AR-010-319

Comparison of Analytical Crack Growth Modelling and the A-4 Wing Test Experimental Results for a Fatigue Crack in an F-111 Wing Pivot Fitting Fuel Flow Hole Number 58

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DSTO-TN-0108

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

This report details a series of analyses which were performed to develop expertise and evaluate the performance of several fatigue crack growth prediction computer codes. The analyses were performed for the case of a fatigue crack in the lower plate of the F-111 Wing Pivot Fitting, adjacent to Fuel Flow Hole No 58. This location is a known fatigue critical location and is designated as DI 86. Fatigue cracking leading to failure occurred at this location on the A-4 wing full scale fatigue test after approximately 12,200 hours of testing. An experimentally derived crack growth curve was available from the A4 wing test. Analytical models were developed using conventional LEFM software codes (FractuREsearch and AFGROW) and the analytical crack closure code, FASTRAN II. The analysis results were compared with the experimental result and also with the analysis originally performed by the manufacturer, General Dynamics. Consistent with previous work, the analytical crack closure code, FASTRAN II, produced the most consistent and accurate results.

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Executive Summary

Fatigue cracking is a well known threat to the structural integrity of the RAAF's F-111 fleet. The high strength D6ac steel used in critical components such as the Wing Pivot Fitting is particularly susceptible to fatigue cracks. Structural integrity management for these areas is reliant upon the ability to accurately model and predict the behaviour of the fatigue cracks which could occur.

Until recently, the RAAF have relied on the manufacturer, Lockheed Martin Tactical Aircraft Systems (LMTAS), to carry out these analyses on their behalf. In the light of the USAF withdrawing their F-111s from service, the RAAF have recently determined that it will not be possible to rely totally on LMTAS to conduct DADTA studies in the future to support the aircraft until the Planned Withdrawal Date (PWD), which may be as late as 2020. A goal has therefore been set to develop and establish a local Australian capability to carry out this work. DSTO and AMRL support is an essential element of this indigenous support capability. This report details work which has been undertaken to assist with the development of DSTO's crack growth modelling capability, with particular application to the F-111 weapon system.

The approach taken was to conduct a review and analysis for a selected known fatigue critical location; the Wing Pivot Fitting lower plate at Fuel Flow Hole No 58 (DADTA Item 86). The purpose was to develop expertise and evaluate the available tools for performing fatigue crack growth analysis, and compare the results with previous studies undertaken by the manufacturer. Several models were developed, and analytical codes including FractuREsearch, AFGROW and FASTRAN II were investigated. The results demonstrate that the analytical crack closure model employed by FASTRAN II produces the most consistent and accurate results.

DSTO's crack growth modelling capabilities have been enhanced as a result of this work. This represents a significant step towards the final goal of the establishment of an indigenous support capability for crack growth modelling and damage tolerance analysis in support of the F-111 weapon system.

Contents

1. Introduction

Structural integrity for the RAAF's fleet of F-111 aircraft is assured on the basis of a Durability and Damage Tolerance Assessment (DADTA). The DADTA process includes the identification of significant structural locations for which an assessment of the implications of structural damage, such as fatigue cracking, is carried out. The assessment process usually involves performing a crack growth and failure analysis using fracture mechanics. Until recently, the RAAF have relied on the manufacturer, Lockheed Martin Tactical Aircraft Systems (LMTAS), to carry out these analyses on their behalf. In the light of the USAF withdrawing their F-111s from service, the RAAF have recently determined that it will not be possible to rely totally on LMTAS to conduct DADTA studies in the future to support the aircraft until the Planned Withdrawal Date (PWD), which may be as late as 2020. It has therefore been decided to develop and establish a local Australian capability to carry out this work. DSTO and AMRL have a major role to play in this regard, and the work reported in this document represents a major first step in establishing the required capability.

The DADTA studies, which have been conducted by LMTAS for many different F-111 models and roles, have identified hundreds of structurally significant locations. The locations have been selected on the basis of cracking observed either in test or service, and on the basis of an analysis which indicates that cracking could occur in service. In this report, one particular DADTA Item, known as DADTA Item 86, was selected for detailed examination.

DADTA Item (DI) 86 is in the Wing Pivot Fitting (WPF) lower plate. The cracking scenario is a chordwise surface flaw initiating on the inside (upper) surface of the lower plate adjacent to the centre spar fuel flow hole #58. The location is shown in Figure 1 (from Reference 1).

DI 86 arose because it was the location at which the A-4 right hand fatigue test wing failed due to a fatigue crack (References 2 and 3). 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 2 summarised the crack growth curve and the fracture mechanics analysis which was performed and calibrated to the test result. LMTAS later performed predictive analyses for various F-111 models under various load spectra. An analysis was performed for the RAAF F-111C aircraft using an Australian developed load spectrum (References 4 and 5).

