shows the influence of external CFRP Stirrups on the torsional behavior of the tested beams which lead to increase the ultimate torsional moment by 100%.

Table 3. Summary of test results

Specimens	Cracking torque (t.m)	Cracking twist angle (rad/mm) x 10-5	Ultimate torque (t.m)	Ultimate twist angle (rad/mm) x 10-5	Increase of ultimate torque (%)
B-1	0.075	3.447	0.275	10	-
B-2	0.075	3.447	0.15	7.7	-
B-3	0.105	6.22	0.167	17.5	12
B-4	0.1925	6.692	0.58	57.5	287
B-5	0.1925	5.691	0.30	37.7	100
B-6	0.1925	5.691	0.35	42.75	134

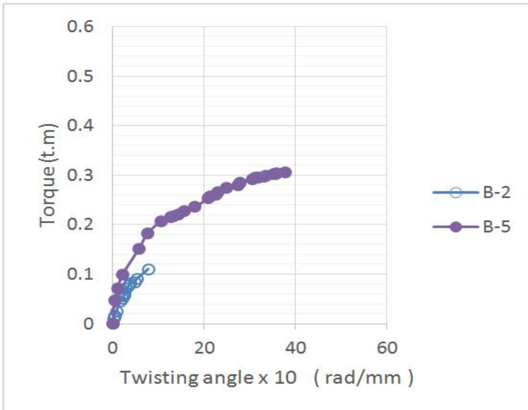

Fig. 6. Torque –twisting angle curve between opening control beam and beam strengthening with external CFRP Stirrups

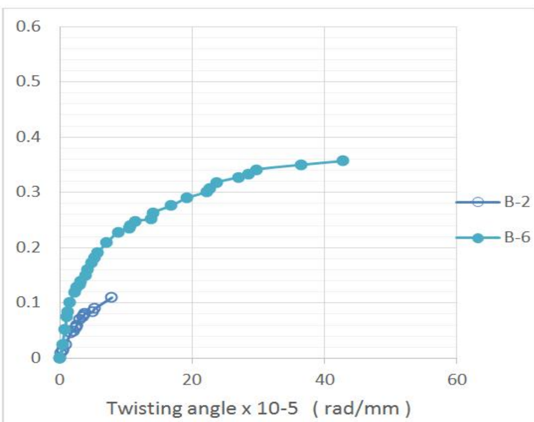

Fig. 7. Torque –Twisting angle Curve between opening control beam and beam strengthening with external GFRP Stirrups

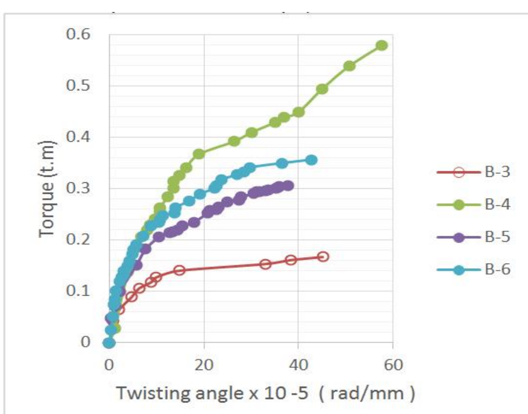

Fig. 8. Torque –twisting angle curve between all strengthening tested beams

Fig. 9. Mode of failure

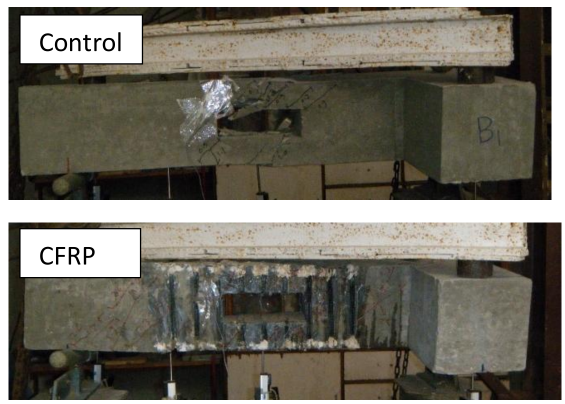

Fig. 10. The effect of FRP strengthening on the cracking distribution of tested RC beams

5.4 Effect of CFRP Stirrups

Fig. 7 shows the influence of external GFRP Stirrups on the torsional behavior of the tested beams which lead to increase the ultimate torsional moment by 134%.

