The Use of Retardation Models in Crack Propagation Simulation

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The objective of this paper is to provide a review of retardation models for constant and variable amplitude spectrum loading in 2D constrained small scale yielding. The models considered use a numerical 2D finite element method to determine crack opening and closing stress intensity factors. The correlation of the predictions of the models with experimental data is examined. Procedures used to edit variable amplitude spectrum loading are also presented and the effects of this editing on fatigue life predictions for structural components are discussed.

INTRODUCTION

The most common technique for predicting the fatigue life of automotive and aircraft structures is Miner’s law [1]. Despite the known deviations, inaccuracies and proven conservatism of Miner's cumulative damage law, it is at present being used in the design of many advanced structures. Fracture mechanics techniques for fatigue life predictions remain as a back up in design procedures. Perhaps the most important and difficult problem in using fracture mechanics concepts in design is the use of crack growth data in predicting fatigue life. This experimentally obtained data is used to derive a relationship between stress intensity range ($\Delta K$) and crack growth per cycle ($da/dN$).

For components containing a flaw under constant stress amplitude fatigue the crack growth can be obtained by simply integrating the relation between $da/dN$ and $\Delta K$. However, for complex spectrum loadings, a simple addition of the crack growth occurring in each portion of the loading sequence produces results that very often are more in error than the results obtained using Miner’s law. In fact, a simple addition of the growth during each portion of a load sequence is the fracture mechanics equivalent of Miner’s law.

In 1960 Schijve [2] observed that experimentally derived crack growth equations were independent of the loading sequence and depended only on the stress intensity range and number of cycles for a given portion of loading sequence. The central problem in the successful utilization of fracture mechanics techniques as applied to spectrum fatigue is to obtain a clear understanding of the influence of loading sequences on fatigue crack growth. Of particular interest in the study of crack growth under variable-amplitude loading is the decrease in growth rate called crack growth retardation that usually follows a high overload.

Stouffler & Williams [3] and other researchers characterized the retardation phenomenon through manipulation of the constants and stress intensity factors in the equation of Paris-Erdogan [4]. Most of the reported theoretical descriptions of retardation are based on data fitting techniques, which tend to hide the behavior of the phenomenon. If the retarding effect of a peak overload on the crack growth is neglected, the prediction of the material lifetime is usually very conservative [5].

This paper will review some of these crack closure models. The small scale yield model employs the Dugdale [6] theory of crack tip plasticity, modified to leave a wedge of plastically stretched material on the fatigue crack surfaces. Fatigue crack growth was simulated by Skorupa and Skorupa [7] using the strip model over a distance corresponding to the fatigue crack growth increment as shown in Figure 1.
In order to satisfy the compatibility between the elastic plate and the plastically deformed strip material, tractions must be applied on the fictitious crack surfaces. Tractions are also needed over some distance in the crack wake ($a_{\text{open}} \leq x < a$), where the plastic elongations of the strip $L(x)$ exceed the fictitious crack opening displacements $V(x)$, in the plastic zone ($a \leq x < a_{\text{fict}}$), as in the original Dugdale model. The simple Paris crack propagation equation [4] with the crack propagation driving parameters, $C$, $\Delta K$ and $m$ are used.


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The Wheeler [10] and Willenborg et al. [11] models were the first models proposed to explain crack-growth retardation after overloads. These models assume that retardation exists as long as the current crack-tip plastic zone is enclosed within the overload plastic zone. The physical basis for these models, however, is weak because they do not account for crack-growth acceleration due to underloads either alone or immediately following an overload. Chang and Hudson [12] clearly demonstrated that both retardation and acceleration are must be included to have a reliable model.

Later models by Gallagher [13], Chang [14] and Johnson [15] included functions to account for both retardation and acceleration.