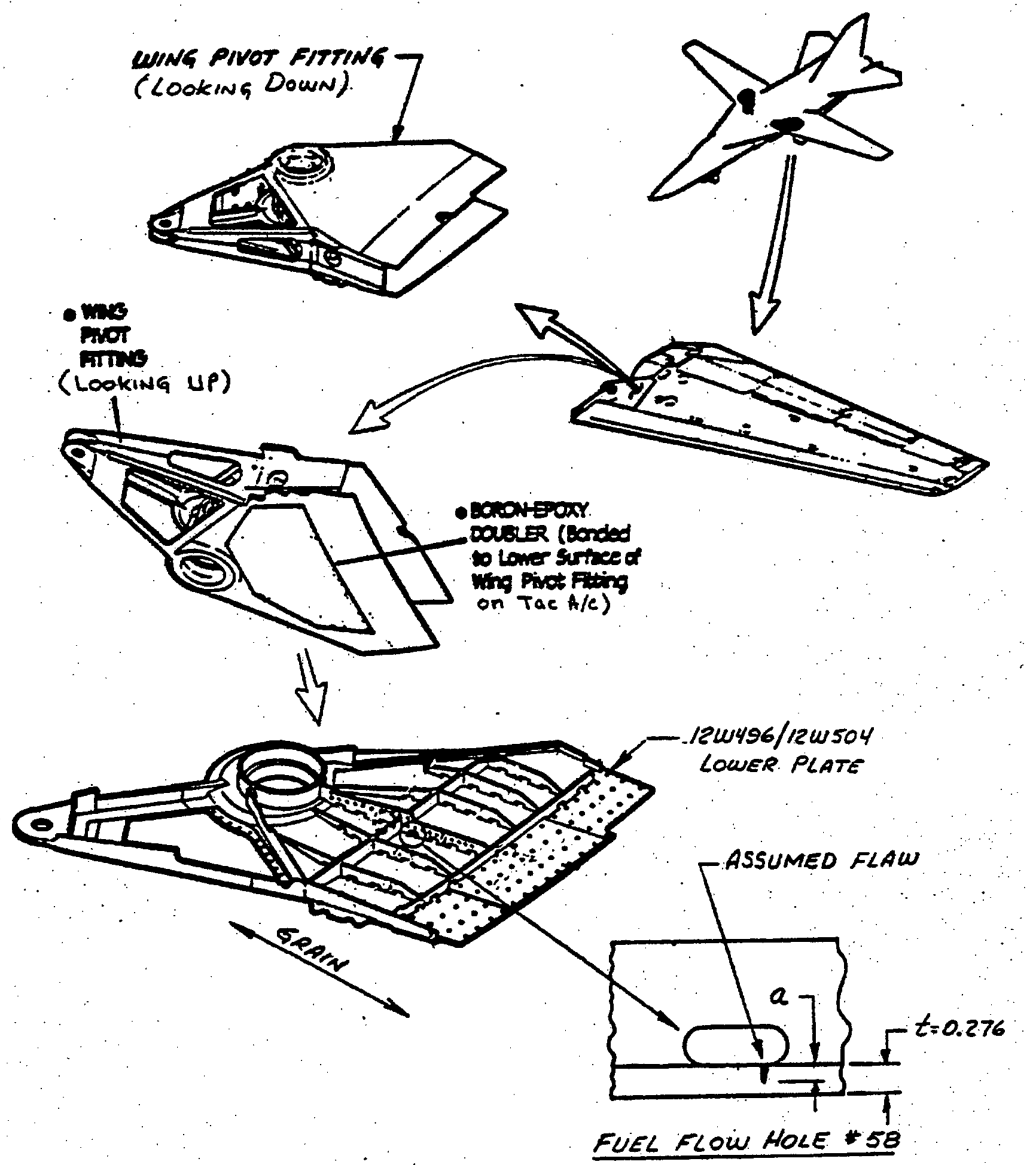

Figure 1 DADTA Item 86

The approach taken in the current work was as follows:

a. Review the A-4 fatigue test analysis using the tools available to AMRL and compare with the original LMTAS (then General Dynamics) results.

b. Perform the analysis using the RAAF F-111C DADTA spectrum (as used by LMTAS) and compare the results.

c. Perform the analysis using more recently derived spectra from the Aircraft Fatigue Data Analysis System (AFDAS) and compare the results.

The purpose was to gain a full understanding of what LMTAS had done in their analyses, and to develop and assess improved techniques where possible. This report details the results for part (a).

2. Analysis Tools

The original LMTAS (General Dynamics) analysis was performed using a program called "TD9", see Reference 2. The more recent LMTAS analysis (Reference 4) was performed using a program called ADAMSYS (Reference 6). The current AMRL analysis was performed using the FractuREsearch software (Reference 7), AFGROW (Reference 8) and FASTRAN II (Reference 9). A brief description of each of these packages is given in this section.

2.1 General Dynamics Crack Growth Program - TD9

The program TD9 is based on simplified Linear Elastic Fracture Mechanics (LEFM). Crack growth rate is calculated using either the Paris or Forman equation. Retardation can be accounted for using the Wheeler model.

2.2 ADAMSys

ADAMSys is also based on LEFM and is more advanced than TD9. Stress intensity solutions are included for a greater range of configurations and loadings, ie through thickness and surface flaws, tension, bending and bearing loads, and various geometries. Crack growth rate is derived from the Forman, Modified Walker or Paris equations. Three options are available for load interaction effects, ie. (i) no retardation, (ii) Wheeler, and (iii) Generalised Willenborg.

