Fatigue behavior of cracked steel beams reinforced by using CFRP materials

Pierluigi Colombi\textsuperscript{a*}, Giulia Fava\textsuperscript{a}, Lisa Sonzogni\textsuperscript{a}

\textsuperscript{a}Department of Architecture, Built environment and Construction engineering (ABC), Politecnico di Milano, Milan, Italy

Abstract

Carbon Fiber Reinforced Polymer (CFRP) strips externally bonded on a damaged steel beams are effective under monotonic loads. Less information is available on the fatigue behavior. Experimental tests were then performed at the Politecnico di Milano on flexural strengthening of cracked steel beams with CFRP strips of different thickness. The results in term of fatigue crack propagation curves showed that CFRP's bonded around the tip zone reduce the fatigue crack growth and extend the fatigue life. In addition, high strain concentration was recorded in the CFRP strip close to the cracked section. This indicates that the cracked zone is a potential debonding area of the CFRP strips from the steel substrate.

Keywords: Fatigue strengthening; Bonded CFRP strips; Cracked steel beams; Debonding.

1. Introduction

Steel structures and bridges may be damaged by fatigue phenomena due to traffic loadings. In this case it is often necessary to study a rehabilitation activity and carbon fibre reinforced polymers (CFRP) are regarded as ideal products for retrofitting steel structures due to their high tensile strength, stiffness and fatigue resistance [1]. Besides, composites are very flexible and their application facilitates the design of the retrofitting system.

CFRP reinforcement is observed also to increase the fatigue life of steel structures [2]. CFRP strips moderate fatigue crack propagation in three different ways: (a) by reducing the stress range around the crack tip; (b) by

* Corresponding author. Tel.: +39 02 2399 4280; fax: +39 02 2399 4220.
E-mail address: pierluigi.colombi@polimi.it
reducing the crack opening displacement and (c) by promoting crack closure. The interaction between CFRP strips and damage (crack) propagation at the mid-span of steel beams under fatigue loading was recently analysed [3-6].

In this paper, five cracked steel beams were reinforced with CFRP strips bonded to the tension flange and tested at the Politecnico di Milano. Experimental bending tests were performed to evaluate the crack propagation and the fatigue resistance of the adhesive bond. The effect of the reinforcement thickness was also investigated. The results indicate that CFRP strips bonded on the cracked steel beam reduce the fatigue crack growth and extend the fatigue life. Besides, a debonded area is present at crack location due to the high stress/strain field. Debonding has a detrimental effect on the reinforcement and it should be considered in fatigue analysis.

2. The experimental campaign

A total of five cracked steel beams were reinforced and tested at the Politecnico di Milano. IPE 120 steel beams (according to EN 10025) were artificially cracked and reinforced with CFRP strips to analyze the repair efficiency. Specimens were machined with a notch at the midspan section through the tension flange and a web portion. Specimens were firstly subjected to fatigue loads to produce an initial crack in the web and were then reinforced before starting the fatigue tests.

The specimen and notch geometry are shown in Fig.1. Details of the experimental program are in Table 1, where $a_i$ is the initial crack size at the time of application of reinforcement, $a_f$ is the final crack length and $t_p$ is the patch thickness. Patch thicknesses of 1.4 mm correspond to one CFRP layer, while patch thicknesses of 2.8 mm correspond to two CFRP layers. One unreinforced beam (specimen B01) was additionally tested as a control specimen.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$a_i$ [mm]</th>
<th>$t_p$ [mm]</th>
<th>Load range [kN]</th>
<th>$a_f$ [mm]</th>
<th>Number of cycles</th>
<th>Normalized initial stiffness (%)</th>
<th>Normalized final stiffness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01</td>
<td>20</td>
<td>/</td>
<td>6-15 (10 Hz)</td>
<td>60</td>
<td>234000</td>
<td>100%</td>
<td>84%</td>
</tr>
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<td>B02</td>
<td>20</td>
<td>1.4</td>
<td>6-15 (10 Hz)</td>
<td>20</td>
<td>280000</td>
<td>136%</td>
<td>134%</td>
</tr>
<tr>
<td>B03</td>
<td>20</td>
<td>1.4</td>
<td>28-70 (3 Hz)</td>
<td>60</td>
<td>19700</td>
<td>136%</td>
<td>119%</td>
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<tr>
<td>B04</td>
<td>20</td>
<td>1.4</td>
<td>28-70 (3 Hz)</td>
<td>60.9</td>
<td>24000</td>
<td>131%</td>
<td>113%</td>
</tr>
<tr>
<td>B05</td>
<td>20</td>
<td>2.8</td>
<td>28-70 (3 Hz)</td>
<td>60.4</td>
<td>183000</td>
<td>146%</td>
<td>134%</td>
</tr>
<tr>
<td>B06</td>
<td>20</td>
<td>2.8</td>
<td>28-70 (3 Hz)</td>
<td>60</td>
<td>114000</td>
<td>142%</td>
<td>133%</td>
</tr>
</tbody>
</table>

Fig. 1. (a) geometry of the beam; (c) notch detail.

