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(RESEARCH ARTICLE)

Experimental investigation of FRP strengthened reinforced concrete T-beams in torsion

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Abstract

In general, reinforced concrete (RC) members are most commonly influenced by flexural moments, axial and shear forces. However, they may also be subject to torsional moments. Torsion in reinforced concrete (RC) beams is an important phenomenon that affects the structural behaviour of buildings. Both the concrete and steel reinforcement contribute to the torsional resistance of a RC member. However, the contribution of concrete is usually neglected by the modern design codes, due to cracking. Moreover, the subject of maintenance and repair or strengthening of existing RC structures is a significant problem. The last years, fibre reinforced polymer (FRP) is widely used as external reinforcement in flexural and shear strengthening. Nevertheless, its use in torsional strengthening is not so widely investigated. In this paper, the torsional behaviour of RC T-beams reinforced in shear with FRPs is experimentally investigated. Five groups of T-beams subject to pure torsion, two of which are control beams and other three beams are strengthened in shear with U-jacketed FRP fabrics. Experimental results reveal that FRPs can increase the ultimate torsional capacity of the member.

Keywords: Torsion; Reinforced Concrete; T-beams; FRP; Strips; Anchored U-jacket; Retrofit

1. Introduction

Torsion is a type of loading that causes a twisting deformation in a structural member. In reinforced concrete (RC) beams, torsion can occur due to various reasons such as eccentric loading, asymmetrical support conditions and earthquakes. The torsional behaviour of RC beams is crucial to the overall structural performance of the building, as torsion failure is an undesirable brittle failure mode that should be avoided. On the other hand, Fiber Reinforced Polymer (FRP) is a material extensively used as an external reinforcement for the flexural and shear strengthening of RC members. The use of FRP in strengthening of inadequate RC members has been established to be a competitive technique. FRPs have small weight and high strength capacity, providing a significant increase in flexural and shear strength and ductility of the member, without changing its stiffness. However, the use of FRPs for strengthening members subjected to torsion has not yet extensively investigated.

External reinforcement of RC members in shear can be achieved mainly by side bond, U-wrap and full wrap. In the U-wrap commonly used, FRPs are attached to the three sides, while in the full wrap the FRP material is wrapped around the cross-section. The latter is the most effective method, however, it cannot be applied to a RC T-beam in which the slab is monolithically connected to the beam. In this case, U-wrap is usually used.

Several studies [1-8] have studied the behaviour of RC beams in torsion, focusing on different aspects such as the effect of reinforcement detailing, concrete strength, aspect ratio, and loading conditions. Experimental [1, 4-8], analytical [1-2,4] and numerical models [3,5] are used for the examination of this behaviour, while other researchers use experimental results to calibrate numerical models and then use these models to further investigate the torsional

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resistance of beams and the parameters that affect it, such as the strength and quantity of longitudinal and transverse reinforcement [4-7], the concrete compressive strength [4] and cross-sectional properties [7].

Several other researchers, studied the improvement of the torsional behaviour of strengthened RC members. The behaviour of FRP strengthened RC beams under pure torsion or combined shear and torsion was experimentally [9-14] and numerically [10,13,14-19] investigated by several researchers.

Most studies examine the behaviour of rectangular beam, although usually there is a slab on top of the beams. There are few published experimental results on the torsional behaviour of T-shaped beams strengthened with FRP materials. Chalioris [20] experimentally investigated the influence of the use of FRP sheets and strips on the torsional capacity of concrete T-shaped beams without stirrups. The experimental program comprised fourteen rectangular and T-shaped beams tested under pure torsion and concluded that strengthening rectangular beams using full wrapping with continuous FRP sheets resulted in higher torsional capacity than using FRP strips. Moreover, U-jacketed T-shaped beams exhibited lower capacity due to premature debonding failure. Deifalla et al. [21] tested eleven flange beams to investigate the effectiveness of externally bonded CFRP strips for strengthening flanged beams under torsion. They concluded that both the anchored U-jacket and the extended U-jacket strips were more effective strengthening techniques compared to the un-anchored U-jacket strips and as effective as the fully wrapped strips. Deifalla and Ghobarah [22] investigated the torsional capacity of FRP strengthened RC T-beams, subjected to combined torsion and shear. They tested six half-scaled beams and examined the effectiveness of different strengthening techniques.

