Applications of a Finite Element Analysis of Fatigue Crack Closure

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ABSTRACT

An elastic-plastic finite element simulation of fatigue crack closure is used to study several practical problems in fatigue crack propagation. Results show the effect of maximum stress, notch stress fields, and stress biaxiality on crack opening levels. These results are consistent with experimentally observed trends in crack growth rates. Simple correlations of the experimental data with closure-modified crack growth parameters are shown to be sufficient for many engineering purposes.

KEYWORDS

Fatigue crack closure; finite element analysis; fatigue crack growth; high strain fatigue; notches; biaxial fatigue.

INTRODUCTION

The most common engineering tool used to analyze and correlate fatigue crack growth data is the Paris-type power-law relationship between da/dN and ΔK. This principle, with occasional minor modifications, has been successfully applied to data from a wide range of stress levels, stress states, crack lengths, materials, and geometries. The discovery of the crack closure phenomenon by Elber (1970) and his suggestion that only the "effective" portion of the stress cycle should be included in the Paris expression was a significant advance. The closure concept has since been used extensively to explain stress ratio and variable amplitude loading effects, and it has further been proposed as a possible factor in other apparently anomalous crack propagation behaviors.

Nevertheless, there remain a number of important problems in fatigue crack growth which have not been solved by traditional application of K-based parameters. These include the growth of short cracks, stress biaxiality effects, notch effects, and thickness effects. In addition, when stresses are high and plastic deformations become large, linear elastic fracture mechanics loses its strict validity. Analogous elastic-plastic parameters have been proposed and have met with some success, but several critical questions remain.

One purpose of the present article is to investigate the possible role of crack closure in explaining some of these unsolved problems. An elastic-plastic finite element analysis of fatigue crack closure was used to determine how crack opening levels change under various conditions. The numerical results were compared with trends in experimental crack growth data and were used to construct simple correlations of that data.

FINITE ELEMENT MODEL

A finite element model of fatigue crack closure has been presented and discussed previously (Lalor and Sehitoglu, 1988; McClung and Sehitoglu, 1988b, c), and the original references should be consulted for further details. The model permitted node release for crack extension on each load cycle. The changing boundary conditions associated with intermittent crack face contact were accommodated through a series of variable stiffness truss elements. The mesh was composed of four-noded isoparametric elements and represented a rectangular plate with symmetric cracks growing from a small center hole. Final crack lengths corresponded to $a/W = 0.124$. The material model employed linear kinematic hardening with a von Mises yield surface translating according to Ziegler's rule. Computations were performed on a CRAY X-MP/48.

RESULTS

Effect of Maximum Stress

The changes in normalized crack opening levels with increasing maximum stress are shown in Fig. 1 for two stress ratios. Here H and E are the plastic and elastic moduli and σ_o is the yield stress in the bilinear constitutive model. These results are for longer cracks and are independent of notch effects. Note that opening levels are a strong function of maximum stress for fully reversed (R=-1) load histories. This phenomenon has been verified previously by direct experimental measurement of opening levels (McClung and Sehitoglu, 1988a.

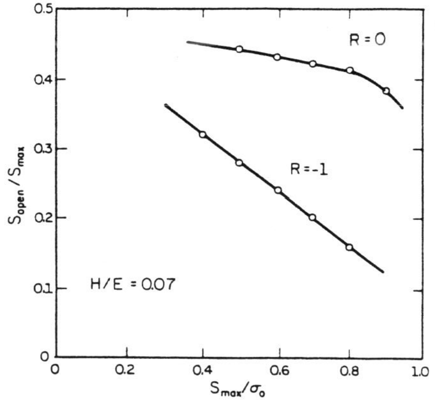

Fig. 1. Normalized crack opening stresses as a function of maximum stress for two stress ratios.