5.5 Effect of Material of Strengthening

Fig. 8 shows the influence of using different material (steel stirrups – steel links – GFRP stirrups – CFRP Stirrups) on the torsional behavior of the tested beams.

5.6 Cracks Pattern of Tested Specimens

All the tested beams failed due to torsional moment Fig. 9. The first crack appeared at the corner of the opening in the case of beams with web opening. With increasing the load, diagonal cracks were propagated forming a spiral trajectory on the four sides of the testing span. The inclination of the crack was about 45° to the longitudinal axis of the beam. In comparison with control beam, more cracks were observed in the strengthened beams, such as shown in Fig. 10.

6. ANALYTICAL MODELING

6.1 Nominal Torsional Moment for Beam with Rectangular Opening

Only very limited literature is available regarding the behavior of reinforced concrete beams with web opening subjected to pure torsion. In addition, no national code gives any guidelines for the design of concrete beams with rectangular web opening under torsion. In this section, ultimate torsional moment for beam with opening has been calculated using the proposed equations by Akhtaruzzaman [13] and Mansur & Tan [14].

Akhtaruzzaman [13] developed an equations to calculate the torsional moment resistance of reinforced concrete beam with rectangular and circular opening, this equations is a modification of the torsion equations of the ACI 318-83 [15]. The equation governing the nominal torsional strength is given by,

$$T_u = T_c + T_{si} \tag{1}$$

Where, Tc and Tsi are the nominal torsional strength provided by concrete and torsional reinforcement, respectively, given by:

$$T_c = 0.8\sqrt{f_c}\, b^2 h \left(1 - \lambda \frac{d_o}{h}\right) \tag{2}$$

$$T_{si} = nA_t\alpha_t x_1 f_{yw} = \left[\, (nA_t f_{yw})_c + (nA_t f_{yw})_s \,\right] \alpha_t x_1 \tag{3}$$

where fc is the design compressive strength of concrete, fyw is the yield strength of steel, b and h represent width and depth of beam section, respectively, x1 and y1 are the shorter and the longer center-to-center dimension of vertical stirrups respectively, λ equal to cos 45° for circular opening and 1.0 for rectangular opening, do is the opening depth and bo is the opening length, At is the area of one leg of vertical stirrup, αt is a coefficient depends on the ratio of beam cross-sectional dimensions and can be equated as in equation (4), and n represents the number of vertical legs of stirrups intersected by a 45° inclined plane on the tension side of the beam and is calculated by equation (5).

$$\alpha_t = 0.66 + 0.33\frac{y_1}{x_1} \le 1.5 \tag{4}$$

$$n_c = \frac{a}{s_h} \quad \& \, n_s = \frac{a}{s_s} \tag{5}$$

Where a is the chord depth, and sh, ss are the center-to-Center spacing between stirrups in chord and solid part, Respectively, (inch).

The subscribe c and s refer to the chords and the solid.

6.2 Torsion Contribution of FRP Stirrups Complete Wrapping to the Torsional Capacity of Beam with Rectangular Opening

Using the Equations that calculate the torsion contribution of CFRP sheets to the torsional capacity of a solid beam which introduced by FIB [16] with some modification, as shown in Fig. 11, to match with beam with rectangular opening and the axis of rotation apart 150 mm from the laminate can be derived as shown in equation (10) through equation (13).

$$T_f = 2F_{fd,v}(b) + 2F_{fd,h}(a) \tag{6}$$

and

$$F_{fd,v} = \varepsilon_{fd,e} E_{fu} \frac{t_f b_f}{S_f} a \cot\theta \tag{7}$$

$$F_{fd,h} = \varepsilon_{fd,e} E_{fu} \frac{t_f b_f}{S_f} b \cot\theta \tag{8}$$

