Computers and Concrete, *Vol. 16, No. 1 (2015) 1-16*
DOI: http://dx.doi.org/10.12989/cac.2015.16.1.001

Finite element analysis of longitudinal reinforcement beams with UHPFC under torsion

Thaer Jasim Mohammed[1,2a], B.H. Abu Bakar[*1], N. Muhamad Bunnori[1b] and Omer Farouk Ibraheem[1c]

[1]School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia
[2]Middle Technical University, Institute of Technology, Baghdad, Iraq

(Received October 2, 2014, Revised June 11, 2015, Accepted June 16, 2015)

Abstract. The proposed techniques to strengthen concrete members such as steel plates, polymers or concrete have important deficiencies in adherence and durability. The use of UHPFC plates can overtake effectively these problems. In this paper, the possibility of using UHPFC to strengthen RC beams under torsion is investigated. Four specimens of concrete beams reinforced with longitudinal bars only were tested under pure torsion. One of the beams was considered as the baseline specimen, while the others were strengthened by ultra-high-performance fiber concrete (UHPFC) on two, three, and four sides. Finite element analysis was conducted in tandem with experimental work. Results showed that UHPFC enhances the strength, ductility, and toughness of concrete beams under torsional load, and that finite element analysis is in good agreement with the experimental data.

Keywords: reinforced concrete; torsion; finite element; strengthen; UHPFC

1. Introduction

Demands on a structure change during the service life of a building. Strengthening is necessary in such cases. The changes may result from an increase in service loads, decrease in serviceability limits, change in usage of the structure, and deterioration due to corrosion in the steel caused by exposure to an aggressive environment and accidents, such as earthquakes. In extreme cases, a structure may need repairs because of an accident or because of errors made during the design or construction phase. Moreover, overall safety factors in current design codes are less than what they used to be. Torsion is thus becoming a common problem. Reinforced concrete members subjected to increasing torsion may fail quite suddenly.

Two possible solutions can be applied in such circumstances: replacement and retrofitting. Complete replacement of an existing structure may be a possible solution, though it is most likely

[*] Corresponding author, Professor, E-mail: cebad@usm.my
[a] Ph.D. student, E-mail: thaer_jasim@yahoo.com
[b] Ph.D., E-mail: cenorazura@usm.my
[c] Ph.D., E-mail: omerfarouk77@yahoo.com

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

not the most cost-effective one. In many cases, strengthening and upgrading is the most cost-effective and convenient solution.

Some of the more popular strengthening techniques developed include steel plate bonding, external prestressing, section enlargement, and reinforced concrete jacketing. Although these techniques can effectively increase the element load-carrying capacity, they are often susceptible to corrosion damage that results in failure of the strengthening system. Consequently, during the last two decades, many designers have demonstrated and accepted the advantages of strengthening concrete elements using fiber-reinforced polymer (FRP) because of its superior properties, which include high strength-to-weight ratio, non-corrosiveness, and easy installation.

Numerous researchers have studied the effect of torsional retrofit by FRP experimentally (Zhang *et al.* 2001, Ghobarah *et al.* 2002, Pancharam and Belarbi 2002, Salom *et al.* 2004, Chalioris 2008, Mohammadizadeh *et al.* 2009, Diefalla *et al.* 2013), analytically (Chalioris 2007, Diefalla and Ghobarah 2010), and numerically (Ameli *et al.* 2007, Santhakumar *et al.* 2007).

Superior results have been obtained from retrofitting by FRP, though this technique still has a few important disadvantages:

- Design and construction require highly trained specialists and large safety margins to compensate for material, fabrication, curing, and durability uncertainties.
- FRPs are very sensitive to transverse actions (corners and discontinuity effects) and are unable to transfer local shear. Furthermore, they do not function effectively in compression when subjected to cyclic loads.
- FRP composite and concrete bonds, and long-term durability of FRPs are of high concern. Therefore, the history of use should be considered for each specific retrofit project.
- FRP behavior is very process-dependent and is greatly influenced by the quality of the parent concrete. As a result, problems such as shrinkage, creep, and debonding may adversely affect structural performance if the FRP is designed and applied improperly.

Therefore, various solutions have been investigated as the demand for new technologies and materials to upgrade damaged structures continue to increase. Ultra-high-performance fiber concrete (UHPFC) displays excellent retrofit potentials in compressive and flexure strengthening, as well as higher bonding strength and bond durability than other concrete types (Tayeh *et al.* 2013a,b). Many applications reveal that UHPFRC technology can significantly improve structural performance in terms of the durability and life-cycle costs of concrete structures (Lei *et al.* 2012). Research on the behavior of UHPFC-RC composites has mainly focused on flexural strengthening, whereas studies on shear strengthening are limited. Several studies have demonstrated the effectiveness of using UHPFC to strengthen RC beams under flexure or combined bending and shear (Habel 2007, Martinola *et al.* 2010, Noshiravani and Brühwiler 2010, Noshiravani and Brühwiler 2013). Thus, research into the use of UHPFC plates to strengthen structural members is a recent development. The use of UHPFC plates can surpass the disadvantages of using steel plates and FRP in retrofitting concrete members. Studying the torsional strengthening of structural elements using this new technique has not received any attention. Reasons for the lack of research in the area include the specialized nature of the problem and the difficulties in conducting realistic tests and representative analyses.

