MODELLING OF FATIGUE CRACK GROWTH IN 7075-T651 ALUMINIUM ALLOY PLATE

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Accurate modelling of variable amplitude fatigue crack growth requires, among other things, judicious estimates of crack opening stresses. A test programme was done with a simplified landing gear spectrum to check assumptions in the NLR crack growth model CORPUS. Crack opening stress intensity factors estimated by CORPUS were compared with clip gauge and fractographic estimates. Furthermore, crack growth predictions were compared with the experimental results. These predictions were made using both CORPUS and a characteristic-K approach.

INTRODUCTION

The NLR cycle-by-cycle crack growth model CORPUS is based on an approximate description of crack opening behaviour that is sufficiently realistic to account for the magnitudes and sequence of peak loads, the growth of fatigue cracks through peak load plastic zones, and the influence of underloads. A full description of the model has been published by de Koning (1).

The basic features of CORPUS will be explained using Figure 1. Consider the load sequence in Figure 1a. The peak load excursion results in plastic deformation which during subsequent fatigue crack growth becomes visible as ridges on the fracture surfaces. The height and width of the ridges depend on the magnitude of the peak load and the associated plastic zone size. The ridges cause a local increase in crack opening stress. A subsequent underload flattens the ridges over a distance corresponding to the reversed plastic zone size and therefore decreases the crack opening stress, though not to the extent it was increased by the peak load.

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This peak load - underload effect on crack opening stress is approximated in CORPUS by changing the crack opening stress immediately after a peak load or underload, as will be illustrated in Figures 1b-1j.

In Figure 1b a load sequence schematically depicting crack growth only during upward load excursions is given. The first load excursion to Smax1 and Smin1, Figure 1c, will eventually result in flattened ridges on the fracture surface. However, CORPUS assumes that the effect of the ridges on crack opening stress occurs immediately during the next load excursion. The opening stress Sop1 for this second load excursion is obtained from analytical or empirical relations between Smax, Smin and Sop as illustrated in Figure 1d.

During the second load excursion crack growth commences at Sop1 and stops at Smax2, Figure 1e. The ridges to be formed by Smax2 (and flattened by Smin2) will be smaller than the ridges formed by Smax1 and will therefore have a lower opening stress Sop2 as shown in Figure 1f.

The modelling of load interaction effects is illustrated by the next load excursion. Here the third upward load excursion to Smax3 is assumed to be effective for crack growth only above the larger of Sop1 and Sop2, Figure 1g. In terms of fracture surface ridges this is equivalent to the assumption that the crack is effectively open at all locations behind the crack tip, i.e. the ridges that are the last to lose contact determine the opening stress at which crack growth commences.

Unloading from Smax3 results in a minimum stress Smin3 below the previous ones, Figure 1h. This means that not only the ridges due to Smax3 will be flattened, but also the ridges due to Smax1 and Smax2 will be flattened further. Thus both Sop1 and Sop2 will be reduced, as shown in Figure 1h. Consequently, during the next upward load excursion to Smax4, Figure 1i, crack growth commences at the lowered value of Sop1.

The load excursion to Smax4 and Smin4 illustrates another feature of CORPUS. This load excursion results in an opening stress Sop4 higher than all previous ones, the effects of which are then lost. Sop4 becomes the opening stress governing further crack growth, as shown in Figure 1j.

Finally, the CORPUS model assumes that the effect of each peak load and its associated opening stress are also lost once the fatigue crack and its current plastic zone have grown through the plastic zone caused by the peak load.

The use of CORPUS has resulted in generally good to very good predictions of fatigue crack growth under variable amplitude loading, for example references (1, 2). However, it is still considered necessary to check and refine the assumptions in the model.

The present paper describes a preliminary check on CORPUS estimates of crack opening stresses for a simplified landing gear load history. In addition the CORPUS predictions of fatigue crack growth are compared with test data and predictions using a characteristic-K approach.