2.3 FractuREsearch

The FractuREsearch software has similar features as for the ADAMSys program. A range of stress intensity solutions are available, and the user has the option of inputting their own solution. The crack growth rate is input either in tabular form or using the Paris, Forman or Threshold equations. Load interaction schemes are (i) Wheeler, (ii) Willenborg, (iii) Calibrated Willenborg, (iv) Broek, and (v) Calibrated Broek.

2.4 AFGROW

AFGROW is also based on the LEFM approach with a range of stress intensity solutions being offered. Crack growth rate is input through the Walker or Forman equations, or through a unique tabular technique. Load interaction schemes are (i) none, (ii) Willenborg, (iii) Closure, and (iv) Wheeler.

2.5 FASTRAN II

FASTRAN II is a life prediction code based on an analytical model of plasticity-induced crack closure based on the Dugdale model representation for the plastic zone at the crack tip, modified to leave a wake of plastically deformed material along the crack surface. This program is significantly different from the others mentioned above (2.1 to 2.4) particularly because of the mechanistic modelling of closure, and consequently of load interaction effects. Stress Intensity Factor, K, is still the driving parameter, but the concept of an effective stress intensity range determined from the analytical crack closure model is used to account for both stress ratio and load sequence effects.

3. A-4 Fatigue Test

The A-4 fatigue test gave a known crack growth result with which to compare predictions. The manufacturer performed an analysis at the time of the test and achieved a good correlation. The analysis tools available at AMRL were used to make predictions which could be compared with the original test result and analysis. Details are contained in this section.

3.1 A-4 Fatigue Test Result and Original Analysis

The A-4 Fatigue Test crack propagation result is shown on Figure 2 below (Reproduced from Reference 2)

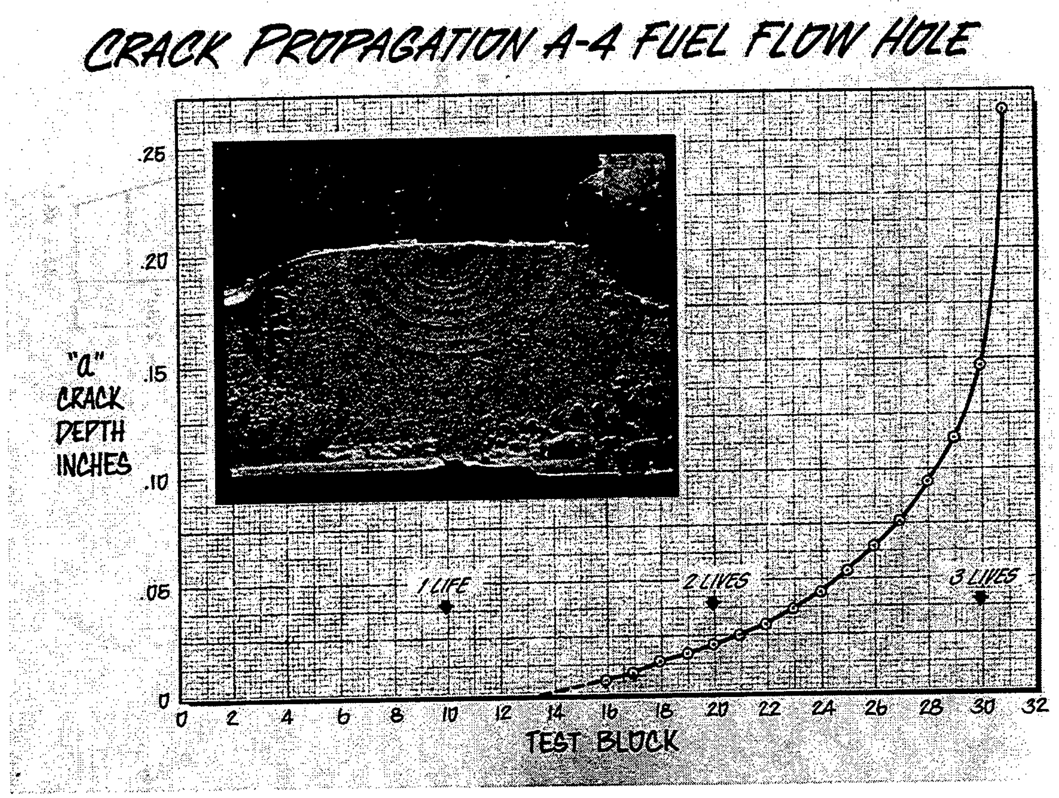

Figure 2 Crack Growth Observed in A-4 Right Hand Wing Test (Reference 2)

The load spectrum, in terms of Wing Pivot Bending Moment (WPBM), applied to the A-4 Test Article was detailed in Reference 2; however, the table given in page E-2 appears to have at least one typographical error. A similar table was given in Reference 3, but it appeared to be more complete and accurate. It was therefore assumed that the spectrum as given in Reference 3 was applicable and it is reproduced in Table 1 below. This was subsequently confirmed to be correct.

