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Intermediate crack induced debonding in steel beams reinforced with CFRP plates under fatigue loading

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ABSTRACT

Externally adhesively bonded Carbon Fibre Reinforced Polymers (CFRP) plates are often regarded as an effective technique to strengthen notched steel beams. However, the possible CFRP intermediate debonding may drastically reduce the reinforced steel beam strength against fatigue crack propagation. It is assumed that, for the beam geometry and materials under analysis, the fatigue load does not directly cause debonding, but it may trigger steel crack propagation, leading to the onset of debonding. In this paper, analytical and numerical models for elasto-brittle adhesives were proposed to evaluate the stress and strain distribution in the reinforcement for a given crack length. The outcomes of experimental campaigns from the literature were considered to validate the proposed numerical and analytical techniques. A good agreement was found among the analytical, numerical and experimental results in terms of strain distribution in the CFRP material, showing the accuracy of the proposed models. Finally, a parametric analysis was performed to investigate the influence of some parameters on the CFRP strain distribution.

1. Introduction

The use of Carbon Fibre Reinforced Polymers (CFRP) as reinforcing materials for retrofitting steel structural elements is nowadays proved to be an efficient technique for strengthening or repairing of steel members (plates or beams) [1]. In particular, CFRP strengthening of undamaged steel elements leads to an increase of the load carrying capacity under monotonic loading with a marginal stiffness increment. On the other hand, CFRP repair of cracked steel elements subjected to cyclic loading may significantly improve the fatigue life since it reduces the stresses at the crack tip, the crack opening displacement and the effective stress range. CFRP materials are even more effective if they are pre-stressed, as compressive stresses are introduced into the reinforced element, reducing the effective stress range and then enhancing the fatigue life.

Concerning the fatigue behaviour of notched steel beams reinforced by using CFRP materials, several experimental campaigns were recently presented. In [2], the influence of crack propagation on the CFRP debonding was analyzed for notched steel beams reinforced by using both non-prestressed and prestressed CFRP strips. In [3], different composite reinforcement types were considered, showing that the reinforcement may postpone crack initiation, reduce the fatigue crack propagation, limit the stiffness decay and decrease the residual deflection. In [4], the experimental outcomes revealed the presence of a debonded area between the steel beam and the reinforcement. Finally, in [5] the cracked steel beams were strengthened using different patch systems and high-strength materials and the reinforcement was attached to the steel beam through adhesive bonding or mechanical anchorage. In particular, adhesively bonded CFRP plates led to the most relevant decrease in the fatigue crack growth rate. In [6], the use of different high-strength reinforcing materials was also experimentally studied. The strengthening significantly increased the member fatigue life not only for the stress redistribution on the cracked steel section but also because it led to a local bridging effect, thus reducing both the crack opening displacement and the stress intensity factor.

All the experimental outcomes also showed that the bond between the composite material and the steel element is the weakest link of the strengthened system. Nonetheless, although debonding at notch location under static or fatigue loads has a significant influence on the CFRP strengthening effectiveness, a limited number of analytical or numerical models were proposed in the literature to estimate the effect of debonding on the fatigue crack growth rate.

1.1. Problem statement

The use of high-stiffness composite materials such as CFRP, is extremely effective for crack bridging in the fatigue retrofit of cracked steel elements, resulting in a relevant decrease of the stresses at the

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crack tip, of the crack opening displacement and of the effective stress range. On the other hand, the notch introduces stress concentrations, which may eventually trigger interfacial debonding. In addition, it was clearly shown that interfacial debonding has a significant influence on the fatigue life [4].

As well known, the fatigue crack propagation is driven by the stress intensity factor (SIF) range at the crack tip. A modified version of the Paris law is often proposed in the literature in order to investigate the fatigue crack growth of CFRP strengthened steel elements [1]:

$$\frac{da}{dN} = C\cdot(\Delta K_{eff}^{m} - \Delta K_{eff,th}^{m}) \tag{1}$$

where a is the crack size, N is the number of cycles, ΔK_{eff} is the effective SIF range, $\Delta K_{eff,th}$ is the effective threshold SIF range and C and m are material parameters (Paris constants). Besides, the effective stress intensity factor range, ΔK_{eff}, is given by:

$$\Delta K_{eff} = K_{\max} - K_{op} = (1-q)\cdot K_{\max} \tag{2}$$

where q is the effective load ratio while $K_{\max}$ is the stress intensity factor at the maximum loading level. A simple formula was proposed in the literature to evaluate the stress intensity factor of unreinforced cracked I-beams [7]. Based on classical beam theory, it reads:

$$K_I^M = M\sqrt{\frac{\beta_M}{I_s\cdot t_w}\left(\frac{I_s}{I_{cr}}-1\right)} \tag{3}$$

where: M is the bending moment, I_s is the moment of inertia of the steel section, I_{cr} is the moment of inertia of the cracked steel section and t_w is the web thickness. For a section subjected to an axial force the following formula is proposed:

$$K_I^N = N\sqrt{\frac{\beta_N}{A_s\cdot t_w}\left(\frac{A_s}{A_{cr}}-1\right)} \tag{4}$$

where: N is the axial force applied to the centroid of the cracked section, A_s is the section area and A_{cr} is the area of the cracked steel section. In Eqs. (3) and (4), β_M and β_N are non-dimensional functions of the crack length and beam geometry for pure bending and axial force, respectively.

