Construction and Building Materials 106 (2016) 533–542

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Torsional improvement of reinforced concrete beams using ultra high-performance fiber reinforced concrete (UHPFC) jackets – Experimental study

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HIGHLIGHTS

- Torsional upgrading of deficient RC beams without transverse reinforcement using UHPFC jacketing technique (4-sided, 3-sided and 2-sided) was evaluated.
- Torsional performances of strengthened beams were compared experimentally and numerically.
- UHPFC jackets enhanced the torsional performance of RC beams.

ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form 3 December 2015
Accepted 22 December 2015
Available online 28 December 2015

Keywords:
Beams
Concrete
Ultra high-performance fiber reinforced concrete (UHPFC)
Jackets
Strengthening
Test
Finite element analysis
Torsional moment

ABSTRACT

The efficiency of using ultra high-performance fiber reinforced concrete (UHPFC) to strengthen reinforced concrete (RC) beams under torsion is investigated. The significant advantages of the applied UHPFC jackets are (i) its high compressive and tensile strength and (ii) its excellent rheological properties led to facilitate concrete casting in strengthening works, and that is of high interest to the researchers and practice engineers. This study includes experimental results of all specimens with different types of configurations and thickness of UHPFC. Ten beams with only longitudinal reinforcement (i.e., without transverse reinforcement) are strengthened with UHPFC on two, three, and four sides. One beam with the same reinforcement ratio but without UHPFC is used as the control beam. As well as, finite element analysis was conducted in tandem with experimental work to compare and justify the effective of repair technique. Results show the effectiveness of the proposed technique at ultimate torque for different beam strengthening configurations, crack patterns, and behavioral curves. Strengthened RC beams four sides with a thin layer of UHPFC exhibit an enhanced torsional behavior and higher capacity than strengthened beams three and two sides. The UHPFC can generally be used as an effective external torsional reinforcement for RC beams without stirrups. It was noted that the behavior of the beams strengthen with UHPFC jackets are better than the control beams. The use of UHPFC had effect in delaying the growth of crack formation. The finite element analysis is a good agreement with the experimental data.

1. Introduction

Many buildings and bridge structures are subjected to significant torsional moment that affects structural design and may require strengthening. Reinforced concrete members may lack torsional shear capacity and be in need of strengthening. 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. 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 not the most cost-effective one. In many cases, strengthening and upgrading is the most cost-effective and convenient solution.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.12.160

Some of the more popular strengthening techniques developed include steel plate bonding, external pre-stressing, 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 [1–7], analytically [8,9], and numerically [10,11].

Superior results have been obtained from retrofitting by FRP, though this technique still has a few important disadvantages. FRP is 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 and concrete bonds, and long-term durability of FRP 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 creep, shrinkage, and de-bonding 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 [12,13]. Many applications reveal that UHPFC technology can significantly improve structural performance in terms of the durability and life-cycle costs of concrete structures [14]. Research on the behavior of UHPFC-RC composites has mainly focused on flexural or shear strengthening. Several studies have demonstrated the effectiveness of using UHPFC to strengthen RC beams under flexure or combined bending and shear [15–18]. Further the UHPFC mixture had good workability and passing ability such self-compacting concrete. The application of a reinforced self-compacting concrete (SCC) jacket for the structural rehabilitation of shear/or flexural damaged reinforced concrete beams was experimentally investigated [19,20]. The test results indicated that the reinforced beams with SCC jackets could be used as a quick rehabilitation option for earthquake-damaged beams and an easily applicable retrofit scheme relying on familiar application techniques from conventional concrete using readily available materials [21–24]. UHPFC material takes advantage of high mechanical strength combined with self-compacting properties and low permeability. Thus, research into the use of UHPFC jackets to strengthen structural members is a recent development. The use of UHPFC jackets 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 reinforced concrete beams with steel fibres (SFRC) were tested to observe the failure under torsional moments [25–28]. The test results indicated that the use of steel fibres exhibited an increase in ultimate load capacity and stiffness response.

The objective of this investigation is to evaluate experimentally and numerically the effectiveness of UHPFC matrix in strengthening longitudinal reinforced concrete beams subjected to torsion. The proposed technique considers the use of a thin layer of UHPFC with a different thickness under the following variations: all four, three, and two sides with UHPFC jackets.

2. Experimental research

Cross-sectional dimensions of the control beam are 100/200 mm. The effectiveness of the proposed UHPFC strengthening technique in all its three variations are investigated by performing experimental tests on eleven beams with lengths of 1600 mm are shown in Fig. 1. All beams have the same longitudinal reinforcement consisting 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 a strengthening material contains the following components: ordinary Portland cement (Type-I); silica fume; well graded, sieved, and dried mining sand; high strength micro-steel fiber; superplasticizer. The steel fiber used in the experiments has a fiber length and fiber diameter of 10 and 0.2 mm, respectively, and the steel fiber has an ultimate tensile strength of 2500 MPa. Cubic samples molds ($100 \times 100 \times 100$ mm) were used to evaluate the compressive strength while cylindrical samples (100×200 mm) were used to evaluate the tensile strength of UHPFC. The compressive strength of the UHPFC with 2% steel fiber volume was up to 150 MPa, and the split tensile test was 14.79 MPa. One of the reinforced beams was used as the control beam, and a thin layer of UHPFC was applied on the other ten beams (i.e. a 10, 15, 20 and 25 mm layer strengthening for full wrap and U-jacket while a 15 and 25 mm layer strengthening for left–right sides are considered). 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 to 2 mm roughness, which is considered adequate to avoid the use of bonding products [16] (Fig. 2a). After the surface was sandblasted, the UHPFC material was directly cast on the beam without any vibration (Fig. 2b). Curing was conducted in a water tank (Fig. 2c). The UHPFC matrix was applied three months after casting the core concrete beams, and the tests were performed 28 days after UHPFC strengthening [16].

3. Test setup

The experimental setup is shown in Fig 3. All beams were tested under pure torsional loading up to the ultimate torque. One end of the beam was supported by a roller support, which allowed the beam to rotate while it was loaded. The other end of the beam was supported by a rigid support. The torsional arm extended 500 mm from the central axis of the beam. 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 beam to prevent bending. Thus, the beam between the two supports was subjected to pure torsion. The end parts of the beams were properly over-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 beam. The measurements of the loads were monitored through a computer-driven data acquisition system. Inclinometer was used to measure the twist angle of the beam.

4. Test results

Fig. 4 shows the torque versus the twist angle of the beams throughout the loading system until failure was obtained in the experiments. The cracking and ultimate 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-S00) reached the cracking torque was (2.306 kNm) with an angle of twist of (0.011 rad/m), while a maximum torque of (2.306 kNm) with a maximum rotation of (0.011 rad/m).

The beams (RS-S00-F25, RS-S00-F20, RS-S00-F15 and RS-S00-F10) were strengthened with a 25, 20, 15 and 10 mm, respectively thin layer of UHPFC done by full wrapping. At the torque of 4.505,