It is worth mentioning, there are some researchers have investigated the torsional strength of concrete beams under steel reinforcement (only longitudinal reinforcement without stirrup) to evaluate the longitudinal steel ratio in the torsional resistance. They concluded that longitudinal reinforcement ratio has a considerable effect on the torsional moment strength (Khagehhosseini *et al.* 2013). In this study, the percentage of steel was chosen from previous research (Chalioris 2008) to illustrate the effective of UHPFC of strengthened beams as compared with the reference beam under steel reinforcement.

The objective of this investigation is to evaluate experimentally and numerically the effectiveness of UHPFC plates in strengthening longitudinal reinforced concrete beams subjected to torsion.

2. Geometry and material properties

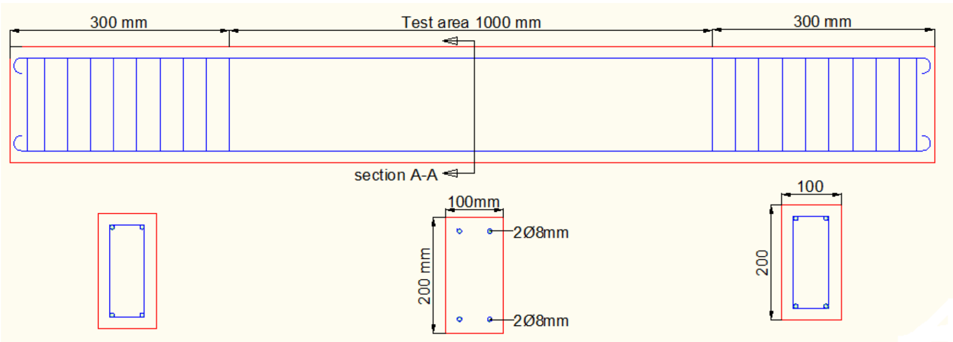
The effectiveness of the proposed UHPFC strengthening technique in all its three variations was investigated by performing full-scale experimental tests on four beams with lengths of 1600 mm, depths of 200 mm, and widths of 100 mm (Fig. 1). All the beams had the same longitudinal reinforcement, which consisted of four longitudinal bars with diameters of 8 mm (4Ø8) at the corners and yield strengths of 420 MPa. No transverse reinforcement was included in the testing zone. The 28-day compressive strengths of the core concrete beams were 32 MPa. Such low resistance without transverse reinforcement was chosen to highlight the effectiveness of the strengthening function. The mix of UHPFC used as strengthening material contained the following components: ordinary Portland cement (Type-I); silica fume; well-graded, sieved, and dried mining sand; high-strength micro-steel fiber; and superplasticizer. The steel fiber used in the experiments was 10 mm long and 0.2 mm in diameter respectively, and had an ultimate tensile strength of 2500 MPa. The compressive strength of the cubes with the 100 mm side was up to 150 MPa at 28 days. One of the reinforced beams was used as the reference beam, and 25 mm-thin layer of UHPFC were applied on the other three beams. The details relevant to the beams are shown in Table 1.

2.1 Specimen preparation

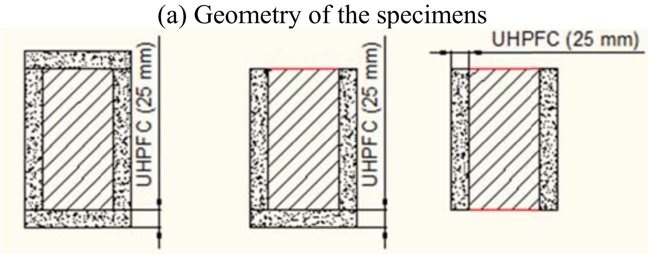
First, the core concrete was cast. The surfaces of the core beam were sandblasted to produce a 1 mm–2 mm roughness, which is considered adequate to avoid the use of bonding products (Martinola *et al.* 2010) (Fig. 2(a)). The UHPFC material was directly cast on the beam without any vibration after the surface was sandblasted (Fig. 2(b)). Curing was conducted in a water tank. The UHPFC wrap was applied three months after casting the core concrete beams, and the tests were performed 28 days after UHPFC wrapping (Martinola *et al*. 2010, Tayeh *et al.* 2013a).

Table 1 Details of the testing and control beams

No.	Beam	Sectional dimensions		Thickness of UHPFC (mm)	Configurations
		Height (mm)	Width (mm)		
1	RS-S00	200	100	-	Reference
2	RS-S00-F25	200	100	25	Fully wrap (4 sides)
3	RS-S00-J25	200	100	25	U-jacketed (3 sides)
4	RS-S00-LR25	200	100	25	Left-right sides (2 sides)



(a) Geometry of the specimens



rapping

(b) Strengthening scheme

Fig. 1 Details of the tested beams

(a) Sandblasting surface preparation before applying UHPFC on the beam

(b) Application of UHPFC layer on the beam

Fig. 2 Specimen preparation

Fig. 3 Testing set-up

2.2 Test setup

The experimental setup was designed (Fig. 3) to conduct pure torsion tests on the specimens. The test specimens were placed between fixed and rotary supports. Rotary support was placed on the reaction wall. This roller support, whose longitudinal support was subjected to torsion, was used to make the beam rotate easily. Torsion was given to the beam through a torsional arm placed at the end of the beam close to the simple support. The torsional arm extended 500 mm from the central axis of the beam. Fixed support was connected to the strong floor of the reaction wall. To avoid local crushing of concrete near the supports, the end parts of the beams were properly over-reinforced so that they could support without cracking the imposed loading. The load was applied at an eccentricity of 400 mm from the longitudinal axis of the beam. Load measurements were monitored through a computer-driven data acquisition system. Twist meters were specifically used to measure the twist of the beam.

