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CRACK GROWTH PREDICTION USING AN ANALYTICAL CRACK CLOSURE MODEL FOR A SEMI-ELLIPTIC SURFACE FLAW LOADED IN COMBINED TENSION AND OUT OF PLANE BENDING

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Abstract

The plasticity induced analytical crack closure model provides a scientifically based approach to predicting fatigue crack growth behaviour under spectrum loading. Stress ratio and load interaction effects are known to occur, and the crack closure concept has been demonstrated to account for these and therefore works well for through cracks in thin sheet materials. This paper details the application of the analytical crack closure model approach to predict the crack growth for a semi-elliptic surface flaw in a non-uniform stress field. This is a problem which hitherto has been analysed using standard LEFM and empirical load interaction models such as Wheeler and Willenborg. The analytical crack closure model has been found to perform better than the empirical models for the simpler through thickness flaw case in a uniform stress field and since it has a more sound theoretical base it was considered that it should also perform better for a more complex case. Basic material data (da/dN versus Δ K) from standard compact tension and centre crack specimen tests was utilised. Data points were treated individually in terms of the constraint conditions which apply, thus enabling an accurate determination of the unique da/dN versus ΔK_{eff} relationship. The resulting prediction compares well with test results.

Introduction

Accurate prediction of fatigue crack growth is an essential element in the structural integrity management strategy for aircraft such as the Royal Australian Air Force (RAAF) F-111. The development of Linear Elastic Fracture Mechanics (LEFM) techniques has enabled predictions to be performed for various cracking scenarios in numerous locations throughout the structure under a variety of possible loading conditions. Advances in computer technology are such that the analyses can now be rapidly performed on a desk top PC or work station.

In the case of the F-111 aircraft, structural integrity management is assured under the basis of a program known as the Durability and Damage Tolerance Assessment (DADTA)[1]. An integral part of the DADTA is to perform a crack growth analysis prediction for various significant structural locations which are potentially susceptible to fatigue cracking. The analysis is typically performed using LEFM techniques. The standard procedure involves the use of equations such as the Forman[2] and Walker[3] equations to account for stress ratio effects on crack growth rate data, and the use of an empirical retardation model such as Wheeler[4] or Willenborg[5] to account for load interaction effects.

An implicit assumption in the process is that it is possible to calibrate the result for a particular loading case by fine tuning the retardation models, and then using the tuned model to accurately predict the behaviour under a different spectrum. This assumption is demonstrated to be not necessarily valid. An alternative approach using an analytical crack closure model is demonstrated to give superior results. The model is applied to a through crack case, and also one involving a surface flaw under combined tension and out of plane bending.

Description of Analytical Crack Closure Model

The analytical crack closure model used in the current work is based on the work of Newman[6]. The technique has been incorporated in a computer program called FASTRAN[7]. The model is based on the Dugdale model[8], but modified to leave plastically deformed material in the wake of the advancing crack tip. The region around the crack is broken up into elements which are assumed to behave in an elastic/perfectly plastic manner. Elements along the crack face can carry compressive loads only, and then only when in contact. Some elements ahead of the crack tip are in a plastic state. The effects of stress state are taken into account by the use of a constraint factor (α) which is used to elevate the plastic flow stress for the intact elements in the plastic zone. In this way, the crack opening stress can be calculated, and therefore the effects of stress ratio (R) and load interaction effects can be estimated for fatigue crack propagation.

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The model is applied in a two step process. The first step is to convert the baseline crack growth data (da/dN vs ΔK) to da/dN vs $\Delta K_{effective}$. The second step is to apply the model, with the baseline da/dN vs $\Delta K_{effective}$ data, to the configuration and loading case of interest.

