FATIGUE ANALYSIS WITHOUT CYCLE COUNTING: SUBCYCLE FATIGUE CRACK GROWTH AND EQUIVALENT INITIAL FLAW SIZE MODEL

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Abstract
Threshold and near-threshold fatigue crack growth (FCG) is critical for the total life prediction as majority of time is spent in this regime. The proposed study includes the fatigue crack growth near-threshold in the time-based subcycle model for fatigue life prediction under arbitrary loading conditions. A novel fatigue-life prediction methodology combining a subcycle fatigue crack growth analysis and equivalent initial flaw size (EIFS) concept is proposed. A previously developed time-based subcycle fatigue crack growth model is extended to near threshold regime and under multiaxial loadings. A new temporal kernel function to include intensity factor corresponding to near threshold region is proposed. The multiaxial load scenario is considered for mixed-mode FCG using a critical plane approach. Model predictions under arbitrary are compared with experimental data from open literatures and internal testing. Most of the predicted fatigue life results lie with error factor range of 2, which shows a good prediction for fatigue life.

1. Introduction

The current study focuses on the FCG-based life prediction. The time-based subcycle crack growth analysis calculates crack growth at any arbitrary time in the loading history. This initial model was mainly for constant amplitude loading and simple variable amplitude loadings. Also,this formulation can only calculate crack propagation in the Paris region, while threshold and near-threshold FCG is critical for the total life prediction as majority of time is spent in this regime. Therefore, study proposes to include the fatigue crack growth near-threshold in the time-based subcycle model for fatigue life prediction. Above discussion is for uniaxial loading and mode I FCG analysis. Very few studies for general multiaxial fatigue life prediction using FCG analysis are found in the open literature. A previous study using a critical a plane concept with FCG was shown to have good accuracy for life prediction of various metallic materials. The FCG is based on the standard cycle-based method and is not applicable to general random loading conditions. Inspired by that approach, another motivation of the proposed study is to extend the time-based FCG analysis using the critical plane concept for overall multiaxial random amplitude loadings.

2. Results

The relation between crack growth and crack tip opening displacement is referred as crack tip opening displacement (CTOD). The crack growth depends on the maximum applied stress intensity factor K_{max} and proposed a crack growth function as a = $\mathrm{A}K_{max}^{B}\delta^{D}$,where a is crack extension, $K_{\max}$ is the maximum stress intensity factor, δ is the CTOD and A, B, D are fitting parameters. Thus, the crack extension is proportional to the square root of CTOD at an instantaneous point in loading history. If we differentiate the above equation with respect to time, we get $da = \mathrm{A}K_{max}^{B}/(2\sqrt{\delta})d\delta$. We are proposing a modification in the kernel function to include the threshold stress intensity factor. The modified form of crack growth function can be written as $da = \mathrm{A}(K_{max} - K_{th})^{B}/(2\sqrt{\delta})d\delta$. In time-based crack growth function, crack increment is a function of CTOD. For Al-7075, it is proportional to the square root of CTOD. Thus, we can write *da* as $da = f(K) * \sqrt{\delta}$, where *f(K)* is the kernel function which depends on material fitting parameters and applied loading condition. Differentiating da with respect to *t,* to get crack growth per unit time $da/dt = f(K) * d\delta/(2\sqrt{\delta_i})$, and $da/dt = f(K) * d\delta/(\sqrt{\delta_i} + \sqrt{\delta_{i-1}})$, where *f(K)* = A*$(K_{max} - K_{th})^{B}$. In case of time-based subcycle fatigue crack growth analysis A and B are material constants and can be found out by using Paris constants C and m for a fully revered loading scenarios as $A = 2^{B}C\sqrt{2\,E\,\sigma_y}/0.6$ and $B = m - 1$. Liu and Mahadevan proposed a critical plane model based on general fatigue limit criteria, described as $\sqrt{(\sigma_c/f_{-1}) + (\tau_c/t_{-1}) + p(\sigma^{H}/f_{-1})} = q$, where p and q are material fitting parameters. σ_c , τ_c and $\sigma^{H}$are the normal and shear stress range acting on critical plane. f_{-1}

