Development and Validation of Fatigue Crack Growth and Lifing Methodologies through Comprehensive Coupon and Component Testing Under Spectrum Loading Representative of P-3C Maritime Surveillance Aircraft

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1.0 Abstract

Fatigue crack growth analyses in support of structural integrity management for the Royal Australian Air Force (RAAF) P-3C maritime surveillance aircraft fleet are performed using the FASTRAN code developed by Newman. Based on previous coupon test program data, the crack growth analysis and inspection interval results are known to be conservative. Recent work by the P-3C manufacturer, Lockheed Martin, revealed some errors and shortcomings in the methods used to determine the sequence of loads and stresses at specific aircraft locations. Previous coupon and full scale testing were performed with load/stress sequences determined under the old load system, so it was considered important to conduct coupon and component testing under sequences accounting for the updated and more accurate loads. There is also a requirement to significantly improve the FASTRAN modelling to reduce the conservatism (while still remaining conservative), thereby extending inspection intervals, realising significant financial savings and improving aircraft availability. Coupon tests to quantify total life from natural crack formation and cold working effects, and sub-component tests replicating complex structure were also conducted. This paper summarises these various coupon and component test programs, and details the latest results with improvements in the FASTRAN modelling process.

2.0 Introduction

Structural integrity management of the Royal Australian Air Force (RAAF) P-3C Maritime Surveillance aircraft fleet is transitioning from a philosophy of safe life to safety-by-inspection (SBI) [1-3]. Inspection intervals are determined analytically with experimental substantiation. The key tool for the analysis is FASTRAN [4], which uses the concept of plasticity-induced crack closure to account for stress ratio and load interaction (retardation/acceleration) during fatigue crack growth. Comparison between measured crack growth data from coupon and full-scale fatigue crack growth tests has revealed that the analysis is generally overly conservative under RAAF P-3C spectra, i.e. it generally produces much faster crack growth (shorter lives) than experiments. Consequently, a comprehensive coupon test program is being carried out to produce data to both directly support the RAAF fleet, and to further develop and validate FASTRAN-based analyses to reduce the extent of conservativeness. The reduction of conservativeness, through more accurate modelling, has the potential of providing significant savings by reducing the inspection burden and increasing lives.

This paper presents the details of the coupon test program currently being carried out, and the preliminary analyses conducted to recalibrate and improve the FASTRAN modelling output. A review of various baseline fatigue crack growth data for the material concerned was conducted, with particular attention given to the data in the threshold and near threshold region, as these data are considered to be important for aircraft such as the P-3C, which experience a large number of cycles of very small amplitude in the loading spectrum. The significance of the constraint loss on crack growth was investigated by comparing different constraint regimes. Finally, numerically calibrated rate and constraint data using one spectrum were applied to other spectra, leading to significant improvement in the crack growth predictions. The paper also discusses an observation of counter-intuitive results from FASTRAN analyses.

3.0 The Coupon Test program

The loads system used by Lockheed Martin (L-M) to calibrate the crack growth model (FASTRAN) used for the USN P-3C Service Life Assessment Program (SLAP)[1] was titled Phase IIB. This loads system was also used to generate the test spectra for all of the P-3C SLAP Full Scale Fatigue Tests (FSFT). It is important to note that the USN P-3C SLAP FSFT's were all conducted to the USN 85th percentile usage spectrum; therefore each of the contributing countries to the P-3C SLAP had to conduct test interpretation activities according to their own in-country usage spectrum. As the FSFT proceeded, a number of

[1] The SLAP was a collaborative program between the United States Navy (USN), Royal Australian Air Force (RAAF), Canadian Forces (CF), and the Royal Netherlands Navy (RNLN)

improvements were made to the P-3C SLAP loads system, such as ground load corrections, an orientation of engine torque change, the inclusion of pressurisation loads in a number of fatigue critical areas (FCA) and the inclusion of the corrected abrupt manoeuvre load which affects the horizontal stabiliser. These improvements were not included in the Phase IIB loads system or the original calibration of FASTRAN by L-M. DSTO therefore decided to conduct a coupon test program using the improved Phase IIC loads system to re-calibrate FASTRAN to the RAAF average usage spectrum, and to investigate other areas of concern with the FSFT results. The objective of the test was to validate and calibrate the performance of FASTRAN under RAAF average usage spectra for two different flying periods. The new test program also covers more locations across the wing span and chord than the previous DSTO tests [5], in order to better encompass wing load due to shear, bending and torsion.

