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# Strengthening of reinforced concrete beams subjected to torsion with UHPFC composites

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**Abstract.** The proposed techniques to repair concrete members such as steel plates, fiber-reinforced polymers or concrete have important deficiencies in adherence and durability. The use of ultra high performance fiber concrete (UHPFC) can overtake effectively these problems. In this paper, the possibility of using UHPFC to strengthen reinforced concrete beams under torsion is investigated. Seven specimens of concrete beams reinforced with longitudinal and transverse reinforcements. One of these beams consider as control specimen while the others was strengthened by UHPFC on four, three, and two sides. This study includes experimental results of all beams with different types of configurations and thickness of UHPFC. As well as, finite element analysis was conducted in tandem with experimental test. Results reveal the effectiveness of the proposed technique at cracking and ultimate torque for different beam strengthening configurations, torque - twist graphs and crack patterns. The UHPFC can generally be used as an effective external torsional reinforcement for RC beams. It was noted that the behavior of the beams strengthen with UHPFC are better than the control beams. This increase was proportional to the retrofitted beam sides. The use of UHPFC had effect in delaying the growth of crack formation. The finite element analysis is reasonably agreement with the experimental data.

**Keywords:** torsion; beam; strengthening; UHPFC; finite element analysis

## 1. Introduction

Repair and strengthening of buildings, bridges, and other civil engineering structures have become necessary due to aging, changes in use of structures, increases in service loads, environmentally induced degradation, changes in design code regulations, design and/or construction errors, and seismic retrofits. Many buildings and bridge structures are subjected to significant torsional strength that affects structural design and may require strengthening. Reinforced concrete members may lack torsional shear capacity and be in need of strengthening.

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There are several reasons for this including insufficient transverse steel resulting from construction errors, or reduction in the effective rebar area due to corrosion, or increased loading due to a change in occupancy. To conclude, different techniques are used for repair material applications, depending on the types of structures and repair conditions in question.

There are many different techniques to improve the torsional capacity reinforced concrete (RC) members like steel plates, fiber-reinforced polymers (FRP) or concrete. Some strengthening methods like the addition of steel plates and jacketing with reinforced concrete may present corrosion problems or failure of the strengthening system (Iskhakov *et al.* 2013). Consequently, during the last two decades, many researchers have demonstrated and accepted the advantages of strengthening concrete members using FRP because of its superior properties, which include high strength-to-weight ratio, easy installation, and non-corrosiveness (Jariwala *et al.* 2013). Many 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, and Diefalla *et al.* 2013), analytically (Chalioris 2007, Diefalla and Ghobarah 2010), and numerically (Ameli *et al.* 2007, Santhakumar *et al.* 2007). Good results have been obtained from strengthening by FRP, though this technique still has a few important deficiencies in adherence and durability. Bond between FRP sheet and concrete and long-term durability of FRP are of high concern. Therefore, the history of use should be considered for each specific retrofitting 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 de-bonding may adversely affect structural performance if the FRP is designed and applied improperly. The use of ultra high performance fiber concrete (UHPFC) materials can be a viable alternative which can effectively solve these problems.

Therefore, various solutions have been investigated as the demand for new technologies and materials to upgrade damaged structures continue to increase. 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 UHPFC 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 reinforced concrete beams under flexure or combined bending and shear (Habel 2007, Martinola, Meda *et al.* 2010, Noshiravani and Brühwiler 2010, Noshiravani and Brühwiler 2013). Thus, research into the use of UHPFC to strengthen structural elements 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.

The objective of this investigation is to evaluate experimentally and numerically the effectiveness of UHPFC in strengthening RC beams under torsion. The proposed technique considers the use of a thin layer of UHPFC with a different thickness under the following variations: four, three, and two vertical sides wrapped with UHPFC.

