Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Development and Evaluation of Mean Stress Correction Techniques for Improved Fatigue Life Prediction

Problem area
The accuracy of fatigue life predictions of aircraft structure has significant consequences for the life cycle costs and sustainment of an aircraft fleet. Shortfalls in achieved life against prediction can have serious consequences for both airworthiness and cost of ownership, whilst under-prediction results in unnecessary weight or manufacturing cost.

This technical paper presents the results of modifications to a local stress-strain based fatigue prediction model to include the effects of continually varying local stress ratios in order to improve fatigue initiation life predictions.

Description of work
As part of a recent full scale fatigue test program on a transport aircraft an 'industry standard' fatigue life prediction model was adopted and used for test interpretation activities. This strain-life based model incorporated local stress-ratio (local minimum stress/local maximum stress) effects in an equivalent strain transfer function, provided predictions of damage initiation life. Comparison of the performance of the model against a series of coupon tests run using transport aircraft wing spectra showed, for some spectra types, very wide variations of predicted fatigue initiation life to that of the experimental fatigue initiation life. The performance of the generic equivalent strain function incorporated into the original model was suspected as one of the causes. A number of alternative equivalent strain transfer functions were developed to improve the life predictions.
The verification of the accuracy of the improved life prediction model was then provided by comparing against coupon fatigue test results.

Results and conclusions
The predicted life to test life ratio range of 1.95-2.87 with the *original* equivalent strain transfer function was improved to life ratio range of 1.05-1.30 with the *developed* equivalent strain transfer function.

Applicability
The inclusion of the developed equivalent strain transfer function improves the fatigue initiation life predictions for complex spectra that vary in spectral content, R-ratio, and peak stress.

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Development and Evaluation of Mean Stress Correction Techniques for Improved Fatigue Life Prediction

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Development and Evaluation of Mean Stress Correction Techniques for Improved Fatigue Life Prediction

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Key Words: Mean Stress Correction, Fatigue life, Durability, Economic Life

ABSTRACT

The accuracy of fatigue life predictions of aircraft structure has significant consequences for the life cycle costs and sustainment of an aircraft fleet. Shortfalls in achieved life against prediction can have serious consequences for both airworthiness and cost of ownership, whilst under-prediction results in unnecessary weight or manufacturing cost.

This technical paper presents the results of modifications to a local stress-strain based fatigue prediction model to include the effects of continually varying local stress ratios in order to improved fatigue initiation life predictions. As part of a recent full scale fatigue test program on a transport aircraft an ‘industry standard’ fatigue life prediction model was adopted and used for test interpretation activities. This strain-life based model incorporated local stress-ratio (local minimum stress/local maximum stress) effects in an equivalent strain transfer function and in conjunction with un-notched cyclic strain-life property of a material, provided predictions of damage initiation life. Comparison of the performance of the model against a series of coupon tests run using transport aircraft wing spectra for the specific purposes of model verification showed, for some spectra types, very wide variations of predicted fatigue initiation life to that of the experimental life. The performance of the generic equivalent strain function incorporated into the original model was suspected as one of the causes. A number of alternative equivalent strain transfer functions were developed to improve the life predictions.

The verification of the accuracy of the improved life prediction model was then provided by comparing against coupon fatigue test results representing two transport wing locations and complex stress spectra based on in-service usage of a transport aircraft operated by four different countries. In the best case, the predicted life to test life ratio range of 1.95-2.87 with the *original* equivalent strain transfer function was improved to life ratio range of 1.05-1.30 with the *developed* equivalent strain transfer function.