4.0 FASTRAN Re-calibration tests and analyses

4.1 Test Details

4.1.1 FASTRAN Re-calibration Coupon Design

The coupon material was 7075-T6 Aluminium alloy sheet, with no cladding. The geometry of the coupons, as shown in Figure 1, based on previous P-3C coupon design used by the Dutch SLAP partners. As the coupon thickness was 2 mm, anti-buckling guides were used during all tests, including the pre-cracking phase. The yield and ultimate strengths as advised on the material data sheets for the coupon material were 511-514 and 578 MPa respectively.

A total of 85 coupons were manufactured, allowing at least three replicates for each of the 15 spectra to be tested and a number of spares for any additional testing.

The tests were conducted under load–control. The loading of the coupons was performed in two phases; pre-cracking under constant amplitude loading, followed by representative variable amplitude spectrum loading. Both the constant amplitude pre-cracking and the representative variable amplitude spectrum loading were applied at a frequency of 10 Hz.

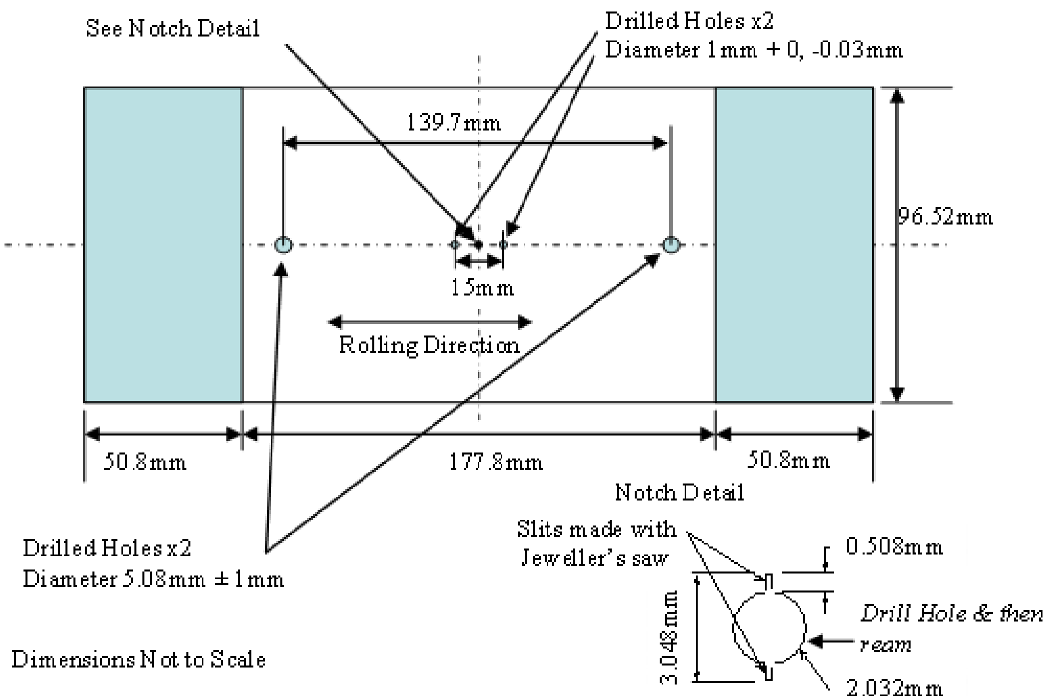

Figure 1 : FASTRAN Re-Calibration Coupon Design. The holes on either side of the notch are for the Direct Current Potential Drop (DCPD) system used to measure crack length.

