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Fatigue behavior of RC T-beams strengthened in shear with CFRP sheets

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Carbon Fiber Reinforced Plastic (CFRP);
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Abstract The objective of this research is to study the fatigue performance of reinforced concrete (RC) T-beams strengthened in shear with Carbon Fiber Reinforced Polymer (CFRP) composite. Experiments were conducted on RC beams with and without CFRP sheets bonded on their web surfaces and subjected to static and cycling loading. The obtained results showed that the strengthened beams could survive one million cycles of cyclic loading (= 50% of maximum static load) with no apparent signs of damage (premature failure) demonstrating the effectiveness of CFRP strengthening system on extending the fatigue life of structures. Also, for beams having the same geometry, the applied strengthening technique can significantly enhance the cycling load particularly, in case of beams provided with U-jacket sheets. Moreover, although the failure mode for the different beams was a brittle one, the strengthened beams provided with U-jacket sheets approved an acceptable enhancement in the structural ductility.

1. Introduction

Structural elements such as beams, slabs and columns may require strengthening during their service life period. The need for strengthening may arise due to one or more combination of several factors including the construction or design factors; increased load-carrying demand; change in use of structure; seismic upgrade, or meeting new code requirements. There is an increasing interest in using high strength composites to strengthen or repair RC elements. Externally bonding CFRP sheets technique is applied more and more and is becoming an attractive solution for strengthening/retrofitting the RC structures.

Since most of these elements are structural members of bridges or parking garages, there is a need to understand the fatigue behavior of RC T-beams strengthened in shear with externally bonded web CFRP sheets. Several studies have been conducted to study the flexural behavior of RC beams strengthened with CFRP sheets under static and repeated loading. Also, several studies concerning the shear behavior of RC beams strengthened in shear with CFRP sheets under static loading were presented [1–11]. However, few are known about the fatigue behavior of RC beams strengthened in shear with CFRP sheets [12–14]. As a result, this research focuses on the study of the fatigue behavior of RC T-beams strengthened externally with bonded web CFRP sheets. The parameters

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studied were, the configurations of the bonded CFRP sheets and the volume of internal steel stirrups and the state of loading (static and repeated).

Tests on twelve RC beams strengthened in shear with externally bonded CFRP sheets have been used in this research to study not only the contribution of the bonded CFRP sheets to the shear strength of RC T-beams, but also the effect of CFRP composite strengthening system on the fatigue performance, where the following parameters are investigated: (1) the configuration of bonded web CFRP strips and (2) the internal transverse-steel ratio. Also, the influence of used strengthening technique on the structural ductility and the occurred failure mode was studied in this research. Moreover, the obtained results concerning the maximum load are used to study the applicability of the analytical models (American Concrete Institute ACI 440 [15] and Egyptian code EC 208 [16]) to predict the load carrying capacity of RC beams strengthened in shear with bonded CFRP sheets.

2. Layout of experiments and test procedure

2.1. Main experimental program

Twelve RC T-beams deficient in shear strength were tested under a two-point loading bending test over a simple span of 2000 mm (shear-span to depth ratio $a/d = 2.5$, effective depth $d \approx 280$ mm). Six were tested statically, designated as *CS*.- and *DS*.- (*CS.0*, *CS.1*, *CS.2*, *DS.0*, *DS.1* and *DS.2*), and six under repeated loading, designated as *CR*.- and *DR*.- (*CR.0*, *CR.1*, *CR.2*, *DR.0*, *DR.1* and *DR.2*).

The different tested beams (*CS*.-, *DS*.-, *CR*.- and *DR*.-) have an identical T-cross-section: flange-450 mm wide × 70 mm thickness, 150 mm web width, 320 mm total height.

The different beams were reinforced with four bottom ribbed bars A_s, 4 Φ 18 mm (Steel 400/600) and four top bars of 8 mm in diameter (Steel 240/350). No internal stirrups were provided along the shear-span for beams designated as *CS*.- and *CR*.-; however, internal stirrups of 6 mm in diameter and 140 mm spacing (Steel 240/350) are provided along the shear-span in case of beams designated as *DS*.- and *DR*.-, see Fig. 1 and Table 1.

