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A cohesive zone model for fatigue crack growth allowing for crack retardation ☆

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ABSTRACT

A damage-based cohesive model is developed for simulating crack growth due to fatigue loading. The cohesive model follows a linear damage-dependent traction–separation relation coupled with a damage evolution equation. The rate of damage evolution is characterized by three material parameters corresponding to common features of fatigue behavior captured by the model, namely, damage accumulation, crack retardation and stress threshold. Good agreement is obtained between finite element solutions using the model and fatigue test results for an aluminum alloy under different load ratios and for the overload effect on ductile 316 L steel.

1. Introduction

The fatigue life of a structure is influenced by mechanical, microstructural and environmental factors, all of which result in material damage, typically equated to crack length (Miller, 1991). Indeed the field of fracture mechanics has had profound influence on fatigue analysis. For mechanical type loads, fatigue life of a component or structure is calculated as the number of loading cycles needed to grow a pre-existing crack to a predetermined critical dimension or to nucleate and grow a crack from a notch or other location of stress concentration.

The focus of this paper is the so-called stage-II fatigue crack growth, i.e., the stable propagation of a dominant crack. Starting with the Paris model (Paris and Erdogan, 1963; Paris et al., 1961), fatigue life predictions have typically been based on equations relating the stage-II rate of crack growth (da/dN) to the stress intensity range (ΔK), also called the driving force, characteristic of a constant magnitude cyclic applied load and of specimen geometry. Here a is the crack length and N is the number of loading cycles. Attempts to incorporate more complex conditions affecting the crack growth rate led to models whose parameters depend on characteristics of the applied load or of the environment, as well as the redefinition of ΔK.

The Paris model and similar approaches are valid under the ideal conditions of linear elastic fracture mechanics (LEFM), small-scale yielding, constant amplitude cyclic loading and long cracks. When these conditions are not met, these approaches lose their predictive capability. In particular, they are unable to model crack retardation due, for example, to roughness induced crack closure (Elber, 1971), oxidation, or the presence of a residual stress field (Noroozi et al., 2008).

We develop a cohesive zone model, i.e., a model of the traction–separation relationship ahead of the crack tip, capable of macroscopically modeling fatigue crack growth. Cohesive zone models can capture the nonlinear behavior occurring in the process zone provided that the latter can be considered as a zone of zero thickness. Since they can be paired with a plasticity model in the bulk material, they can be especially useful in simulating fatigue behavior of materials that violate small scale yielding assumptions at the crack tip. Their use in fracture problems has become common in recent years. Cohesive zone models are also useful when micromechanical processes acting at a scale smaller than the grid size used in the finite element analysis affect the rate of crack growth. The relevant micromechanics can then be incorporated in the cohesive zone model. This process is sometimes called "subgrid modeling".

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Examples are the interaction of asperities as a cause of crack closure and the effect of residual stresses when the plastic zone is not adequately resolved. A crack retardation mechanism as introduced in the proposed model can be used to capture these effects. Subgrid modeling is ideally carried out through multiscale analysis, which is not addressed in this paper. In that light, one could envision obtaining the parameters of the proposed model from micromechanical analysis at a smaller scale.

Cohesive zone fatigue models have most commonly been implemented as cohesive interface finite elements. de Andres et al. (1999) proposed a bilinear traction–separation relationship, which unloads to the origin with no cyclic degradation of either the stiffness or the peak traction. Nguyen et al. (2001) pointed out that such a model can lead to plastic shakedown that arrests crack growth after a few cycles. Hence, a distinction between loading and unloading paths is necessary, which allows for subcritical crack growth. In Nguyen et al. (2001), a cohesive model with an unloading–reloading hysteresis was developed. In this work, the stiffness and the peak load degrade proportionally to the unloading stiffness as the number of cycles increases. Roe and Siegmund (2001) introduced a damage variable, whose evolution resulted in the degradation of the cohesive zone traction. The cohesive relationship under monotonic loading was based on the potential proposed by Xu and Needlemanm (1994). Maiti and Geubelle (2005) proposed a cohesive model of fatigue fracture in polymeric materials in which the cohesive stiffness evolves as a function of the rate of opening displacement and of the number of loading cycles since the onset of failure. Crack retardation or healing due to artificial crack closure (a wedge introduced in the wake of the crack) was addressed by these authors in Maiti and Geubelle (2006). Maiti et al. (2006) incorporated healing kinetics at the atomic level for a class of self-healing materials.