4.1.2 Pre-Cracking

Following ASTM Standard 647 [6], constant-amplitude load was used for pre-cracking, and it was applied to grow the crack by at least 2 mm beyond the saw-cuts on either side of the coupon. The load shedding procedure in ASTM Standard E 647-00 [6] was employed during the initiation phase.

It was discovered during the initial testing of pre-cracking that some localised compressive residual stress had been introduced around the tip of the saw-cuts during machining, which led to a delay in crack initiation. In order to eliminate the residual stress, all coupons were modified by removing a layer of material from the edge of the slots using a jeweller's saw.

4.1.3 Spectrum Loading

The detailed test matrix is shown in Table 1. All tests were conducted at a frequency of 10 Hz. The sequence in each case represented 15,000 flying hours, and was repeated until failure of the specimen. The spectra represent the load experienced by five representatives FCAs under three different loading regimes; FSFT, RAAF P-3C and RAAF AP-3C[2].

[2] The RAAF P-3C fleet went through an avionics upgrade about 7 years ago and they were then re-designated as the "AP-3C". The AP-3C usage is less severe due to reduced all up weight and a reduction in the amount of training missions flown (more training is now done on the simulator).

The primary method used for measuring crack length was the Direct Current Potential Drop (DCPD) system, which enabled testing overnight and through the weekend. The DCPD system measures crack length tip-to-tip but records the half length, i.e. the average length from the centre of the notch hole to the crack tip.

Optical readings and crack camera images were also taken at regular intervals by the test laboratory staff to complement the DCPD data. The results correlated well with the DCPD data.

Table 1 : FASTRAN Re-Calibration Test Matrix (frequency: 10 Hz, minimum two coupons per load sequence)

FCA	Sequence	Spectrum Cycles	Max Stress (MPa)	Min Stress (MPa)
170	FSFT	430,932	192.56	-37.78
170	RAAF P-3C	1,036,527	154.59	-68.95
170	RAAF AP-3C	882,922	162.28	-68.95
301	FSFT	439,404	214.84	-38.05
301	RAAF P-3C	1,101,729	151.68	-65.50
301	RAAF AP-3C	935,340	143.41	-65.50
357	FSFT	428,520	144.76	-51.32
357	RAAF P-3C	873,948	106.87	-68.95
357	RAAF AP-3C	761,272	101.70	-68.95
361	FSFT	422,624	166.21	-98.28
361	RAAF P-3C	1,252,688	124.80	-117.21
361	RAAF AP-3C	1,080,726	118.25	-117.21
375	FSFT	412,056	177.21	-61.74
375	RAAF P-3C	1,159,953	131.00	-89.63
375	RAAF AP-3C	1,000,499	131.00	-89.63

4.2 Test and Analysis Results

At least two, and typically three, coupons were tested for each spectrum and it was found that the repeatability of results was excellent. Also, the DCPD, optical and crack camera measurements of crack length were very consistent. A vindication of the decision to conduct this work became clear when the coupon test results started to become available. A good example is FCA 301 under the FSFT spectrum. Figure 2 shows the experimental results compared with analysis using the current growth rate curve and constraint options in FASTRAN. It is clear that the current analysis settings were giving overly conservative results, particularly as the crack grew larger than about 12.5 mm.

