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Analysis of the plastic zone under mixed mode fracture in bonded composite repair of aircraft structures

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ABSTRACT

Material fracture by opening (mode I) is not the only failure criteria responsible for fracture propagation. Many industrial examples show the presence of mode II and mixed mode I + II. In the present work, numerical analyses of the three-dimensional and non-linear finite element method are used to estimate the performance of the bonded composite repair of metallic aircraft structures with a pre-existent damage by analyzing the plastic zone size ahead of repaired cracks under mixed mode loading, to assess the effect of the composite repair system on the plastic zone. The Von Mises stress is used to predict yielding of materials under this loading condition. The extension of the plastic zone, which takes place at the tip of a crack, strictly depends on many variables, such as the yield stress of the material, the loading conditions, the crack size and the thickness of the cracked component.

The obtained results have demonstrated that the plastic zone ahead of the crack is significantly reduced by the presence of composite patch materials. Furthermore, parametric analysis has been carried out to evaluate the effect of lay-up and material system variation on the J integral.

1. Introduction

Bonded composite repairs of locally damaged metallic structures has gained considerable interest in aircraft structural maintenance and life extension solution in the last two decades [1,2]. These repairs provide an efficient method for restoring the ultimate load capability of the structure [3]. The analysis of the effects of the geometrical properties of the composite on the repair performance has great interest in the literature. A good way to design a patch repair is to maximize the safety to cost ratio by finding the optimal composite patch shape [4,5]. Riccio et al. [6] presented repair design tool aimed to help the designer by suggesting different repair typologies and proper repair size by means of optimization analyses that can provide the best repair solution with minimal adhesive shear stress and size of the repair patch. Their work has been tested against a literature case study on multistep composite-metal joints. They showed that minimization of the overlap length (which can be a fundamental requirement for repair design, especially for components with complex geometry) has been proven possible within an optimization process in order to provide practical repair configurations.

The bonded repair reduces stresses in the cracked region and prevents the crack from opening and therefore from growing. The fiber composite patches have improved directional stiffness, high durability under cyclic loading, low density and excellent formability. Khodja et al. [7], have investigated, using finite element analysis, variation of the integral J depending on the crack size for different fiber orientations and different number of plies of repaired cracks in AA7075-T6 structures subjected to biaxial tensile stresses. Their study was carried out in order to estimate numerically the effect of biaxial tensile loading on the behavior of cracks in the presence of the bonded boron/epoxy repair in aircraft structures. The results show the beneficial effect of the patch composite in those cases and the relationship between the fiber orientations and it was noted that the best results are given by the orientation of 0° where the fibers are perpendicular to the crack direction.

Baker [1] has initiated repair of aircraft aluminum structures using composite patch in the early 1970s mainly in order to enhance fatigue life of cracked components. From geometrical consideration, bonded repairs fall into two categories: double-sided (symmetric) and single-sided (asymmetric). In most of the practical cases, both sides of the cracked panels are not available to perform a symmetrical repair. Therefore, single-sided repair is often adopted such as in case of aircraft wings. This asymmetric repair causes a significant bending field which increases the stress

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intensity factor (SIF) at the crack tip beyond the value compared to unrepaired panel. This bending stress reduces the repair efficiency, hence static strength or fatigue life of the repaired model gets lower. Umamaheswar and Ripudiman Singh [8] performed finite element modeling and analysis of single-sided composite patch repairs applied to thin aluminum sheets. They showed the SIF variation through the thickness of the panel assuming straight crack front. Chukwujekwu Okafor [9] developed a finite element model for analyzing the stress distribution of cracked plates repaired with a single-sided octagonal patch. They found that the zone of maximum stress shifted from the crack front (for unpatched specimen) to the edge of the patch (for the patched specimen) because of high peel stress development at overlay edge. Pastor et al. [10] have conducted experimental and numerical investigation of damaged and undamaged specimens patched with carbon epoxy composite material. They observed that the failure of the repaired model occurs when the maximum shear stress in the adhesive is close to its maximum shear strength.