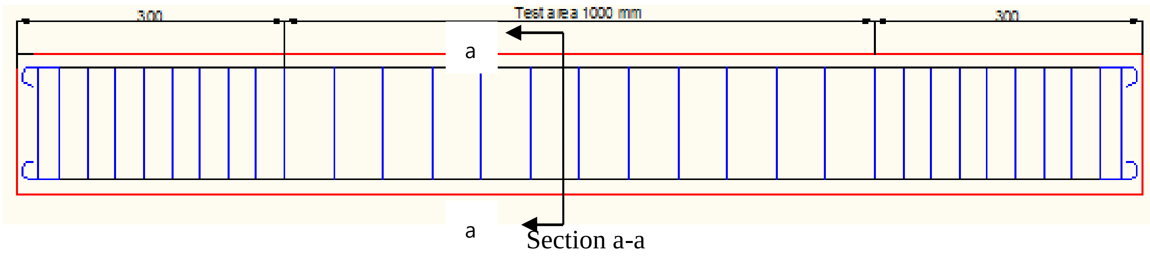


Fig. 1(a) Geometry of the specimens

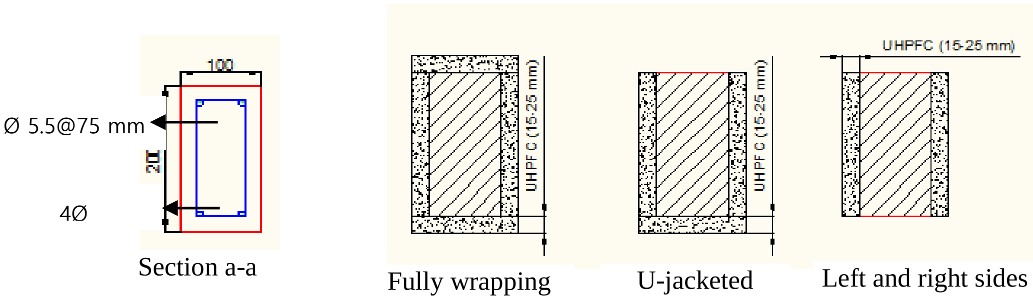


Fig. 1(b) Strengthening scheme.

Table 1 Details of testing beams and control beam

| No. | Beam | Configurations | Thickness of UHPFC (mm) | Sectional dimensions | |
|---|---|---|---|---|---|
| | | | | Height (mm) | Width (mm) |
| 1 | RS-S66 | Reference | - | 200 | 100 |
| 2 | RS-S66-F15 | Fully wrap (4 sides) | 15 | 230 | 130 |
| 3 | RS-S66-F25 | Fully wrap (4 sides) | 25 | 250 | 150 |
| 4 | RS-S66-J15 | U-jacketed (3 sides) | 15 | 215 | 130 |
| 5 | RS-S66-J25 | U-jacketed (3 sides) | 25 | 225 | 150 |
| 6 | RS-S66-LR15 | Left-right sides (2 sides) | 15 | 200 | 130 |
| 7 | RS-S66-LR25 | Left-right sides (2 sides) | 25 | 200 | 150 |

## 2. Beam characteristics

The effectiveness of the proposed UHPFC strengthening technique in all its three variations are investigated by performing full-scale experimental tests on seven beams with lengths of 1600 mm (Fig. 1). All beams have the same longitudinal reinforcement consisting of four longitudinal bars with diameters of 8 mm (4Ø 8) at the corners and transverse reinforcement ratios of 0.66% in the testing zone. Steel yield strength was 420 MPa.

This research deals with two types of concrete, normal concrete as an old concrete beam while UHPFC as a strengthening material. The 28-day compressive strength of the normal concrete beams was 32 MPa. This strength value is average from three cubes (100*100*100 mm). Such low resistance of compression concrete was chosen to highlight the effectiveness of the strengthening function. For the strengthening beams, the compressive strength of UHPFC was up to 150 MPa at

28 days. This strength value is average from three cubes having a side of 100 mm.

The cross-section of seven specimens was rectangular. One of the RC beams was used as the control beam, and a thin layer of UHPFC was applied on the other six beams (i.e., a 15 mm and 25 mm layer strengthening for full wrap, U-jacket and left-right sides are considered). The details relevant to the beams are shown in Table 1.

### *2.1 Specimen preparation*

First, the ordinary beam was cast, the surfaces of the RC beam were sandblasted to produce a roughness, which was enough to ensure sufficient bond strength between concrete and UHPFC without the use of bonding products (Martinola *et al.* 2010, Tayeh *et al.* 2013a) (Fig. 2(a)). The UHPFC material was directly cast on the beam without any vibration after the surface was sandblasted (Fig. 2(b)). The curing was carried out by ponding in a water tank. The UHPFC material was applied three months after casting the RC beams, and the tests were performed 28 days after UHPFC wrapping (Martinola *et al*. 2010, Tayeh *et al.* 2013a).

## 3. Test setup

The experimental setup was performed using a structural testing frame to conduct pure torsion