One of the most important inputs to the analysis is the growth rate versus the effective stress intensity factor relation, and the corresponding constraint factor assumption. These data were, therefore, reviewed to see if any improvements/changes were required/possible. The starting point was to use data originally from L-M, which is a single rate curve to cover 7075-T6 or –T651 material[3], and two different constraint assumptions, depending on whether the spectrum was considered to be Tension-Tension (T-T) or Compression-Tension (C-T). Details are shown in Figure 3. In order to check if their curve was reasonable, L-M compared their rate curve with one from [7] for 7075-T6 and concluded that the comparison was good. However, it turns out that there is a typographical error in [7][4] and they were actually comparing against data for LC9cs alloy (see Fig. 3). Further, a recent report [8] provided yet another set of data for 7075-T651 material, albeit determined from thicker specimens (5.7 mm compared with about 2 mm). These data are all shown in Figure 3.

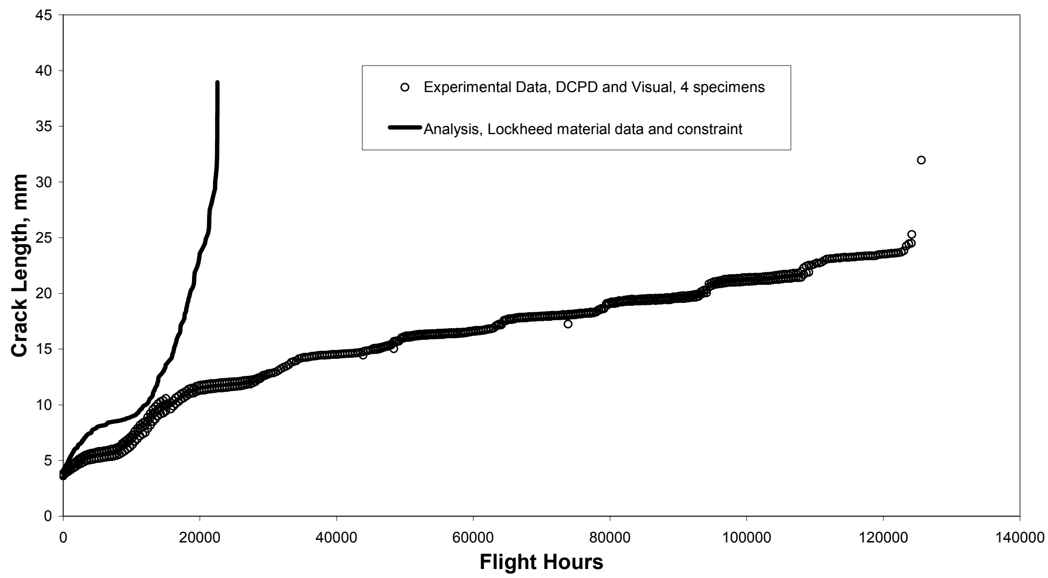

Figure 2 : Comparison of experimental crack growth 7075-T6 against FASTRAN analysis using standard L-M material data and constraint for FCA 301 FSFT.

[3] The actual aircraft wing skins are manufactured from 7075-T651 extrusion material, but the coupons are machined from 7075-T6 sheet.
[4] Confirmed via e-mail by the author of [7].