INTRODUCTION

Fatigue initiation life (durability) is an important economical factor in the design of aircraft structure. Meeting the design life goal without fatigue crack initiation has benefits for sustaining airworthiness and in reducing the ownership costs. Minimizing the incidents of fatigue cracks due to the aircraft operational usage, also minimizes aircraft downtime for repairs and maintenance actions. A longer fatigue life, however, typically requires lower operating stresses that will increase the design weight of the structure with consequential operational inefficiencies. Transport type aircraft with their multi-load path structural design features can often tolerate the growth of small cracks, However, to maintain optimized weight of the structural design, a balance between the crack initiation stage and crack propagation stage is essential. An accurate method to predict fatigue initiation and crack growth life is essential for economical and efficient structural design.

This paper presents work that resulted in improved predictions of fatigue initiation life. The development of improved mean stress correction techniques in equivalent strain formulations within a strain-life based fatigue prediction model is presented and the predicted fatigue lives of four different complex operational usage spectra at two lower surface wing locations are compared to test demonstrated fatigue lives for the same spectra and locations.

SPECTRA TESTS CORRELATION

In support of a recent transport aircraft Service Life Assessment Program[1] a notched coupon test program was conducted to evaluate the relative criticality of operational usage of four countries flying the same aircraft. The partners in the program were aware that they flew their aircraft differently, so the correct prediction of the severity of their in-service spectra was of vital concern, not only so their aircraft could be correctly correlated to the full scale test results, but that their proposed Individual Aircraft Tracking programs would be effective but safe. Fatigue life predictions of the in-service spectra using an existing strain-life based Fatigue Analysis of Metallic Structures[2] code, FAMS, were obtained and correlated to coupon test results for the same spectra. The details of the coupon test program, test results and the analysis to test correlation are presented in the following sections. A brief overview of the local stress-strain based FAMS code is provided prior to the details of the coupon test program.

Crack Initiation Life Prediction Approach

The FAMS code determines crack initiation life based on local stress and strain at stress raisers, accounting for the localized plastic deformation caused by infrequent occurrence of severe loadings. Using modified Neuber's rule, far-field nominal stresses are converted into the corresponding local stress-strain with its characterizing hysteresis loops. The local stresses-strains from continually varying nominal cyclic stresses are rainflow cycle counted, which pairs peaks and valleys into full and half cycles, with each pair having a defined strain amplitude and mean stress. To account for non-zero local mean stress, Morrow's mean stress correction is employed through an equivalent strain formulation:

$$\varepsilon_{eq} = \delta_{\varepsilon} \ / \ \{1 - \sigma_m/\sigma_f\},$$

where: δ_{ε} = strain amplitude; σ_m = local mean stress; σ_f = fracture stress

The damage associated with each equivalent strain cycle is computed using an experimentally derived strain-life curve (typically generated from small round smooth specimens with Kn=1.0 and R=0), and the total damage is summed using Miner's rule.

Coupon Spectra Tests

All the variable amplitude spectra notched coupon tests were conducted by the National Aerospace Laboratory(NLR) of The Netherlands. A standard notched coupon specimen, shown in Figure 1, was used for all the spectra tests. The flight-by-flight spectra for the operational mission mix of four countries were developed for two fatigue critical areas (FCAs) on the lower surface of the wing of the transport aircraft. Table 1 summarizes the details of various test spectra [3]. Three to four replicates were tested for each spectrum.

