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Debonding of adhesively bonded composite patch repairs of cracked steel members

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ABSTRACT

Rehabilitation of steel bridge members using composite patches is increasingly becoming a popular method for fatigue mitigation. However, the long-term performance of these patches is an issue of considerable concern and the focus of ongoing research. In this paper, the debonding (bond failure) of an adhesively bonded composite reinforcement acting on a steel member is investigated. Two debonding scenarios are considered. In the first, a patched, uncracked, steel plate is examined, while in the second, a steel plate with a crack growing into the thickness direction is considered. For the latter scenario, the influence of debonding on the crack driving force is also investigated. To this end, debonding is modelled here as a crack located at the interface between the steel and the adhesive and the finite element method (FEM) is employed in order to determine the strain energy release rate (G), which is a measure of the interface crack driving force and hence characterises the propensity for fatigue-induced debonding.
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1. Introduction

Adhesive bonding of composite reinforcing plates on steel bridge members that have been damaged due to corrosion or fatigue is a relatively novel technique, which is increasingly finding wider applications [1,2]. The main weakness of this technique, both in terms of strength and durability, is found within the bond. Bond failure, herein referred to as debonding, may initiate at areas of stress concentration, such as, for example, existing bondline defects. This may lead to complete detachment of the reinforcing plate from the parent member.

A number of researchers have investigated the case where a debond or a crack grows along the interface of two different materials. This effort has concentrated on the mechanics of interface fracture, in a variety of applications but mostly focused on aerospace structures, and has led to the development of methods for the computation of the strain energy release rate (G) for interface crack tips, which is a measure of the crack driving force. An overview of these studies is given by Hutchinson and Suo [3] and Krueger [4]. Pradhan et al. [5] computed G numerically, and used it as a criterion for the propagation of cracks at the interface of bonded aluminium joints. With emphasis on civil engineering applications, Au and Buyukozturk [6] developed fracture energy models for various debonding scenarios, including interface debonding, for fibre reinforced polymer (FRP) strengthened concrete elements. Colombi et al. [7] determined G for near-crack, elliptical delaminations of patched metallic plates with through-thickness cracks. Although the effect of parameters such as the Young's modulus of the patch, the thickness of the adhesive, and even patch pre-stressing were considered in this study, the authors did not vary the debonding length and hence ignored delamination growth. Following this work, Colombi [8] presented a simplified, fracture mechanics-based approach for the edge debonding of metallic beams reinforced with FRP strips, where the strain energy release rate was evaluated both numerically and analytically. Having developed appropriate fracture mechanics models for CFRP-bonded center-notched steel plates Taljsten et al. [9] were able to demonstrate the beneficial effect of patching on the specimens' fatigue behaviour. More recently, Bocciarelli et al. [10] carried out experiments on double shear lap specimens in order to determine the failure load and compare this to their analytical/numerical predictions.

The authors of the present work investigated the beneficial effect of the fully bonded patch on a cracked steel member [11]. In a significant departure from previous studies they examined the behaviour of a crack growing in the thickness direction of patched steel members. The objective of this work was to quantify the repair effectiveness in relatively thick steel plates, typically encountered in the flanges of bridge girders, which have developed fatigue cracks. Such cracks may initiate on the surface of the flange in areas of high stress concentration, e.g. web stiffener toes. As a further development of the work presented in [11], the existence of defects in the patch repair caused by debonding is considered in this paper. Thus, a patched steel plate with and without a crack growing into its thickness direction, is investigated. For the plate with the crack, two debonding scenarios are considered, namely, patch end debonding and crack mouth debonding. The strain energy release rate G is determined from FE analyses, thus quantifying the effect of a number of parameters such as the Young's

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Nomenclature

r, θ	polar coordinates	v	Poisson's ratio
t	thickness	σ	remotely applied stress
E	Young's modulus	σ_{xx}	steel/adhesive interface peel stress
G	energy release rate	τ_{xy}	steel/adhesive interface shear stress
J	path independent contour integral	ℓ_c	patch length
K	mode I stress intensity factor	ℓ_d,ℓ_d^*	debonded length; patch end debonding, crack mouth debonding
K_I, K_{II}	real and imaginary parts of the complex stress intensity factor for interface crack tips		
Y	stress magnification factor for a crack ($= K/\sigma\sqrt{\pi\alpha}$)	*Subscripts*	
α	crack depth	a	adhesive
β	Dundurs' elastic mismatch parameter	c	CFRP patch
ε	bimaterial interface constant	s	steel plate
μ	shear modulus	1, 2	material 1, material 2

modulus, the thickness of the patch and the adhesive, the depth of the crack in the steel plate and the debonded length.