2.3 Experimental results

The torque versus the twist angle of the specimens throughout the loading system until failure was obtained in the experiments. Table 2 includes the ultimate values and the percentage increase in the ultimate torque relative to the control specimen. As expected, the ultimate torque of the beams strengthened with UHPFC (left-right sides) RS-S00-LR25 exhibits the lowest increase in torsional strength.

The specimens strengthened with the UHPFC matrix exhibited increased torsional capacity and improved performance relative to the control beam. This improvement in torsional response was significant in the RC beams fully wrapped with the UHPFC matrix. Torsional capacity of the beam (RS-S00-F25) increased by 267% relative to that of the control specimen. The increase in torsional strength of the U-jacketed beam (RS-S00-J25) was 195% of the capacity of the control beam. The strengthened beam whose two sides were wrapped with UHPFC (RS-S00-LR25) exhibited a limited increase in torsional capacity of only 82% relative to that of the control beam.

The beam whose four sides were wrapped with UHPFC (RS-S00-F25) exhibited considerably higher torsional strength (approximately 1.24 to 2.01 times) than the beams (RS-S00-J25 and RS-S00-LR25) whose three and two sides were strengthened with UHPFC respectively. The strengthened beam whose three sides were U-jacketed with UHPFC (RS-S00-J25) showed a significant increase in torsional strength.

These findings indicate that full wrapping with UHPFC is far more effective for torsional upgrading than wrapping only two or three sides. Resistance to torsion is significantly enhanced by a closed form of reinforcement because circulatory torsion induces shear stresses on all four sides of a beam. Therefore, strengthened schemes where the cross section is wrapped in a closed form are more effective than other schemes.

3. Numerical study

3.1 Finite element modeling

SOLID65 (or 3D RC solid) was used for the 3D modeling of the solids with or without reinforcing bars (rebars). Solids are susceptible to cracking under tension and crushing under compression. The element is defined by eight nodes with three degrees of freedom at each node, namely, the translations of the nodes in the x, y, and z directions. Up to three different rebar specifications may be defined.

The most important aspect of the Solid65 element is the treatment of nonlinear material properties. In this study, the eight-node brick element was used to simulate concrete behavior and the UHPFC plates.

LINK8 is a spar (or truss) element that may be used in the ANSYS program for various engineering applications. The 3D spar element is a uniaxial tension–compression element with three degrees of freedom at each node, namely, the translations of the nodes in the x, y, and z directions. Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are likewise included. This element is used in the present study to simulate the behavior of rebars.

SOLID45 element is used for the 3D modeling of solid structures. It is defined by eight nodes with three degrees of freedom at each node, namely, the translations in the nodal x, y, and z directions. The element possesses plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. SOLID45 was used in this study to model the steel supports and steel loading arms (ANSYS 10).

Table 2 Ultimate Torque Value (Tu) and the Corresponding Twist Angle (Θu) Obtained from Experiments

No.	Beam Name	Tu (kNm)	% Increase in Tu	Θu (rad/m)
1.	RS-S00	2.306	-	0.011
2.	RS-S00-F25	8.462	267	0.058
3.	RS-S00-J25	6.798	195	0.023
4.	RS-S00-LR25	4.201	82	0.017

3.2 Material properties

3.2.1 Concrete

A nonlinear elasticity model was adopted for the concrete. This model is based on the concept of variable moduli and matches well with several available test data. For normal strength concrete, the simplified compressive uniaxial stress–strain model (Fig. 4) suggested by Kachlakev *et al.* (2001) was used for the concrete material model in ANSYS.

The simplified stress-strain curve was constructed from six points connected by straight lines. A numerical expressions proposed by Gere and Timoshenko(1997) were used to construct the uniaxial compressive stress–strain curve for the concrete in this study.

Thus, ANSYS requires input data for the material properties of concrete. The parameters required to define the material models of concrete for beam RS-S00 are listed in Table 3.

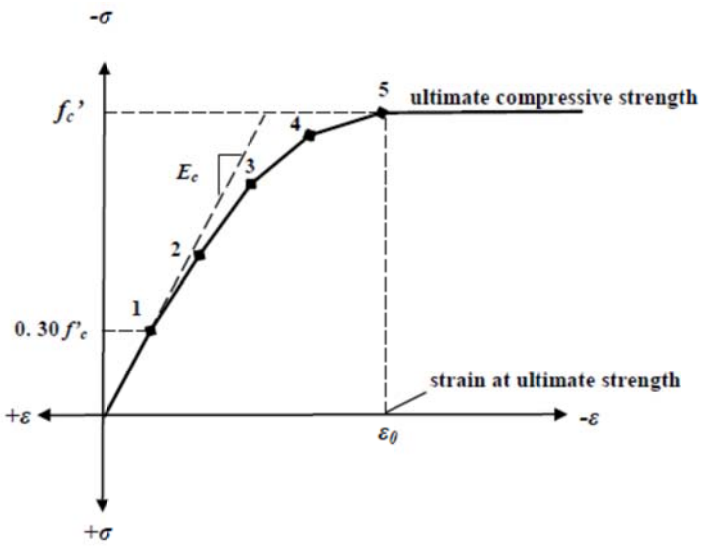


Fig. 4 Simplified compressive uniaxial stress–strain curve for concrete

Table 3 Materials properties for concrete

Material Number	Element Type	Properties	
1	Solid 65	Age	28 days
		STOC	200×10^{-3}
		STCC	800×10^{-3}
		f_t	$2.84 \times 10^{+6}$ Pa
		f_c	$32.2 \times 10^{+6}$ Pa
		f_{cb}	0
		SIGh	0
		f_1	0
		f_2	0
		SMCT	600×10^{-3}