The objective of the present experimental study is to obtain more information on the torsional behaviour of FRP strengthened T-shaped beams which is limited. For this reason, five groups of specimens are tested in pure torsion and the results are presented in the followings.

2. Material and method

The experimental investigation involves five groups of specimens tested under pure torsion. Two indicative specimens without FRP fabrics (noted as TV01 and TV02) were reported for control specimens and three indicative specimens were reported as strengthened using epoxy-bonded carbon FRP materials as external transverse reinforcement and noted as TS01, TS02, TS03.

2.1. Specimen characteristics and test setup

The configuration of beams consisted of T-shaped cross-section with width b_w = 100 mm, height h = 250 mm, effective width b_{eff} = 400 mm and flange depth h_f = 100 mm. The total length of the beams was 1100 mm (Figure 1). The loading was applied through a plate at the opposite flanges of beam. Two roller supports were used so that the specimens would be free to twist (Figure 2).

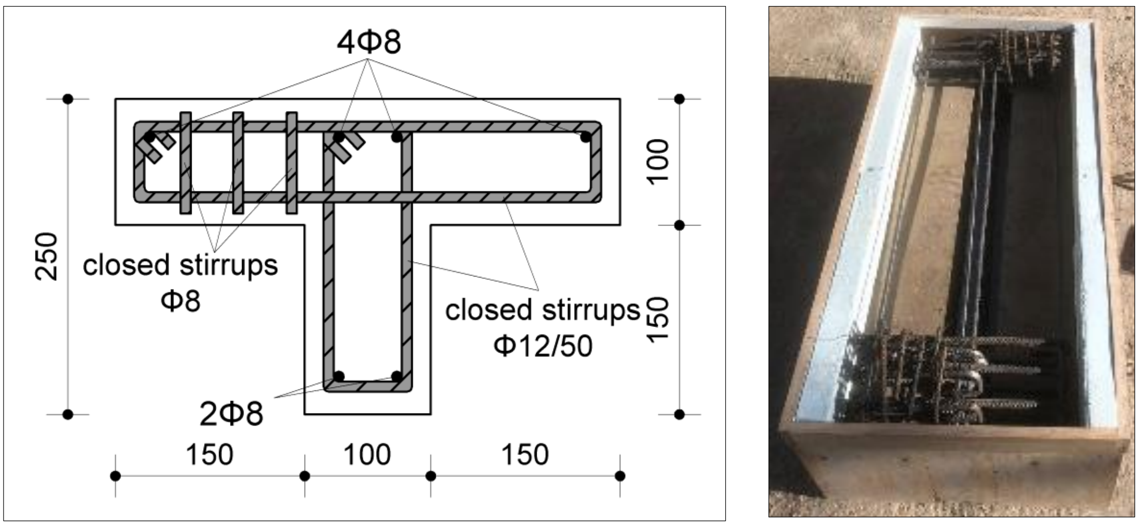

Figure 1 Cross section of beams tested and formwork

Cast-in-place concrete was used for the construction of the specimens. The longitudinal and transverse reinforcement of all tested beams was the same. Two rebars of diameter 8 mm were placed at the top, similarly two at bottom of the web of the beam and two more rebars of the same diameter at the top flange. In total, six longitudinal rebars were placed allover the beam, as shown in Figures 1 and 2. The transverse reinforcement was three closed stirrups at the web and the flange of diameter 12 mm being at distance of 50 mm at each end of the beam. Moreover, at the flange and nearby the loading is applied, in order to prevent shear failure of the slab, there were placed closed stirrups of diameter 8 mm at distances of 50 mm, in the longitudinal direction of the beam, as shown in Figures 1 and 2.

