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Finite element fatigue propagation of induced cracks by stiffeners in repaired panels with composite patches

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ABSTRACT

Fatigue crack growth analyses of aluminum panels with stiffeners repaired by composite patches have been rarely investigated. Generally, cracks may occur around the rivets which are capable to propagate under cyclic loadings. A composite patch can be used to stop or retard the crack growth rate. In this investigation, finite element method is used for the crack propagation analyses of stiffened aluminum panels repaired with composite patches. In these analyses, the crack-front can propagate in 3-D general mixed-mode conditions. The incremental 3-D crack growth of the repaired panels is automatically handled by a developed ANSYS Parametric Design Language (APDL) code. Effects of rivets distances and their diameters on the crack growth life of repaired panels are investigated. Moreover, the obtained crack-front shapes at various crack growth steps, crack trajectories, and life of the unrepaired and repaired panels with various glass/epoxy patch lay-ups and various patch thicknesses are discussed.

1. Introduction

Adhesively bonded composite repair and using stiffeners are efficient and cost-effective methods to extend the fatigue life of damaged or weakened parts of structures and cracked components in aerospace and other industries. Therefore, many industries have shown substantial interest in the use of composite materials as reinforcement to repair the cracked structures and therefore enhance the life of them.

Crack growth behavior of adhesively repaired thin panels with stiffeners under cyclic loading has been rarely investigated in the literature. Rivet joints between the stiffener and panel cause stress concentration regions capable to produce cracks closed to a rivet or stiffener. In fact, if a crack is created in a stiffened panel its generally occurred around the rivets. Therefore, in this study, the crack is considered to be near the stiffener around a rivet and capable to propagate under cyclic loadings.

A considerable number of investigations on fatigue crack growth of repaired panels without stiffeners have been already reported in the literatures. Fredell et al. [1] conducted fatigue experiments using bonded glare and boron/epoxy patches on the cracked panels. Naboulsi and Mall [2–4] performed several finite element analyses to predict the fatigue crack growth rate of repaired aluminum panels with composite patch and compared the results with the results of unrepaired cracked aluminum panels. Chung and Yang [5] presented fatigue crack growth tests for repaired thick plates with an inclined edge crack. Hosseini-Toudeshky et al. [6–10] conducted three-dimensional finite elements analyses and experimental tests to obtain fatigue crack growth life and crack trajectory of the repaired panels containing a central inclined crack. Moreover, three-dimensional finite element crack growth analyses were performed for the single-side repaired panels with composite patches considering the general mixed-mode fracture conditions and real crack-front modeling.

Actual aircraft structures and skin are not generally made of plain aluminum panels without any reinforcement; they are stiffened structures as they consist of skin, stiffener, webs, and spars. Stiffened aluminum panels influences the fatigue characteristics of an aircraft significantly. Stiffener-reinforced sheet structures are extensively used in aircrafts and they are often subjected to fatigue loading. A considerable amount of research on crack-tip stress intensity analyses have been conducted by many researchers [11–19]. In these studies, cracked panels with multiple intact stiffeners and broken stiffeners, bending flexibilities of panels and stiffeners, nonlinear shear deformation of fasteners, and cracked stiffeners have been studied. Poe [11] performed fatigue tests on stiffened panels constructed with bolted and integral stringers. It was experimentally observed that crack growth rate in stiffened panel is reduced by the bolted stringers. Vlieger [12] presented a method to predict the residual strength of a cracked sheet structure contains of stiffening elements as crack stoppers. Chu et al. [13] conducted an experimental study to characterize the fatigue

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crack growth behavior of stiffened panels under uniform lateral pressure loading. Mellings et al. [14] presented a new method for automatically predicting the growth of cracks in stiffened panels and they realized that the rate of crack growth is reduced when stiffeners are used and that the life is increased correspondingly. Yeh [15] presented an analytical method to predict high-cycle fatigue crack growth of a cracked stiffened panel and the required inspection intervals was determined according to the damage tolerant design method. Schubbe and Mall [16,17] studied the effects of patch geometry and stiffness ratios on single sided repairs of thick plates. Jones et al. [18,19] presented design formulae for composite repairs of rib stiffened wing skins. They also examined the crack growth history of a range of test specimens, and cracks repaired with a composite patch, and showed that in the low to mid-value of stress intensity range (ΔK) there is a nearly linear relationship between the logarithm of crack length and number of cycles. Sabelkin et al. [20] investigated fatigue crack growth behavior of a stiffened thin 2024-T3 aluminum panel repaired with single-side adhesively bonded composite patch through experiments and three dimensional finite element analyses in mode-I. They considered a crack between two stiffeners and crack-front shape was not studied in their works. They also performed the crack growth analyses for unrepaired cracked panels with and without stiffeners.

In this study, effects of various characteristics of both repair and stiffeners' on fatigue crack growth of stiffened panels and repaired with composite patches are studied. For this purpose, 3-D finite element analyses of stiffened panels with single-side repair of glass/epoxy composite are performed. In these analyses general mixed-mode conditions and real crack-front shape modeling (RCFM) during the crack propagation procedure are considered. The major objective of this study is to deal with the used rivets between the stiffeners and panel. Effects of rivet's diameter and rivets spacing on crack growth rate and fatigue life of repaired panels are discussed. Moreover, the influences of composite patch lay-ups and also patch thickness on fatigue crack growth of the stiffened panels are perused.

