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Composite patch repair of steel plates with fatigue cracks growing in the thickness direction

E.S. Aggelopoulos [a,*], T.D. Righiniotis [b], M.K. Chryssanthopoulos [b]

[a] The Steel Construction Institute (SCI), Silwood Park, Ascot, UK
[b] Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, UK

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ABSTRACT

The behaviour of steel members with fatigue cracks growing in the thickness direction and strengthened with an adhesively bonded composite patch is assessed in this paper both analytically and experimentally. Analytical models for two different fracture fatigue parameters, namely the stress magnification factor for the crack in the steel member and the energy release rate for debonding at the steel/adhesive interface, are developed based on finite element analyses. These models can be readily employed in fatigue calculations. In order to verify the analytical models, an experimental investigation is also carried out. To this end, fatigue tests of specially designed and prepared patched cracked steel specimens are carried out and crack growth data are found to correlate reasonably well with their analytically obtained counterparts.

1. Introduction

Over the past few years, the use of adhesively bonded composite patches for strengthening steel members has been attracting the interest of a growing number of researchers. The potential of the technique was first investigated by researchers working in the field of aeronautics, who examined its application for repairing aluminium aircraft components with cracks [1–3].

Some of the advantages of the composite patch repair technique over traditional methods, such as plate bolting/welding, are its better corrosion characteristics, its superior fatigue performance since bolt holes and welds are fatigue prone details and its overall higher repair efficiency. Although most research efforts to date have focused on the strengthening of corrosion deteriorated steel members [4,5], there has also been a number of studies where the strengthening of fatigue-damaged steel bridge components was investigated.

Thus, researchers have employed the finite element method and carried out experiments in order to establish the bonded composite patch technique as an effective way of repairing fatigue cracks in steel structural members [6,7]. However, only a handful of results, aiming to provide analytical tools for direct use in fatigue life calculations for patched repairs, are currently available [8,9].

The vast majority of the previously mentioned studies dealing with the crack patching problem have involved through-thickness cracks, i.e. cracks that have fully extended in the thickness direction and are, therefore, growing parallel to the surface of the member. Surface cracks that have formed and extended in the direction parallel to the surface and are growing in the thickness direction have not been considered in these studies. Composite patch repair of this type of crack is the focus of the present study.

Recently, the authors of this paper presented a numerical study on patched steel components with and without a crack that also addresses the problem of adhesive debonding [10]. Here, analytical models for two different fracture parameters, namely the stress magnification factor Y and the energy release rate G, which, respectively, control crack growth in the steel member and debonding at the steel/adhesive interface of patched members, are developed based on the finite element results presented in [10,11]. In addition, fatigue tests are carried out on patched steel specimens with cracks and the results, in terms of crack growth, are compared with those obtained analytically.

2. Analytical modelling

2.1. Stress magnification factor Y_p (crack in steel)

In this section, an approximate analytical expression for the stress magnification factor Y of the cracked geometry shown in Fig. 1 is sought. The geometry comprises a cracked steel plate, under tensile loading and a fully bonded composite patch. The crack whose characteristic dimension is α is growing in the thickness direction of the steel member. Other relevant dimensions are depicted in Fig. 1.

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* Corresponding author. Tel.: +44 1344 636533; fax: +44 1344 636570.
E-mail address: e.aggelopoulos@steel-sci.com (E.S. Aggelopoulos).

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Nomenclature

m	Paris fatigue exponent
t	thickness
y	characteristic load transfer length associated with closing force P
z_0	distance from crack mouth to the point of application of closing force P
C	Paris fatigue constant
E	Young's modulus
F_c	finite thickness correction function
G	energy release rate
K, K_p	stress intensity factor (remote tension); unpatched, patched
N	number of cycles
P	crack closing force
R	stress ratio (=$\sigma_{\min}/\sigma_{\max}$)
Y	stress magnification factor for a crack ($= K/\sigma\sqrt{\pi\alpha}$)
Y_p	stress magnification factor for a patched crack
Y_σ	stress magnification factor for an edge cracked plate (tension)
Z	tangent of angle φ (= $\tan\varphi$)
$\Delta\sigma$	stress range (=$\sigma_{\max} - \sigma_{\min}$)
α	crack depth
α_n	notch length
β	curve-fitted function associated with the characteristic load transfer length y
γ	curve-fitted function associated with the shear stress τ_{xy}
σ	remotely applied stress
$\sigma_{\min}$, $\sigma_{\max}$	minimum, maximum applied stress in a cycle
τ_{xy}	steel/adhesive interface shear stress
φ	angle between the crack line and the line connecting the crack tip with the point of application of closing force P (=z_0/α)
ℓ_c	patch length
ℓ_d	patch end debonded length