TEST PROGRAMME

An overview of the test programme is given in table 1. The flight-by-flight block programme loading is shown in Figure 2. This is a simplified version of the landing gear load histories developed in references (3, 4).

TABLE 1 - Test Programme Overview.

● MATERIAL	16 mm thick 7075-T651 aluminium alloy plate	
● SPECIMENS	110 mm wide centre cracked tension (CCT) panels	
● FATIGUE LOADINGS	1. Constant amplitude, R = 0.1 2. Flight-by-flight blocks	cycle frequency 15Hz
● ENVIRONMENT	Laboratory air at 295 K	
● SPECIAL CONSIDERATIONS	1. Clip gauge measurements of crack opening 2. Fractographic measurements of fatigue striation spacings per flight block	

Crack growth was measured using travelling microscopes at both sides of the specimens. During testing numerous measurements of crack opening were made using a clip gauge mounted in a central hole at the specimen centre of thickness. Crack opening stress intensity factors were determined from graphical treatment of load/offset displacement data in the following way:

(1) For each load excursion a least squares straight line was fitted to a minimum of 7 data points from the upper parts of the load-displacement plots. This straight line then became the y-axis on an x-y diagram.

(2) Measurements of deviations of the lower parts of the load-displacement plots from the least squares straight line were plotted on the x-y diagram. A smooth curve was drawn through these points to intersect the y-axis.

(3) The intersection at the y-axis was taken to be the point at which the crack was fully open. The crack opening stress intensity factor was calculated using the appropriate stress and crack length in the Feddersen secant formula for centre cracked tension panels (5).

RESULTS

Constant Amplitude Fatigue Crack Growth

The constant amplitude fatigue crack growth data are shown in Figure 3. The log da/dn versus log ΔK data can be approximated bilinearly with the intersection point corresponding to a change in Kop/Kmax. Such changes have been observed by others, for example references (6, 7). The average Kop/Kmax lines have been used to derive the log da/dn versus log ΔKeff plot in Figure 3.

Determination of Kop for Block Programme Loading

Three methods of estimating Kop for flight-by-flight block programme loading were used. Firstly CORPUS with the following approximation to Newman's plane strain relation (8) between Sop/Smax and R for $0 \leqq R \leqq 1$:

$$\mathrm{Sop} = \mathrm{Smax}[0.25 + 0.06R + 1.13R^2 - 0.44R^3][1-0.25(1-R)^3(\mathrm{Smax}/\mathrm{Sy})^3] \quad (1)$$

where Sy is the yield limit (550 MPa for 7075-T651). Secondly, clip gauge measurements of load/displacement, as mentioned in the previous section. And thirdly the fractographic measurement of fatigue striation spacings, to be discussed next.

The fractographic measurement of fatigue striation spacings may be used to estimate Kop as follows. Consider a load excursion i. The crack growth increment for this load excursion is given by

$$\Delta ai = C(\Delta Ki)^m \quad (2)$$

where

$$\left.\begin{aligned}(\Delta Ki)^m &= (Kmaxi-Kopi)^m - (Kmini-Kopi)^m \quad \text{for } Kopi < Kmini\\ &= (Kmaxi-Kopi)^m \quad \text{for } Kopi \geqq Kmini\end{aligned}\right\} \quad (3)$$

and m is the slope of the constant amplitude log da/dn versus log ΔKeff plot.

Equations (3) were derived by de Koning (9) and are compatible with the successful method of cycle counting known as "rainflow" or "range-pair-range" (10). These equations may now be used in two ways:

(1) Assume Kop to be constant during the flight-by-flight block programme loading. Choose several hypothetical Kop levels and calculate the relative spacings of fatigue striations in a flight block. Compare calculated and actual relative striation spacings and flight block lengths to obtain a best fit and hence an estimate of Kop.