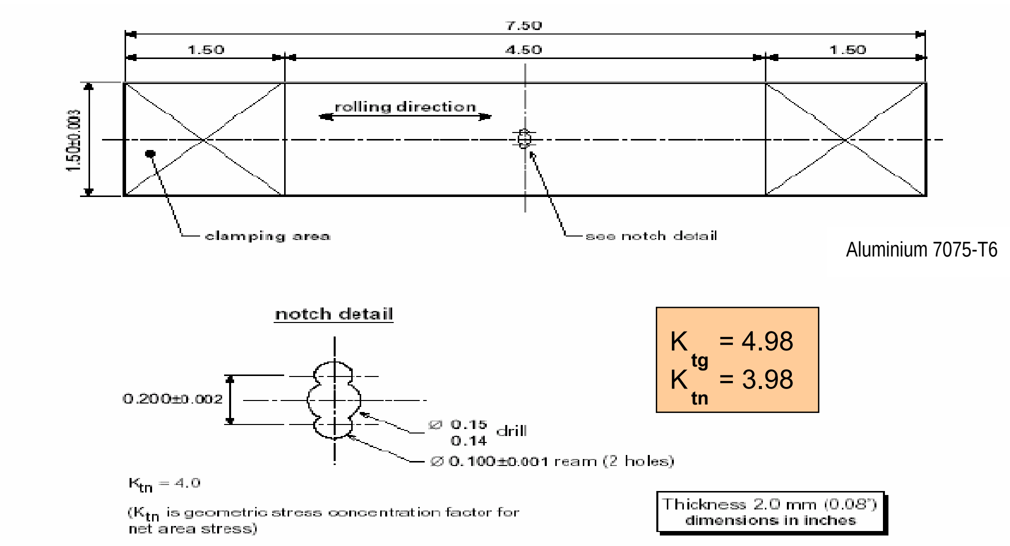

Figure 1 Test Coupon Geometry

Table 1 Test Spectra Details

Spectrum	No. of Flights Per Pass	Peak/Valley Pairs FCA301	Peak/Valley Pairs FCA361	Flight Hours Per Pass
A	4,244	437,650	474,062	14,462
B	3,103	302,546	291,206	15,000
C	3,121	483,387	433,217	15,000
D	3,548	633,797	590,602	15,000

Figures 2 and 3 shows the comparison of cumulative exceedance curves for FCA301 and FCA361 for all the flight-by-flight test spectra. FCA301 is located at the wing/fuselage chord joint and has tension stress dominated spectra. FCA361 is located outboard of the inboard nacelle and has tension-compression stress dominated spectra.

FCA301 stress spectra-A in Figure 2 clearly shows that Spectra-A is most severe for the up bending followed by Spectra-C. Spectra-B through Spectra-D are more severe than Spectra-A, in the wing down bending events. FCA361 stress Spectra-A is more severe than the Spectra-B through Spectra-D, in both the up bending and down bending events. The relative severity of the cumulative stress exceedance curves does not necessarily depict the relative severity of ensuing test life, because of stress sequence effects. The results of the spectra tests presented in Table 2 confirms this.