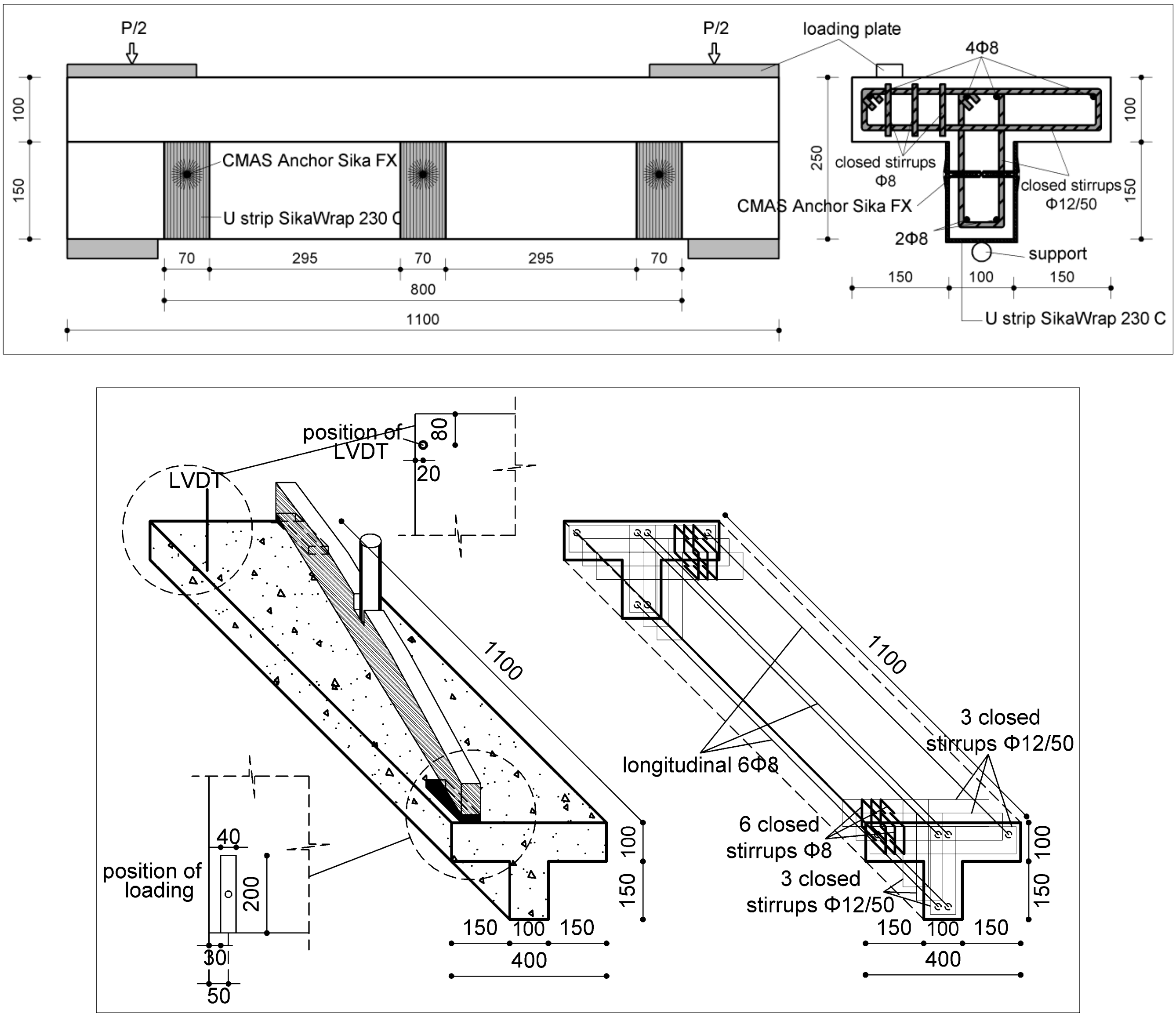

Figure 2 Geometry and steel reinforcements of beams tested

For strengthening the beams tested, FRP U-strips were wrapped at the bottom and sides of the web. The width of the strips was 70 mm, positioned at a distance of 150 mm from each end of beam and at the middle of the beam, as shown in Figure 2. SikaWrap FX carbon fiber tufts were used for the anchorage of the strips. In order to avoid peeling of the end of the fabrics and significant reduction of the overall member's strength, an embedded end-anchor was created using SikaWrap FX anchor tufts. The one part of the SikaWrap FX was bonded into holes predrilled in the substrate and the other part was spread out into slots cut in the concrete surface. By employing this approach, the substrate and the structural connection are both strengthened, resulting in a substantial enhancement of the system's peel-resistance.

The test configuration, the loading position, the position of the torsion angle metering system, of the transverse reinforcement and the U-strips are shown in Figure 2. The control beam TV01, the loading position, the position of LVDT and the torsion angle metering system are shown in Figure 3.