Table 1 A-4 Wing Test Applied Block Spectrum

Maximum WPBM (MIPS)	Minimum WPBM (MIPS)	Cycles per 400 Hr. Block
6.84	0.99	255
8.54	0.99	196
10.19	2.88	29
12.22	2.88	5
14.96	2.88	1
6.84	0.99	1
2.88	-2.4	4
2.88	-3.59	1
2.88	-2.4	1
6.9	0.58	1044
8.49	0.58	321
10.08	2.79	267
11.21	2.79	46
12.99	2.79	1
6.9	0.58	1
2.79	-1.5	5
2.79	3.07	1
2.79	-1.5	1
5.49	0.65	142
7.97	1.58	34
9.87	1.58	15
11.82	1.58	5
14.9	1.58	2
5.49	0.65	1

The stress distribution at the crack location (Reference 2) is as follows :

$$\sigma \text{ (ksi)} = (11.31 - 15.42 \times X) \times \text{WPBM} \qquad [1]$$

where X = depth, in inches, below the inner surface
WPBM = Wing Pivot Bending Moment in Millions of Inch Pounds (MIPS)

The original analysis performed by General Dynamics (Reference 2) had the following features :

a. The "Surface Flaw Model" was used. Specimen width was infinite and thickness = 0.288 inches.

b. The A-4 Test Spectrum was applied.

c. High (75-90%) relative humidity da/dN data was used.

d. Two retardation cases were examined: Wheeler with m=0 (no retardation) and Wheeler with m=1.4.

The analysis result is shown in Figure 3 below (Reproduced from Reference 2)

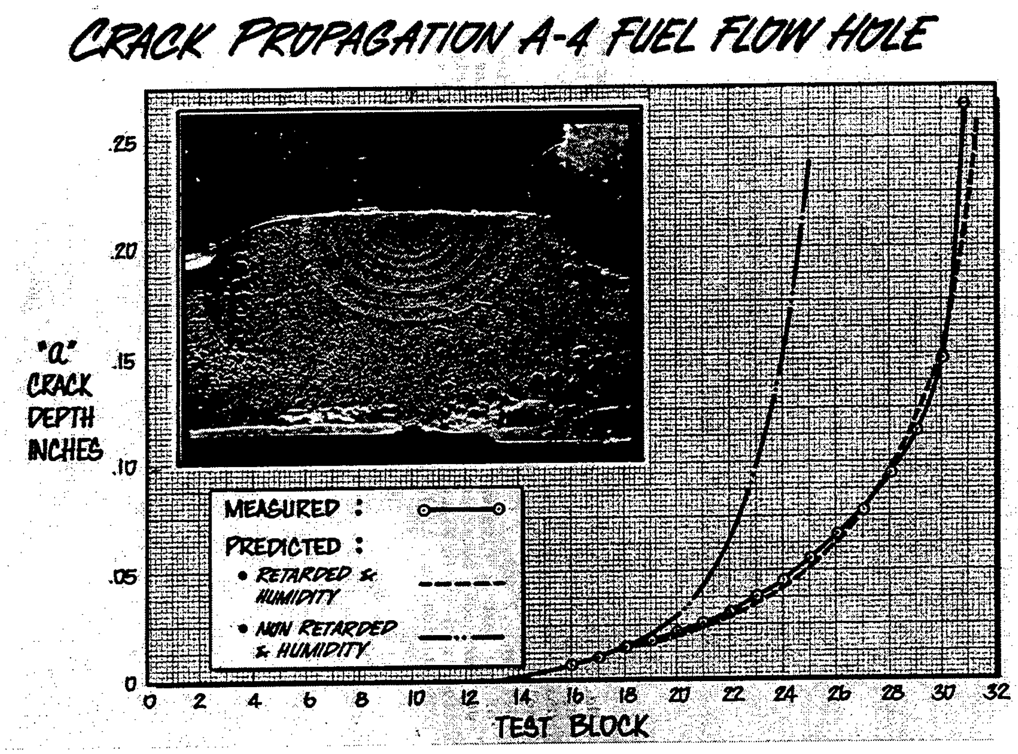

Figure 3 Observed and Predicted Crack Growth, A-4 Wing Test.

It was not clear from Reference 2 exactly which da/dN data was used to obtain the Figure 3 result. However it appears most likely that the data from page D-9 was used. It was later confirmed through communication with LMTAS that this was indeed the case. The data is for D6ac, 220/240 ksi, Cad Plated, Room Temperature, 75-100% RH, R=0.3, 6 CPM. K_{IC} = 83 ksi$\sqrt{}$inch. The Paris Equation details are as follows :

$$\frac{da}{dN} = 0.0035 * 10^{-6} (\Delta K)^{2.6} \qquad [2]$$

where $\frac{da}{dN}$ = crack growth rate, inches per cycle
ΔK = stress intensity range, ksi$\sqrt{}$inch

For the purpose of reproducing the analysis, the section of growth examined was from a=0.0075 inch to a=0.265 inch.

3.2 FractuREsearch Prediction

The FractuREsearch analysis was performed with the following inputs :

a. Crack Growth Rate The Forman equation (3) was used, with constants extrapolated from the Paris equation (2) details given earlier. The Forman equation details are as follows :

$$\frac{da}{dN} = C_f * \frac{\Delta K^n}{(1-R)K_c - \Delta K} \qquad [3]$$

where $C_f = 2.0*10^{-7}$, n = 2.6 and K_C = 83 ksi$\sqrt{}$inch

b. Crack Model The module "GEOFAC" was run for a surface flaw of constant aspect ratio (surface half length (c)/crack depth (a) = 1.0) growing in a stress gradient (ie the stress distribution given by Equation 1 in Section 3.1)

c. Retardation The model was run with no retardation and also with the Wheeler retardation model and m=1.4 as per the GD analysis.