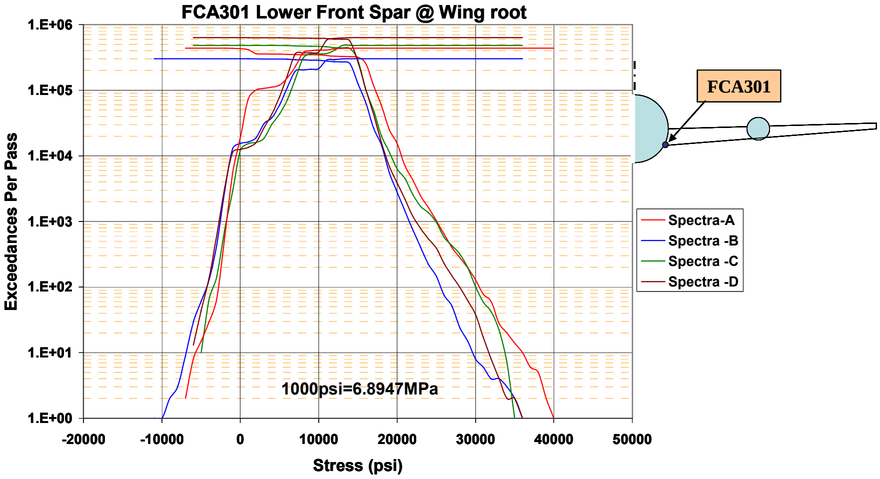

Figure 2 Gross Area Stress Exceedance Comparison – FCA301

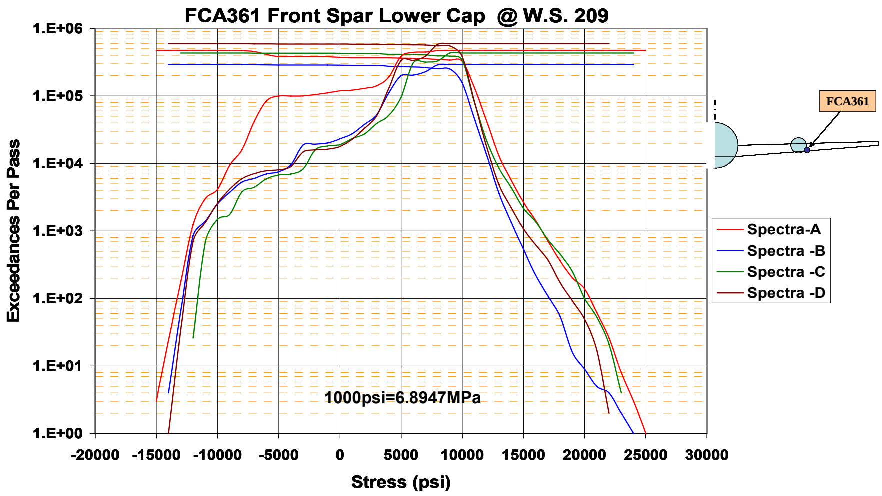

Figure 3 Gross Area Stress Exceedance Comparison – FCA361

Individual coupon spectra test results in terms of test hours to 0.008” crack and test hours to failure are presented in Table 2 for two lower surface wing locations. The average test lives at failure are also presented and utilized for correlation with the FAM’s predictions.

Table 2 – NLR Coupon Test Results

Spectrum (No. of Flights Per Pass/ Flight Hours per Pass)		FCA301 - Wing Lower Front Spar @ Wing Root		FCA361 - Wing Lower Front Spar @ WS 209	
		Life in Hours		Life in Hours	
		@0.008 inches	@ Failure	@0.008 inches	@ Failure
A (4244/14462)		19,222 19,026 15,245 17,213	33,673 34,369 33,374 33,673	8,663 9,578 9,578	17,755 18,969 18,225
	Mean Life	17,677	33,772	9,273	18,316
B (3103/15000)		28,838 28,838 29,669	43,901 43,901 43,901	25,800 37,333 32,938 24,836	36,354 49,634 43,842 37,237
	Mean Life	29,115	43,901	30,227	41,789
C (3121/15000)		11,782 12,251 13,188	20,051 23,371 23,596	16,624 15,374 13,801	27,862 23,831 23,649
	Mean Life	12,407	22,339	15,266	25,114
D (3548/15000)		24,019 25,277 17,884	32,810 32,373 30,985	15,410 15,410 15,721	23,210 22,978 22,681
	Mean Life	22,393	32,056	15,514	22,956

FAMS Fatigue Life Prediction and Correlation

The strain-life approach uses a ‘Neuber notch factor’ or ‘fatigue notch factor’ to describe the effect of the stress concentration. The fatigue notch factor, K_f , accounts for the stress gradient effects near notches and as such it is smaller than the geometrical stress concentration factor, K_t. Instead of using the conventional relation between K_t, the radius at the notch, and a characteristic dimension for the material to provide an estimate of fatigue notch factor, the fatigue notch factor based on gross area stress, K_{fg} was determined experimentally from the mean test life of FCA301 and Spectra A. This test demonstrated K_{fg} was found to be 3.67 and can be compared to the K_{tg} of 4.98. Since, the coupon specimens are identical for all the tests, analytical predictions for all the remaining test spectra was made using a K_{fg} of 3.67. For the test coupon specimen configuration, “q” (=(K_{fg} -1)/{K_{tg} – 1}), the notch sensitivity parameter, was back derived and found to be 0.6759.