Recently, such relationships were extended for CFRP reinforced cracked I-beams [8]. The composite material, in fact, introduces a compressive force, N_s, in the steel beam that is clearly not applied at the centroid of the cracked section (Fig. 1).

According to Fig. 1, it holds:

$$N_s = -N_{f0} \tag{5}$$

where $N_{f,0}$ is the CFRP axial force in the cracked section and:

$$M_s = M - N_{f0}\cdot z \tag{6}$$

In Eq. (6), M_s is the total bending moment acting in the steel section, M is the bending moment induced by external loads and z is the distance between the centroid of the steel beam and the centroid of the CFRP strip. After having introduced the additional bending moment to account for the load eccentricity, the stress intensity factor, K_I, of the reinforced cracked steel beam is finally evaluated by taking into account Eqs. (3)–(6):

$$K_I = (M - N_{f0}\cdot z)\sqrt{\frac{\beta_M}{I_s\cdot t_w}\left(\frac{I_s}{I_{cr}}-1\right)} - N_{f0}\sqrt{\frac{\beta_N}{A_s\cdot t_w}\left(\frac{A_s}{A_{cr}}-1\right)} \tag{7}$$

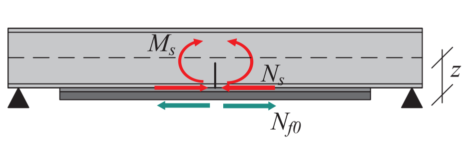

Fig. 1. Axial force acting on the reinforcement and axial force and bending moment acting on the steel beam.

An alternative formulation based on the best fitting of numerical results was proposed in [9]. In Eq. (7), the compressive force N_{f0} strongly affects the stress intensity factor evaluation. Analytical or numerical models for evaluating the CFRP axial force are then fundamental to reliably estimate the fatigue life in retrofitted steel beams. Besides, the slip between the reinforcement and the steel substrate and the possible CFRP debonding should be taken into account.

1.2. Scope of the research

In this paper, reference is made to I-shaped simple supported steel beams. The main aim of this work is to propose both a numerical and an analytical model to evaluate the CFRP axial force in strengthened cracked steel beams. Recently, an analytical model was presented in [10] to provide an estimation of the axial force for long crack lengths, but it was unable to predict the debonded zone length. Besides, a simplified finite element (FE) model was proposed to validate the analytical results [4]. In this work, a more refined numerical analysis employing a cohesive damaged contact interaction is suggested to precisely estimate the CFRP axial force. Additionally, an analytical cohesive zone model is used to evaluate the axial force in the reinforcement together with the debonded zone length. Numerical and analytical analyses are performed for given crack lengths. It is also assumed that, for the adopted reinforced beam geometry and materials, the effect of fatigue load on debonding is negligible. Based on [11], indeed, the fatigue load does not directly influence debonding but it may induce crack propagation in the steel element, resulting then in debonding propagation. The proposed numerical and analytical models are validated with respect to the experimental outcomes presented in [4,12]. Finally, a parametric analysis is performed to investigate the influence of the most significant parameters on the CFRP strain distribution.

1.3. Previous studies

Several analytical and numerical studies were performed with reference to plate end debonding. Analytical solutions were developed assuming an elastic behaviour at the interface between the steel beam and the reinforcement [13,14] or considering a softening interface behaviour and a cohesive crack modelling approach [15]. An energy based analytical formulation was proposed in [16]. In [17], a closed form solution of interfacial stresses and strain was proposed for undamaged FRP-plated steel beams bonded with ductile adhesives. FE models were also presented in [18,19].

Less attention, either analytically or numerically, was devoted in the literature to the evaluation of intermediate crack induced debonding in cracked steel beams reinforced by using CFRP materials. In [20], the interaction between the CFRP debonding and the damage level in the steel beam was considered. Debonding at the damage location was due to stress concentration and the initial damage level influenced the debonding propagation rate. In [21], different levels of initial damage (i.e. notch depth) were considered and a numerical model accounted for both the crack propagation and the CFRP debonding. It turned out that the initial damage level significantly affected the steel beam behaviour and the CFRP debonding. In [22], a model accounting for the bond-slip behaviour of CFRP-steel interface was proposed and experimentally validated. Results of a parametric analysis showed the effectiveness of high modulus reinforcements. In [12], a closed form solution for the interfacial shear and normal stresses in steel beams strengthened with a CFRP plate was presented. A parametric study indicated that the maximum stresses at the notch locations decreased as the adhesive thickness reduced. In [4,10], analytical and numerical models were discussed to predict the CFRP stress redistribution and evaluate the fatigue crack growth curve. A debonded area was experimentally detected and its effect on the fatigue crack growth was captured by the model.