3.3 AFGROW

The AFGROW analysis was performed with the following inputs :

a. Crack Growth Rate The Forman equation (3) was input with the same constants as per the FractuREsearch case (Section 3.2). A threshold value of stress intensity range for crack growth of ΔK=7 ksi$\sqrt{}$inch was used because this appeared to have been used in the Reference 2 analysis. A threshold value could not be input in the FractuREsearch model. The threshold is a value of ΔK below which the crack is assumed not to grow. This is not considered to be a significant factor for the present analyses because even the smallest loads at the shortest crack lengths result in ΔK levels in excess of 7 ksi$\sqrt{}$inch.

b. Crack Model AFGROW gives the user the option of a surface flaw in tension which is then adjusted for growth into a stress gradient. The aspect ratio is kept as a constant 1.0, ie growth is modelled in one direction only.

c. Retardation As per FractuREsearch, the model was run with no retardation and also with the Wheeler retardation model with m=1.4.

3.4 FASTRAN II

The FASTRAN II analysis was performed with the following inputs :

a. Crack Growth Rate A crack growth rate versus ΔK effective curve was established based on data for a humid air environment (Reference 10). An important parameter to be considered in this is the constraint factor, α, which is discussed in some detail in Reference 9. For ideal full plane strain conditions, α = 3.0, and for full plane stress α = 1.0. Newman (Reference 9) 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 9) 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 4 below, along with the mean curves as per Reference 10. Inputting the raw data with α = 3.0 to DKEFFNEW produced the result shown in Figure 5, and performing the same procedure for the mean curve data produced the results shown in Figure 6. The mean curve result for R=0.5 as shown in Figures 5 and 6 was considered to be a reasonable estimate for the collapsed data and this was used for the predictions.