(2) Assume a value of Kop for one or more load excursions and derive other Kop values from the actual relative spacings of fatigue striations in a flight block.

The result of the first method is illustrated in Figure 4. Calculated and actual relative striation spacings did not match well for load excursions 2-4 (flight segment B in Figure 2). Comparison of calculated and actual relative flight block lengths indicated an average Kop of about 18 % of the maximum stress intensity factor in the spectrum. (This maximum stress intensity factor corresponds to 100 % stress or load in Figure 2.)

For the second method a Kop of 20 % of the maximum stress intensity factor was assumed for load excursions 6-9. This assumption was based on CORPUS results. The other Kop levels were derived using equations (3) and the actual relative striation spacings.

Figure 5 shows the complete set of Kop determinations using CORPUS, clip gauge measurements and fractography. The clip gauge measurements are averages from rather variable data obtained at five different crack lengths and are considered unreliable for estimating the contributions of individual load excursions to crack growth. However, the average Kop per flight block was 18.3 % of the maximum stress intensity factor in the spectrum, and this agrees very well with the fractographic estimation.

Block Programme and Constant Amplitude Data Correlation by a Characteristic-K Approach

Root mean (rm) ΔK values were used to correlate the block programme and constant amplitude fatigue crack growth data. The general expression for ΔKrm is

$$\Delta Krm = \sqrt[m]{\frac{\Sigma(\Delta Ki)^{m} ni}{\Sigma ni}} \qquad (4)$$

where ni is the number of load excursions corresponding to ΔKi; m is the slope of the constant amplitude log da/dn versus log ΔKeff plot; and ΔKi is derived from equations (3) and estimates of Kopi. Note that for constant amplitude loading ΔKrm = ΔKeff. Also note that when m = 2 one obtains the root mean square value ΔKrms. This has been used for correlating random load and constant amplitude fatigue crack growth data (11, 12) albeit without accounting for crack closure.

The correlations are shown in Figure 6: for clarity only the bilinear approximation of the constant amplitude log da/dn versus log ΔKeff data is given. The CORPUS and fractographic estimates of Kop values for block programme loading gave virtually identical ΔKrm values and resulted in a good correlation of the block programme and constant amplitude fatigue crack growth data.

Use of a constant average Kop per flight block, based on clip gauge measurements and fractography, gave slightly higher ΔKrm values and a less good correlation of the data.

Predictions of Block Programme Fatigue Crack Growth

Predictions of fatigue crack growth under flight-by-flight block programme loading were made in two ways:

(1) Using CORPUS with the constant amplitude da/dn versus ΔK data as input. (ΔKeff is calculated by CORPUS using Newman's plane strain relation between Sop/Smax and R, as mentioned previously.)

(2) By numerical integration of the bilinear approximation of the constant amplitude log da/dn versus log ΔKeff data and using appropriate ΔKrm values.

Comparisons of the predictions and test data are shown in Figure 7. Very good predictions were obtained using ΔKrm based on CORPUS and fractographic estimates of Kop for each load excursion. CORPUS itself also gave very good predictions. The use of ΔKrm based on a constant average Kop per flight block gave more conservative, though still reasonable, predictions.

CONCLUDING DISCUSSION

The present results support the CORPUS approach to estimating crack opening stresses for each load excursion, and also the general applicability of Newman's plane strain relation between Sop/Smax and R. However, this relation does not account for the trend of increasing crack closure at lower ΔK values, e.g. Figure 3 and references (6, 7). This trend warrants further investigation and possible modification of the relation between Sop/Smax and R in order to obtain accurate predictions of fatigue crack growth in the low ΔK regime.

The characteristic-K approach to prediction of fatigue crack growth gave very good results when ΔKrm was based on CORPUS and fractographic estimates of Kop for each load excursion. The results were still reasonable when a constant average Kop per flight block was assumed. This is encouraging for efficient estimation of fatigue crack growth lives for load histories containing peak loads with short recurrence periods that result in a regular, quasi-stationary crack growth process. A similar conclusion was obtained for a previous investigation on ultrahigh strength landing gear steels (13).

