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Evaluation of mixed mode-I/II criteria for fatigue crack propagation using experiments and modeling

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Abstract In this study, in-plane mixed mode-I/II fatigue crack growth simulations and experiments are performed for the Al 7075-T651 aluminum alloy which is widely used in the aerospace industry. Tests are carried out under different mode mixity ratios to evaluate the applicability of a fracture criterion developed in a previous study to mixed mode-I/II fatigue crack growth tests. Results obtained from the analyses and experiments are compared with existing and developed criteria in terms of crack growth lives. Compact Tension Shear (CTS) specimens, which enable mixed mode loading with loading devices under different loading angles, are used in the simulations and experiments. In an effort to model and simulate the actual conditions in the experiments, crack surfaces of fractured specimens are scanned, crack paths are modeled exactly, and contacts are defined between the contact surfaces of a specimen and the loading device for each crack propagation step in the analyses. Having computed the mixed mode stress intensity factors from the numerical analyses, propagation life cycles are predicted by existing and the developed mixed mode-I/II criteria and then compared with experimental results.

1. Introduction

Fracture mechanics and its applications, including mixed-mode fracture, are being studied extensively in such important areas as energy, defense, aviation, and space industries in developed countries that produce high-technology products. Fracture and crack propagation analyses are performed for airframe, helicopter, and aircraft engine parts even during the design phase. Many of the fracture and fatigue crack propagation problems that have been encountered in the aviation industry are related to fuselage of military and passenger aircraft, gas turbine engines and turbine blades.[1–13]

Fatigue crack growth studies for many practical engineering problems have mostly concentrated on pure mode-I loading condition over the past six decades. Unfortunately, pure mode-I loading condition rarely occurs in practice, and in

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many cases, cracks are exposed to mixed mode loads, i.e., directions of the loads are not normal to the crack plane. During crack growth under mixed mode loading, crack growth direction changes in accordance with mode mixity ratios. Thus, for accurate assessment of life predictions, crack growth direction plays a key role along with the fatigue crack growth rate under mixed mode loading conditions. Mixed mode fracture and crack propagation problems are encountered due to different reasons: multi-axial and mixed mode loads, non-perpendicular orientations of crack surfaces with respect to global uniaxial loading, and different types and combinations of boundary conditions.