and t_{-1} are fully reversed normal and shear fatigue limit. One more important material parameter we need to define which related to the material ductility and used in the critical plane orientation calculation is the ratio of shear fatigue limit to the normal fatigue limit, abbreviated as $s = t_{-1}/f_{-1}$. If frictional crack (e.g., EIFS) is introduced in the components, corresponding mixed-mode SIF can be defined as follows. Mode I stress intensity factor can be written as $K_I = \sigma\sqrt{\pi a}$, and Mode II stress intensity factor can be written as $K_{II} = \tau\sqrt{\pi a}$. The loading related parameters at any time t during the loading history is given as $k_{1,t} = \frac{K_{I,t}}{2}(1 + \cos 2\alpha) + K_{II,t} \sin 2\alpha$, $k_{2,t} = -\frac{K_{I,t}}{2}(sin\, 2\alpha) + K_{II,t}\, cos\, 2\alpha$, and $k_t^H = K_{I,t}/3$, where angle α is a critical plane angle, $\alpha = \beta + \gamma$, β is maximum normal stress amplitude plane, γ is material parameter. An equivalent stress intensity factor can be written as $K_{mixeed,eq} = \frac{1}{q}\sqrt{(k_1)^2 + (k_2/s)^2 + p(k^H)^2}$. With this formulation we can convert mixed-mode loading into an equivalent uniaxial loading and can use the same time-based subcycle fatigue life model to compute the fatigue life of a specimen.

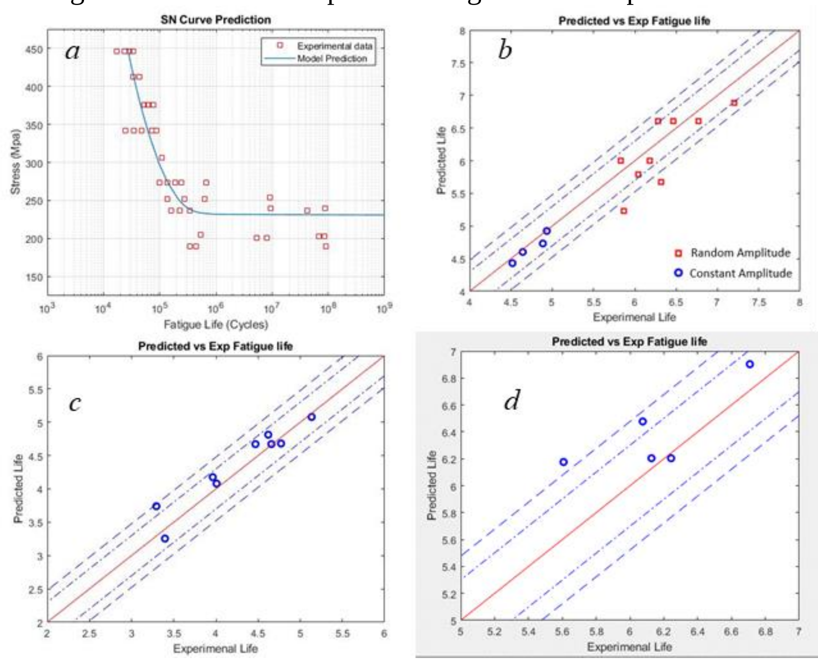

Fig.1 – Prediction results. (a) Uniaxial constant amplitude loading. (b) Uniaxial random amplitude loading. (c) Multiaxial constant amplitude loading. (d) Multiaxial random amplitude loading.

The proposed model has been validated for uniaxial constant amplitude loading, uniaxial random amplitude loading, multiaxial constant amplitude loading, and multiaxial random amplitude loading. The results are shown in Fig. 1 (a), (b), (c) and (d), respectively. Most of the predicted fatigue life results lie with error factor range of 2, very few points lie within the error factor range of 3.

3. Conclusions

Previously developed time-based subcycle crack growth model has been modified to consider the effect of threshold stress intensity factor. Modification has been done in main kernel function for crack increment calculation by introducing threshold stress intensity factor range. Concept of EIFS has been integrated with this modified kernel function with fracture mechanics approach to calculate fatigue life. The model prediction results are validated under conditions of constant and variable amplitude, uniaxial and multiaxial loading conditions.

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