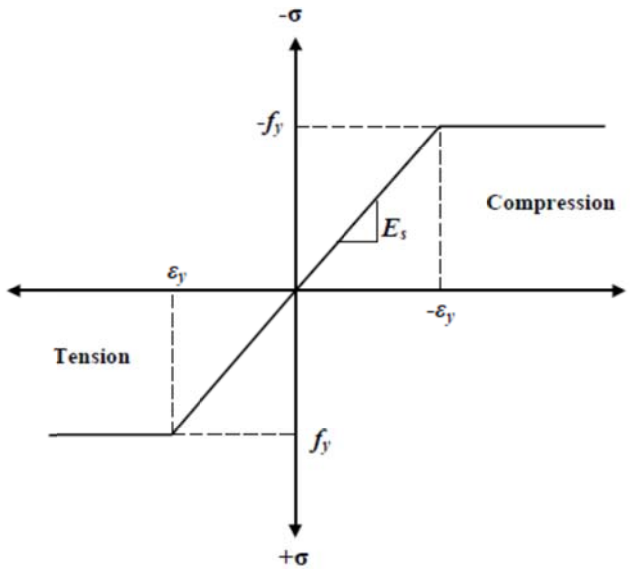


Fig. 5 Stress–strain curve for steel reinforcement

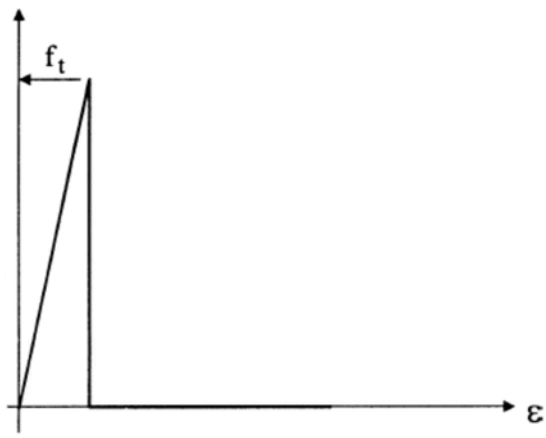


Fig. 6 Stress–strain model for UHPFC plate

3.2.2 Steel reinforcement

The steel reinforcement used for the finite element model is always assumed to be elastic-perfectly plastic material and identical in tension and compression as shown in Fig. 5. Properties of steel reinforcement used in this study, such as elastic modulus and yield stress, followed the design material properties used for the experimental investigation.

Material properties for the steel reinforcement model were as follows:

Elastic modulus: E_s = 200,000 MPa, Yield stress: f_y = 420 Mpa, Poisson's ratio: υ = 0.3.

3.2.3 Ultra-high-performance fiber concrete plate

A linear elastic tensile model until failure was assumed to represent the material of UHPFC plates. The stress–strain model is shown in Fig. 6. The stress was linear up to the tensile strength and dropped sharply to zero, which represented the fracture of plate material.

3.3 Beam geometry

The beam, steel arm, and supports were modeled as volumes. Given that a full size of the beam was being modeled, the model was (1600) mm long with a cross-section measuring (100) mm wide and (200) mm high. The origin point for the X, Y and Z coordinates coincides with the lower corner of the web.

3.4 Beam meshing

The concrete was modeled using the element SOLID65 (nonlinear RC element). The use of a rectangular mesh was recommended to obtain good results from SOLID65. Therefore, the mesh was set up such that square elements were created with a dimension of (20) mm in all three directions. The 3D spar elements and Link8 were employed in the FE models to represent longitudinal steel reinforcement, referred to here as link elements. Fig. 7 shows the FE mesh for the concrete model, the longitudinal steel reinforcement and strengthening.

The width and length of the elements in the support and loading arm were defined properly to be consistent with the elements and nodes in the concrete portions of the model. Fig. 8 shows the location of the applied loading (torsion) on the model with the boundary conditions.