Figure 4 graphically shows FAMS predicted life to test life ratio for each of the four spectra. For FCA 301 spectra A the test to analysis ratio is 1.0 as this result was used to obtain the test demonstrated K_{fg} of 3.67. The mean test life for each spectrum in hours from Table 2 are also shown in the bars for comparison. For tension dominated spectra of FCA301, Spectra C shows relatively good correlation, but the life predictions for Spectra B and D are overestimated by factors of 1.35 and 1.58 respectively. For the tension-compression dominated spectra of FCA361, the analysis to test life ratio range is between 1.95 to 2.87, significantly unconservative.

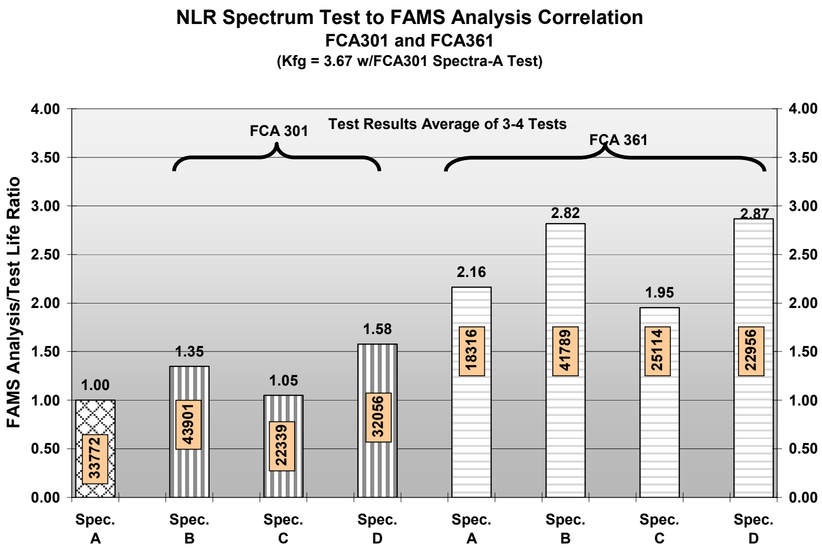

Figure 4- Analysis to Test Correlation

Potential Reasons for Discrepancy

In comparing the test results and evaluating the predicted fatigue life for different spectra and analysis locations, the influence of two potential factors could result in the observed differences. To a degree, smooth specimen simulation with Neuber's approach applied to notched structure is quite empirical and may result in this behavior, depending upon the notch factor, material properties; cyclic stress-strain relationship of the material as well as strain-life relationship of the material. But since the K_{fg} is derived using the same material properties in the analysis of the different spectra, material properties do not appear to be the prime factor. On the other hand, the validity of equivalent strain in addressing the effect of variable local compression or tension mean stress is largely unverified, and appears to be a prime factor influencing the accuracy of fatigue life predictions.

The influence of local mean stress can be characterized as the influence of stress ratio, R, the ratio of a local minimum stress to a local maximum stress in a fatigue load cycle. In flight by flight spectra, R-ratios can vary any where from minus infinity to approaching positive 1. For improved prediction of fatigue life, the variable R-ratio effect needs to be addressed satisfactorily.

The FAMS software calculates the local stress and strain state for every maximum and minimum stress pair in the rainflow counted sequence. At the commencement of the analysis, the residual stress and strain state will be zero. The software includes an option to carry over the residual stress/strain state at the completion of the initial processing of a spectrum sequence or 'block' (Pass #1) and use that stress/strain state at the commencement of a second processing of the same sequence (Pass #2). R-ratio distributions from the damaging cycles within each of the eight flight-by-flight spectra were generated and studied.