Figure 3 Test configuration, loading position and position of LVDT and torsion angle metering system

2.2. Material properties

Different concrete mixtures were used for each group of beams. The average 28-day compressive strength of cube concrete was varied from 14.5 MPa for the 1st group of control beams (TV01) to 37.5 MPa for the 2nd group of control beams (TV02), whereas for the group of strengthened beams attained 19.5 MPa for the 3rd group of beams (TS01), 27.5 MPa for the 4th group of beams (TS02) and 34.7 MPa for the 5th group of beams (TS03).

Rebars were subjected to uniaxial tensile tests to evaluate their parameters. The Young's modulus was found equal to 189 GPa., while the yielding and ultimate stress was 528 MPa and 643 MPa, respectively.

SikaWrap 230 C, a unidirectional woven carbon fibre fabric for the dry application process, was used to form U-jackets of FRPs. The strong fibres' orientation was perpendicular to the longitudinal axis of the beam. Sikadur -330 was applied as an impregnation resin between FRP and concrete. For SikaWrap 230C dry fabric, as provided by the supplier, the Young's modulus is 225 GPa, the tensile strength is 3500 MPa, the strain at fracture 1.7%, the thickness 0.129 mm and the density 235 g/cm^3. For Sikadur-330 two-component adhesive epoxy resin the Young's modulus is 4.5 GPa and the tensile strength is 30 MPa.

3. Results and discussion

Control specimens and FRP strengthened T-shaped beams exhibited typical torsional failures modes with intense spiral diagonal cracks. The failure mechanisms of the retrofitted specimens were different. The crack patterns at failure of typical control and strengthened beams are presented in Figures 4 to 6.

Figure 4 Crack pattern of control beams TV01

Figure 5 Crack pattern of the sides of the U-jacketed FRP strips at strengthened beam TS01

Figure 6 Crack pattern of the sides of the U-jacketed FRP strips at strengthened beam TS02

The torsional moment versus the torsion angle is presented in Figure 7 for two of the control beams and in Figure 8 for three of the FRP strengthened beams. Figure 7 illustrates that control beams (TV01) made of high strength concrete attain higher, about double, ultimate torsional moments than that occurred at control beams (TV02) made of poor strength concrete.

