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The extended McEvily model for fatigue crack growth analysis of metal structures

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Abstract

An extended McEvily model for fatigue crack growth analysis of metal structures is proposed in this paper. In comparing with our previous work, the extension is mainly concerned with the following two aspects: (1) the slope of the fatigue crack growth rate curve is regarded as a variable rather than a fixed value for different materials; (2) both the maximum stress intensity factor at the crack opening level, $K_{op,max}$ and the effective stress intensity factor range at the threshold level, $\Delta K_{eff,th}$ are functions of load ratio, R and they are determined by the curve fitting method. Results indicate that the value of $K_{op,max}$ tends to decrease slightly as load ratio increases where crack closure is experimentally detected. According to the present data obtained through the nonlinear least squares fitting method and discussions on the experimental results in the published literature, the parameter $\Delta K_{eff,th}$ increases with increasing load ratios where crack closure exists and decreases at high load ratios where the experimental data are closure free. In this paper, all the parameters in the extended McEvily model are assumed to be unknown in advance and they are estimated through the curve fitting method based on the experimental data. The method is also put forward to determine material constants in the crack growth rate law based on the fitting parameters under different load ratios. Comparison between the predicted results and the corresponding experimental data with different load ratios reveals that the extended McEvily model can account for the load ratio effect reasonably well. Based on our previous work this model can also be expected to explain other fatigue phenomena.

Keywords: Fatigue crack growth; Threshold; Effective stress intensity factor range; Load ratio; Crack closure

1. Introduction

Marine structures such as ships and offshore platforms are frequently subjected to complex loading histories and one of the most significant failure modes is fatigue. Marine structures are mostly made of metals. Though fatigue of metals and metal structures has been studied for more than 160 years [1], mechanisms of metal fatigue have not been fully understood [2]. Generally speaking, two different theories for predicting the fatigue life of metal structures have been developed [3,4]. One is the cumulative fatigue damage theory based on S–N (or ε–N) curves and the other is the fatigue crack propagation theory based on the crack growth rate curve. Large scatter always appears in the predicted fatigue lives, because the cumulative fatigue damage theory cannot account for the effects of initial crack size and load sequence [5]. The fatigue crack propagation theory can overcome these difficulties. Hence, much progress has been made for the fatigue crack propagation theory since the famous Paris equation [6] was proposed.

As one of the fatigue crack growth models, McEvily model [7–12] cannot only account for the effects of initial crack size and load sequence, but also explain various other phenomena of metal fatigue observed in tests. McEvily model is valid for both physically short crack and

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macroscopically long crack [11,13]. The model has been successfully applied to many fatigue problems such as fatigue problem under classical two-step fatigue loading [14], fatigue problem under multiple two-step fatigue loading [15], fatigue problem with overload [16] and fatigue problem under biaxial loading [17]. The model shows promising capability and is worthy of being further studied. Cui and Huang [18] suggested a general fatigue crack growth model with nine parameters by extending McEvily model. The general fatigue crack growth model is valid from near threshold region to unstable fracture region. Zhou and Cui [19] proposed a method of estimating the nine parameters in the general model according to the existing experimental data and carried out sensitivity analyses for the nine model parameters. Wang et al. [20] studied the effect of parameter reflecting crack closure development on the fatigue crack growth rate through the nonlinear least squares fitting method. The results were not entirely the same as that of Zhou and Cui [19]. Results showed that for macroscopic cracks the parameter reflecting crack closure development has little effect on the fatigue crack growth rate when it exceeds a certain value. However, when the fatigue crack propagation is in the short crack region, the parameter has significant effect on the fatigue crack growth rate. Li et al. [21] pointed out that McEvily model with the fixed slope of two is not in agreement with many experimental results. It is strongly recommended that the slope should be a variable.