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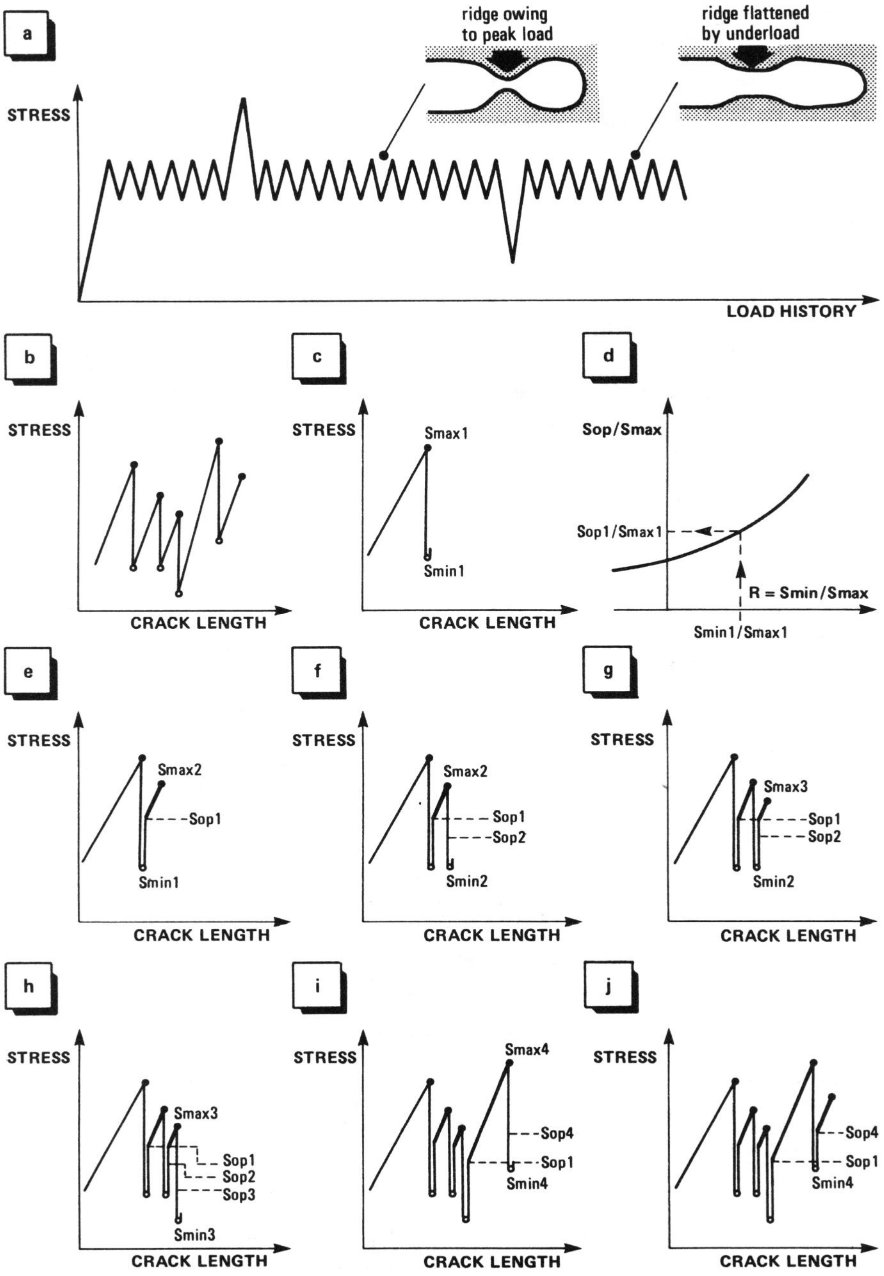