There are only a few investigations available on repairing panels in mixed-mode condition by the linear elastic and nonlinear fracture mechanics [11–17]. Hosseini-Toudeshky performed fatigue crack growth tests of single-sided repaired thick and thin panels containing center inclined cracks with various patch lay-ups configurations and various composite patch thicknesses [12,13]. Ayatollahi and Hashemi [14,15] used a finite element analysis to investigate the effect of composite patching on the SIF reduction for an inclined center crack panel under different mixed loading case. Bachir Bouiadjra et al. [16] have conducted FEA to estimate SIF in single and double-sided repairs in mode I and mixed mode edge-cracked panels. They have shown that the adhesive and composite patch properties have a significant and beneficial effect on the symmetrical patch. All these previous work do not thoroughly investigate the effect of bending in case of asymmetric repair, which in turn causes the peaking of stresses at the unpatched side generating higher SIF. Recently, Ramji et al. [17] have investigated that in the case of an asymmetrical patch, at the unpatched surface, the SIF value exceeds the value of SIF obtained in unrepaired panel. Therefore, the static strength of the repaired panel is reduced. The peel stresses in bonded joints normally peaks at the end of the overlap, which in turn can cause failure of the adhesive layer; thereby, reducing the performance of the repair. To avoid the severity of these peel stresses occurring at the overlapped ends, Duong [18] suggested usage of tapered patch.

In the present work, the non-linear three-dimensional finite element method is used to compute the contour and the size of the plastic zone ahead of repaired cracks with bonded composite patch. The effects of the patch properties and the crack orientation on the plastic zone size are highlighted.

1.1. *Stress field near the crack tip*

Irwin [19] has shown that the stress distribution near the crack tip can be described by the stress intensity factors (K_I, K_{II}, K_{III}) where each stress intensity factor is associated with a fracture mode. The relation that gives the stresses at the crack tip can be put in the form:

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) \tag{1}$$

For the case of a mixed mode (I + II), the relation (1) can be written as

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi\ r}}\left(K_I f_{ij}^{I}(\theta) + K_{II} f_{ij}^{II}(\theta)\right) \tag{2}$$

Where r and θ are the polar coordinates of the considered point, K_I and K_{II} are the stress intensity factors in mode I and II, and f_{ij} is a function dependent upon the polar angle.

1.2. *Form and size of the plastic zone*

Due to the fact that the stress field at the crack tip reaches significant high values, it contributes to the creation of a plastic zone at the crack tip which depends more or less on the ductility of the material. The computation of the size depends on both the loads and the state of the stresses. Many authors have attempted to determine the form and to evaluate the size of the plastic zone at the crack tip on the basis of the classical criteria of elasticity or by calculation using the finite element method. In mode I, Irwin [20] proposed that the form of the plastic zone of dimension r_y is circular and computed it as:

$$r_y = \frac{1}{\alpha\pi}\left(\frac{K}{\sigma_Y}\right)^2 \tag{3}$$

Where σ_Y is the yield stress, $\alpha = 2$ for plane stress and $\alpha = 6$ for plane strain.

$$r_y = a_r K_I^2 + b_r K_{II}^2 + c_r K_I K_{II} \tag{4}$$

Where a_r, b_r and c_r are the constants function of the Poisson coefficient ν and the yield stress σ_Y.

$$\begin{Bmatrix} a_r \\ b_r \\ c_r \end{Bmatrix} = \frac{1}{16\pi R_e^2}\begin{Bmatrix} 4(1-2\upsilon)^2(1+cos\theta)+3(1-cos2\theta) \\ 4(1-2\upsilon)^2(1-cos\theta)+6+9(1+cos2\theta) \\ -8(1-2\upsilon)^2 sin\theta + 12 sin2\theta \end{Bmatrix} \tag{5}$$

The J-integral value is evaluated using domain integral method [21] as shown in equation (6):

$$J = \int\left[W n_1 - \sigma_{ij} n_j \frac{\partial u_i}{\partial x_i}\right] ds \tag{6}$$

2. Geometrical and materials properties

The basic geometry of the cracked structure considered in this study is shown in Fig. 1. Consider rectangular elastic–plastic aluminum 2024-T3 plate with dimensions of 39 × 160 × 3 mm^3, with an inclined center crack '*2a*' of length 10 mm. The crack is inclined at an angle of $\beta = 45°$ with the horizontal as shown in Fig. 1. The plate is subjected to a uniaxial load of 17.5 kN ($\sigma = 150$ MPa). The boron–epoxy patch of dimensions 25 × 25 × 1.5 mm^3 is bonded asymmetrically using 0.1 mm thin film FM73 structural adhesive. The layer thickness of the laminate is taken as 0.375 mm. The composite had unidirectional lay-up where the fibers were oriented along the specimen length direction (parallel to the direction of load). The general material properties of aluminum panel, composite patch and adhesive are given in Table 1. The specimen dimensions follow the ASTM E-647 standard [12].

Standard tensile tests were carried out on Aluminum 2024-T3 and FM73 adhesive. The obtained stress–strain curves are presented in Figs. 2 and 3 respectively.

3. Finite element model

The analysis involved a three-dimensional finite element method by using a commercially available finite element package code ABAQUS [22]. The finite element model consists of three subsections to model the cracked plate, the adhesive, and the composite patch. The plate had four layers of elements in the thickness