Then T_{fd} can be expressed as

$$T_f = 2\,[\,2\, \varepsilon_{fd,e} E_{fu} \frac{t_f b_f}{S_f} (ab) \cot\theta \tag{9}$$

Which implies that Tfd= 2 Tfd,v = 2 Tfd,h. Therefore, the torsion contribution of FRP, on the two chords, to the torsional capacity of the beam when the section rotate about a point apart 150 mm from the bottom of the beam is equal to the sum of the torsion contribution of FRP, on the one chord, to the torsional capacity of the chord when it rotate about its centroid.

Where Ffd,h and Ffd,v are define as the forces carried by horizontal and vertical FRP sheets, respectively, εfd,e is the characteristic value of FRP strain and can be calculated for FRP from equation (10), Efu is the elastic modulus of FRP laminate, tf is the thickness of FRP laminate, bf width of FRP strip, Sf is the spacing between strips, θ is the angle of inclination of the diagonal crack to the longitudinal axis of the beam, and can be taken as 45° and,

$$\varepsilon_{fd,e} = 0.17\, E_{fu} \frac{{f_{cm}}^{2/3}}{\rho_f\, E_{fu}}\ \varepsilon_{fu} \quad (10)$$

Where εfu is the ultimate strain of FRP, fcm is defined as the concrete compressive strength, MPa, Efu is the elastic modulus of FRP laminate, GPa, and ρf is the FRP reinforcement ratio with respect to concrete and can be

$$\rho_f = \frac{2t_f\, b_f}{bs_f} \quad (11)$$

For complete wrapping (b_f / s_f = 1.0).

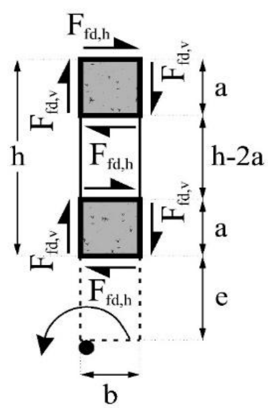

Fig. 11. Tensile force carried by CFRP sheet complete wrapping on the chords due to torsional moment

6.3 Torsion Contribution of Steel Links to the Torsional Capacity of Beam with Rectangular Opening

Using the Equations that calculate the torsion contribution of CFRP sheets to the torsional capacity of a solid beam which introduced by ACI 318-83

$$T_{so} = nA_t\alpha_t x_1 f_{yw} = [\,(nA_t f_{yw})_c + (nA_t f_{yw})_s\,]\, \alpha_t x_1 \quad (12)$$

Where x1 and y1 are the shorter and the longer center-to-center dimension of vertical stirrup respectively, λ equal to cos 45° for circular opening and 1.0 for rectangular opening, do is the opening depth and bo is the opening length, At is the area of one leg of vertical stirrup, αt is a coefficient depends on the ratio of beam cross-sectional dimensions and can be equated as in equation (13), and n represents the number of vertical legs of stirrups intersected by a 45° inclined plane on the tension side of the beam and is calculated by equation (14).

$$\alpha_t = 0.66 + 0.33\frac{y_1}{x_1} \le 1.5 \quad (13)$$

$$n_c = \frac{a}{s_h} \ \& \ n_s = \frac{a}{s_s} \quad (14)$$

Where a is the chord depth, and s_h, s_s are the center-to-Center spacing between stirrups in chord and solid part, respectively, (inch).

The subscribe c and s refer to the chords and the solid.