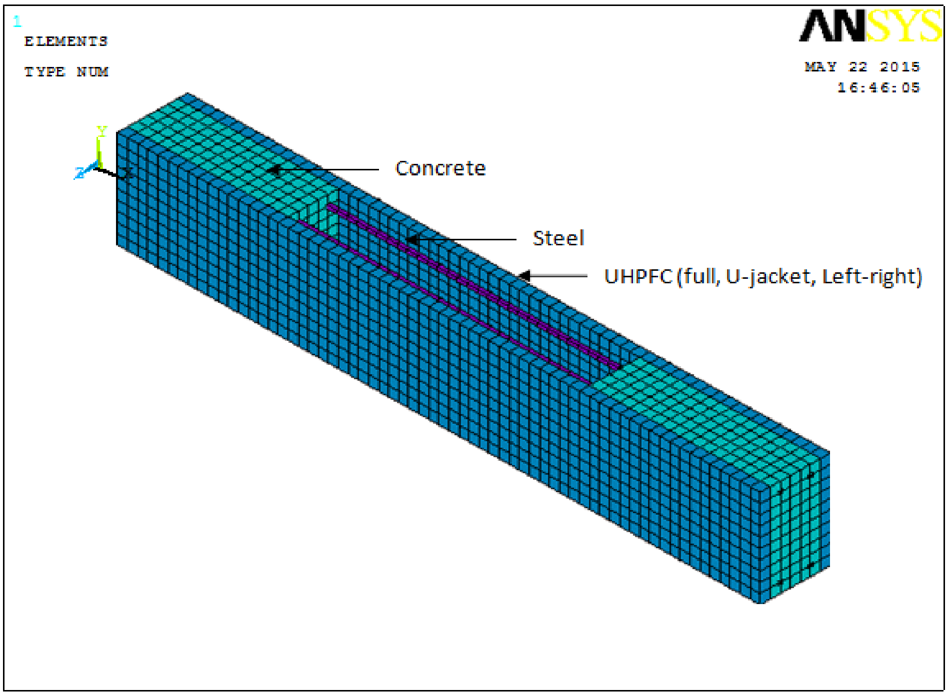


Fig. 7 Concrete, steel and strengthening mesh

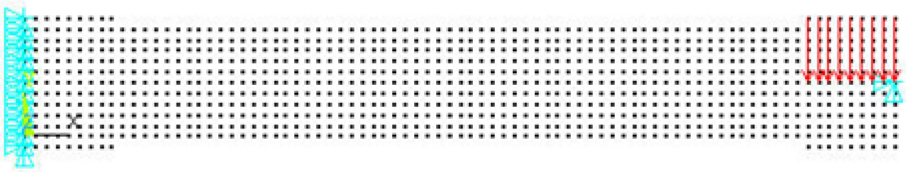


Fig. 8 Applied loading and boundary conditions

3.5 Load stepping and failure definition

The total load applied was divided into a series of load steps in this study. Newton–Raphson equilibrium iterations provide convergence at the end of each load increment within tolerance limits. The automatic time stepping in the ANSYS program predicts and controls load step sizes, which require maximum and minimum load step sizes. The number of load steps, that is, the minimum and maximum step sizes, was determined after several attempts. The loads were applied gradually with smaller load increments during concrete cracking, steel yielding, and ultimate staging, in which numerous cracks occurred. Beam failure occurred when convergence failed with small load increments.

4. Results and discussion

4.1 Baseline specimen

The torque–twist response of the control specimen (without strengthening) is explained in Fig. 9. The beam behaved almost linearly, and it justified that the elastic response extended until the first cracking of the concrete and that strength dropped suddenly just before specimen failure. The longitudinal steel reinforcement had a minor effect on the torsional response, and reinforced concrete element behaved approximately as a plain concrete member.

Tracing the torque–twist response of the member by finite element model is also explained in Fig. 9. The finite element model agreed well with the experimental data up to 55% of the ultimate strength. A disagreement was noted between the curves before the model failure, and the finite element model looked stiffer than the experimental data. This result was mainly caused by the microcracks produced by drying shrinkage and handling present in the concrete to some degree, which reduce the stiffness of the actual beams, while the finite element models did not include microcracks (Kachlakev *et al.* 2001). Finally, the finite element model failed at 2.25 kNm with a difference of –2.4% from the experimental data.

4.2 Strengthened specimens

The torque–twist response of the strengthened specimen (RS-S00-LR25) is shown in Fig. 10. This specimen was strengthened by UHPFC sheets on two vertical sides of the beam. The torsional strength of the beam increased by about 82% compared with that of the baseline specimen. The beam behaved almost linearly up to the ultimate load where sudden failure occurred. A clear disagreement between the finite element model and experimental data was obtained for this specimen. The finite element torque–twist plot in the linear range was stiffer than the experimental plot. This mismatch between the two curves can be attributed to the assumption of a perfect bond between the concrete and UHPFC sheets in the finite element analyses, but the assumption was not true for the actual beam. An addition to microcracks developed within the actual beam reduced the stiffness of the beam at an elastic range. The disagreement reduced when the load reached the ultimate strength and the model failed at 4.22 kNm with a difference of 0.5 % from the experimental data.

Strengthening the beam from three sides by UHPFC sheets improved the torsional strength obtained, as shown in Fig. 11. The torque strength of the beam increased linearly with the twist value, and the beam failed suddenly after sheets failed at ultimate load. A reasonable tracing of the finite element model to the experimental behavior of torque–twist curve was obtained, and the model failed with a difference of –9.5% with experimental data.

Maximum torsional strength was obtained when the beam was strengthened by UHPFC sheets from four sides (Fig. 12). The strength value increased by about 267%, 101%, and 24% compared with that of the baseline specimen, 2-sided strengthened specimen, and 3-sided strengthened specimens, respectively. The disagreement between the finite element model and the experimental data increased with the increase in the UHPFC sheets, and thus we can note the maximum disagreement at the four-sided strengthened specimen. This finding is attributed mainly to the assumption of a perfect bond between the surface of concrete beams and the UHPFC sheets, as well as the bond between the concrete and steel reinforcement. However, the model reasonably described the behavior of the beam and failed approximately at the same load level. The model failed at 8.28 kNm for this beam (4-sided strengthened), that is, with a difference of –2.2% from the experimental data.

