Fatigue reinforcement of steel elements by CFRP materials: experimental evidence, analytical model and numerical simulation

Pierluigi Colombi⁎, Giulia Fava, Carlo Poggi, Lisa Sonzogni

⁎Department of Architecture, Built environment and Construction engineering (ABC), Politecnico di Milano, Milan, Italy

Abstract

Carbon Fiber Reinforced Polymer (CFRP) composites have been proven to be effective in extending the fatigue life of cracked steel members. Fatigue tests were executed on cracked steel plates (single edge specimen) reinforced by strips bonded to a single side. Different patch configurations, reinforcement thicknesses and initial damage levels were investigated. CFRP materials bonded around the tip area extend the fatigue life of the damaged steel elements. The stress intensity factor of the reinforced elements was evaluated through FEM. Finally the fatigue crack propagation curves were evaluated by integration of the Paris law and compared to the experimental data.

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1. Introduction

CFRP materials are a good alternative to standard techniques for the reinforcement of steel civil engineering structures [1]. Externally bonded CFRP materials improve the fatigue lifetime of steel plates [2-6]. Both single side [5] and double side patch configurations were investigated [2-4, 6]. The adhesive layer is the weakest point of the system and debonding is the dominant failure mode. In particular, crack mouth debonding has an important role [2]. CFRP strip reduces fatigue crack propagation: (a) by reducing the stress range around the crack tip; (b) by reducing the crack opening displacement and (c) by promoting crack closure.

In this paper the results of an experimental campaign performed at the Politecnico di Milano are shown. Single
edge notched tension (SENT) specimens were considered to represent a crack emanating from the border of a beam flange under bending. Specimens were reinforced with CFRP strips bonded by epoxy adhesive. Experimental tests were performed under tensile cyclic loads to evaluate the crack propagation and the fatigue resistance. The effects of different initial crack length, patch configuration and thickness were investigated. The stress intensity factor (SIF) was evaluated through FEM. The fatigue crack propagation curves were evaluated by integration of the Paris law.

2. The experimental campaign

A total of 9 specimens were reinforced and tested at the Politecnico di Milano using an axial testing machine with a total capacity of 250 kN. One unreinforced specimen (P06) was additionally tested as a control specimen. Uniaxial sinusoidal loading cycles were applied with maximum and minimum loads of 60 kN and 24 kN. The corresponding maximum and minimum stress levels in the bare steel plate section are of 150 MPa and 60 MPa. The loading frequency was of 18 Hz, a loading ratio of 0.4 was selected to simulate a severe fatigue crack propagation scenario.

Details of the experimental program are in Table 1 where $a_i$ is the (initial) crack size at the time of reinforcement and $t_p$ and $E_p$ are the patch thickness and Young’s modulus, respectively. Two types of patch configuration were designed (Fig. 1). Case a) is the steel plate fully covered by the patch while case b) is the steel plate partially bonded by the patch. A patch thickness of 1.4mm corresponds to one reinforcing layer, while a patch thickness of 2.8mm corresponds to two CFRP layers. Finally, $R_G$ is the reinforcement ratio, i.e. the ratio between the patch and the steel plate section.

| Specimen | Patch conf. | $a_i$ [mm] | $t_p$ [mm] | $E_p$ | Cycles to failure | $R_0$ |
|----------|-------------|------------|------------|-------|------------------|-------|
| P06      | /           | 6          | 15         | /     | 196714           | /     |
|          |             |            |            |       | 29264            |       |
| P07      | a           | 6.1        | 2.8        | 0.353 | 584000           | 2.97  |
| P08      | a           | 14.8       | 2.8        | 0.353 | 172000           | 5.88  |
| P09      | a           | 6.4        | 2.8        | 0.353 | 565000           | 2.87  |
| P10      | a           | 6          | 2.8        | 0.353 | 605000           | 3.08  |
| P11      | a           | 14.9       | 2.8        | 0.353 | 133000           | 4.54  |
| P12      | a           | 6          | 1.4        | 0.175 | 512500           | 2.61  |
| P13      | b           | 14.8       | 1.4        | 0.0875| 66800            | 2.28  |
| P14      | b           | 15.0       | 2.8        | 0.175 | 100000           | 3.42  |
| P15      | a           | 14.7       | 1.4        | 0.175 | 77000            | 2.63  |

2.1. Materials and specimens preparation

The steel plates were realized with a steel type S275J0 according to European standard and measured 450mm × 50mm × 8mm. The specimens were machined with a side notch consisting of a slot 5 mm long and 0.20 mm wide. The steel mechanical properties were determined through tensile tests: the mean yielding stress and tensile strength were 330 MPa and 444 MPa, respectively. The steel Young’s modulus was assumed equal to 210 GPa.