Several stress- or energy-based fracture criteria have been proposed so far to understand the fracture mechanism of in-plane mixed mode problems. Maximum Tangential Stress (MTS),[14] minimum Strain Energy Density (SED),[15] Maximum Energy Release Rate (MERR)[16,17] and Maximum Tangential Strain (MTSN)[18] criteria are some of the most common theoretical criteria used in fracture and crack propagation analyses for mixed mode-I/II fracture problems. Tanaka,[19] Richard[20–22] and Pook[23] et al. also proposed different fracture criteria by defining equivalent Stress Intensity Factor (SIF) equations. For predictions of the crack growth increment and direction under in-plane mixed mode loading, definition of an equivalent SIF representing a combination of mode-I and mode-II SIFs is essential. Although many criteria have been proposed with regard to predictions of crack growth increment and its direction for mixed mode-I/II fracture problems, there is no standard criterion for mixed mode crack growth tests. Biner[24] investigated the crack growth behavior of AISI-304 stainless steel under mixed mode-I/II loading conditions by using Compact Tension Shear (CTS) specimens, and compared experimental crack growth directions with those obtained using the SED criterion and the Maximum Energy Release Rate (MERR) criterion. The author reported that the SED criterion significantly over-estimates the deflection angle of crack growth at high mode mixities. Zafosnik et al.[25] also performed mixed mode-I/II crack growth simulations and tests using CTS specimens made of Al alloy and results obtained from simulations combined with MTS and SED criteria were compared with experimental data. The results showed that, as is the case with Biner's results, the SED criterion is less accurate for determination of the kink angle under high mode mixities, and the MTS criterion provides good prediction agreement, but for further crack extensions the criterion deviates from experimental data. A literature survey about various criteria proposed for predictions of mixed mode crack growth directions and rates was given by Qian and Fatemi.[26] They reported by referring to studies existing in the literature that significant discrepancies occur between crack growth criteria when the mode-II component is dominant under mixed mode-I/II loading conditions. Ren et al.[27] reviewed several widely accepted fracture criteria in terms of crack initiation angle and fracture toughness ratio under in-plane mixed mode fracture. The authors indicated that many criteria can provide a good prediction for predominately mode-I fractures, but none of them yields good predictions under predominately mode-II conditions. In a previous paper,[28] mixed mode-I/II fracture analyses and experiments were performed for different types of CTS specimen, and data obtained from the experiments was compared with predictions from the analyses using existing criteria in the literature. Results showed that existing criteria yield reasonably close predictions to those of experiments for up to moderate levels of mode mixity in the loading. However, most existing criteria start deviating from experimental measurements for highly mixed mode loading conditions. Therefore, using all data obtained from analyses and experiments, improved empirical mixed mode-I/II fracture criteria were proposed in terms of fracture loads and crack deflection angles, and the developed criteria[28] were validated by applying them to the results of the experiments. Although the previous study[28] focused on mixed-mode fracture toughness tests under static loading, in this study, fatigue crack growth modeling and experiments are performed to validate the developed equivalent SIF equation in terms of propagation life cycles. In this context, in-plane mixed mode-I/II fatigue crack growth experiments are performed by using CTS specimens. Fracture surfaces of broken specimens are modeled exactly by scanning the surfaces, and fracture analyses are performed by simulating the real conditions in the experiments for all crack growth increments of the tests. Having computed the mixed mode stress intensity factors from the numerical analyses, equivalent SIFs on the crack fronts are calculated using existing and developed criteria, and life cycles are computed for each criteria. Finally, crack growth lives under different loading angles (30°, 45°, 60° and 75°) are compared with experimental results.

2. Existing in-plane mixed mode criteria

For determination of fracture behaviors under in-plane mixed mode loading conditions, there are various criteria that exist in the literature. Some of these criteria are summarized in this section.

The Erdogan and Sih criterion[14] is one of the most commonly used criterion for in-plane mixed mode problems. According to this criterion, crack propagates from the crack tip radially at a direction which contains the maximum tangential stress. If this tangential stress exceeds a critical value or an equivalent stress intensity factor (K_{eq}) reaches the fracture toughness (K_{IC}) value of the material, crack propagation becomes unstable, and fracture occurs. K_{eq} and the crack deflection angle for this criterion are expressed by

$$K_{\mathrm{eq}} = \cos\frac{\phi_0}{2}\left[K_{\mathrm{I}}\cos^2\frac{\phi_0}{2} - \frac{3}{2}K_{\mathrm{II}}\sin\phi_0\right] = K_{\mathrm{IC}} \tag{1}$$

$$\phi_0 = -\arccos\left(\frac{3K_{\mathrm{II}}^2 + K_{\mathrm{I}}\sqrt{K_{\mathrm{I}}^2 + 8K_{\mathrm{II}}^2}}{K_{\mathrm{I}}^2 + 9K_{\mathrm{II}}^2}\right) \tag{2}$$

where K_{I} and K_{II} are the SIFs of mode-I and mode-II, respectively; φ_0 is the crack deflection angle.

Another criterion developed for mixed mode-I/II problems is the Richard criterion.[21,22] The equivalent SIF and crack deflection angle can be determined by the following equations:

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

$$\phi_0 = \mp\left[155.5^\circ\frac{|K_{\mathrm{II}}|}{|K_{\mathrm{I}}| + |K_{\mathrm{II}}|}\right] - 83.4^\circ\left[\frac{|K_{\mathrm{II}}|}{|K_{\mathrm{I}}| + |K_{\mathrm{II}}|}\right]^2 \tag{4}$$

In Eq. (3), α_1 is a material parameter describing the ratio of $K_{\mathrm{IC}}/K_{\mathrm{IIC}}$ and generally taken as 1.155.

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