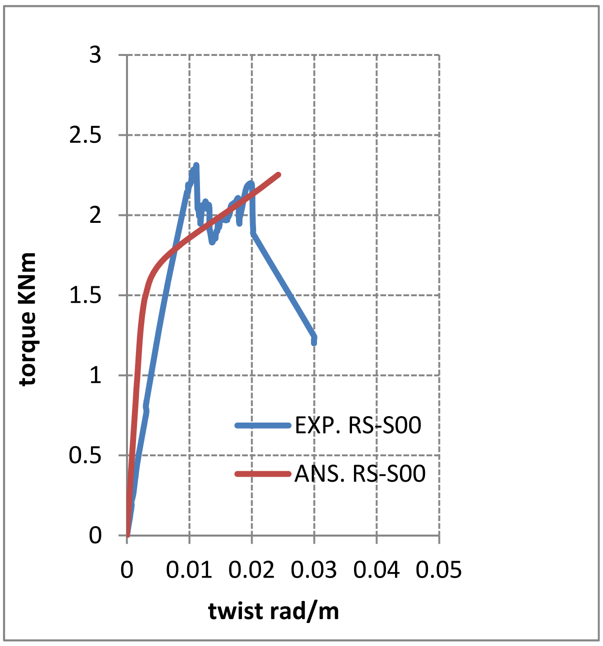


Fig. 9 Torque–twist curve for baseline specimen

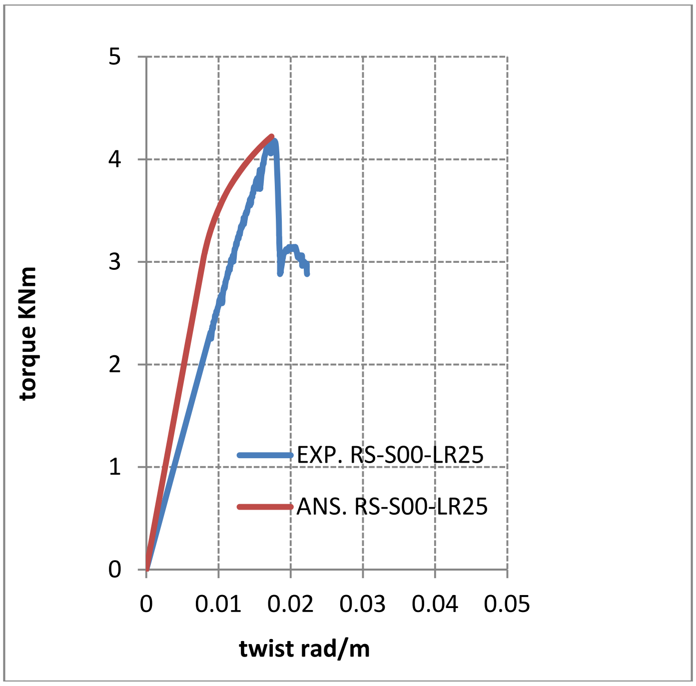


Fig. 10 Torque–twist curve for 2-sided strengthened specimen

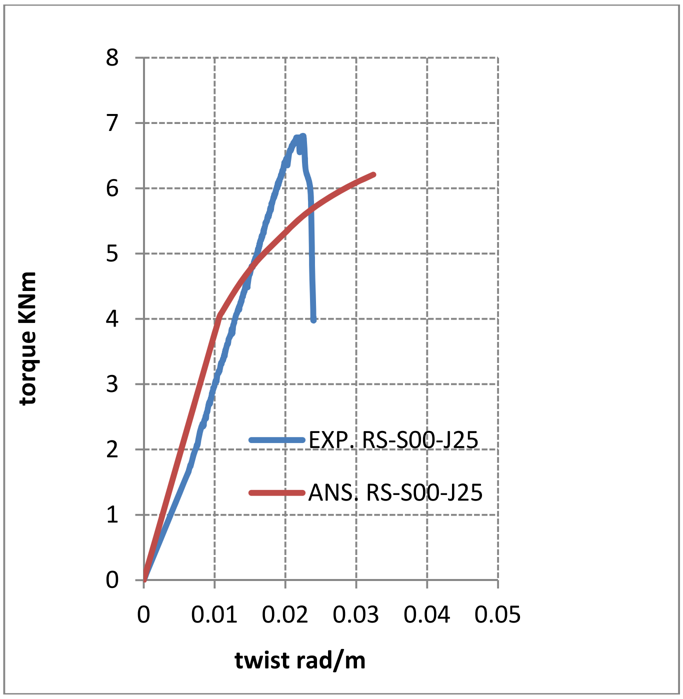


Fig. 11 Torque–twist curve for 3-sided strengthened specimen

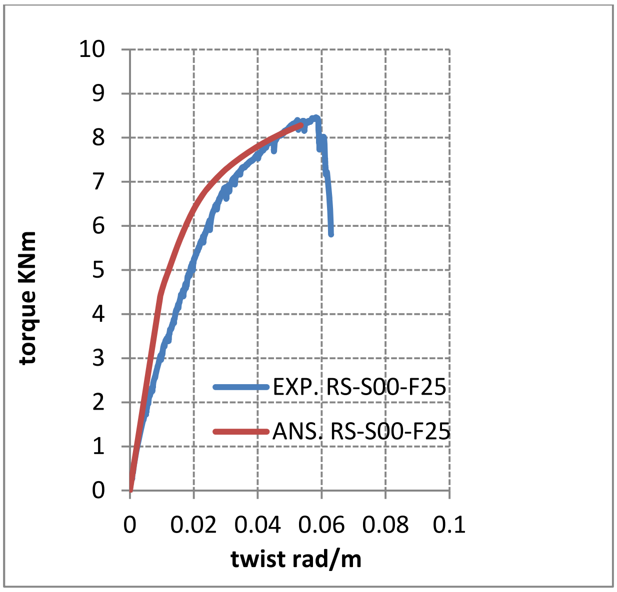


Fig. 12 Torque–twist curve for 4-sided strengthened specimen

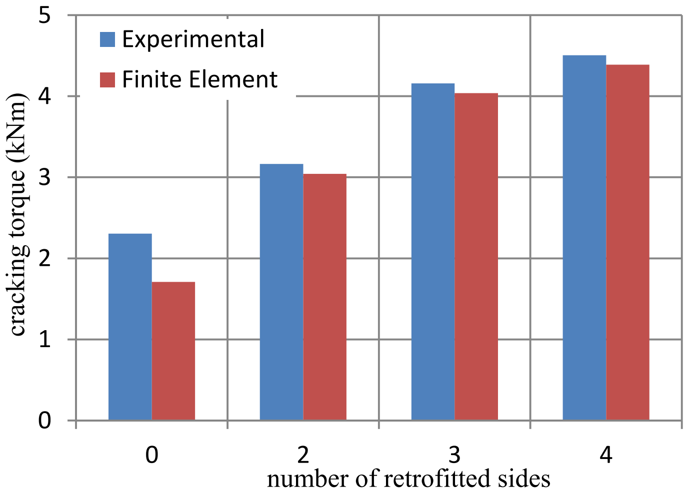


Fig. 13 Cracking torque for experimental and finite element study

4.3 Contribution of retrofitting by UHPFC plate

Fig. 13 explains the effect of retrofitting on the cracking torque value for experimental and finite element study. The experimental results showed that the cracking strength improved after retrofitting the beam with UHPFC. The cracking strength increased by about 37% for the beam retrofitted on two sides only, and this value increased to about (95%) for the four-sided retrofitted beam. The finite element analysis provided results close to the experimental data for the retrofitted specimens, while the clear disparity was noted in the control specimen analysis.

Good agreement existed in the maximum torque value between the experimental and finite element analysis for baseline and retrofitted specimens (Fig. 14). The figure also shows the improvement obtained in the maximum strength of the beams after retrofitting with UHPFC. This increase was proportional to the retrofitted beam sides.

