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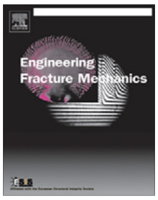

An equivalent thickness conception for evaluation of corner and surface fatigue crack closure

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ABSTRACT

The out-of-plane constraint-based equivalent thickness conception developed previously for corner cracks is extended here to surface-cracked plates based on systematical finite element simulations for the purpose to evaluate the plasticity-induced fatigue closure of corner and surface cracks. A semi-analytical solution for equivalent thickness of semi-elliptic surface cracks is obtained by numerical analyses of three-dimensional stress fields near the crack borders and comparing with that of ideally straight-through cracks in plates of finite thickness. The fatigue opening stresses of corner and surface cracks are evaluated based the recognized equations of straight-through cracks using the equivalent thickness conception. Comparison against available finite element and experimental results shows that the developed method can provide satisfied prediction of fatigue closure for both corner and surface cracks.

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1. Introduction

In 1970, Elber [1] observed that a fatigue crack can remain closure even when a tensile load is applied to a specimen, which implies that some internal forces hold the crack faces together until the applied tensile load is large enough to separate them. Though different crack closure mechanisms have been identified, the plasticity-induced fatigue crack closure is recognized as the primary closure mechanism in many engineering situations for fatigue crack propagation. This effect causes a deviation of crack growth rate, the crack growth per cycle of fatigue loading da/dN, from the basic curve of crack growth rate against the full range of stress intensity factor (SIF) $\Delta K = K_{\max} - K_{\min}$ always obtained by through-the-thickness cracked specimens at fixed stress ratio. When an effective stress intensity factor range ΔK_{eff}, defined as $\Delta K_{\text{eff}} = K_{\max} - K_{\text{op}}$, is used, the $da/dN - \Delta K_{\text{eff}}$ data for different stress ratios can collapsed into a unique curve. Here the $K_{\max}$ and $K_{\min}$ are the maximum and minimum values of the SIF within a load cycle, respectively, and K_{op} is the lowest SIF at which the crack can open fully.

The $K_{\max}$-distributions along the crack front line can be obtained by empirical equations or numerical analyses. For evaluation of K_{op}, modified strip-yield models [2–5] have been specifically developed. Elastic–plastic finite element (FE) methods can also be used for K_{op} calculations [6], but much more complicated and need professional researchers to properly conducted. The original strip-yield model for fatigue crack closure [2] specialized in small-scale yield condition of elastic-perfectly-plastic material model for plane stress cracks in an infinitely large sheet. Further, the out-of-plane constraint factor was proposed and calculated using FE method by Newman [3,7] and theoretically evaluated by Guo et al. [8–10] to describe adequately the three-dimensional (3D) effect. Modified the plane stress strip-yield by properly incorporating the

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out-of-plane constraint factor, the strip-yield model can be extended to make efficient prediction for fatigue crack closure for through-the-thickness cracked plates with finite thickness. This type of modified strip-yield models is much more convenient than detailed FE analyses and have been widely used to predict fatigue crack growth in straight through-the-thickness cracked plates [11]. However, for structures with part-through curve cracks, how to use the strip-yield models with satisfied precision remains to be a challenge. On the other hand, the FE analyses can involve complex crack configurations and various elastic–plastic material models and has been used method to simulate the plastic-induced crack closure in both two-dimensional (2D) and three-dimensional (3D) solids [6,12–17]. From the conceptual perspective, FE analysis for plasticity induced fatigue crack closure is straight forward, but still complicated for engineering applications. First, the FE model requirements are prohibitively large and complex for large number of loading cycles; second, the FE incremental crack advance by releasing the element node strongly depends on element size in front of crack tip and difficult to reflect real crack extension during fatigue crack growth.