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

(b) Application of UHPFC layer on the beam

Fig. 2 Specimen preparation

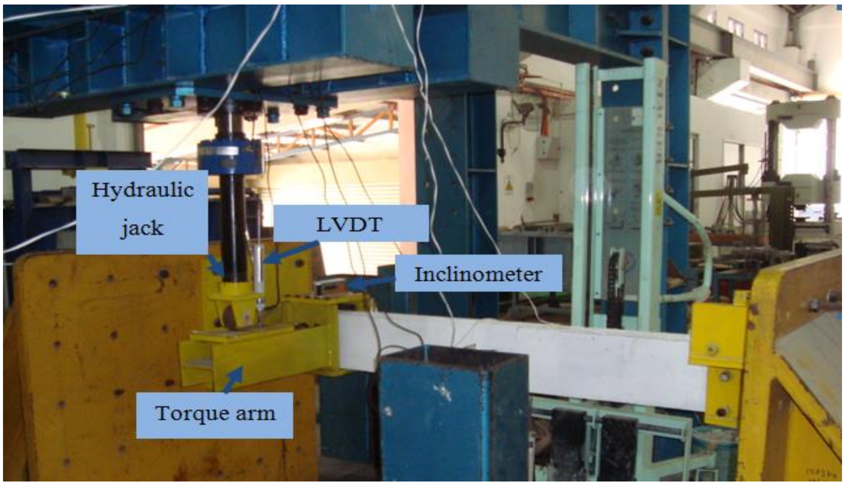

Fig. 3 Testing set-up

tests on the specimens as shown in Fig. 3. One end of the specimen was supported by a roller support, which allowed the specimen to rotate while it was loaded. The other end of the specimen was supported by a rigid support. The torsional arm extended 500 mm from the central axis of the specimen. The load on the twist arm was applied through a mechanical screw jack. Proper care was taken to ensure that the loading lever arm was perpendicular to the longitudinal axis of the specimen to prevent bending. Thus, the specimen between the two supports was subjected to pure torsion. The end parts of the specimens were properly enough reinforced to ensure that they can support the imposed loading without cracking and prevent the concrete near the supports from being locally crushed. The load was applied at an eccentricity of 400 mm from the longitudinal axis of the specimen. The measurements of the loads were monitored through a recorded data system. Inclinometer was used to measure the twist angle of the specimen.

## 4. Test results

A possible use of low thickness, ultra-high performance fiber concrete for torsion strengthening purposes is analyzed herein. In this section, the effect of UHPFC layers (full wrapping, U-jacket and left-right wrapping) with different thicknesses on increasing torsional capacity under a torsional load is determined. Fig. 4 shows the torque versus the twist angle of the beams throughout the loading system until failure was obtained in the experimental test. The cracking and ultimate torsional strength of beams and the percentage increase in the cracking and ultimate torque relative to the control beam are included in Tables 2. The control beam (RS-S66) reached a maximum torque of (2.619 kNm) with a maximum rotation of (0.079 rad/m), while the cracking torque was (2.109 kNm) with an angle of twist of (0.009 rad/m).

The beams (RS-S66-F15 and RS-S66-F25) were strengthened with a 15 mm and 25 mm, respectively thin layer of UHPFC done by full wrapping. The torque-twist curve was linear up to cracking torque. After cracking, there was a drop in the torsional stiffness as indicated by the reduced slope of the torque-twist curve, but the beams continued to carry a higher amount of torque with increasing angle of twist until yielding of the stirrups and longitudinal bars occurred.

