SIMULATION AND VALIDATION OF A CONCURRENT FATIGUE CRACK GROWTH MODEL

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Summary In this paper, a concurrent simulation methodology for mixed-mode fatigue crack growth (FCG) analysis is described, and a novel small time scale formulation for fatigue crack growth prediction under mixed-mode loadings is proposed. The proposed concurrent mixed-mode fatigue crack growth model is based on the critical plane approach and a sub-cycle crack growth method. It is incorporated into the extended finite element method (XFEM) to simulate the fatigue crack growth for an arbitrary curvilinear crack. The accuracy of the XFEM results is verified by numerical examples with classical finite element solutions. To further validate the model, experimental testing on modified compact specimens is performed under two different types of loadings, one with constant amplitude and the other with proportional variable amplitude. The orientations and extents of the crack growth experimentally measured are compared with those from numerical simulations. First it is confirmed that variable amplitude loadings have no significant impact on the crack growth orientations. Secondly both experimental and simulation results manifest the overload retardation behavior under mixed-mode loadings. The simulation results agree well with the experimental ones.

INTRODUCTION

Most existing fatigue crack growth (FCG) analysis methodology and experimental testing are for planar crack under uniaxial loading [1-3]. Very few theoretical and experimental studies have been reported for mixed-mode FCG under variable amplitude loadings, especially for general curvilinear crack growth. FCG problem of engineering structures under realistic loading conditions are usually in mixed-mode due to the inclined initial crack, applied multiaxial loading, and crack kinking.

Two critical components are required for a sound FCG methodology for curvilinear cracks under general mixed-mode loadings: 1) a material FCG model or criteria under general mixed-mode loadings; (2) a computational mechanics simulation framework for the tracking of crack growth and the stress intensity factor (SIF) solution.

In this study, a generalized critical plane approach [4] for fatigue crack growth and a small time scale FCG model [5] for mode I crack are combined as the FCG criterion for general mixed-mode loading. The newly-proposed FCG criterion will be incorporated into a meshless finite element method - eXtended Finite Element Method (XFEM) [6, 7] for the SIF solution tracking. Since very few experimental investigations of general curvilinear crack growth under variable amplitude loadings have been reported in the literature, the proposed study will perform such kind of experiments to validate the proposed XFEM-based simulation methodology.

CONCURRENT SIMULATION METHODOLOGY FOR FATIGUE CRACK GROWTH

The objective of this study is to develop a simulation methodology for the mixed-mode fatigue crack growth, based on a critical plane-based multiaxial crack growth model, a small time scale model and the XFEM method. The flow chart of the proposed general algorithm is shown in Fig. 1.

The small time scale model (Eq.(1)) is based on the incremental crack growth at any arbitrary time instant . It could be used for the fatigue crack growth analysis under random variable amplitude loading without cycle-counting and includes the stress ratio effect intrinsically.

$$\dot{a} = H(\dot{\sigma})\cdot H(\sigma-\sigma_{ref})\cdot\frac{2C\lambda\sigma}{1-C\lambda\sigma^2}\cdot\dot{\sigma}\cdot a \qquad (1)$$

The above small time scale model was derived under uniaxial loading condition. Modifications are required to extend the discussion to general mixed-mode loading conditions. By transforming the mixed-mode stress intensity factor to an equivalent stress intensity factor, a developed critical plane approach [8] (Eq. (2)) could be adopted to predict general mixed-mode crack growth rate. The proposed small time scale formulation can then be easily applied using the equivalent SIF history.