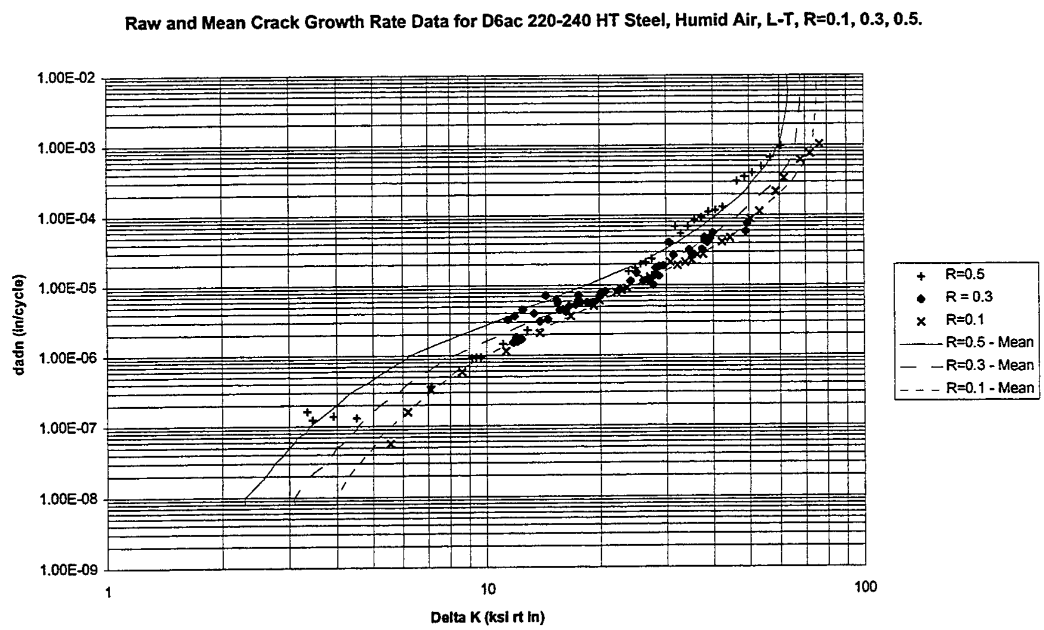

Figure 4 da/dN vs ΔK Data for D6ac steel in Humid Air Environment

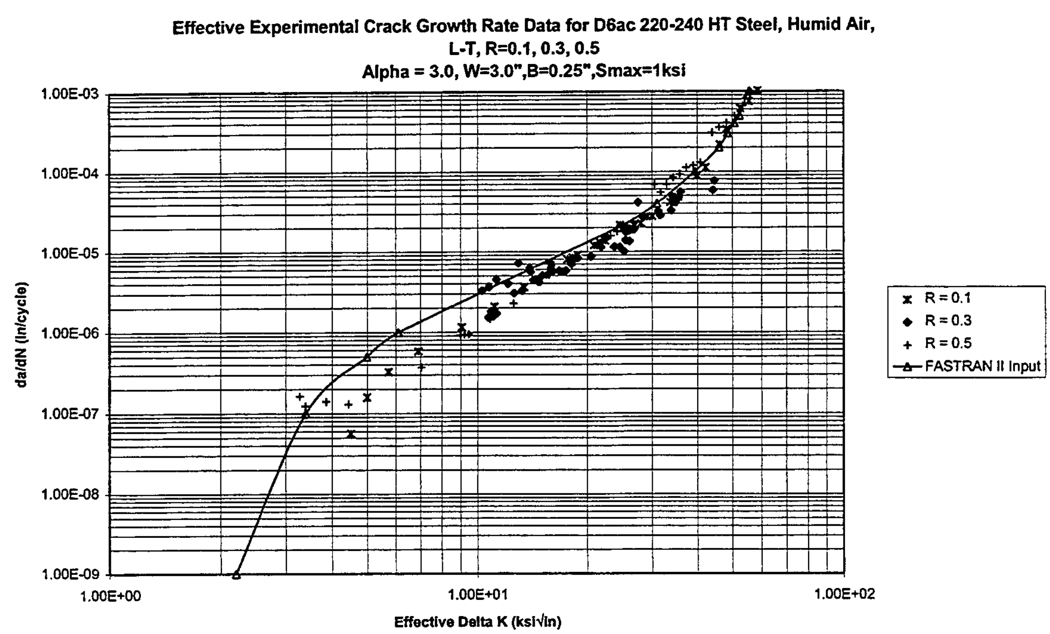

Figure 5 da/dN vs ΔK Effective Data for α = 3.0, based on raw data

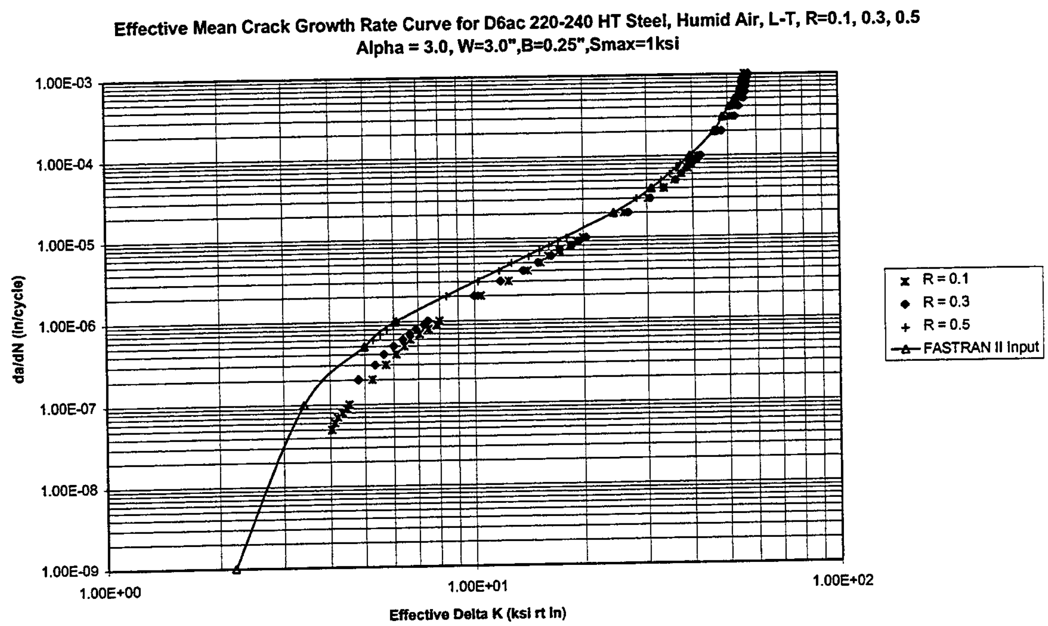

Figure 6 da/dN vs ΔK Effective Data for $\alpha = 3.0$, based on Mean Curves

a. Crack Model FASTRAN II has the geometry option of a surface flaw in a plate under combined tension and bending, hence this option was used. The crack is allowed to grow separately in the depth and surface directions, ie the aspect ratio is not fixed.

b. Retardation FASTRAN II inherently accounts for stress ratio and load interaction effects through the crack closure model. The approach is summarised for constant amplitude loading in Figure 7 below. Due to closure effects the crack does not fully open until an applied stress of σ_{op} is reached. The effective cyclic stress range is therefore reduced from $\Delta\sigma_{app}$ (the applied stress range) to $\Delta\sigma_{eff}$ (the effective stress range), and the effective stress intensity range is also reduced accordingly.