Figures 5 and 6 shows the number of damaging cycles in R-ratio bands varying from -2.5 to 0.95, in increment of 0.05, plotted using mid-value of each band. R-ratio distribution is shown for both passes of the spectra within FAMS. The influence of carry-over residual stress from the pass #1 to pass # 2 is evident. The magnitude of the shift to the left in pass #2 (more negative R-ratio) is dependent upon the magnitude of residual stress carry-over and application position of maximum spectrum stress in the first pass. Figure 5 shows FCA361 R-ratio distribution for Spectra-C and Figure 6 shows FCA361 R-ratio distribution for Spectra-B. In Spectra-C, the peak stress in the spectra occurs very early in the test and hence R-ratio shift in the pass #2 is very little. On the other hand, in Spectra-B, the peak stress occurs near the end of the test resulting in significant shift in R-ratio distribution for pass #2.

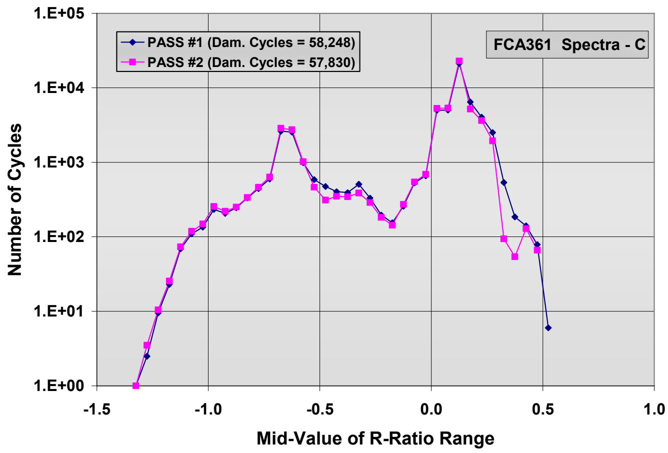

Figure 5 – Damaging Cycles Distribution in R-Ratio Bands – FCA361- Spectra C

In addition to the damaging cycles distribution in the ranges of R-ratio, the percentage of total damage distribution in R-ratio ranges were also evaluated to discriminate the distribution of damage and identify value of R-ratio at which the median damage for each test spectra take place. Figures 7 and 8 shows the damage distribution for FCA301 and FCA361, respectively, and also show the R-ratio at which median damage occurs. The figures show the spectral variation that can occur, not only along the lower surface of a wing but also from among the operators of nominally the same aircraft type. For FCA301, median damage is in a R-ratio range of -0.76 to -1.10. For FCA361, median damage is in the R-ratio range of -0.85 to -1.0. This damage distribution shows alarming high percent damage in negative R-ratio regime beyond R=-1. The inference can be made that FAMS equivalent strain equation over predicts equivalent strain for compressive mean stress and also under predicts equivalent strain for tensile mean stress.