The proposed cohesive zone model, an earlier form of which was presented in Ural and Papoulia (2004), is bilinear under monotonic loading and shows a degrading peak traction and stiffness behavior under cyclic loading due to an evolving damage variable. The model is a constitutive relationship of the material, i.e., unlike the Paris and other models, its parameters do not depend on loading characteristics such as the load ratio, defined as the ratio of minimum to maximum load. Rather, it contains three physically motivated parameters, which govern crack advance, threshold, and retardation, respectively. As in Roe and Siegmund (2001), the model introduces a scalar (energy like) damage variable, governed by an evolution equation, which provides a phenomenological framework to account for the nonlinear processes associated with fatigue failure. Special emphasis is placed on the ability of the model to capture crack retardation, which is known to depend on the load ratio. In particular, the damage variable can evolve nonmonotonically; a decrease in damage partially restores the strength of the material and therefore retards crack growth. However, we do not specifically attribute crack retardation to any of the possible physical mechanisms mentioned earlier, namely roughness induced crack closure or the effect of residual stresses. Indeed, crack retardation and damage nonmonotonicity could even correspond to physical crack healing. Several recent proposals have been made for self-healing structural materials (White et al., 2001; Toohey et al., 2007). Regardless of the physical mechanism, we show that the model captures the effect of mean stress (load ratio) and of overload.

The remainder of the paper is organized in the following manner. Section 2 presents the details of the proposed cohesive model. Section 3 includes a mathematical analysis of well-posedness of the model. Section 4 presents aspects of the finite element implementation and some preliminary testing. In Section 5, the predictive capability of the proposed model is evaluated through two dimensional finite element simulations of cyclic fatigue tests of A356-T6 compact-tension (CT) specimens at two load ratios. Section 6 illustrates the ability of the model to capture the effect of overload.

2. A damage-based cohesive model allowing for crack retardation

We postulate a degrading linear traction–separation relationship of the form

$$T = F(\kappa)\delta, \tag{1}$$

where κ is a damage variable, δ is the effective opening displacement, defined in Section 4, and T is a scalar effective cohesive traction, also defined in Section 4.

The dependence of the elastic coefficient F on κ is specified by

$$F(\kappa) = \frac{\sigma_c(1-\kappa)}{\kappa(\delta_u - \delta_c) + \delta_c}; \tag{2}$$

δ_c is the critical displacement at which the crack initiates and damage starts to accumulate, δ_u is the failure displacement, i.e., the displacement at which the traction becomes zero, and σ_c is the initial peak traction of the interface. The traction T is also required to satisfy the inequality $T \leqslant C(\kappa)$, where $C(\kappa)$ is specified by

$$C(\kappa) = \sigma_c(1-\kappa). \tag{3}$$

Under cyclic loading, the model exhibits a degrading peak traction, i.e., a decreasing value of $C(\kappa)$, and a degrading stiffness, i.e., a decreasing value of $F(\kappa)$ as the value of κ increases (Fig. 1), resulting in eventual loss of load transmission ability of the interface. The variable κ takes values between 0 and 1 corresponding to no damage and complete fracture, respectively. The expression proposed in (2) has the desirable property that the elastic coefficient $F(\kappa)$ is strictly decreasing so that the traction T decreases from σ_c (when $\kappa = 0$) to 0 (when $\kappa = 1$). The ascending and descending linear branches of the monotonic response are not explicitly defined by the above equations but rather are a consequence of these equations. On the ascending branch, the relationship $T = F(\kappa)\delta$ holds with $\kappa = 0$ and hence $F(\kappa)$ is a fixed constant. Therefore, the relation between T and δ is linear on the ascending branch.

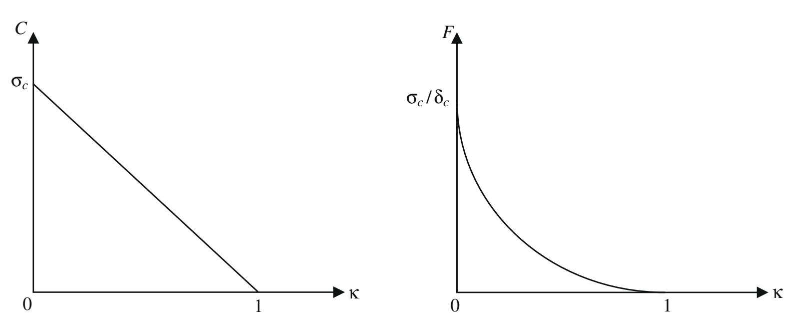

Fig. 1. Evolution of peak traction (left) and stiffness (right) with accumulation of damage.