2. Computational fracture analysis

Fig. 1 shows typical geometry, loading and dimensions of a stiffened panel with single-side composite repair containing typical induced cracks by a rivet. Having the displacement and stress fields around the crack-tip, fracture parameters such as K_{I}, K_{II} and K_{III} are calculated, and then they are used to predict the new fatigue crack-front shape, crack propagation path and crack growth life of the repaired stiffened panels. These analyses are based on the linear elastic fracture mechanics (LEFM) assumptions and it is also assumed that the cracks will grow in the aluminum panels only and the patch is not de-bonded from the panel. The computational fracture analyses are based on the calculation of strain energy release rates (SERRs) by the aid of the modified virtual crack closure technique (MVCCT) to obtain the local SERR along the crack front.

Fig. 2a shows typical eight nodes solid elements at the crack-front showing the required parameters in MVCCT. The calculation procedure in the virtual crack closure technique (VCCT), are traditionally performed in two stages [21]. At first, the internal nodal forces are computed for crack-front node, F_j, and then the crack is extended for a value of Δa and the analysis is performed to yield the displacement components u_x, u_y and u_z at nodes j and j^* as shown in Fig. 2a which have been coincided before crack growth. For the crack-front modeling the energy release rates are calculated for each node at the crack-front as follows [21]:

$$
\begin{aligned}
G_{\mathrm{I}} &= \frac{1}{2\Delta A} F_y^i (u_y^j - u_y^{j^*}) \\
G_{\mathrm{II}} &= \frac{1}{2\Delta A} F_x^i (u_x^j - u_x^{j^*}) \\
G_{\mathrm{III}} &= \frac{1}{2\Delta A} F_z^i (u_z^j - u_z^{j^*})
\end{aligned}
\tag{1}
$$

where $\Delta A = b \times \Delta a$ as shown in Fig. 2a and G_{I}, G_{II} and G_{III} are the energy release rates for mode I, II and III respectively.

Then the stress intensity factors can be computed from the following relations:

$$
\begin{aligned}
K_{\mathrm{I}} &= \sqrt{E' G_{\mathrm{I}}} \\
K_{\mathrm{II}} &= \sqrt{E' G_{\mathrm{II}}} \\
K_{\mathrm{III}} &= \sqrt{2\mu G_{\mathrm{III}}}
\end{aligned}
\tag{2}
$$

where E' is the modulus of elasticity, and $E' = E$ for plane stress condition and $E' = E/(1 - \nu_2)$ for plane strain problems and μ and ν are the shear modulus of elasticity and Poisson's ratio respectively.

For three-dimensional problems, in general mixed-mode condition the Richard et al. [22] criterion has been used for crack growth analyses. This criterion suggests an equivalent stress intensity factor that is comparable to the equivalent stress in the classical stress theories as follows:

$$
K_{\mathrm{eq}} = \frac{K_{\mathrm{I}}}{2} + \frac{1}{2}\sqrt{K_{\mathrm{I}}^2 + 4(\alpha_1 K_{\mathrm{II}})^2 + 4(\alpha_2 K_{\mathrm{III}})^2} \tag{3}
$$

where $\alpha_1 = K_{\mathrm{Ic}}/K_{\mathrm{IIc}}$, $\alpha_2 = K_{\mathrm{Ic}}/K_{\mathrm{IIIc}}$ and K_{Ic}, K_{IIc} and K_{IIIc} are critical stress intensity factors in various fracture modes. Deflection angles of φ_0 and ψ_0 defined in Fig. 2b are also required to calculate the crack

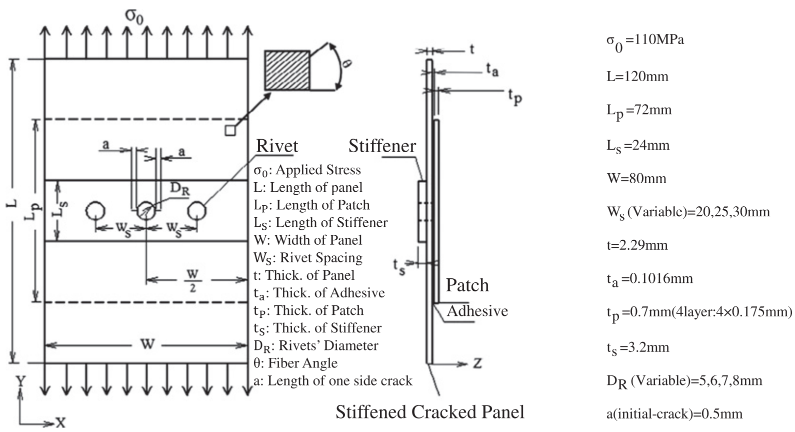

Fig. 1. Geometry, loading and dimensions of typical repaired stiffened panel.