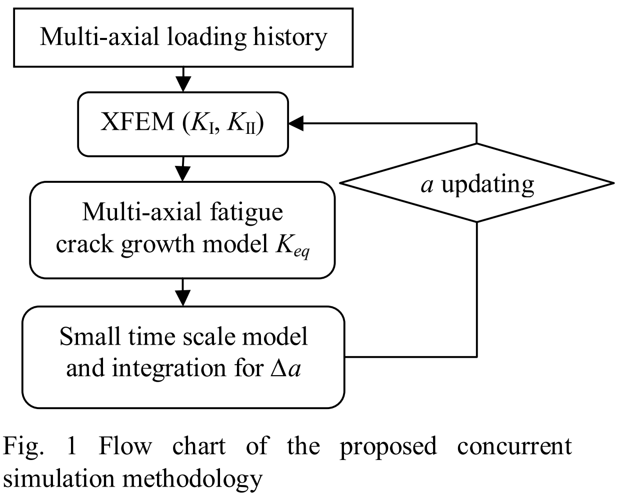

Fig. 1 Flow chart of the proposed concurrent simulation methodology

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$$K_{mixed,eq} = \frac{1}{B}\sqrt{(k_1)^2 + \left(\frac{k_2}{s}\right)^2 + A\left(k^H\right)^2} \quad (2)$$

The above discussion proposed an innovative mechanism for modeling mixed-mode fatigue crack growth. For fatigue crack growth analysis of arbitrary curvilinear crack growth, a computational mechanics method is required to calculate the stress intensity factors since the analytical solution is very difficult. In this study, the XFEM is used for this purpose.

The XFEM is a numerical method by introducing extra enrichment functions [6,7] based on the concept of partition of unity to accommodate the internal boundaries in the discrete model. After the instantaneous SIFs (K_{I} and K_{II}) are obtained by the XFEM, an equivalent SIF could be calculated by the mixed-mode crack growth methodology (Eq. (2)). The crack growth is updated based on the small time scale model predictions. With the updated crack length, the new SIFs could be obtained by the XFEM again. Repeating the above procedure, the mixed-mode fatigue crack growth behavior could be simulated.

The proposed methodology integrating the small time scale fatigue model and the XFEM has two major advantages. First, the mechanical stress analysis and fatigue crack growth simulation can be performed concurrently due to the implementation of the novel small time scale formulation. Second, the XFEM has no remeshing requirement for a growing crack, which makes the structural level simulation very efficient and flexible.

EXPERIMENTAL VALIDATIONS

In this part, experimental testing on modified compact specimens under both constant and variable amplitude loadings was designed to verify the orientations and extents of the fatigue crack growth from the numerical simulations.

Modified Al 2024-T3 compact tension specimens are used to promote curvilinear crack during the fatigue crack growth. The basic idea is to put a through-thickness hole above the possible crack path. Different mode mixities can be generated by adjusting the distance of the hole to the middle plane of the compact tension specimen. Two different specimens with different mode mixities are designed: sink-hole specimen and miss-hole specimen. Different crack growth directions for the miss-hole and the sink-hole specimens are observed. The crack bypassed the upper-left hole for the miss-hole specimen. The crack links with the inner edge of the hole for the sink-hole specimen. According to the comparison between the predicted and measured crack paths, the predicted crack growth paths match the observed paths well. The measured a-N curves were also compared for the sink-hole and miss-hole specimens.

Experimental testing under both constant and variable amplitude loading histories is performed on sink-hole specimens to confirm a) variable amplitude loadings have no significant impact on the crack growth orientations, and b) the overload retardation effect of mixed-mode crack growth. The model predictions agree with the experimental observations very well.

CONCLUSIONS

An advanced simulation technique is developed for fatigue crack growth prediction. The proposed methodology is based on a new mixed-mode FCG model using small time scale formulation. The extended finite element method (XFEM) is integrated with the developed small time scale model for crack growth simulation and stress intensity factor calculation. The developed methodology is demonstrated in numerical simulations to show its efficiency and flexibility. Experimental testing data for two aluminum alloys under constant and variable mixed-mode loadings are used to validate the proposed simulation framework. The simulation results agree well with the experimental ones. Thus the proposed methodology and its implementation model are very promising in the fatigue crack growth prediction.

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