Centre Through Crack Case

The FASTRAN analytical crack closure model approach has been applied to the case of centre cracked 7075-T651 aluminium alloy plate specimens subjected to variable amplitude loading under uniaxial tension[9]. Test data was available from specimens which had been pre cracked and subjected to a simplified variable amplitude fighter aircraft load spectrum. The peak load in the baseline spectrum (equal to a cg acceleration of N_z = 7.5 g) was approximately 28% of the yield stress of the material. The spectrum was altered to simulate placard flight restrictions which may be imposed to conserve the fatigue life of an aircraft. The restrictions (at 6.5 g and 5 g) and an artificial peak load increase (to 8.5 g) resulted in significant changes to the crack growth life which would not be predicted by a model which does not account for load interaction effects.

The experimental results which are plotted in Figure 1 below clearly demonstrate load interaction (retardation) effects.

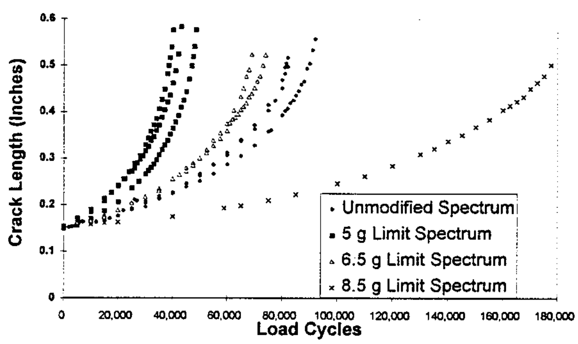

FIGURE 1 - Experimental Crack Growth Results for Four Spectrum Variations[10]

This case was modelled under standard LEFM techniques using several different software packages including CRACKS84[11], FractuREsearch[12], and AFGROW[13]. Several retardation models were used including Willenborg, Wheeler and Broek. The results[2] were poor. The Broek retardation model produced the best results, but the shape of the crack growth curve exhibited some irregularities. The Wheeler model was the next best, and the Willenborg model was the worst. Not only were the results poor in an absolute sense, there was also a lack of consistency between different software packages for nominally the same input for a given retardation model. A comparison of the results obtained for the Willenborg retardation model are summarised in Figure 2 below:

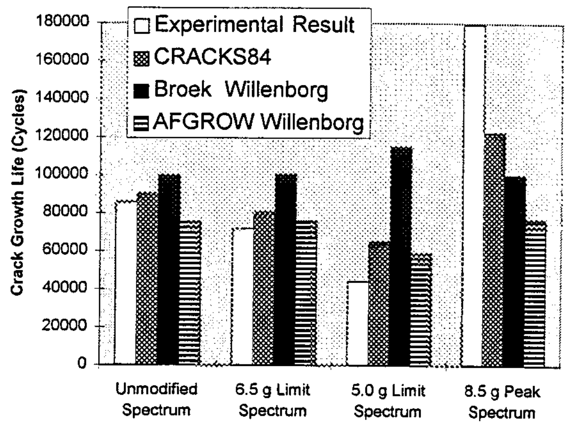

FIGURE 2 - Comparison of Experimental and Predicted Crack Growth Lives (cycles) Using the Willenborg Retardation Model

The case was also modelled using the analytical crack closure model, FASTRAN. The results obtained were significantly better than those obtained with the standard LEFM models. The FASTRAN predictions for the four different spectra are shown in Figure 3 to 6 below.