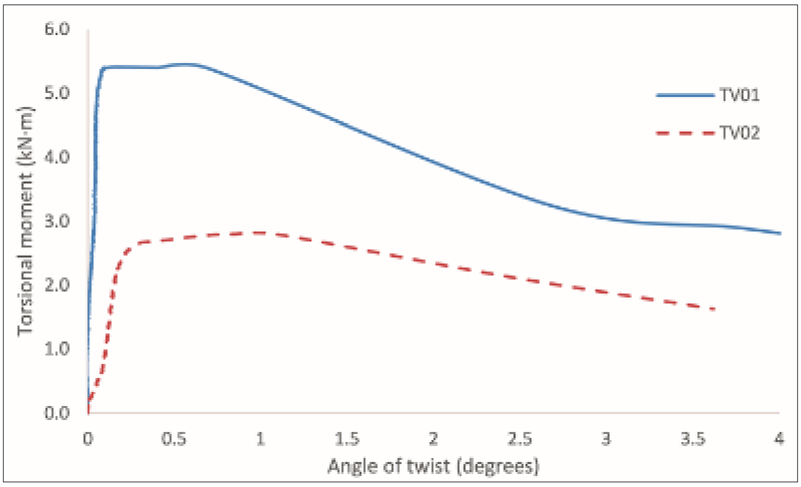

Figure 7 Variation of Torsional moment vs angle of twist at control beams

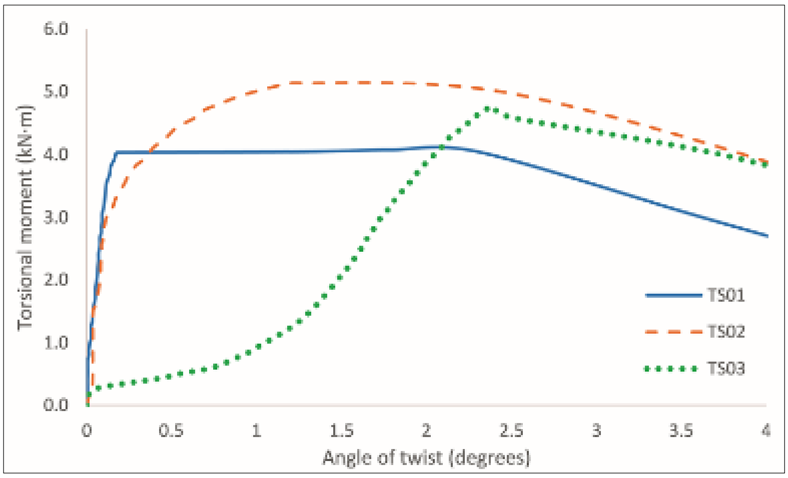

Figure 8 Variation of torsional moment vs torsion angle at strengthened beams

The FRP strengthened beams presented a small increase on the initial torsional rigidity and a higher increase on the torsional moment at cracking, compared to the control beams. Due to absence of transverse reinforcement, after cracking there was no further increase of the torsional moment. As mentioned by other researchers [20], this increase of the torsional moment was observed at cracking and could be significantly higher if, instead of FRP U-strips, FRP fabrics were placed as fully wrapped around the cross-section of the beam with one ply of continuous FRP sheets.

As shown in Figures 5 and 6, FRP strips prevented crack propagation at the retrofitted parts of the beam, but failure of the strengthened specimens occurred at the unwrapped concrete without any fibre rupture. The cracks propagated at the flange, above and between the FRP U-strips.

To reveal the concrete strength as well as the FRPs influence on the ultimate torsional capacity of RC T-beams. In Figure 9 the maximum experimental torsional moment is plotted against the corresponding concrete compressive strength. As concerns the torsional capacity increases vs. the compressive strength of concrete in strengthened RC T-beams, it occurs almost similar variation as that appeared previously in similar control beams. The torsional capacity increases from low values at low strength control beams until maximum values attained at control or strengthened beams with high strength concrete.

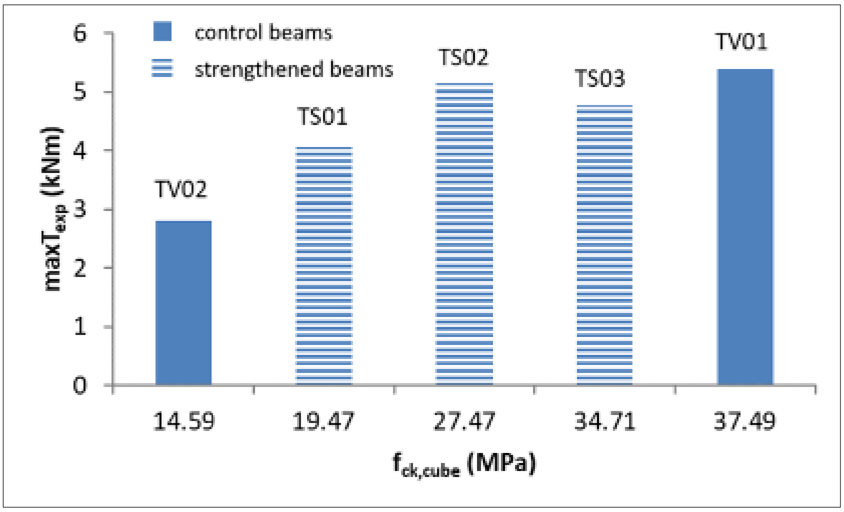

Figure 9 Experimental variation curve of maximum torsional moment vs concrete compressive strength of beams

4. Conclusion

The aim of this paper was the investigation of the torsional behaviour of T-shaped RC beams strengthened with FRP fabrics. Five groups of T-shaped RC beams were used in this study, two of which are control beams and the remaining three are FRP strengthened.

The main conclusions are summarized as follows:

- Torsional moments vary as torsion angles until torsional capacity in control RC T-beams as well as in similar strengthened beams.
- Torsional capacity increases as the compressive strength of concrete more in control T-beams than in strengthened beams.
- The presence of FRP U-strips in strengthened RC T-beams seems to affect the ultimate torsional capacity of these beams in conjunction with high strength concrete used for casting the beams.
- The numerical results verifying the results of the present experimental study will be announced in the future.

Compliance with ethical standards

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Disclosure of conflict of interest

We have no conflicts of interest to disclose.

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