Subscripts

a	adhesive
c	CFRP patch
s	steel plate
A	patch end region of the steel/adhesive interface
B	crack mouth region of the steel/adhesive interface

The reduction in the stress magnification factor of a cracked steel plate due to the presence of a patch is attributed to the load transfer from the plate to the patch through the adhesive. The reason for stress magnification factor reduction due to the patch is also because of its stiffening effect on the parent plate. This stiffening results in lower crack opening displacements and hence an accompanying reduction in the stress magnification factor. The load transfer mechanism mentioned above is responsible for the generation of shear stresses at the interfaces, which are higher near the patch end and crack mouth positions of the steel/adhesive interface. The analytical evaluation of the interfacial shear stress distribution exhibits some complexity, notwithstanding the presence of the crack. Furthermore, although there are analytical solutions for the adhesive shear stress distribution of double-sided, patch-reinforced plates without a crack [12,13], which could be used for the shear stress evaluation away from the crack, these solutions do not take into account the bending effect associated with single-sided repairs. Moreover, they do not take into account the stress concentration effect invariably present at the crack mouth and patch edges. Here, in order to circumvent these problems, the shear stress distribution is approximated via two triangular stress blocks A and B, representing predominantly the stress concentration effect, and is shown in Fig. 2a. The magnitude and distribution of the shear stresses, given by the shear stress τ_{xy} near the free end and a characteristic load transfer length y, were found by curve-fitting the results of FE analyses [11]. The "area" of each of these triangular stress blocks may be interpreted as a crack-closing force P, concentrated at the centre of mass of each block and acting along the steel/adhesive interface. Therefore, under the application of remote tension σ on the patched plate, the steel plate free-body diagram will consist of three load systems, namely, σ, P_A and P_B shown in Fig. 2a. The contribution of the peel stresses on the stress magnification factor is here ignored and for this reason these are omitted from Fig. 2a.

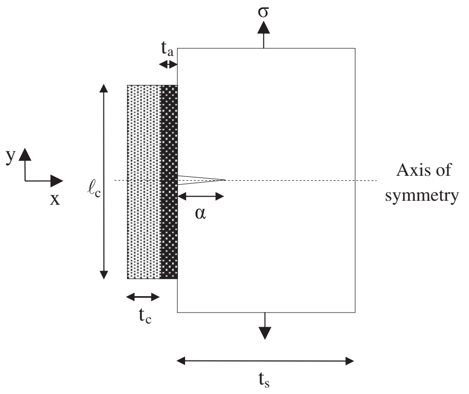

Fig. 1. Cracked steel plate with fully bonded composite patch.

The stress state of the steel plate may be seen to arise from the superposition of σ, P_A and P_B. Consequently, the stress intensity factor for a patched crack in a finite thickness plate will be given as

$$K_p = \sigma\sqrt{\pi\alpha}Y_\sigma - \frac{2}{\sqrt{\pi\alpha}}P_A \cdot f(\alpha/t_s, \varphi) - \frac{2}{\sqrt{\pi\alpha}}P_B \cdot f(\alpha/t_s, \varphi) \tag{1}$$

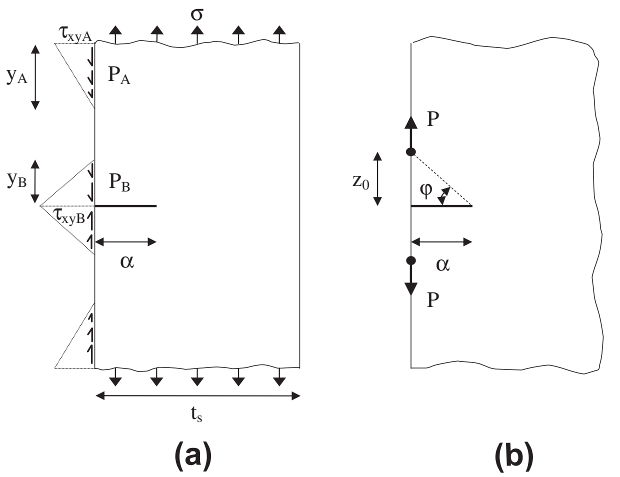

Fig. 2. (a) Simplified free body diagram of a patched steel plate and (b) cracked steel plate subjected to a pair of opening forces.