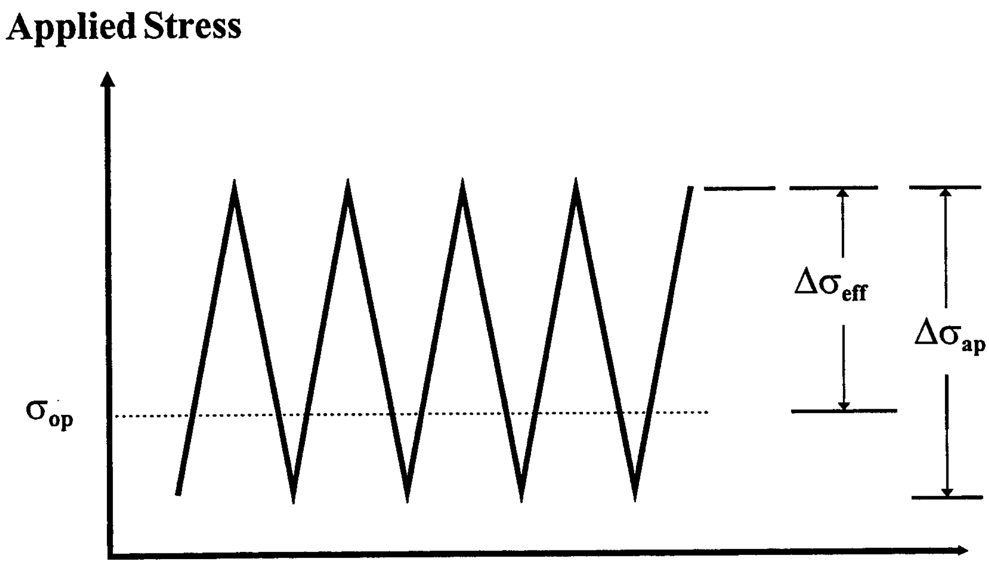

Figure 7 Effective Stress Range Concept

3.5 Results

A comparison of the crack growth predictions is summarised in Table 2 and Figure 8 below.

Table 2. *A-4 Wing Test and Predicted Lives in Hours for a Crack to Grow from Depth a=0.0075 inches to Failure or 0.265 inches*

Final Crack Growth Predictions					
	Experimental	LMTAS	FractuREsearch	AFGROW	FASTRANII
No Retardation	-	3360	3039	3090	-
Retardation	5680	5920	8765	5965	5682

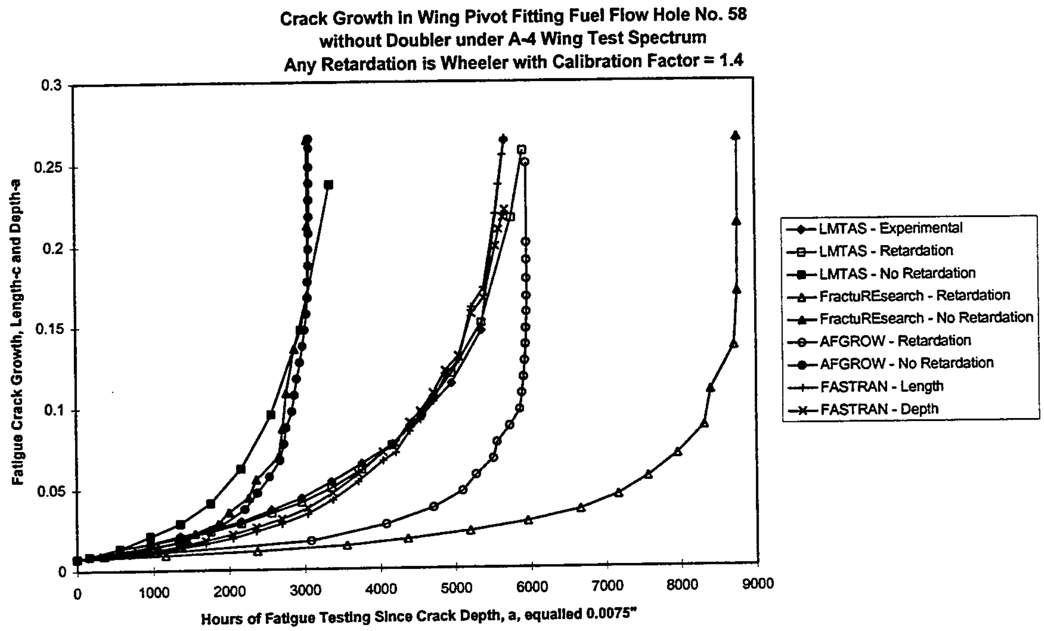

Figure 8. A-4 Wing Test Experimental and Predicted Crack Growth Curves

4. Discussion

The original analysis performed by General Dynamics using the program "TD9" produced a result very close to the experimentally observed crack growth from the A-4 Wing Test. Consistent with the standard industry practice when using such models, this was achieved by adjusting the Wheeler retardation factor (m) until a match was obtained. The Wheeler retardation factor was therefore probably taking more than just retardation into account; it was also adjusting for other uncertainties in the analysis such as the crack growth rate model.

The General Dynamics, FractuREsearch and AFGROW programs all produced similar crack growth curves for the no retardation case (see Figure 8). This is expected because every effort was made to use the same crack growth rate data and crack geometry assumption for the FractuREsearch and AFGROW predictions as was used in the General Dynamics work. However, when retardation was introduced, the FractuREsearch result differed considerably from the General Dynamics prediction. This was not expected because the same retardation model and factor (Wheeler with m=1.4) was selected in each case. The AFGROW result matched the final General Dynamics prediction very well, although the shape of the crack growth curve differed markedly. The shape of the crack growth curve for the FractuREsearch result was also different from the General Dynamics curve, and was similar in shape to the AFGROW curve. These variations are cause for concern when every effort was made in these analyses to re-create the same analysis using different software programs. The software packages all offer the Wheeler retardation model, and account for a surface flaw growing into a stress gradient (ie combined tension and out of plane bending). The software packages should, in theory, have produced identical results. The fact that they did not do so indicates a significant programming difference which requires further investigation.

As shown in Figure 8, the FASTRAN II software produced a prediction which was almost identical to the observed crack growth. The final aspect ratio, a/c, was about 0.85, which compares well with the estimated a/c of 0.9 for the experimental result from Reference 2. This is considered to be a remarkable achievement given that as shown in Section 3.4, the crack growth rate data after collapsing exhibited significant scatter. It effectively indicates that the crack growth rate approximation is well calibrated to the actual material behaviour, and as was seen in Reference 11, this indicates that it a good prediction for crack growth under a different spectrum can be expected.