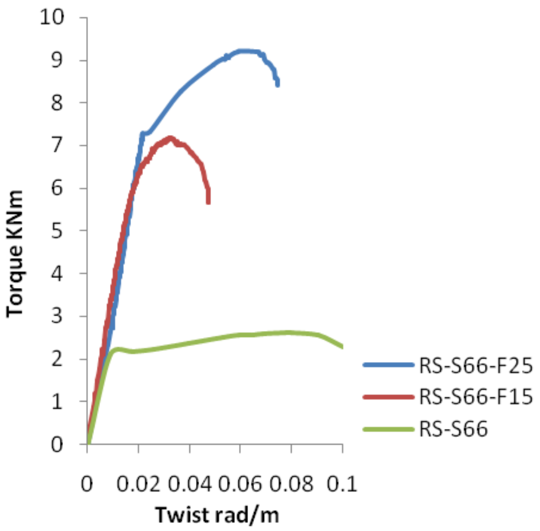


Fig. 4(a) Effect of full wrap

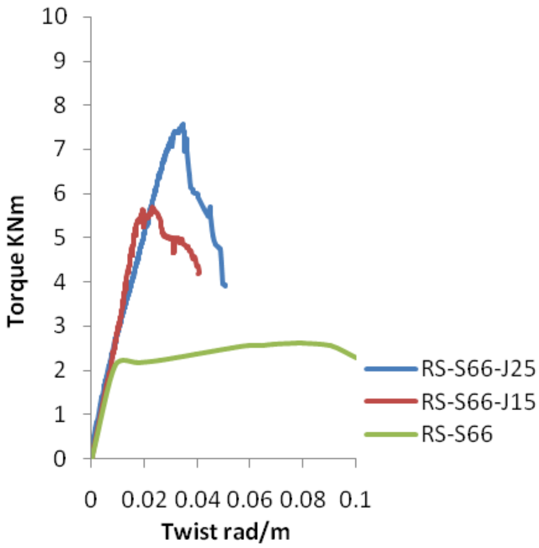


Fig. 4(b) Effect of U-jacket

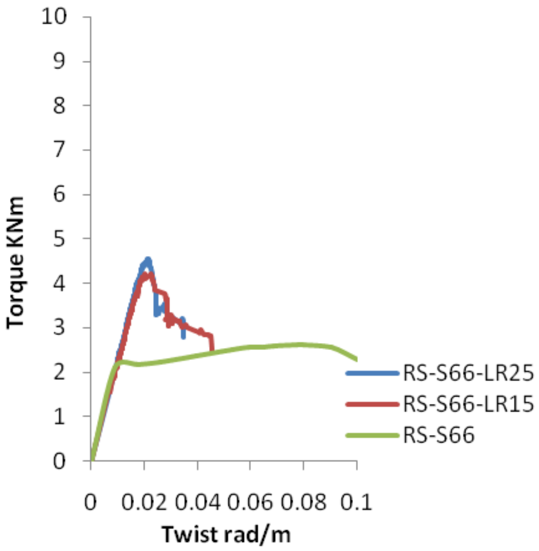


Fig. 4(c) Effect of left-right sides

A plateau of torque with increasing angle of twist was observed to failure specimen as shown in Fig. 4(a). At the torque of 4.05 and 5.527 kNm initial hairline cracks appeared for beams (RS-S66-F15 and RS-S66-F25), respectively. Later with the increase in loading values the crack propagated further. It has failed completely in torsion at torsional moment 7.174 and 9.203 kNm for beams (RS-S66-F15 and RS-S00-F25), respectively. Increase strength of beam was 174% and 251% for beams (RS-S66-F15 and RS-S66-F25), respectively as the control beam as outlined in Table 2. This improvement in the torsional response was very significant in the RC beams fully wrapped with UHPFC.

Table 2 Cracking and ultimate torque values (*Tcr* and *Tu*) obtained from experiments, corresponding percentage increase, cracking, and ultimate torques ratios for beams.

| No. | Beam Name | *Tcr* (kNm) | % Increase in *Tcr* | *Tcr* UHPFC (kNm) | *Tu* (kNm) | % Increase in *Tu* | *Tu* UHPFC (kNm) |
|---|---|---|---|---|---|---|---|
| 1 | RS-S66 | 2.109 | - | - | 2.619 | - | - |
| 2 | RS-S66-F25 | 5.527 | 162 | 3.418 | 9.203 | 251 | 6.584 |
| 3 | RS-S66-F15 | 4.050 | 92 | 1.941 | 7.174 | 174 | 4.555 |
| 4 | RS-S66-J25 | 4.444 | 111 | 2.335 | 7.569 | 189 | 4.950 |
| 5 | RS-S66-J15 | 3.652 | 73 | 1.543 | 5.694 | 117 | 3.075 |
| 6 | RS-S66-LR25 | 3.461 | 64 | 1.352 | 4.554 | 74 | 1.935 |
| 7 | RS-S66-LR15 | 2.577 | 22 | 0.468 | 4.139 | 58 | 1.520 |

While the beams (RS-S66-J15 and RS-S66-J25) were strengthened with a 15 mm and 25 mm, respectively thin layer of UHPFC having U-jacket. The torque-twist curve of jacket beam is linear at cracking torque as shown in Fig. 4(b). This linearity ends once the torque strength reaches to maximum torque. Torque strength beyond this point of inflection is coincides with the failure specimen. It is observation the torque-twist behavior gives an understanding that the stiffness has not reduced after initiation of micro-cracking. Then few micro-cracks propagated and stiffness might not also reduce. So, the micro-cracking is initiated from phase of linearity and ends with formation of first macro crack. Visible major crack is noticed beyond the end of the linearity in the torque-twist curve at maximum torque. In general, no de-bonding of UHPFC layer was observed at the interface of concrete till maximum torque. At the torque of 3.652 and 4.444 kNm initial hairline diagonal cracks appeared on un-wrap for beams (RS-S66-J15 and RS-S66-J25), respectively. With the increase of load diagonal cracks appeared in the concrete to the UHPFC. Further increasing the load that it has failed completely in torsion at torsional moment 5.694 and 7.569 kNm for (RS-S66-J15 and RS-S66-J25), respectively. The RS-S66-J15 and RS-S66-J25 resulted in a 117%, and 189%, respectively increase in torsional capacity over the control beam as outlined in Table 2. This improvement in the torsional response was significant in the RC beams U-jacket with UHPFC.