2.1. Materials and specimen preparation

The steel beams were realized with a steel type S275J0 (according to EN 10025). Coupon tests were performed and the real yield stress was equal to 330 MPa while the Young’s modulus was 208000 MPa.
The pultruded CFRP strips (Sika CarboDur® M614) had a thickness of 1.4 mm, a width of 60 mm and a length of 800 mm. The nominal Young’s modulus and tensile strength values were greater than 210 GPa and 2800 MPa.

The CFRP reinforcement was bonded using a thixotropic epoxy resin (Sikadur® 30). The adhesive Young’s modulus and tensile strength were greater than 4500 MPa and 28.4 MPa. For specimens reinforced with two CFRP layers, a less viscous epoxy (Sikadur® 330) was used to bond the outer CFRP strip to the inner one. The nominal values of the Young’s modulus and tensile strength were greater than 3800 MPa and 30 MPa.

Steel beams were initially machined with a notch 18 mm long and 2.5 mm wide and then subjected to fatigue loads to create an initial precrack of 20 mm. Before bonding the CFRP reinforcement across the cracked steel section, the tension flange was cleaned to remove dust and create a chemically active surface. The epoxy adhesive was then uniformly applied, the CFRP strip was laid and the reinforced specimens were finally cleaned and cured.

2.2. Experimental tests

All beams were subjected to four-point flexural loading over a simply supported span of 1000 mm. A test rig was designed to perform the tests by using a hydraulic testing machine with a loading capacity of 250 kN (Fig. 2a).

Details of the loading range and frequency are reported in Table 1. The adopted loading ratio $R=0.4$ was selected to reproduce a severe fatigue crack propagation scenario. After positioning a piece of graph paper close to the ligament on the beam web, the crack growth was recorded at intervals from 10000 to 500 cycles, depending on the crack front speed, by using a travelling microscope with a magnifying power up to 220x. A total of 8 strain gauges (Fig. 2b) were also installed close to midspan to collect the strain in the reinforcement strip.

3. Experimental results

The experimental results are detailed in Table 1, including: the number of cycles to achieve a final crack length of about 60 mm and the normalized specimen stiffness at the initial and final crack size. The specimen stiffness recorded at the initial and final crack size is the ratio between the applied load $P$ (measured by the load cell) and the crosshead displacement $\Delta$ (measured by the stroke displacement transducer). The stiffness of each specimen was normalized with reference to the initial stiffness of the same unreinforced specimen. At the final crack size of 60 mm specimen B01 showed a stiffness reduction to 84%. In the case of specimen B02, the fatigue test was stopped at 280000 cycles since no crack propagation was observed and no beam stiffness variation was recorded. For the same number of cycles, the unrepaired beam B01 presented significant fatigue damage and then this clearly indicates the effectiveness of the CFRP repair.

In order to allow fatigue crack propagation, other specimens (B03-B06) were tested at a higher load range, as shown in Table 1. In Fig. 3(a), the crack propagation curves are plotted. It may be noticed that the crack propagation
rate increases as the crack develops in the web; i.e. the stress intensity factor increases with crack propagation. Markedly slower crack propagation rate is also observed for the double reinforcement compared to the single one.

For specimen B03, the strain distributions along the CFRP strip for increasing crack lengths are shown in Fig. 3b. The strain distributions are symmetric with respect to the midspan, but the strains tend to spread as far as the crack size increases due to the damage progress in the adhesive layer. The strain profiles thus indicate the presence of a debonded area close to the cracked section and explain the shape of the fatigue crack propagation curves (Fig. 3(a)).

4. Conclusions

This paper illustrates the results of an experimental program performed on five cracked steel beams reinforced by using CFRP strips. The main conclusions are: the presence of a debonded zone close to the cracked section and a significant reduction of the fatigue crack propagation for the double reinforcement. In fact, strain distributions clearly show the progressive CFRP debonding that influences the shape of the crack propagation curves.

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References