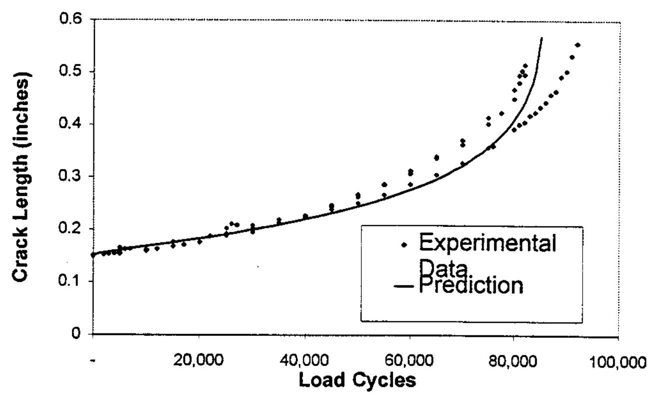

FIGURE 3 - Unmodified Spectrum, Experimental Data and FASTRAN Prediction

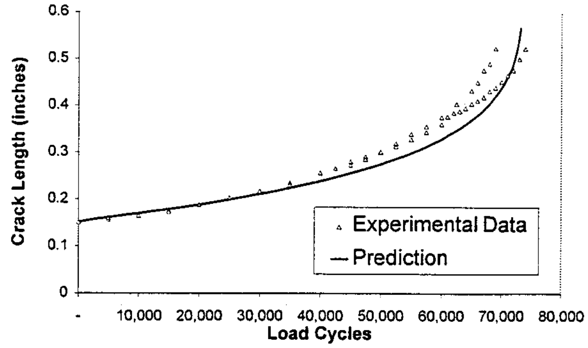

FIGURE 4 - 6.5 g Limit Spectrum, Experimental Data and FASTRAN Prediction

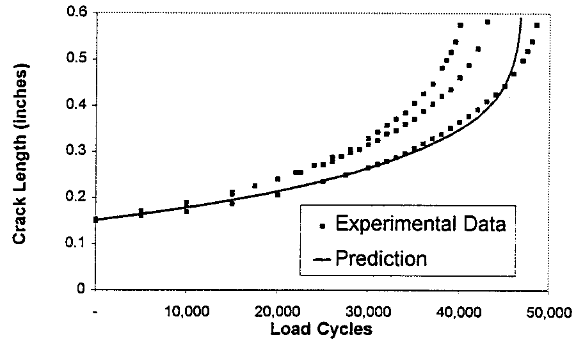

FIGURE 5 - 5 g Limit Spectrum, Experimental Data and FASTRAN Prediction

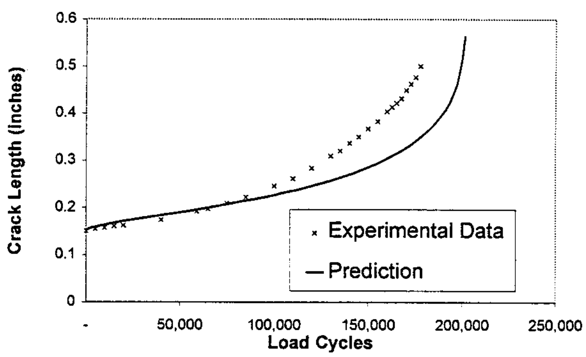

FIGURE 6 - 8.5 g Peak Spectrum, Experimental Data and FASTRAN Prediction

It needs to be highlighted here that in the case of the standard LEFM runs (ie. CRACKS84, FractuREsearch and AFGROW) every effort was made to input the same data to each program. Different results were obtained. The reason for these differences requires further investigation.

Surface Flaw Under Combined Tension and Out of Plane Bending Case

The previous example was for a centre through crack. A similar exercise was performed for a surface flaw. The example chosen related to a particular location on the F-111 Wing Pivot Fitting designated as DADTA Item 86 (see Figure 7 below). DADTA Item 86 is a surface flaw initiating on the inside (upper) surface of the lower plate adjacent to centre spar fuel flow hole number 58. The crack grows into a stress field which varies linearly with depth from the surface, ie combined tension and out of plane bending. This is a cracking scenario which the software packages can readily accommodate.