Two sets of previously published crack growth data for a hot rolled 1026 steel (McClung and Sehitoglu, 1988a; Sehitoglu, 1983) were available to determine if this phenomenon is significant for correlation purposes. One set was based on edge cracks of length 0.1 mm - 1.0 mm grown under constant amplitude strain cycling with $\Delta\varepsilon/2 = 0.001$ to 0.007 (S_{max}/σ_o from 0.6 to 1.2). Another set was obtained from center cracks of half-length 5 mm - 10 mm growing under constant amplitude load control with S_{max}/σ_o ranging from 0.30 to 0.51. The parameter σ_o was set equal to the 0.2% offset cyclic yield stress, which was 322 MPa. Because general yielding occurred in some tests, an elastic-plastic crack growth parameter was used to analyze the data. The range of the J-integral, ΔJ, was chosen here although other parameters would have given similar results. ΔJ was estimated according to formulas given by Dowling (1987). Note that when far-field plastic strains are small, ΔJ reduces to $(\Delta K)^2/E$.

The limited success of ΔJ in correlating the data without consideration of crack closure is shown in Fig. 2(a). Crack closure information was incorporated by replacing ΔS with ΔS_{eff} in the appropriate equation for ΔJ, where $\Delta S_{eff} = U\Delta S$ and $U = \left(1-(S_{open}/S_{max})\right)/(1-R)$. The opening levels were taken directly from the finite element analysis except at the very highest stresses, where numerical results were not available and guidance was provided by the experimental measurements. The correlation was much improved (Fig. 2(b)). Note that the data here ranged over a factor of 100 in crack length and a factor of 20 in strain amplitude.

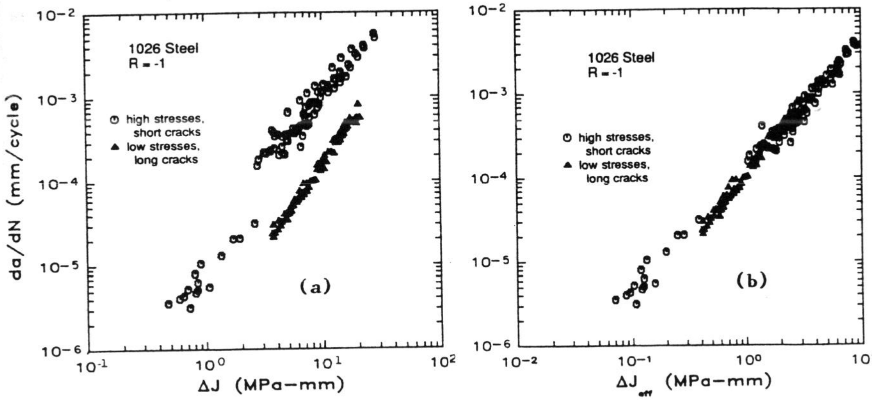

Fig. 2. Crack growth rates at a wide range of maximum stresses and crack lengths in a 1026 steel. **(a)** correlated with ΔJ, **(b)** correlated with ΔJ_{eff}

Effect of Notches

The accelerated growth of small cracks at notches has been noted previously (Sehitoglu, 1983, El Haddad et al., 1979). A finite element analysis of the closure behavior of these cracks is shown in Fig. 3. Normalized opening levels are shown in the bottom diagram (solid lines) in comparison to stress distributions (in the corresponding uncracked body) in the top diagram. Note that changes in the opening level are not restricted to the region of the original notch plastic zone. In general, opening levels are quite low for very short cracks and gradually increase with crack length until a stable level is reached.

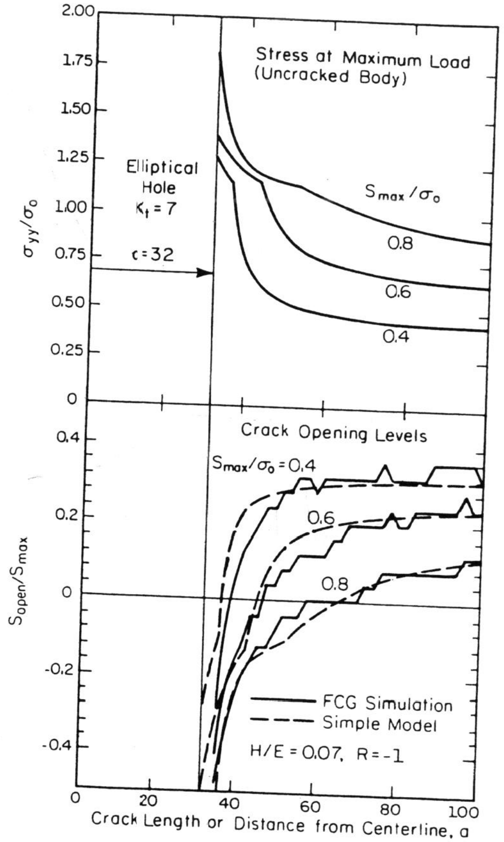

Fig. 3. Stress distributions at maximum load for an elliptically center notched, uncracked body (top), and changes in opening stresses for cracks growing from the notch, as determined by a complete finite element simulation and a simple model.