According to these previous studies, further extension to McEvily model is proposed in this paper. The extended McEvily model is valid from near threshold region to unstable fracture region and the slope of the fatigue crack growth rate is viewed as a variable. As mentioned by McEvily et al. [10], both the maximum stress intensity factor at the crack opening level for a macroscopic crack, $K_{\mathrm{op,max}}$ and the effective stress intensity factor range at the threshold level, $\Delta K_{\mathrm{eff,th}}$ are functions of load ratio, R. Two equations representing $K_{\mathrm{op,max}}$ and $\Delta K_{\mathrm{eff,th}}$ using load ratio R, respectively will be presented based on the experimental data. The process is accordingly shown to determine the parameters in the extended McEvily model. Finally, the predicted results based on the obtained parameters are compared with the corresponding experimental data under different load ratios.

2. The extended McEvily model for fatigue crack growth analysis

2.1. Modified constitutive relation by McEvily and his co-workers

The modified linear elastic fracture mechanics approach is based on the following constitutive relation:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A(\Delta K_{\mathrm{eff}} - \Delta K_{\mathrm{eff,th}})^2 \tag{1}$$

where a is the crack length; N is the number of load cycles; A is a material- and environmentally-sensitive constant of dimensions $(\mathrm{MPa})^{-2}$; ΔK_{eff} is the range of the effective stress intensity factor which is defined as

$$\Delta K_{\mathrm{eff}} = K_{\max} - K_{\mathrm{op}} \tag{2}$$

where $K_{\max}$ is the maximum stress intensity factor in a loading cycle and K_{op} is the stress intensity factor at the crack opening level. $\Delta K_{\mathrm{eff,th}}$ in Eq. (1) is the effective stress intensity factor range at the threshold level as mentioned above. Eq. (1) has been shown to be valid for a wide range of alloys [10].

In order to use Eq. (1) in the analyses of a range of topics such as (1) anomalous fatigue crack growth behavior; (2) small crack behavior; (3) mean stress effect; and (4) load sequence effect, McEvily and his co-workers [10–13] have introduced some modifications to Eq. (1) to account for (a) the elastic–plastic behavior of small cracks; (b) the variation of the crack closure level; and (c) the transition from the threshold level to the endurance limit as a controlling parameter in the small crack growth regime.

The modified constitutive relation for fatigue crack growth has been expressed as follows [9–11]

$$\frac{\mathrm{d}a}{\mathrm{d}N} = AM^2 \tag{3}$$

$$M = K_{\max}(1-R) - (1-\mathrm{e}^{-ka})(K_{\mathrm{op,max}} - RK_{\max}) - \Delta K_{\mathrm{eff,th}} \tag{4}$$

$$K_{\max} = \sqrt{\pi r_{\mathrm{e}}\left(\sec\frac{\pi}{2}\frac{\sigma_{\max}}{\sigma_{\mathrm{Y}}} + 1\right)}\left(1 + Y(a)\sqrt{\frac{a}{2r_{\mathrm{e}}}}\right)\sigma_{\max} \tag{5}$$

where r_{e} is the size of an inherent flaw, a parameter whose magnitude is of the order of several microns in length [10]; σ_{Y} is the yield stress of the material, MPa; $\sigma_{\max}$ is the maximum stress in a loading cycle; R is the stress ratio; $Y(a)$ is a geometrical factor; k is a material constant which reflects the rate of crack closure development with crack advance.

2.2. The general constitutive relation by Cui and Huang [18]

The modified constitutive relation for fatigue crack growth proposed by McEvily and his co-workers is further generalized in the following three aspects in Ref. [18]:

(1) To introduce an unstable fracture condition into the crack growth rate curve in order to cover the whole fatigue crack propagation regimes.
(2) To define a 'virtual strength' to replace the yield stress in order for the constitutive relation to be applicable from 'crack-free' plain specimen to cracked body and from fatigue limit to ultimate strength.
(3) To introduce an overload/underload parameter for modeling the overload retardation and underload acceleration.

Thus the general constitutive relation for fatigue crack growth can be described as the following equations

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{AM^2}{1 - \left(\frac{K_{\max}}{K_{\mathrm{c}}}\right)^n} \tag{6}$$