Table 4. Presents the comparison between the experimental and analytical ultimate torsional moments for strengthened beams

Specimens	Tu $_{ex}$	Tu $_{analytic}$	Ratio
B-4	0.58	0.537	1.08
B-5	0.30	0.33	1.1
B-6	0.35	.395	1.13

The ultimate torsion moment for strengthening beams with opening can be obtained with the following equation in case of using external steel links:

$$T_u = T_c + T_{si} + T_{so} \quad (15)$$

The ultimate torsion moment for strengthening beams with opening can be obtained with the following equation in case of using external steel links:

$$T_u = T_c + T_{si} + T_{so} \quad (16)$$

7. CONCLUSIONS

Based on the research work, the following conclusions and recommendation can be summarized:

1. The provision of the opening in the beams leads to noticed decrease in the cracking and ultimate torsional strength of the beam by 45%.
2. Strengthening of the beam with web opening using external stirrups enhance the torsional capacity by 12%.
3. Strengthening of the beam with web opening using external steel links around the chords and the solid parts near the opening region are the most effective strengthening system, where the torsional strength increased by 386% of the control beam with opening.
4. Using CFRP stirrups instead of GFRP stirrups of the same fiber area increases

the ultimate torsional moment by an average value of 134% for various fiber areas. However, the same improvement in the torsional capacity could be achieved by increasing the fiber area in the GFRP sheets by about 100%, which is a better alternative from the economic point of view.

5. A proposed equation for calculate the contribution of external FRP Stirrups and Steel Links are given as follow:

$$T_{nh} = T_c + T_s + T_f$$

ACKNOWLEDGEMENTS

I would like to record our appreciation for the Faculty of Engineering in Benha, Benha University, for rendering the necessary support to carry out this research.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Fawzy K, Hashem MM, Elnady AM. Performance of RC beams with web opening subjected to pure torsion strengthened with CFRP. IJEIT. Jule. 2014;4.
2. Soluit AK, Motawea MA, Elsayed KM, Shalaby SH. Torsional behavior of RC beams strengthened with fiber reinforced polymer sheets. Mataria Engineering Research Journal. 2007;114.
3. Hasnat A, Akhtaruzzaman AA. Beams with small rectangular opening under torsion, bending and shear. Journal of Structural Engineering. ASCE. 1987; 113(10):2253-2270.
4. ACI Committee, American Concrete Institute & International Organization for Standardization. Building code requirements for structural concrete (ACI 318-05) and commentary. American Concrete Institute; 2005.
5. BS 8110. Structural use of Concrete: Part 1: Code of Practice for Design and Construction. British Standard Institution, London; 1997.
6. ECP 203, Egyptian code of practice for design and construction of concrete structures; 2009.
7. JSCE. Standard specifications for concrete structures. Japan Society of Civil Engineers, Yotsuya 1-chome, Shinjuku-ku, Tokyo; 2007.
8. Mansur MA, Paramasivam P, Lee SL. Torsion in reinforced concrete beams containing circular opening. International Journal of Structures. 1982;2(3):89-98.
9. Daniel HR, McMullen AE. Torsion in concrete beams containing openings. Journal of the Structural Division, ASCE. 1977;103(3):607-617.
10. Mansur MA, Ting SK, Lee SL. Torsion tests of RIC beams with large openings. Journal of the Structural Division, ASCE. 1983a;109(8):1780-1791.
11. Alwis WAM, Mansur MA. Torsional strength of R/C beams containing rectangular openings. Journal of Structural Engineering. 1987;113(11):2248-2258.
12. El-Badawy MA, Essawy AS, Khalil AH, Torsional behavior of RC beams with Web Opening. M.Sc., AIN SHAMS University, CAIRO; 2010.
13. Akhtaruzzaman AA. ACI code torsion equations modified for rectangular concrete beams with an opening. JAKU: Eng. Sci. (1410 A.H, 1990 A.D);2:95-117.
14. Mansur MA, Tan KH. Concrete beam with opening analysis and design. U.S.: CRC Press LLC; 1999.
15. ACI Committee, American Concrete Institute & International Organization for Standardization. Building code requirements for structural concrete (ACI 318-86) and commentary. American Concrete Institute, Detroit; 1983.
16. FIB, Federation International du Beton, Externally bonded FRP reinforcement for RC structures. The International Federation for Structural Concrete, Technical report, Fib Bulletin. 2001;14.

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/17364