Figure 1 Crack opening behaviour modelled in CORPUS

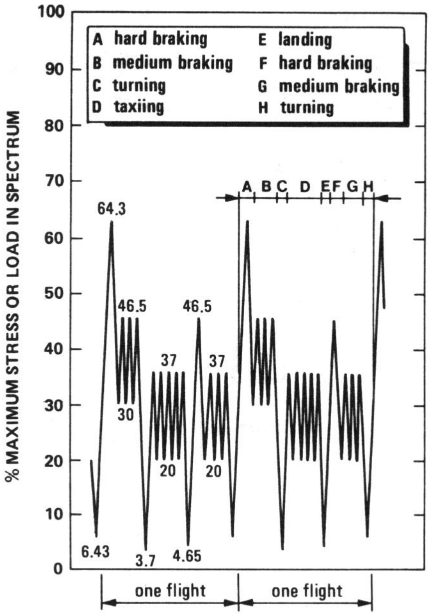

Figure 2 Block programme landing gear loading

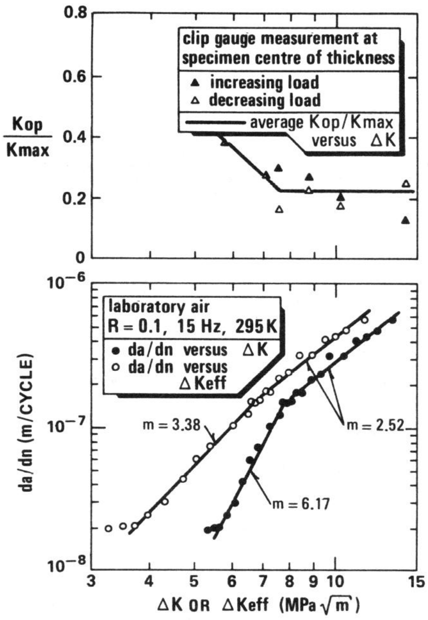

Figure 3 Constant amplitude crack growth data

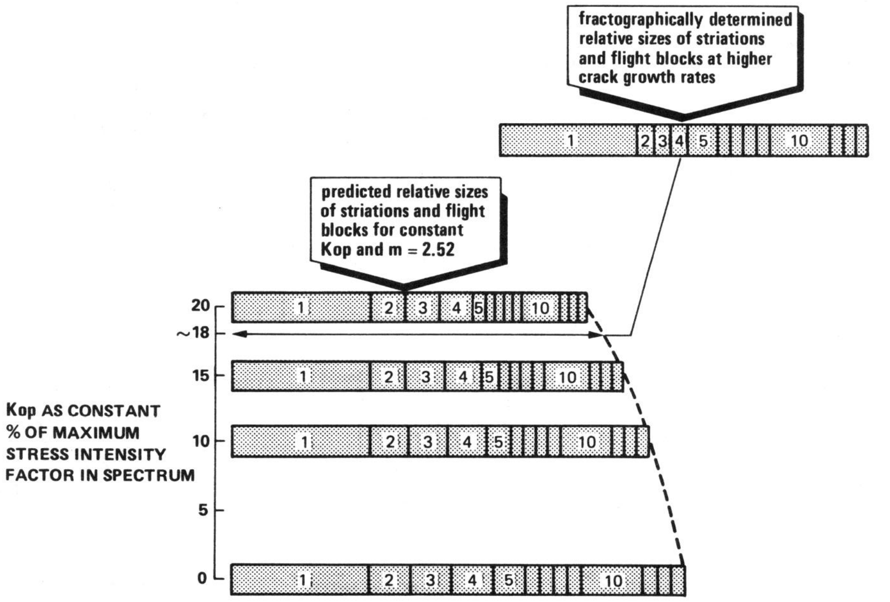

Figure 4 Predicted and actual sizes of striations and flight blocks normalized to the largest load excursion