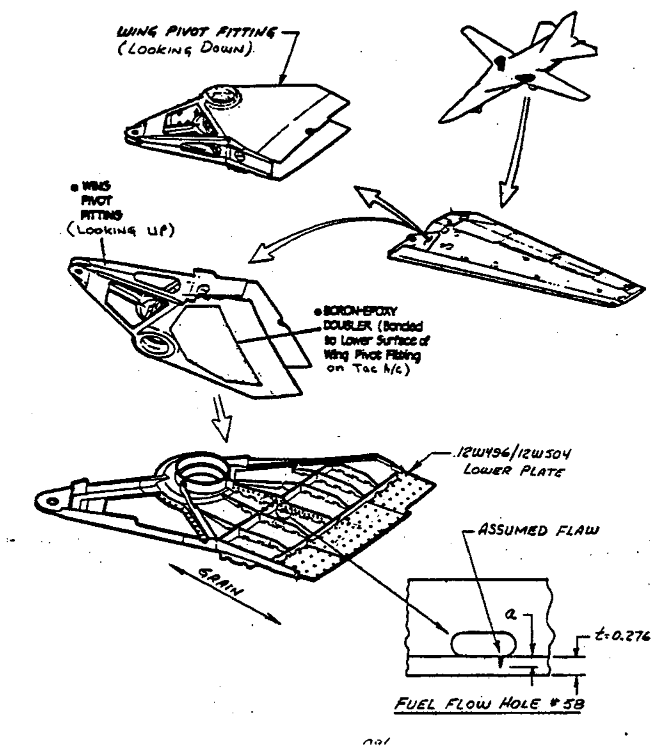

FIGURE 7 - DADTA Item 86

DI 86 arose because it was the location at which the A-4 right hand fatigue test wing failed due to a fatigue crack[14, 15]. The A-4 right hand wing fatigue test was conducted to provide the fatigue substantiation for the F-111A aircraft. The test was performed in 1969/70 using a spectrum considered to be representative of F-111A anticipated usage. Reference 15 details the crack growth curve and the fracture mechanics analysis which was performed at the time by the manufacturer, General Dynamics (GD), and calibrated to the test result. The result is shown in Figure 8 below.

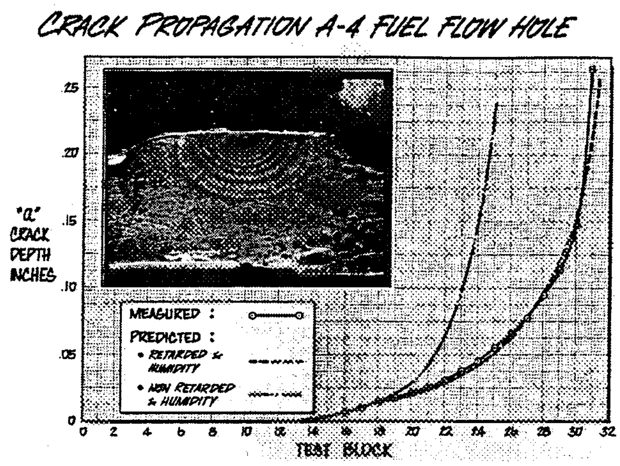

FIGURE 8 - Observed and Predicted Crack Growth , A-4 Wing Fatigue Test (From Reference 15)

This case was also modelled using the FractuREsearch and AFGROW programs. All input data was made as close as possible to the GD prediction as shown in Figure 8, including a Wheeler retardation model with a calibration factor of 1.4 (m=1.4). The rationale was to reproduce the GD result using the conventional LEFM techniques. The problem was also analysed using the analytical crack closure model approach with FASTRAN.

Input Data for FractuREsearch and AFGROW Predictions

The input data for the FractuREsearch and AFGROW predictions are fully detailed in Reference 16. They are summarised below.

Stress History

The full stress history details were known and are detailed in Reference 15.

Flaw Model

For both AFGROW and FractuREsearch it was possible to select a surface flaw propagating into a linear stress distribution, ie combined tension and out of plane bending.

Crack Growth Rate

The material is high strength D6ac steel, and as per the GD analysis, a Paris Law was used to describe the crack growth rate as follows:

$$\frac{da}{dN} = 0.0035 * 10^{-6} (\Delta K)^{2.6}$$

where $\frac{da}{dN}$ = crack growth rate, inches per cycle

ΔK = stress intensity range, ksi$\sqrt{\text{inch}}$

Input Data for FASTRAN Predictions

The input data is fully detailed in Reference 16. The important points are summarised below.