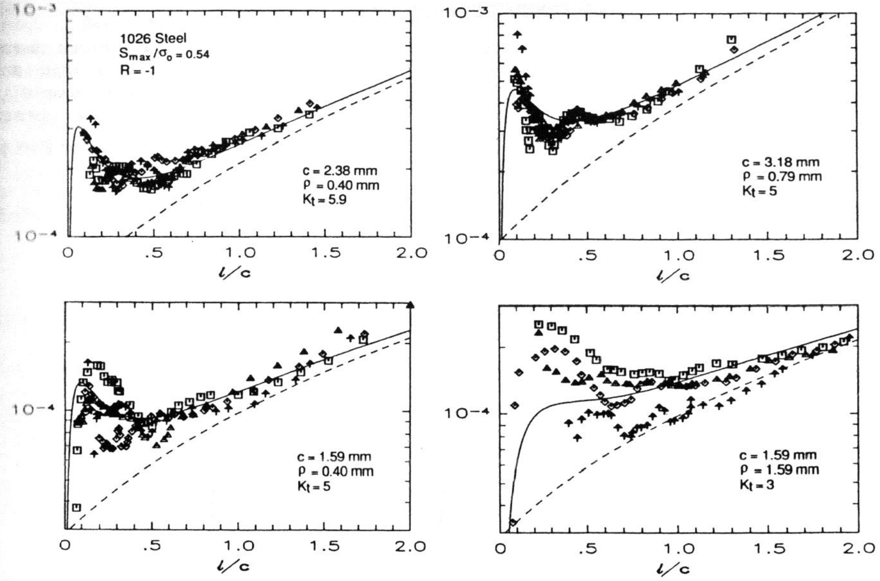

Fig. 4. Experimental data for cracks growing from center holes in a 1026 steel, compared with the predictions of a simple short crack model (solid line) and a long crack model (dashed line).

A simple model can be constructed to simulate this behavior. The maximum stress level at a given location along the crack line, but in the uncracked body (Fig. 3 (top)), can be equated to the same maximum stress in an unnotched body in order to find the corresponding crack opening level (Fig. 1). The result is the dashed line of Fig. 3 (bottom). This simple model is based on the assumption that the notch effect is due entirely to the impact of the stress gradient on closure behavior, and does not consider crack length or notch plastic zone contributions.

This information about crack closure is compared with experimental crack growth data in Fig. 4. The material was the same 1026 steel. Cracks were grown from center slot notches, where 2c was the total notch width and ρ was the root radius. The predicted crack growth curve was obtained by (a) estimating the stresses in a notched, uncracked body with the Neuber relationship; (b) estimating the opening levels from Fig. 1 according to the simple model described in the previous paragraph; (c) estimating ΔK from an empirical representation of Newman's results (1971); and (d) estimating da/dN from the Paris Law using ΔK_{eff}, where the Paris Law constants were determined from long crack data. The dashed line represents the predictions of a long crack model which included the notch only as a contributor to the total length of a center crack. Further details of this analysis and the other applications discussed in the present paper are available (McClung, 1988).

Effect of Biaxial Stress

The effect of biaxial stressing on fatigue crack closure is summarized in Fig. 5. The finite element model is essentially simulating a cruciform specimen with mode I cracks. The biaxiality is specified by λ, where $\lambda = S_x/S_y$ and the y-axis is normal to the crack. Note that crack opening levels are lowest (and therefore crack growth rates highest) for pure shear loading ($\lambda = -1$) and highest for equibiaxial loading ($\lambda = +1$).