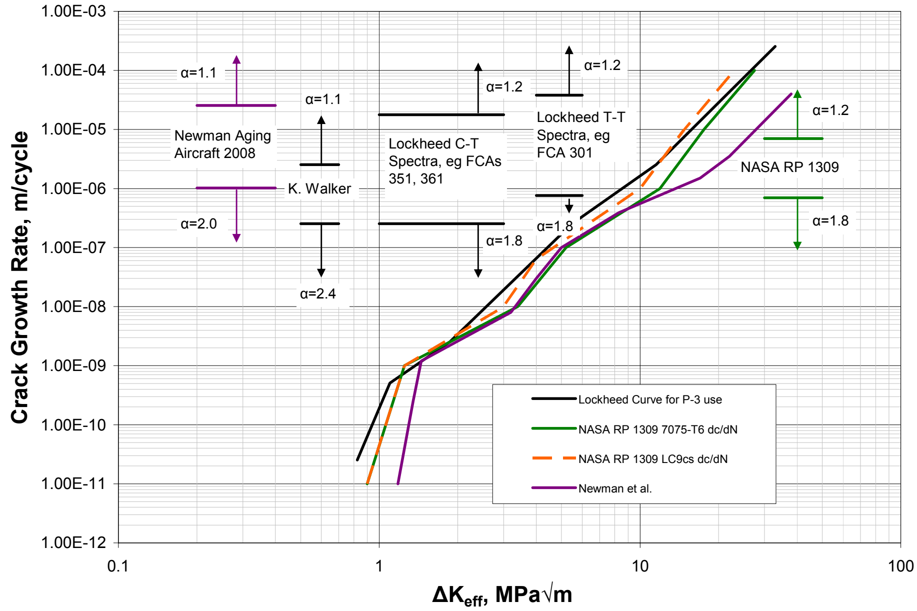

Figure 3 : Fatigue crack growth rate and constraint factor comparison

The crack growth analysis as shown in Figure 2 was repeated, but with the 7075-T6 material data and constraint from [7] which is detailed in Figure 3. The result shown in Figure 4 (solid green curve) was a significant improvement on that obtained previously (solid black curve). An analysis was then conducted using Newman's 7075-T651 material data from [8] as shown in Figure 3 using the constraint factors as per the NASA RP 1309 [7]. The result was the solid red curve in Figure 4. This result was counter intuitive because the rate curve for the 7075-T651 case was below the L-M P-3C curve, and mostly lower than the NASA RP 1309 7075-T6 curve. However, there was a small section around 3-5 MPa√m where the 7075-T651 curve was higher. So, a special analysis case was conducted where the 7075-T651 curve was artificially adjusted down by a small amount to ensure that it was always lower than the 7075-T6 curve. All other aspects of the analysis were kept the same. The result was the red shaded curve, which exhibits (counter intuitively) faster crack growth and a shorter life than the solid green curve. In order to examine the effect of constraint, a case was also run where the 7075-T651 rate curve from [8] was used along with its recommended constraint assumptions (see Fig. 3). The result was the most rapid growth shown in the short-dashed red curve in Figure 4.

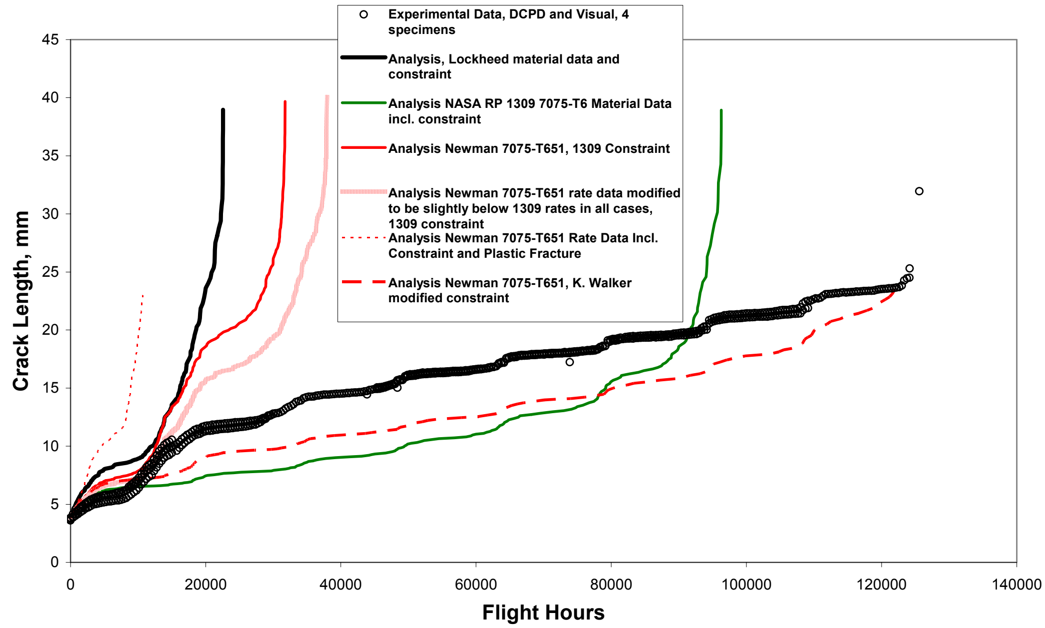

Figure 4 : Comparison of experimental crack growth against FASTRAN analyses using various material data and constraint factors for FCA 301 FSFT.