While beams (RS-S66-LR15 and RS-S66-LR25) were strengthened by wrapping with a 15 mm and 25 mm, respectively thin layer of left-right sides UHPFC. Fig. 4(c) can be seen that the torque-twist relationship was linear up to cracking torque. The torque started to drop with slight increased angle of twist therefore indicates that strengthened from left-right faces alone do not provide effective torsional resistance in the post-cracking range. At the torque of 2.577 and 3.461 kNm, respectively first cracking sound was heard. The beams RS-S66-LR15 and RS-S66-LR25 failed completely in torsion at torsional moment 4.139 and 4.554 KNm, respectively. The increase strength of beams RS-S66-LR15 and RS-S66-LR25 was 58% and 74%, respectively as compared to control beam as outlined in Table 2. The ultimate torque of the beams strengthened with UHPFC (two-side variation), and RS-S66-LR15 exhibits the lowest increase in torsional strength.

The beams strengthened with the UHPFC matrix exhibited increased torsional strength and improved performance relative to the control specimen. The experimental results show the effectiveness of the proposed technique in improving the torsional capacity of all cases strengthened RC beams with UHPFC matrix.

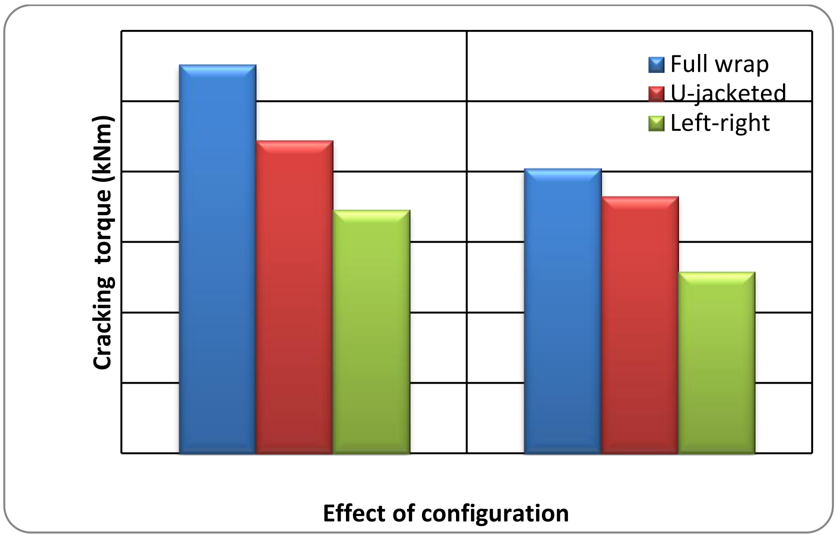


Fig. 5(a) Effect of the configuration on the cracking torque of tested beams

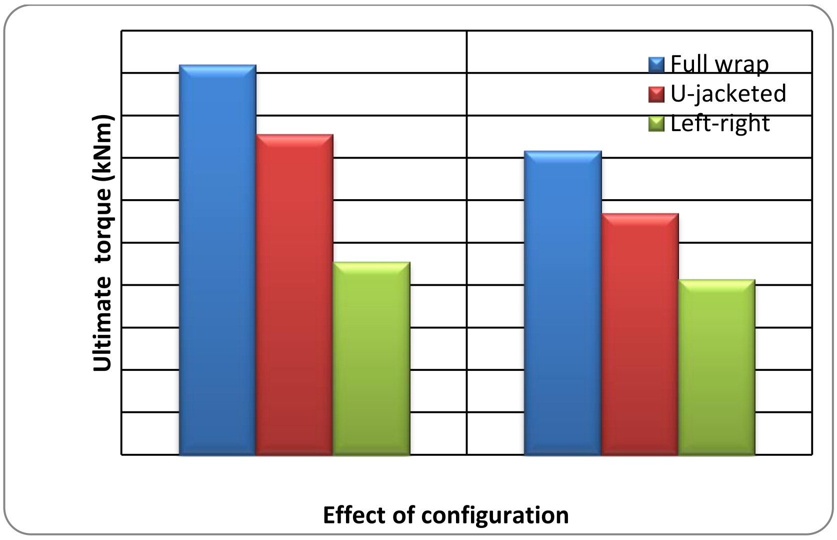


Fig. 5(b) Effect of the configuration on the ultimate torque of tested beams

### *4.1 Effect of schemes strengthening and thickness*

Torsion is resisted well 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) or two vertical sides wrap is more practical because of the inaccessibility of the entire cross section due to extension of flange in monolithic beam - slab construction.

Fig. 5 shows the influence configuration of strengthening on crack and ultimate torsional moment of the RC beams strengthened with UHPFC matrix. The thickness of UHPFC increases the crack torsional moment of the RC beams. The beam whose four sides were wrapped with a 25 mm thin layer of UHPFC (RS-S66-F25) exhibited a considerably higher crack torsional moment (approximately 1.24 times to 1.60 times) and higher torsional capacity (approximately 1.22 times to 2.02 times) than the specimens (RS-S66-J25 and RS-S66-LR25) whose three and two sides were strengthened with UHPFC, respectively. Meanwhile, the beam whose four sides were wrapped with a 15 mm thin layer of UHPFC (RS-S66-F15) exhibited a considerably higher crack torsional moment (approximately 1.11 times to 1.57 times) and higher torsional capacity (approximately 1.26 times to 1.73 times) than the specimens RS-S66-J15 and RS-S66-LR15, respectively.