5. Conclusions and Recommendations

Analytical predictions of fatigue crack propagation at a specific location in the F-111 wing have been compared with measured data from the A-4 wing fatigue test. The original analysis performed by the manufacturer matched the observed behaviour very well, presumably through the use of the Wheeler retardation parameter as a calibration variable. The software packages available at AMRL (FractuREsearch, AFGROW and FASTRAN II) were also able to closely predict the observed behaviour <u>if</u> the appropriate input parameters were adjusted. The FractuREsearch program produced different results when equivalent input data was used, while both FractuREsearch and AFGROW produced crack growth curves with a shape different to the observed crack growth. This indicates an inconsistency in the way the retardation models or some other aspect of the programs have been written. FASTRAN II produced a prediction which closely followed the observed behaviour, and is considered to offer the greatest potential as a consistent and logical predictive code.

Planned future work is as follows :

a. A set of benchmark crack growth prediction cases will be developed, and the performance of the FractuREsearch, AFGROW and FASTRAN II programs evaluated against them.

b. In the case of AFGROW and FractuREsearch, the reason for a difference in retarded crack growth for the particular example described in this report will be investigated.

c. The predictive capability of FASTRAN II will be investigated further, with application to crack growth in the F-111 wing under more recent spectra.

6. Acknowledgments

The authors wish to acknowledge the assistance of FLTLT Greg Hoffman, RAAF F-111 Technical Liaison Project Officer who submitted queries concerning DI 86 to LMTAS. The assistance and advice provided by Drs L.R.F. Rose and C.H. Wang from AMRL, and Drs J.C. Newman and D.S. Dawicke from NASA Langley, Virginia USA, was also greatly appreciated.

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Appendix A: Input Data for Crack Growth Programs

A.1 FractuREsearch

Geometry Input = Beta File
Number of hours in Stress File = 400
Stress Conversion Factor = 11.26
Yield Strength = 210 ksi
Fracture Toughness = 83 ksi$\sqrt{\text{in}}$
Forman Equation Co-efficient = 2 e-7
Forman Equation Exponent to ΔK = 2.6
Stress Input File = A4WING.STR
Beta File = DI86D6A4.BET
(Beta file generated using GOEFAC module in FractuREsearch for a surface flaw with a/c=1 growing in a stress distribution. Flaw origin at x=0)
Stress Distribution File for GEOFAC = DI86A4.DIS
Plate Width = 42 inches
Initial Crack Size = 0.0075 inches
Final Crack Size = 0.265 inches

A.2 AFGROW

General Input File = D6A4DI86.DA3 containing :
Yield Strength = 210 ksi
Fracture Toughness = 83 ksi$\sqrt{\text{in}}$ (Plane strain and plane stress)
Young's Modulus = 2900000 ksi
Poisson's Ratio = 0.32
Forman Equation Co-efficient = 2 e-7
Forman Equation Exponent to ΔK = 2.6
Forman Equation Threshold Value at R equal to 0 = 7 ksi
Flaw Model = Centre Semi-Elliptic Surface Flaw
Plate Width = 42 inches
Plate Thickness = 0.288 inches
Initial Crack Size (a and c directions) = 0.0075 inches
Keep a/c ratio constant = Yes
Stress Conversion Factor = 11.26
Beta Correction :

Distance from Origin (r)	Stress Intensity Factor (r,0)	Stress Intensity Factor (0,r)
0	1	1
0.288	1	0.607

No Residual Stresses
Plane Strain Conditions Apply (Stress State Condition Value = 6)

Stress Input Files = D6A4.SP3 and D6A401.SUB
Number of Hours per Pass (of input spectrum) = 400
Maximum Growth Increment = Cycle by Cycle Beta Calculation
Stop Crack Propagation at Crack Length = 0.265 inches.

A.3 FASTRAN II

Input File for DKEFFNEW :
Experimental (Raw) Crack Growth Rate Data = EXDELKHA.DAT
Mean Crack Growth Rate Data = MNDELKHA.DAT

Input File for FASTRAN II = MND6A4HA.DAT
(Uses crack growth rate data from the R=0.5 mean curve)

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B.J. Murtagh and K.F. Walker	Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001 Australia

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19. ABSTRACT

This report details a series of analyses which were performed to develop expertise and evaluate the performance of several fatigue crack growth prediction computer codes. The analyses were performed for the case of a fatigue crack in the lower plate of the F-111 Wing Pivot Fitting, adjacent to Fuel Flow Hole No 58. This location is a known fatigue critical location and is designated as DI 86. Fatigue cracking leading to failure occurred at this location on the A-4 wing full scale fatigue test after approximately 12,200 hours of testing. An experimentally derived crack growth curve was available from the A4 wing test. Analytical models were developed using conventional LEFM software codes (FractuREsearch and AFGROW) and the analytical crack closure code, FASTRAN II. The analysis results were compared with the experimental result and also with the analysis originally performed by the manufacturer, General Dynamics. Consistent with previous work, the analytical crack closure code, FASTRAN II, produced the most consistent and accurate results.

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