An estimate of the rate at which the transition from flat to slant growth occurs was then made using the equation $(\Delta K_{eff})_T = 0.5\sigma_0\sqrt{B}$ [8]. Using B=0.002 m and σ_0=425 MPa, the result was 1 x 10^{-6} m/cycle. A constraint loss regime centred around this value was used along with the 7075-T651 rate curve from [8], but with some adjustment to the constraint factors as shown in Figure 3 (labelled as "K. Walker"). Interestingly, the transition rate calculated above corresponds with an upward kink in the rate curve which adds support to the concept that there is a change in growth behaviour at that stage. The crack growth result, shown as the red long dash curve in Figure 4, compared well with the experimental result.

In addition to performing the analyses already discussed, the issue of sensitivity to changes in the threshold and near threshold region was also investigated. From Figure 3, significant differences are evident in the various rate curves around 0.8~1.1 MPa√m. Generally, based on previous L-M/SLAP analyses a threshold of 0.75 MPa√m with no R ratio dependence is assumed. However, it was found that the analyses were relatively insensitive (i.e. the results didn't change much) for assumed threshold values anywhere below about 2 MPa√m. The 7075-T6 and 7075-T651 rate curves are very similar between about 2 and 10 MPa√m, and this appears to be the region where most of the crack growth activity is taking place. However, it is important to point out that these tests commenced from a relatively large initial crack. Separate tests are also planned where the crack will be allowed to develop naturally from an open hole. In those tests the threshold and near threshold region is expected to be more significant.

The major factor, which appears to improve the correlation between the analytical and the experimental results, was an adjustment of the constraint factors. Adjustment of the constraint factors to match spectrum test results is a process endorsed by the author of FASTRAN, J. Newman, and is what has been done previously by L-M.

Results for other locations (FCAs) under different usage sequences were then compared. The purpose was to see how well the revised modelling worked for other scenarios, including spectra, which had previously been defined as "Compression-Tension" and required a different constraint factor assumption. The results were very good for a range of FCAs, including 170 (previously categorised as T-T), 357, 361 and 375 (previously categorised as C-T), and for all three sequences, i.e. FSFT, P-3C and AP-3C. Results for FCA 361 for the three sequences are shown in Figure 5 to Figure 7.