Beams *CS.0*, *DS.0*, *CR.0* and *DR.0*, were tested in their original condition as control ones (without strengthening). These beams were designed to fail mainly due to shear. Beams *CS.1*, *DS.1*, *CR.1* and *DR.1*, were strengthened with twelve CFRP strips of 100 mm width and 200 mm spacing (six strips per shear-span, effective cross-sectional area of fiber sheets of 78 mm^2 per shear-span). These strips of CFRP sheets were bonded to the two vertical sides of the beam. However, beams *CS.2*, *DS.2*. *CR.2* and *DR.2* were strengthened with six U-jacket strips (three U-jacket strips each of 100 mm in width per shear-span). The CFRP strips were with the fibers oriented vertically ($\theta = 90°$) and distributed uniformly along the shear-span of the beam, see Fig. 2.

2.2. Materials

The tested beams were made by a normal strength coarse aggregate concrete of 20 mm maximum nominal size. The concrete mix achieves mean splitting strength and Young's modulus of 2.85 and 23,000 N/mm^2 respectively. The mean compressive strength for the standard cube (f_c) and standard cylinder (f'_c) after 28 days (the time of testing) for the different tested beams is listed in Table 1.

Deformed bars (Steel 400/600: Proof stress, tensile strength and Young's modulus are 412, 673 and 215,000 N/mm^2) of 18 mm diameter were used as main internal bottom reinforcement. However, plain bars (Steel 240/350: yield strength, tensile strength and Young's modulus are 255, 380 and 205,000 N/mm^2) of 6 mm diameter were used for internal stirrups. Also, plain bars (Steel 240/350: yield strength, tensile strength and Young's modulus are 265, 390 and 208,000 N/mm^2) of 8 mm diameter were used internal top reinforcement.

The external reinforcement was a CFRP sheet. Such CFRP sheet is available in rolled sheet of 0.13 mm effective thickness, 300 mm width and 50 m length. The effective thickness gives the section of the fibers in each single ply. The rupture strength, ultimate strain and Young's modulus of such CFRP sheet are (in accordance with the manufacturer [17]) 3500 N/mm^2, 1.5% and 230,000 N/mm^2 respectively.

An epoxy mortar layer of about 2 mm thickness was applied to all the strengthened beams as a substratum to the CFRP sheets. This epoxy mortar is completely cured within a period of 24 h after application. The compressive, bending and tensile strengths of this mortar are (in accordance with the manufacturer [17]) 80, 20 and 6.5 MPa respectively.

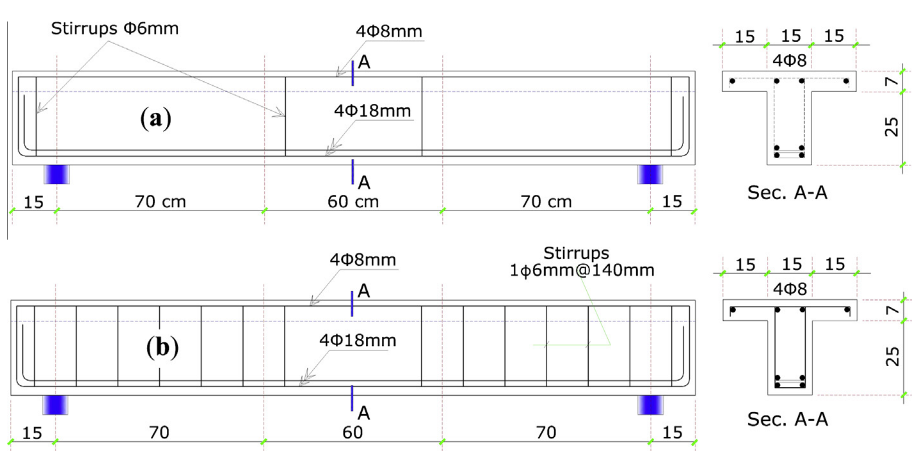

Figure 1 Details of internal reinforcement of tested beams: (a) group *C* and (b) group *D*.