Figure 1 - Schematic Small Scale Yield Model [7]
A new generation of models that were based on the crack-closure concept were introduced by Bell and Wolfman [16], Schijve [17], de Koning [18], Baudin et al. [19] and Aliaga et al. [20]. Newman [21] presented the first finite element model based on the crack closure concept. The simplest model is the one proposed by Schijve [2], who assumed that the crack-opening stress remains constant during each flight in a flight-by-flight sequence. The other models developed empirical equations to account for retardation and acceleration, similar to the yield-zone models.

RETARDATION PHENOMENON

Corbly & Packman describe [22] some aspects of the retardation phenomenon. Despite the recent large increase in research into retardation effects in crack propagation there are many aspects of load interaction phenomena that lack adequate explanations. Aspects of the retardation phenomena that are generally agreed upon are presented below.

1. Retardation increases with an increase in the values of the peak load $\sigma_{\text{peak}}$ for given values of lower stress levels [23,24].
2. The number of cycles at the lower stress level required to return to the non-retarded crack growth rate is a function of $\Delta K_{\text{peak}}, \Delta K_{\text{lower}}, R_{\text{peak}}$, $R_{\text{lower}}$ and number of peak cycles [25].
3. If the ratio of the peak stress to lower stress intensity factors is greater than 1.5 complete arrest at the lower stress intensity range is observed. Tests were not continued long enough to see if the crack ever propagated again [25].
4. For a given ratio of peak stress intensity to secondary stress, intensity the number of cycles required to return to non-retarded growth rates decreases with an increased time at zero load before cycling at the lower level [25].
5. The percentage delay due to a given a percent overload increase with an increase in the baseline stress intensity factor [26].
6. Significant second order effects have been noticed in decreasing staircase sequences. In a decreasing three step sequence, the delay increases with an increase in the value of initial stress in the sequence [26].
7. For a three step decreasing sequence, the delay increases with an increased intermediate step stress (the initial step remains constant) [27].
8. Delay is decreased if compression is applied immediately after a tensile overload [28].
9. Underloads do not substantially influence crack growth rates at secondary stress levels if $R > 0$ for the lower stress [29].
10. Negative peak loads can cause an up to 50 per cent increase in fatigue crack propagation with $R = -1$ [28].
11. Low-high sequences do not affect in crack propagation at the higher load level [30].
12. Low-high sequences cause an initial acceleration of crack propagation at the higher stress level which rapidly stabilizes [31].

The major links between fatigue and fracture mechanics were pointed out by Christensen [32] and Elber [33]. The crack closure concept put crack propagation theories on a firm foundation and allowed the development of practical life prediction methods for constant and variable amplitude loading, such as that experienced by modern commercial aircraft.

Numerical analysis using finite elements has played a major role in the stress analysis of crack problems. Swedlow [34] was one of the first to use the finite element method to study the elastic-plastic stress field around a crack. The discovery of crack closure mechanisms, such as plasticity, roughness, oxide, corrosion, and fretting product debris, and the use of the effective stress intensity factor range, has provided an engineering tool to predict small and large crack growth rate behavior under service loading conditions.

Ricardo et al. [35] presented an example of small scale yielding under constant amplitude loading. A compact tension specimen was modeled using a commercial finite element code, ANSYS, version 6.0 [36]. Half of the specimen was modeled and symmetry conditions applied. Figure 4 shows the compact tension specimen from ASTM 647-E95a [37], and Figure 2 shows the model used in this work.

Figure 2 - FEM Model of the CT

Their analysis showed that it was possible to simulate crack propagation and obtain values such as opening and closure stress intensity factors by the finite element method. The correlation of their analysis with experimental results was good until a value of $a/W = 0.40$ was reached, after which point the experimental plastic zone increased more rapidly than the calculated plastic zone, and the trends diverged.
Skorupa [38] found that for simple load histories containing combinations of overload and underload cycles, an underload applied immediately after an overload reduced the post-overload retardation more significantly than an underload that immediately preceded the overload.

Suresh [39] provided an extensive review of small cracks. A small crack has little length behind its tip, so that the interference between the crack faces that constitutes closure is lessened. One effect of this reduced closure is that crack growth rates are increased, in the low-growth-rate, threshold region. However, a review of the extensive literature on this topic is beyond the scope of the present review.