The beam whose four sides were wrapped with UHPFC exhibited a considerably higher torsional capacity than the specimens whose three and two sides were strengthened with UHPFC, respectively. The strengthened beam whose three sides were *U*-jacketed with UHPFC showed a significant increase in torsional capacity (Fig. 5). 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 wherein the cross section is wrapped in a closed form are more effective than other schemes.

In addition, test results show that the UHPFC contribution to torsional strength of the strengthened beams is increased significantly with an increase in the thickness of UHPFC. By comparing the results in Table 2, it can be seen that the percentage increase in cracking and ultimate strength due to UHPFC depends on the thickness of layer of UHPFC. The UHPFC contribution to cracking and ultimate torque for strengthened beams is shown in Fig. 6(a) and Fig. 6(b), respectively. Hence, it can be concluded that the increase of UHPFC contribution to torsional strength corresponding to the beams strengthened with increase thickness of UHPFC (full wrap, U-jacket and Left-right sides) would be very significant.

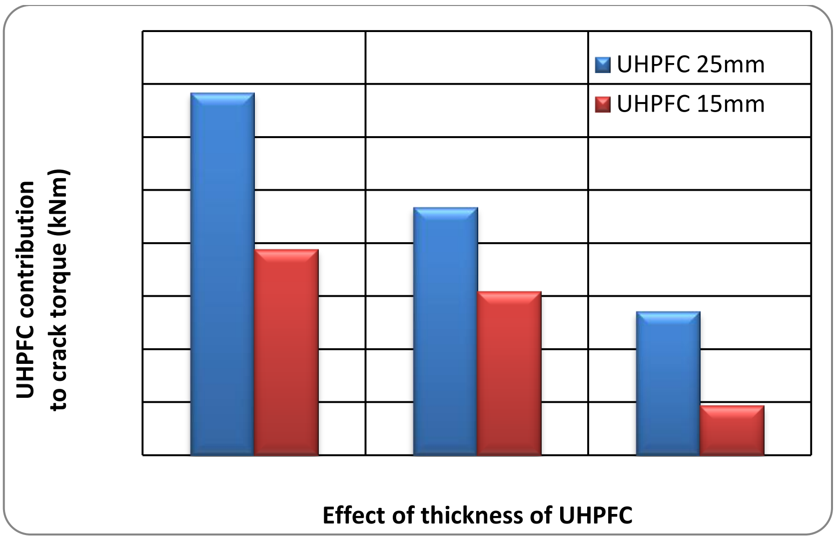


Fig. 6(a) UHPFC contribution to crack torque capacity of tested beams for different thickness

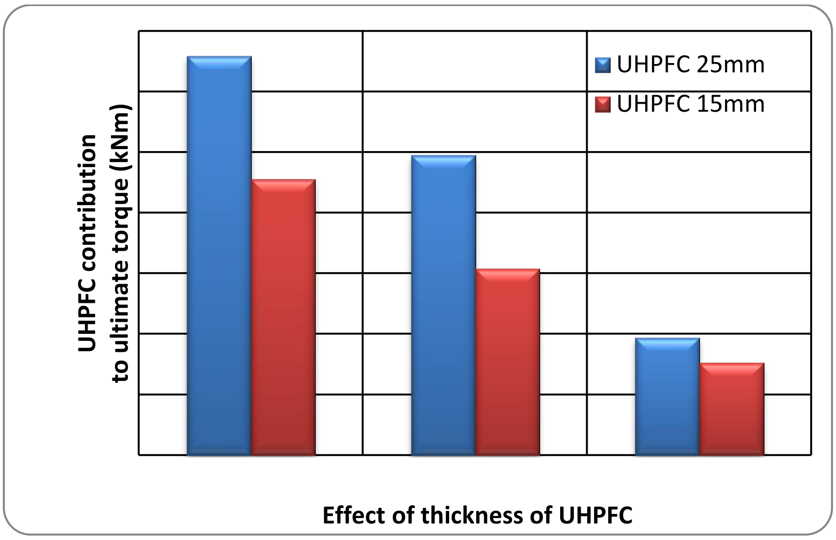


Fig. 6(b) UHPFC contribution to ultimate torque of tested beams for different thickness

## 5. Crack pattern

The control specimen RS-S66 exhibited a wider range of crack propagation and a faster rate of crack progression than the other beams because of the absence of any thickness of UHPFC along the beam. According to elasticity theory, the cracks of a beam subjected to pure torsion occur on the large faces of a rectangular cross section because these faces undergo the largest shear stresses. New diagonal cracks occurred as the torque increased, and the number of cracks parallel to the initial cracks increased until the ultimate torque was reached. Thus, cracks developed spirally around the beam. When the beam reached its peak load, one specific crack significantly widened relative to the other cracks in the specimen (Fig. 7(a)). The tested specimen RS-S66-F15 also behaved in this manner (Fig. 7(b)). For example, the crack behavior of beam RS–S66–F15 was examined. The first crack was observed diagonally at a torque of 4.05 kNm. New diagonal cracks formed as the torque increased, and cracks were observed spirally around the beam. The width of the crack also increased as the torque increased. After the peak torque of 7.174 kNm was reached, the torque gradually decreased.