The approximate toughness developed in the beams under torsional loading was calculated and explained in Fig. 15. Retrofitting greatly improved the toughness of the beams, especially for the 4-sided retrofitted beam. We can note the great disagreement between the experimental data and the finite element analysis based on the toughness in the area under the cracked portion of the torque-twist curve (see Figs. 9-12).

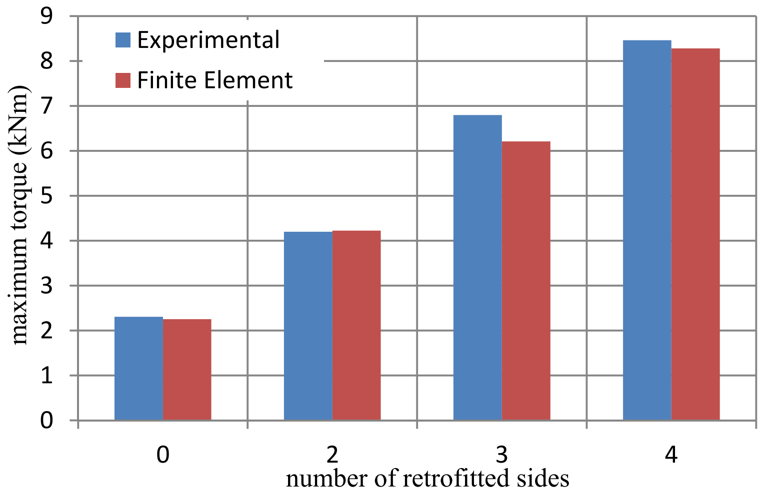


Fig. 14 Maximum torque for experimental and finite element study

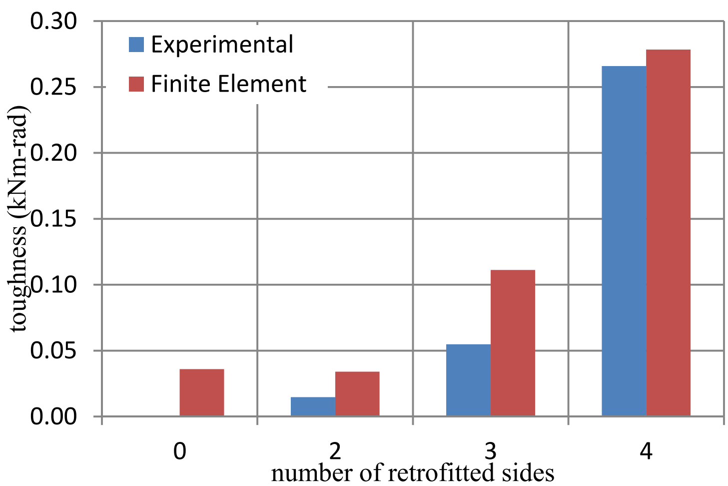


Fig. 15 Approximate toughness for experimental and finite element study

5. Conclusions

The following conclusions were drawn based on the experimental and numerical results obtained from this study

- UHPFC plates improve the strength of reinforced concrete beams with longitudinal bars only under pure torsion.
- It is observed that the increase in beam strength is proportional to the number of strengthened beam sides.
- Ductility and toughness also increased after retrofitting with UHPFC.
- In general, the results obtained using the finite element analysis represented by the torque-twist response show reasonably agreement with the experimental data of beams considered in this study.
- The bond modeling between UHPFC plates and concrete beam has significant effects on the behavior of the retrofitted beam.