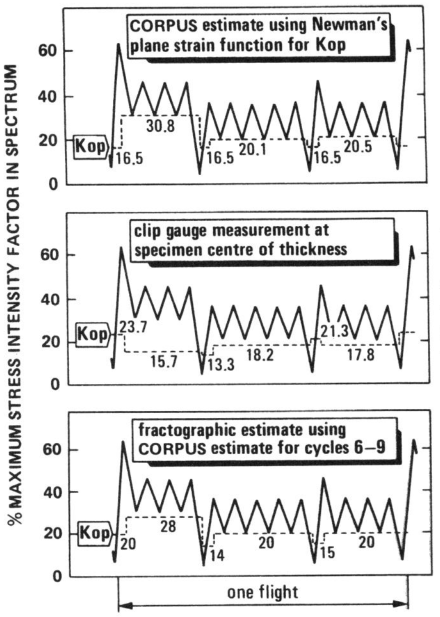

Figure 5 Variation of Kop during a flight block

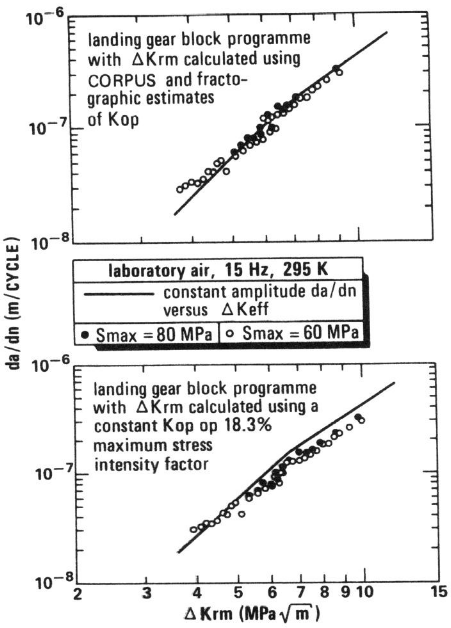

Figure 6 Correlation of crack growth data by ΔKrm

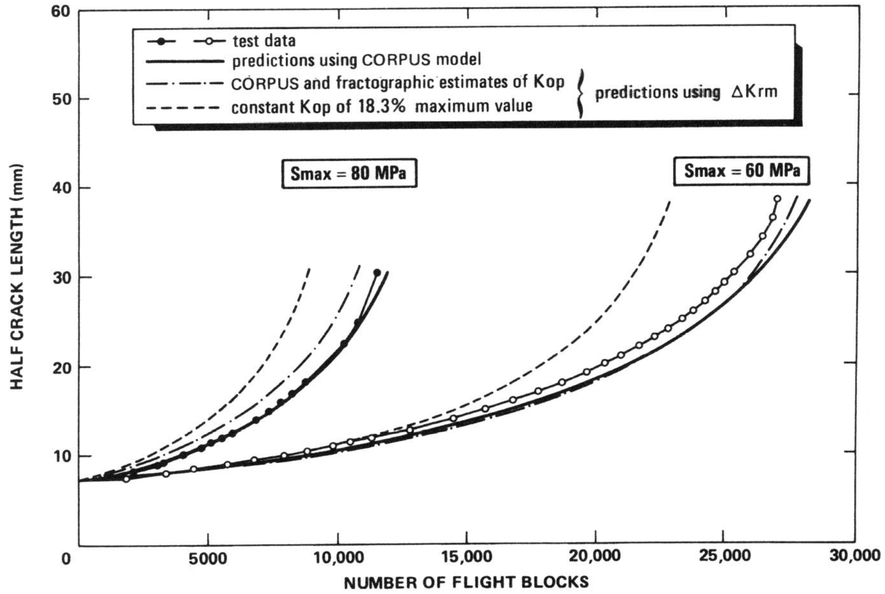

Figure 7 Comparisons of test data and predictions of crack growth