2. Fully bonded composite patch on a cracked steel plate

A steel plate under tensile loading and containing a crack growing in the thickness direction was considered in [11]. The significant results from that study are summarised in this section. This simple configuration was selected in order to model cracked steel members (see Fig. 1). The steel plate was reinforced with a long, perfectly bonded CFRP patch, thus ensuring minimal interaction between the patch edges and the crack. Two-dimensional (2D), plane strain, fracture mechanics, FE analyses were performed using ABAQUS [12] by varying different parameters of the previously mentioned configuration, such as the crack depth (α) as well as the patch and adhesive Young's modulus (E_c, E_a) and thickness (t_c, t_a) in order to extract values of the stress magnification factor Y at the crack tip. For the purposes of these analyses, the range of values of the above parameters was selected so that they are representative of bridge repairs that may be encountered in practice. The values of Y were obtained by normalising the stress intensity factor $K(= \sqrt{JE_s/1-v^2})$ by $\sigma\sqrt{\pi\alpha}$. Fig. 2 shows the results for Y in terms of the crack depth α normalised by the thickness of the steel plate t_s, for different patch and adhesive configurations. By way of comparison, the results for the unpatched case are also shown in Fig. 2, in order to demonstrate for this case the excellent agreement between the Y values obtained from FE analysis and their analytical counterparts [12]. The results for the patched plate

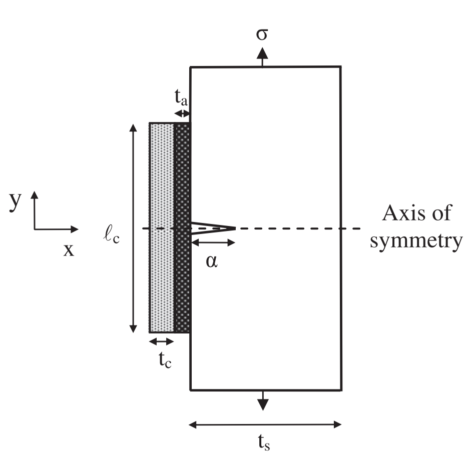

Fig. 1. Edge-cracked plate with adhesively bonded composite patch.

suggest that even for a low-stiffness patch (t_c/t_s = 0.06, E_c/E_s = 0.7, t_a/t_s = 0.01, E_a/E_s = 0.01), which is taken here as the reference case, a significant reduction in Y, when compared with the unpatched plate, is observed. This reduction ranges from approximately 25–55% for α/t_s values of 0.1 and 0.5, respectively.

Furthermore, with reference to Fig. 2, doubling each of the patch and adhesive properties, while keeping the remaining non-dimensional ratios constant, leads to a further reduction in Y, with the exception of increasing adhesive thickness, which leads to a slight increase in Y. The latter may be explained in terms of the smaller load transfer to the patch due to the greater load being carried by the adhesive itself.

Fig. 3 shows the variation of the peak values of the peel (σ_{xx}) and shear (τ_{xy}) stresses at the regions of highest stress concentrations, namely near the patch edges (Fig. 3a) and near the crack mouth (Fig. 3b). The results are normalised by the remotely applied stress (σ) and are shown, again, for different combinations of material/geometric properties. As expected, the peak stresses near the patch edges were found to be relatively insensitive to the size of the crack, in contrast to the shear stresses near the crack mouth.

As shown in Fig. 3b, doubling of the patch thickness ($2t_c/t_s$) or its Young's modulus ($2E_c/E_s$), compared to the reference case, leads to a slight shear stress reduction near the crack mouth area. By contrast, the same changes result in the shear and peel stresses near the patch edges being increased (Fig. 3a). It is worth noting that, in relation to the area near the patch edges (Fig. 3a), stress elevation is far more pronounced for the peel stresses ($\sigma_{xx} \approx 3\tau_{xy}$). Moreover, the shear stresses near the crack mouth are considerably greater (depending on geometric configuration by approximately 10–40 times) than their counterparts at the patch edges. This implies that, notwithstanding various factors affecting the patching operation, debonding may initiate from the crack mouth.

3. Debonded composite patch on a steel plate

Following the investigation of a fully bonded patch on a cracked steel plate, the case of debonded patch on a steel plate is considered in the following. In this context, two cases are examined, namely, a cracked steel plate with edge debonding (Fig. 4a) or crack mouth debonding (Fig. 4b) and an uncracked steel plate with symmetrically located edge debonding (Fig. 4c). The results of a parametric FE study, varying the material/geometric properties, are presented here in terms of the stress magnification factor Y of the crack in the steel member (Section 3.1) and the energy release rate G of the interface crack (Section 3.2). For the purposes of the analyses, debonding is modelled as a sharp crack by

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