Here a relatively simple method is developed based on the equivalent thickness conception for calculating K_{op}-distribution along the front line of corner and surface crack by use of the well recognized crack closure model for straight-through cracked plates. The T_z-based equivalent thickness B_{eq} conception [18,19] will be used. Here T_z is a out-of-plane constraint factor proposed to reflect the 3D effect on crack tip fields by Guo [8,20],

$$T_z = \frac{\sigma_{33}}{\sigma_{11} + \sigma_{22}}, \tag{1}$$

where the subscripts 1, 2 and 3 stand for the local coordinates x, y and z or r, θ and z respectively, with z axis being tangential to the crack front line. For the plane stress state, $T_z = 0$; for the plane strain state, T_z equals to Poisson's ratio v in elasticity and 0.5 in incompressible pure plastic solids. Based on the parameter T_z, the 3D normal stress field in the vicinity of crack border can be measured precisely. This equivalent thickness conception reveals an equivalent relationship of 3D stress constraint state near the crack tip between curved cracks and through-the-thickness cracks, and has been efficiently used for fracture prediction of corner cracked specimens by the thickness-dependent fracture toughness obtained from the standard through-the-thickness cracked specimens [19]. More generally, it is reasonable to expect that the fatigue crack closure results of through cracked plates can be extended to evaluate crack opening stress along curved crack front line based on the equivalent thickness conception B_{eq} which builds a bridge in some respects between curve crack and straight-through crack.

In the present work, the opening stresses along the most important craved cracks, the corner cracks and surface cracks, are systematically investigated. The equivalent thickness B_{eq} for a point on the front line of a curved crack is evaluated by a unified expression of the 3D distribution of T_z of the curved crack and comparison with that of a straight-through crack. A semi-analytical B_{eq}-solution of quarter-elliptic corner cracks has been obtained in a previous work [19] and extended to semi-elliptic surface cracks here by detailed 3D analyses. Then the B_{eq} expressions are applied to evaluate the crack opening stress of corner and surface cracks. Comparison with available finite element and experimental results shown that the crack opening stress of the corner and surface cracked specimens can be efficiently predicted by the equations obtained from straight-through cracked specimens.

2. Foundation of equivalent thickness for curved cracks

The 3D distribution of T_z in the vicinity of through-the-thickness, corner and surface cracks have been studied extensively [21–27]. From these studies it is found that T_z can be expressed by a general function as follows

$$T_z = v \cdot f(r, \theta, z, B, t, \ldots), \tag{2}$$

where (r, θ, z) are the local polar coordinates at the crack tip, B is the thickness of the plate, t is the shape factor of semi-elliptic surface cracks or corner cracks. In the normal plane of the crack front line, T_z is nearly independent of θ in the range of $0 \leqslant \theta \leqslant \pi/2$ near the crack tip [21,22,27]. In addition, the previous studies showed that the distributions of T_z for various types of curved cracks are similar to that of through-the-thickness cracks in plates with finite thicknesses [18,21,22].

For through-the-thickness cracked plates, She et al. [18] proposed to define the equivalent thickness B_{eq} on the basis of the 3D distribution of the out-of-plane stress constraint factor T_z. In view of the similarity of T_z-distributions between corner cracks and through-the-thickness cracks, as shown in Fig. 1a and b, Yu et al. [19] extended the T_z-based conception of equivalent thickness to quarter-elliptic corner cracks and applied it to predict fracture toughness for corner-cracked specimens. The equivalent thickness B_{eq} at a point P on the front line of curve crack can be determined by matching the local T_z distribution curves in the normal plane of the crack front line at P to that at the middle plane of a through-the-thickness cracked plate with thickness B_{eq}, as illustrated by Fig. 1.

Based on B_{eq}, the T_z distribution in the front of through-the-thickness crack and quarter-elliptic corner crack in a plate with thickness B_{eq} can be empirically expressed as a uniform formula by fitting the FE results [18,19],

$$T_z = v \cdot \exp(-8(r/B_{\text{eq}})^{1.5} - 1.6(r/B_{\text{eq}})^{0.5}) \quad \text{at } \theta = 0, \tag{3}$$

where v is Poisson's ratio. The B_{eq} of quarter-elliptic corner crack can be evaluated from a set of empirical equations as follows [19],

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