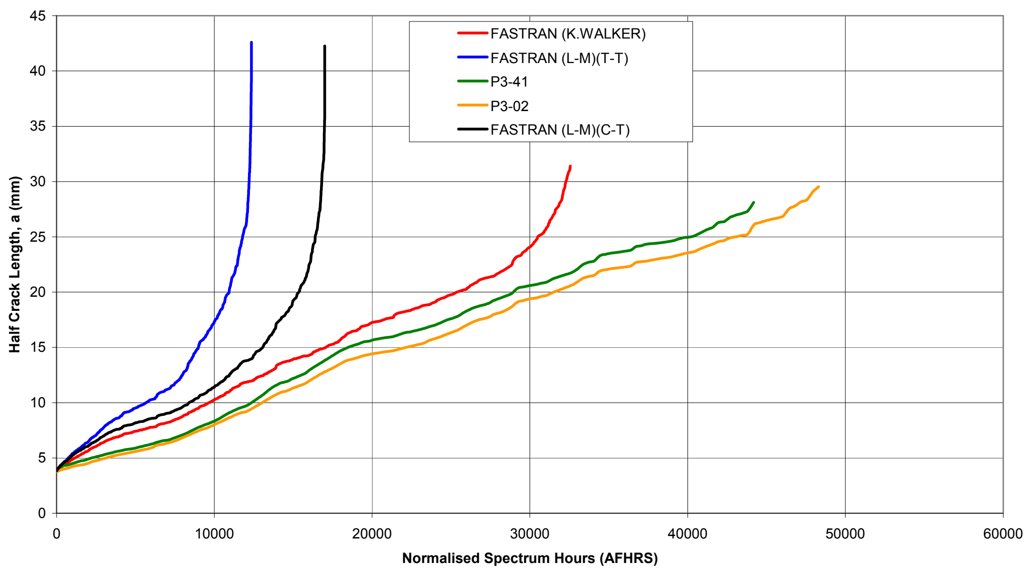

Figure 5 : Comparison of experimental crack growth against FASTRAN analysis using 7075-T651 material data and modified constraint for FCA 361 FSFT

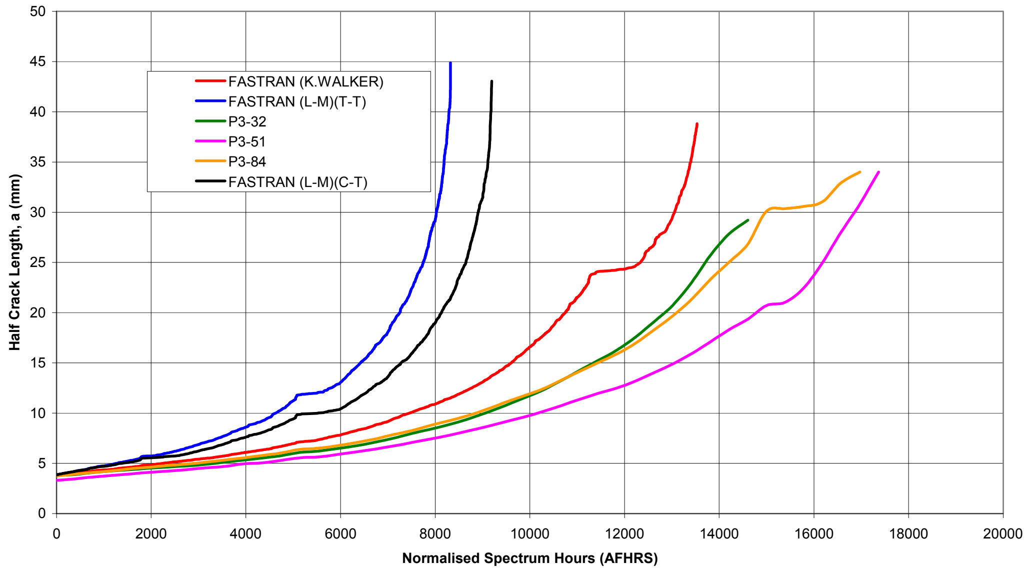

Figure 6 : Comparison of experimental crack growth against FASTRAN analysis using 7075-T651 material data and modified constraint for FCA 361 P-3C