Fatigue crack closure and growth behavior under random loading have been investigated by Youb and Song [40] using a side-grooved CCT specimen of 2024-T351 aluminum alloy. They discuss the effects of load spectrum and history length on crack closure and crack growth behavior in detail. Random loading tests were performed using narrow and wide band random load histories of various history lengths ranging from 500 cycles to 2000 cycles. The conclusions they came to are summarized as follows:

1. The crack opening load is nearly constant during a random loading block histories of lengths ranging from 500 cycles to 2000 cycles, and is predominantly a function of the largest load cycle in the random load history, irrespective of random load spectrum and history length.

2. The crack opening load under random loading is different from that under constant amplitude loading. This implies that the crack closure behavior under random loading cannot be estimated from constant amplitude tests.

3. Fatigue crack growth under random loading can be successfully described by the crack closure concept. Consistent effects of random load spectrum and history length on crack closure and growth behavior were not observed within the range of load levels examined in this study.

4. The maximum crack opening loads observed in single overload and periodic single overload tests agree well with the crack opening loads under random loading. This means that the crack closure behavior under random loading can be estimated from single overloading or periodic single overloading tests.

Many models [41-45] for predicting fatigue crack growth under random loading have been developed. Kikukawa et al. [46-49] made extensive measurements of crack opening loads under various random load histories.

They reported that the crack opening point is controlled by the maximum range-pair load cycle (which we call hereafter “the largest load cycle”) in a random load history. Furthermore, this crack opening level is identical with that for constant amplitude loading corresponding to the largest load cycle. Based on this crack opening behavior, they proposed a simple predictive procedure for crack growth under random loading.

Zheng [50] provided a criterion for omitting small loads. In the past, an underload (or subload) was defined as a nominal stress amplitude lower than or equal to the endurance limit, and the effect of underloads on fatigue life was investigated experimentally by using smooth specimens. Test results showed that underload cycles applied to smooth specimens increased the fatigue life or the endurance limit of low-carbon steel [51] and cast iron [52], which was called “coaxing”. However, past research on the underload effect was not associated with the omission of small load cycles in making life predictions [53-54].

The omission of small load cycles is necessary and important in the compilation of a load spectrum [55], in the prediction of the fatigue life and in the assessment of the fatigue reliability of structures [56-57], and is cost effective in fatigue tests of components and structures under long-term variable-amplitude or random loading histories.

SUMMARY

The paper provides a review of the retardation models that have been used for constant and variable amplitude loading. Small scale yield models used to determine crack closure levels are discussed and an example is given of the use of the finite element method to estimate crack closure levels. Editing to shorten variable amplitude load histories is also discussed a general procedure to generate, edition and utilization of the variable amplitude loadings in the automotive and aircraft structures.
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Definitions

\( \sigma_{\text{peak}} \) Peak Stress Level

\( \Delta K_{\text{peak}} \) Peak Stress Intensity Factor Range

\( \Delta K_{\text{lower}} \) Lower Stress Intensity Factor Range

\( R_{\text{peak}} \) Peak Load Ratio

\( R_{\text{lower}} \) Lower Load Ratio

\( \frac{da}{dN} \) Crack Propagation Rate

C Fatigue Crack Growth Coefficient

\( \Delta K \) Stress Intensity Factor Range

\( m \) Fatigue Crack Growth Exponent

\( K_{\min} \) Minimum Stress Intensity Factor

\( K_{\max} \) Maximum Stress Intensity Factor

\( K_c \) Critical Stress Intensity Factor

\( \Delta K_{\text{eff}} \) Effective Stress Intensity Factor Range

\( K_{op} \) Opening Stress Intensity Factor

\( S_{op} \) Opening Stress

\( \Delta K_{th} \) Threshold Stress Intensity Factor

\( K \) Stress Intensity Factor

\( B \) Specimen Thickness

\( W \) Width of Specimen

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