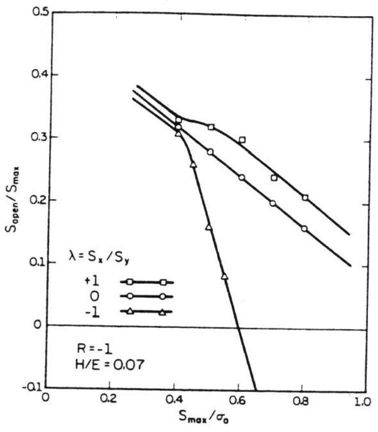

Fig. 5. Normalized crack opening stresses as a function of maximum stress for three different biaxiality ratios.

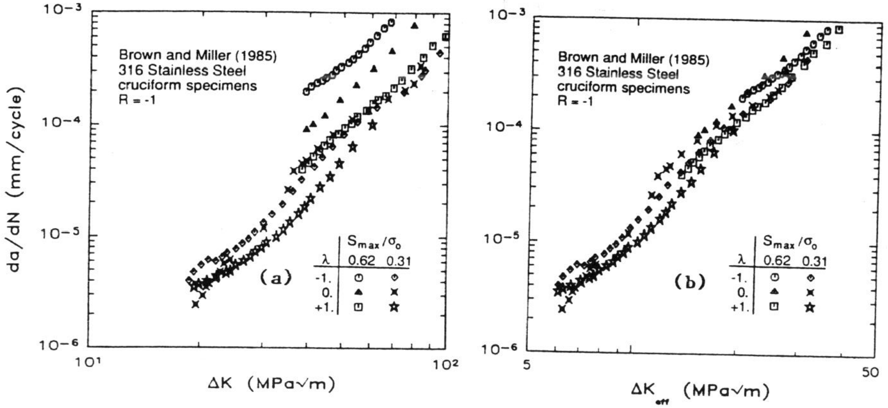

Fig. 6. Crack growth rates for different biaxiality ratios and maximum stress based on data of Brown and Miller for a 316 stainless steel. **(a)** correlated with ΔK , **(b)** correlated with ΔK_{eff}

These results are consistent with experimentally observed crack growth rates. Data of Brown and Miller (1985) for a 316 stainless steel are reproduced in Fig. 6. Correlation of the data with a simple ΔK (Fig. 6(a)) shows the differences in growth rates. These differences were accommodated in Fig. 6(b) by the parameter ΔK_{eff}, where $\Delta K_{eff} = U\Delta K$ and U is taken from the finite element analysis. These numerical results are also consistent with the data of Hoshide et al. (1981) and Smith and Pascoe (1985). The analysis further suggests that closure differences with changing biaxiality are negligible at lower maximum stresses, and this is supported by the experimental observations of Kitagawa et al. (1979) and Liu et al. (1979).

DISCUSSION

The purpose of this short paper is not to argue for the specific details of any comprehensive analytical scheme. A full treatment of any of the three problems discussed here would require consideration of many other variables. Analysis of the notch problem, for example, should properly include discussion of short crack effects, elastic-plastic crack growth parameters, stress redistribution, etc. The reader may object to the use of the J-integral for the analysis of crack growth during general yielding, and certainly other parameters could be explored. But this was not our purpose.

The primary purpose of this paper has been to demonstrate that crack closure can provide a first-order explanation for a variety of crack growth problems. Correlation of experimental data with simple closure-modified crack growth parameters may be entirely sufficient for many engineering purposes, even if other aspects of the problem are temporarily neglected.

Furthermore, crack closure can provide a unifying framework within which to consider many effects simultaneously. There are, of course, a number of other approaches which have been suggested for each of these three problems, and they have met with some success. There are particular parameters which have been proposed for biaxial effects, other parameters for notch effects, and so on. But crack closure provides a single parameter which can explain a variety of phenomena, including interaction between different effects. The biaxial data of Brown and Miller, for example, show a layering effect due both to differences in maximum stress and differences in biaxial stress.

CONCLUSIONS

1. A finite element analysis of fatigue crack closure predicts that crack opening levels will change with maximum stress, proximity to a notch, and biaxial stress.
2. These changes are consistent with experimental crack growth data.
3. Correlations of the experimental data based only on simple closure-modified crack growth parameters are sufficient for many engineering purposes.
4. Crack closure provides an attractive unifying framework within which to consider many different crack growth phenomena simultaneously.

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