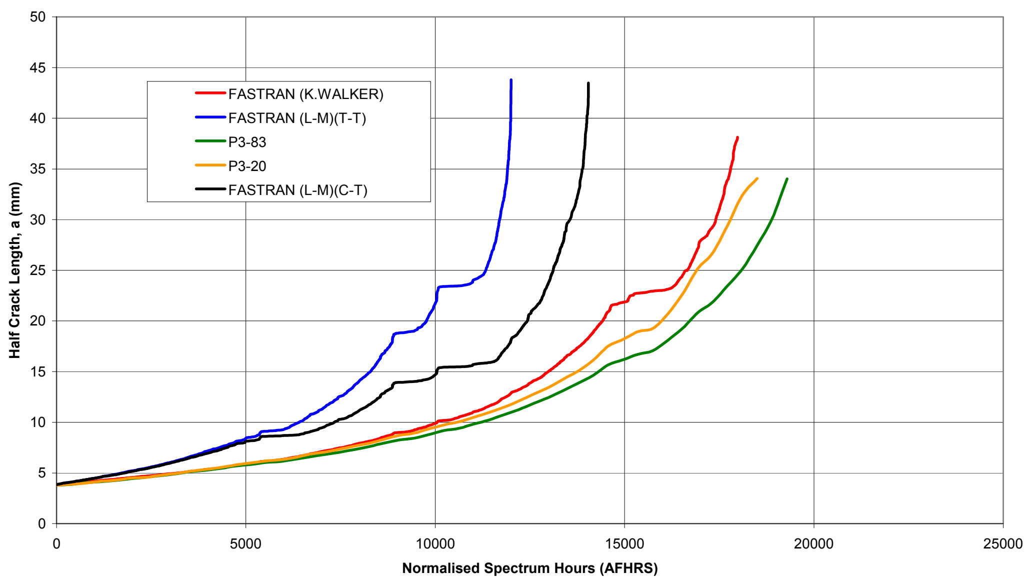

Figure 7 : Comparison of experimental crack growth against FASTRAN analysis using 7075-T651 material data and modified constraint for FCA 361 AP-3C

5.0 Discussion

Results obtained from the FASTRAN re-calibration coupon testing have confirmed that the current modelling produces overly conservative results at most fracture critical areas on the P-3. While conservative results are desirable for safety reasons, excessive conservatism results in a cost burden due to earlier retirement and/or more frequent inspections. There appears to be considerable scope to remove some of this conservatism by improving the modelling process.

The plasticity induced closure model inherent in FASTRAN is complex and as explained it may lead to counter-intuitive results. There is a complex interaction between the growth rate for a given applied effective stress intensity range, the constraint factors, and the spectrum itself. One example has shown that by keeping everything the same, inputting a lower crack growth rate curve led to a faster crack growth in FASTRAN, which is not only counter-intuitive but also illogical. This problem may have been caused by the way and the frequency the crack opening stress was calculated, but varying the frequency did not alleviate this problem. Another possibility is the calculation of growth rates when an upward ratchetting load sequence is encountered, but the current investigation along this line has been inconclusive. Whatever the reason, the numerical stability of FASTRAN needs to be studied further in order to make it a more robust tool.

In the cases studied in this paper, it seems that the constraint factor settings are the most important issue. It appears crucial to get the constraint factor and the transition rates correct. In the case of constant amplitude loading this transition is much easier to understand, where a smooth transition occurs as the crack grows. In the case of spectrum loading, however, the choice is inherently not well defined as the same load cycle applied to the early stage of crack growth may produce a lower growth rate, hence a higher constraint factor, while the situation may be reversed when the crack length is large. It was, therefore, very encouraging to see that in this study a good correlation between the analytical and the experimental results could be obtained by fine-tuning the baseline material data and the constraint settings. The result for FCA 301 FSFT shown in Figure 2 for example is particularly encouraging. The test result exhibits noticeable "bumps" every 15,000 hours, which is once per spectrum repeat. The "bump" corresponds to the peak load in the spectrum which occurs at about 5,000 hours. It is very encouraging to see the analysis follow this behaviour so consistently. It was then found that the same model settings produced similarly good results for several other locations under the three different sequences. In this case there was no need to have different constraint factor settings for C-T or T-T spectra, which is also encouraging.

6.0 Conclusion

The work carried out here highlights the importance of both analysis and testing in support of structural integrity management for aircraft. No analytical tool is perfect and FASTRAN is no exception, but it does seem to be a highly capable tool, which enables us to obtain the greatest possible performance from the RAAF P-3C fleet. Work is ongoing to further improve the modelling and to ensure that accurate modelling can be achieved for a broad array of cases. The areas of baseline material properties, threshold and near-threshold growth, and constraint factors continue to be investigated.

7.0 References

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