The first crack in the reinforced concrete beams jacketed with UHPFC wraps appeared on the unwrapped concrete face. New cracks then appeared on the wrapped long faces of beam RS-S66-J15, and further loading increased small segmental cracks. The ultimate failure was caused by the formation of a single spiral crack around the beam. The crack appeared on the unwrapped face with an inclination of approximately 45° to the longitudinal axis. After the beam reached its peak

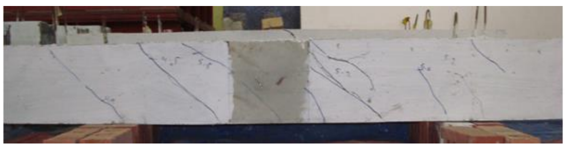

Fig. 7(a) Control beam (RS-S66)

Fig. 7(b) Full wrapping (RS-S66-F15)

Fig. 7(c) U-jacked (RS-S66-J15)

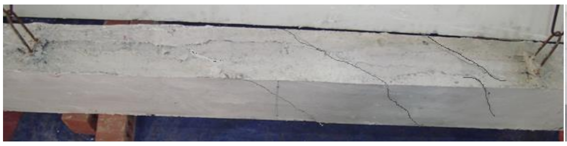

Fig. 7(d) Left and right sides (RS-S66-LR15)

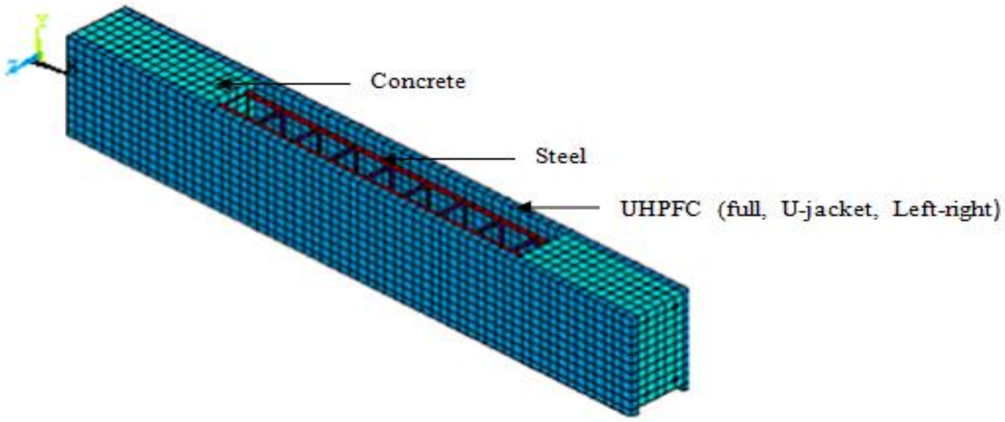


Fig. 8 Concrete, steel and strengthening mesh

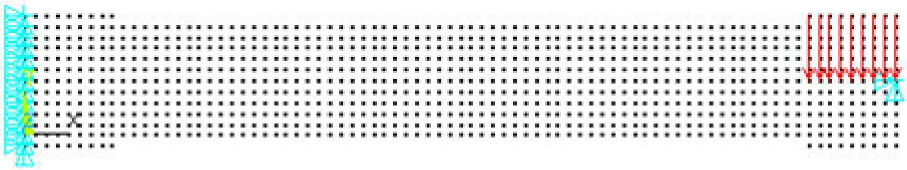

Fig. 9 Applied loading and boundary conditions

load, de-bonding was noticed at the interface of RC and UHPFC at failure after the damage in the ordinary concrete (Fig. 7(c)). The tested specimen RS-S66-LR15 also behaved in the same manner (Fig. 7(d)).

## 6. Finite element analysis

The present study used the computer software ANSYS for performing the nonlinear model analysis (ANSYS 10.0). The concrete was modeled using the element SOLID65 (nonlinear RC element). The concrete beam was modeled as volumes. The use of a rectangular mesh was recommended to obtain good results from SOLID65. The 3D spar elements and Link8 were employed in the FE models to represent rebar reinforcement, referred to here as link elements (Kachlakev *et al.* 2001). Fig. 8 shows the FE mesh for the concrete model, the steel reinforcement and strengthening. Other details can be found in Mohammed *et al.* (2015).