Stress History

The same stress history as per the other models was used.

Flaw Model

FASTRAN also allows the user to select a surface flaw propagating into a linear stress distribution.

Crack Growth Rate

A crack growth rate versus ΔK effective curve was established based on data for a humid air environment[17]. An important parameter to be considered in this is the constraint factor, α, which is discussed in some detail in Reference 7. For ideal full plane strain conditions, α = 3.0, and for full plane stress α = 1.0. Newman (Reference 7) recommends a procedure whereby a higher α is assumed for low crack growth rates where ΔK is low and there is higher constraint. A lower α is used at higher crack growth rates in the constraint loss regime where ΔK is high. It is important to obtain a good collapsing of the da/dN vs ΔK data and desirable to use the same specimen thickness for the da/dN vs ΔK data as the thickness of material in the case being investigated. The same α assumption is therefore used for both the reduction of the raw da/dN vs ΔK data and for the FASTRAN prediction.

In this case there is considerable scatter in the raw da/dN data and the specimen type and thickness is not known. Also, the prediction being attempted is for a surface flaw where conditions closer to plane strain rather than plane stress could be reasonably assumed. It was therefore decided to use an α of 3.0 for both the data reduction (using DKEFFNEW, Reference 7) and the AFGROW prediction. This collapses the data at least as well as any other α assumption, and FASTRAN II produces a reasonable crack growth prediction.

The basic da/dN vs ΔK data is shown in Figure 9 below, along with the mean curves as per Reference 17. Inputting the raw data with α = 3.0 to DKEFFNEW produced the result shown in Figure 10, and performing the same procedure for the mean curve data produced the results shown in Figure 11. The mean curve result for R=0.5 as shown in Figures 10 and 11 was considered to be a reasonable estimate for the collapsed data and this was used for the predictions.

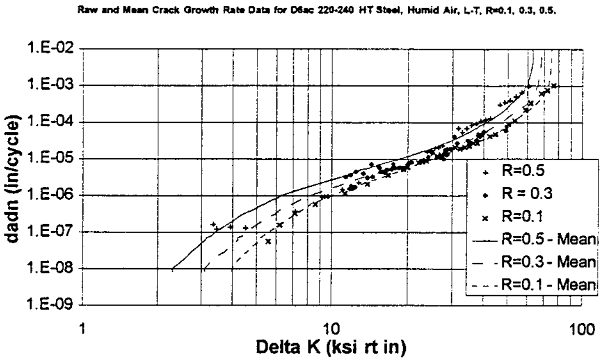

FIGURE 9 - da/dN vs ΔK Data for D6ac steel in Humid Air Environment

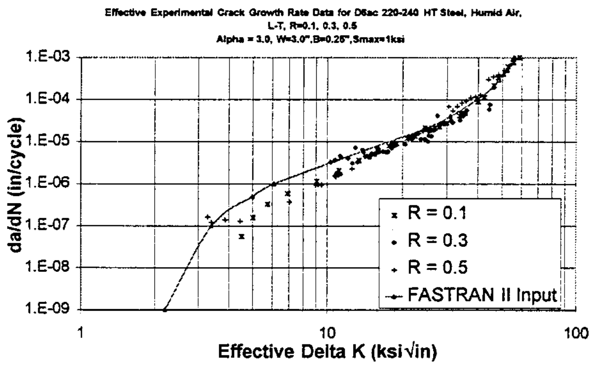

FIGURE 10 - da/dN vs ΔK Effective Data for α = 3.0, based on raw data

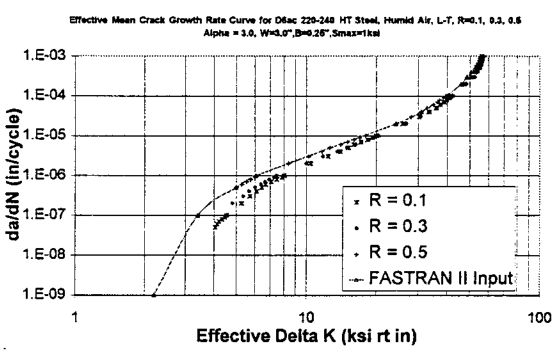

FIGURE 11 - da/dN vs ΔK Effective Data for α = 3.0, based on Mean Curves

Results

The results are shown in Figure 12 below.