Acknowledgements

This study was made possible by the support of the School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia.

References

Ameli, M., Ronagh, H.R. and Dux, P.F. (2007), "Behavior of FRP strengthened reinforced concrete beams under torsion", *J. Compos. Constr.*, **11**(2), 192-200.

ANSYS Structural Analysis Guide (2005), Version 10.0, "ANSYS", Inc., Canonsburg, Pennsylvania.

Chalioris, C.E. (2007), "Analytical model for the torsional behaviour of reinforced concrete beams retrofitted with FRP materials", *Eng. Struct.*, **29**(12), 3263-3276.

Chalioris, C.E. (2008), "Torsional strengthening of rectangular and flanged beams using carbon fibre-reinforced-polymers–experimental study", *Constr. Build. Mater.*, **22**(1), 21-29.

Deifalla, A. and Ghobarah, A. (2010), "Strengthening RC T-beams subjected to combined torsion and shear using FRP fabrics: experimental study", *J. Compos. Constr.*, **14**(3), 301-311.

Deifalla, A., Awad, A. and Elgarhy, M. (2013), "Effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion: An experimental study", *Eng. Struct*., **56**, 2065-2075.

Gere, J.M. and Timoshenko, S.P. (1997), "Mechanics of Materials", PWS Publishing Company, Boston Massachusetts.

Ghobarah, A., Ghorbel, M. and Chidiac, S. (2002), "Upgrading torsional resistance of reinforced concrete beams using fiber-reinforced polymer", *J. Compos. Constr.*, **6**(4), 257-263.

Habel, K. (2007), "Experimental investigation of composite ultra-high-performance fiber-reinforced concrete and conventional concrete members", *ACI. Struct. J.*, **104**(1).

Kachlakev, D., Miller, T., Yim, S., Chansawat, K. and Potisuk, T. (2001), "Finite element modeling of reinforced concrete structures strengthened with FRP laminates", Oregon Dept. of Transp., USA, Res. Group, Final Report SPR 316.

Khagehhosseini, A., Porhosseini, R., Morshed, R. and Eslami, A. (2013), "An experimental and numerical investigation on the effect of longitudinal reinforcements in torsional resistance of RC beams", *Struct. Eng. Mech.*, **47**(2), 247-263.

Lei, Y., Nematollahi, B., Mohamed, A., Gopal, B. and Shun, T. (2012), "Application of ultra high performance fiber reinforced concrete–The malaysia perspective", *Int. J. Constr. Eng. Technol.*, **3**(1), 26-44.

Martinola, G., Meda A., Plizzari G.A. and Rinaldi Z. (2010), "Strengthening and repair of RC beams with fiber reinforced concrete", *Cement. Concrete. Comp.*, **32**(9), 731-739.

Mohammadizadeh, M.R., Fadaee, M.J. and Ronagh, H.R. (2009), "Improving torsional behaviour of reinforced concrete beams strengthened with carbon fibre reinforced polymer composite", *Iran. Polym. J.*, **18**(4), 315-327.

Noshiravani, T. and Brühwiler, E. (2010), "Behaviour of UHPFRC-RC Composite Beams Subjected to Combined Bending and Shear", *Proceeding of the 8th fib PhD Symposium*, Denmark, June.

Noshiravani, T. and Brühwiler, E. (2013), "Experimental investigation on reinforced ultra-high-performance fiber-reinforced concrete composite beams subjected to combined bending and shear", *ACI. Struct. J.*, **110**(2).

Panchacharam, S. and Belarbi, A. (2002), "Torsional Behaviour of Reinforced Concrete Beams Strengthened with FRP Composites", *Proceeding of the 1st FIB Congress on Concrete Structures in the 21st Century,* Osaka, Japan.

Salom, P., Gergely, J. and Young, D. (2004), "Torsional retrofit of spandrel beams with composite laminates", *J. Compos. Constr.*, **8**(2), 157-162.

Santhakumar, R., Dhanaraj, R. and Chandrassekaran, E. (2007), "Behaviour of retrofitted reinforced concrete beams under combined bending and torsion: A numerical study", *Electron. J. Struct. Eng.*, **7**, 1-7

Tayeh, B.A., Abu Bakar, B.H., Megat Johari M.A. and Voo, Y.L. (2013a), "Evaluation of bond strength between normal concrete substrate and ultra high performance fiber concrete as a repair material", *Procedia. Eng.*, **54**, 554-563.

Tayeh, B.A., Abu Bakar, B.H., Megat Johari M.A. and Voo, Y.L. (2013b), "Utilization of ultra-high performance fibre concrete (UHPFC) for rehabilitation – A review", *Procedia. Eng.*, **54**, 525-538.

Zhang, J.W., Lu, Z.T., and Zhu, H. (2001), "Experimental Study on The Behaviour of RC Torsional Members Externally Bonded with CFRP", *Proceedings of the International Conference on FRP composites in Civil Engineering*, Hong Kong, China, December.

CC