The width and length of the elements in the loading arm and support were defined properly to be consistent with the elements and nodes in the concrete portions of the model. Fig. 9 shows the

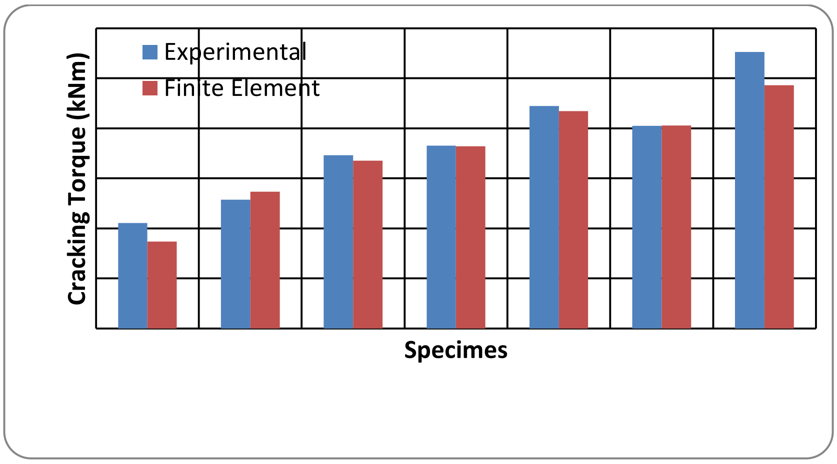


Fig. 10 Cracking torque for experimental and finite element study

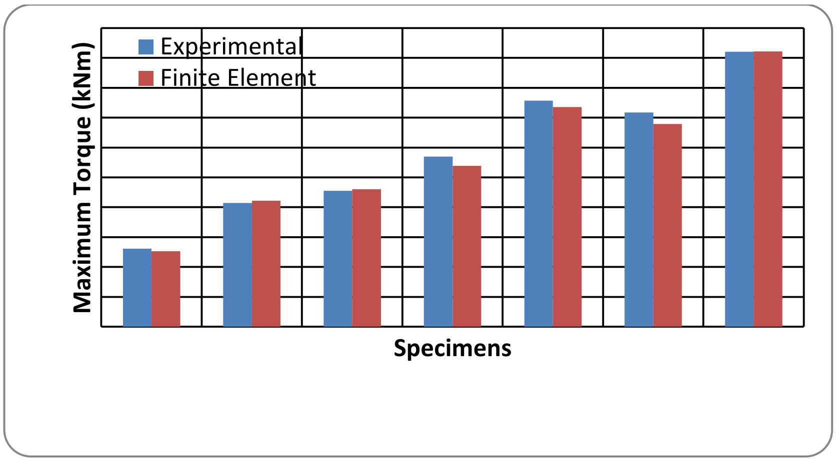


Fig. 11 Maximum torque for experimental and finite element study

boundary conditions with the location of the applied loading (torsion) on the model.

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.

### *6.1 Contribution of retrofitting by UHPFC*

Fig. 10 explains the effect of strengthening on the cracking torque for experimental and finite element study. The experimental results showed that the cracking torsional strength improved after strengthening the beam with UHPFC. For example the cracking strength increased by about (64%) for the beam strengthened on two sides only, and this value increased to about (162%) for the four-sided strengthened beam (a 25 mm thin layer of UHPFC). The FE analysis provided results close to the experimental data for the strengthened specimens, while the clear disparity was noted in the control beam analysis.

Good agreement existed in the maximum torque value between the experimental and finite element analysis for control and strengthened specimens (Fig. 11). The figure also shows the improvement obtained in the maximum torsional strength of the beams after strengthening with UHPFC. This increase was proportional to the strengthened beam sides.

## 7. Conclusions

This study provides information on the torsional behavior of beams strengthened by a thin layer of UHPFC. The experimental and numerical results show that the proposed method is a promising technique. On the basis of the results of this study, the following conclusions can be drawn:

The application of a thin layer of UHPFC on RC beams (four, three, and two vertical sides wrapped with UHPFC) increased the cracking torque and torsional capacity.

Fully wrapping the cross section of a beam with UHPFC significantly increases the ultimate strength. Full wrapping with UHPFC exhibits a considerably higher torsional capacity than wrapping only three or two vertical sides.

The UHPFC contribution to torsional strength is increased when thickness increases, for all strengthened beams.

The possibility of cracks can be remarkably reduced because the UHPFC matrix initially prevents cracking in all cases.

The bond strength between UHPFC matrix and RC beam has significant effects on the behavior of the strengthened beam.

In general, the results obtained using the finite element models represented by cracking and ultimate strength show reasonably agreement with the experimental data of beams considered in this study.

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