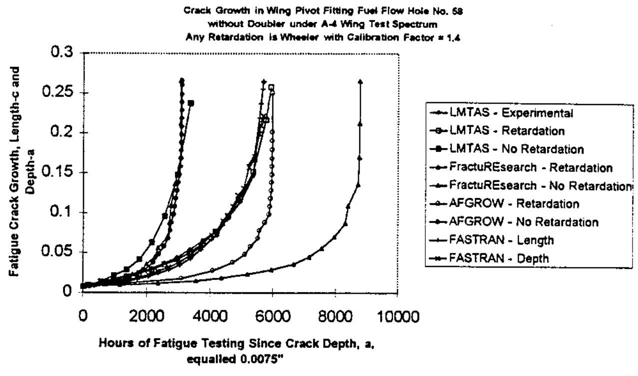

FIGURE 12 - A-4 Wing Test Experimental and Analytical Crack Growth Curves.

Figure 12 shows that although the original analysis performed by LMTAS/GD modelled the test result well, the more recent analyses using AFGROW and FractuREsearch did not produce good results. The AFGROW prediction is reasonable in terms of life, but the shape of the curve does not match the experiment. The FractuREsearch prediction is inaccurate in both life and the shape of the curve. The FASTRAN analysis produced a prediction which is consistent with the experimentally observed behaviour.

Discussion

Conventional LEFM techniques including models to account for stress ratio effects[2,3] and load interaction effects[4,5] are being applied by aircraft manufacturers to estimate fatigue crack growth in aircraft structures. These results are then used to set inspection intervals and retirement lives to assure structural integrity is maintained throughout the service life of the aircraft. The work presented in this paper indicates that although these techniques are also featured in software which is available either commercially[12] or to a specific group (such as the Defence Community)[13] , it is difficult to obtain consistent results. This has been demonstrated for both a simple through crack example, and a more complex case involving a surface flaw under combined tension and out of plane bending. The analytical crack closure model has been demonstrated to produce superior results, and is more robust in terms of prediction the behaviour when minor but significant spectrum changes are introduced.

The conventional LEFM approaches need to be fully understood because in many cases the current inspection intervals and retirement times are based on LEFM analyses. In the case of the F-111, although it is known that standard LEFM techniques were used by the manufacturer, the software used is proprietary. It is therefore important to be able to re-produce the results using the same techniques, if not the same software. It appears, however, that there are significant differences in the software packages which need to be understood. Some possible explanations are as follows:

a. Yield Zone Modelling. An important factor for any retardation model is the size and nature of the plastic yield zone ahead of the crack tip. There are many possible equations to estimate it (Irwin, Dugdale etc.), and the state of stress (plane strain, plane stress or somewhere in between) is also important. The influence of this factor is currently being explored.

b. Negative Loads. The Walker and Forman crack growth rate equations apply for positive stress ratio cycles only. The load spectra, however, have significant compressive cycles in them. The way in which the software handles these negative R cycles can have a significant impact. This aspect is currently being investigated.

c. Programming Details. Some programs deal with the loading on a cycle by cycle basis, and in other cases the crack growth rates are only revised at certain increments of crack growth. These types of details can also have a significant impact.

In the case of the analytical crack closure code FASTRAN, encouraging results have been obtained. Once the crack growth for a known case has been estimated accurately, the program gives good results for a range of different spectra variations.

Conclusion

A significant amount of caution must be exercised when carrying out LEFM analyses to predict fatigue crack propagation under spectrum loading. The work presented in this paper demonstrates that despite the fact that a user may attempt to provide consistent input data, the software packages can produce varying results. The analytical crack closure model appears to give the best results.

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