The pultruded reinforcements were realized using CFRP strips (Sika CarboDur® M514) with a thickness of 1.4 mm, bonded to the steel plates using a thixotropic epoxy resin (Sikadur® 30). The nominal values of the Young’s modulus and tensile strength were greater than 210 GPa and 2800 MPa, respectively.

The CFRP strips were bonded to the steel plates with a thixotropic epoxy resin (Sikadur® 30). The Young’s modulus and tensile strength were greater than 4500 MPa and 28.4 MPa. For specimens reinforced with two layers of pultruded CFRP strips 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.

Specimens were subjected to fatigue loads for creating initial pre-cracks of approximately 7 or 15 mm long to investigate the influence of initial damage on the effectiveness of the reinforcement technique. The steel plate...
surface was cleaned, the epoxy adhesive was uniformly applied and the CFRP strip was laid with a small pressure to eliminate the adhesive in excess. The reinforced specimens were finally cleaned and cured at room temperature.

![Fig. 1. Patch configurations.](image)

### 2.2. Experimental tests and results

The experimental results are detailed in Table 1 while the crack propagation curves are plotted in Fig. 2a. Failure consisted of debonding at the composite/adhesive interface and sudden collapse of the steel plate. The number of cycles to failure indicates the fatigue life of each repaired specimen and it is compared to the one of the reference case P06 (unreinforced steel plate). In detail, for P06, the cycles to failure are reported for an initial crack length of both 6 mm and 15 mm. For a certain initial crack length, the ratio between the fatigue life of each reinforced specimen and the unreinforced one is calculated and referred to as the fatigue life increase ratio $R_N$.

![The Fig. 2. (a) Crack propagation curves; (b) comparison with the analytical results](image)

On the basis of $R_N$ value, it is observed that configuration b) with a single layer is also competitive. The effect of patch configuration was analysed by comparing the configurations of type a) and b) (see Fig. 1). Fully covered steel plates result in better fatigue performance than partially covered ones. Finally, when the number of CFRP layers increases the fatigue life increase ratio is extended, especially for longer initial cracks.

### 3. Analytical and numerical model

Both an analytical and a numerical analysis were performed to investigate the patch efficiency in cracked elements exposed to extended fatigue life. The analytical model requires the evaluation of the SIF and the integration of the Paris law. The number of cycles to failure, $N_f$, is then evaluated as:
\[ N_f = \frac{1}{C \left( \Delta K^{\infty} - \Delta K_{th}^m \right)} \int_{a_0}^{a_f} da \]  

(1)

where \( C \) and \( m \) the Paris constants, \( a_0 \) and \( a_f \) are the initial and final crack sizes respectively, \( \Delta K \) is the SIF range and \( \Delta K_{th}^m \) is the threshold SIF range. In the present analysis \( C=3.786 \times 10^{-14} \) (MPa units), \( m=3.257 \) and \( \Delta K_{th}^m=132.5 \) MPa m\(^{1/2}\) and they were calibrated from the unreinforced steel plate propagation data.

The SIF in the notched plates was computed by means of a two-dimensional finite element model in connection with the three layer technique, in order to reduce the computational effort (Fig. 3). To detect the strain singularity at the crack tip, a special mesh with proper elements was used, allowing to the calculation of the SIF in the steel. SIF values were extracted from the FE models for different crack lengths. The experimental results are compared to the analytical crack propagation curves in Fig. 2b.

Fig. 3. Numerical model.

4. Conclusions

Fatigue tests on cracked steel plates reinforced by CFRP strips were performed at the laboratories of the Politecnico di Milano. The results showed that CFRP materials bonded around the tip area allows extending the fatigue life of the damaged steel elements about 3 times. Different patch configurations, reinforcement thicknesses and initial damage levels were investigated. In particular fully covered steel plates result in better fatigue performance than partially covered ones and the fatigue life is extended when the number of CFRP layers increases. For longer initial cracks the reinforcement thickness has a stronger effect on the fatigue life. Analytical and numerical analyses were also performed and a good agreement with the experimental results was found in representing the crack propagation curves.

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