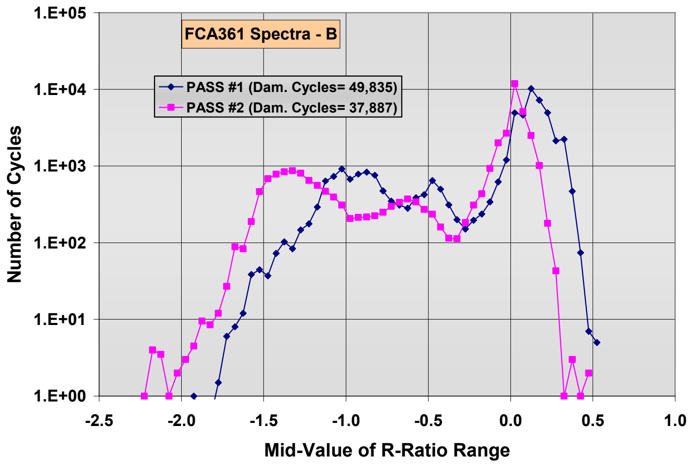

Figure 6 - Damaging Cycles Distribution in R-Ratio Bands – FCA361 Spectra B

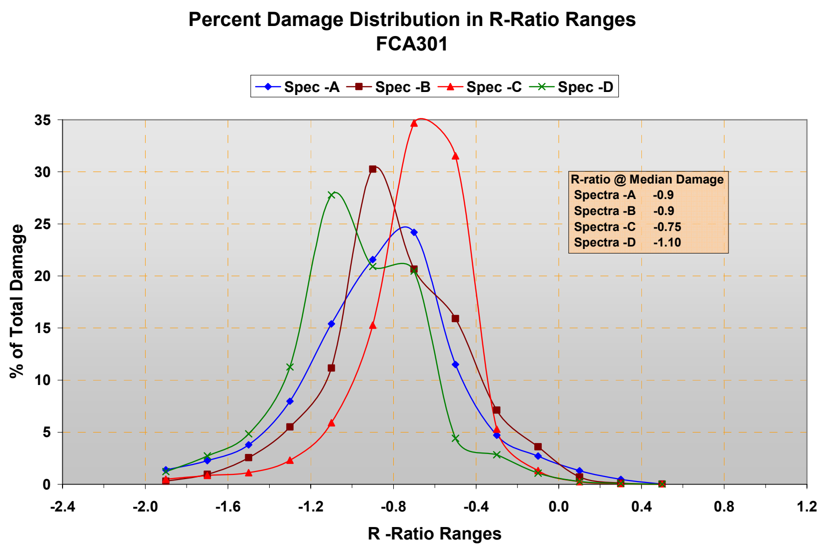

Figure 7 - Damage Distribution in R-Ratio Bands – FCA301

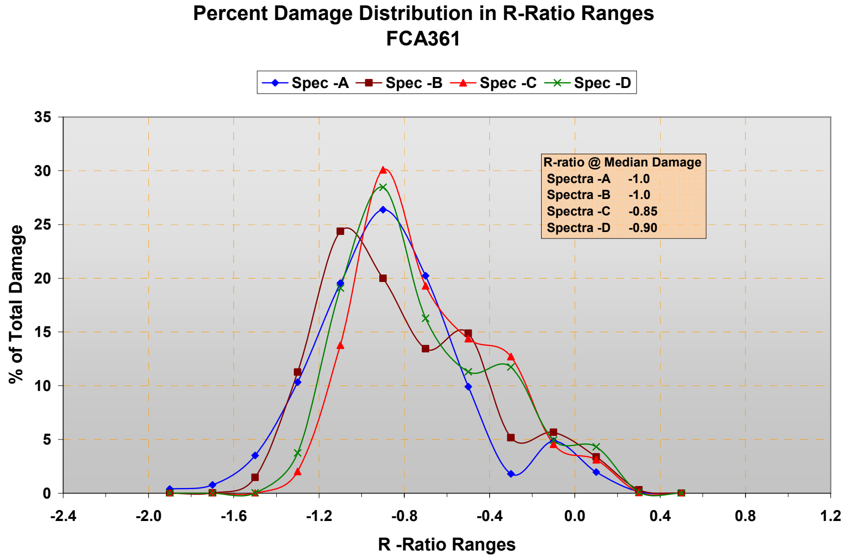

Figure 8 - Damage Distribution in R-Ratio Bands – FCA361

PROPOSED ENHANCEMENTS AND VERIFICATION

In this section of the paper three proposed alternate Equivalent Strain Equations (ESEs) are identified. The coupon test data generated by DSTO-Australia[6] were used in the derivation of material dependent parameters for the proposed ESEs. The verification of the developed ESE was accomplished with modified ESE analysis prediction of the eight test spectra (2 analysis locations for each of the four spectra) and comparison of the predicted results with the NLR spectra coupon test results.

Modified Equivalent Strain Equations

The parameters that effects the accuracy of equivalent strain amplitude (and in turn, fatigue life predictions) may include: notch factor, stress ratio, local strain amplitude or range, and local maximum stress. Three alternate equivalent strain equations are proposed to include the effects of above mentioned parameters and to improve fatigue initiation life prediction. The material dependent parameters will have to be developed empirically for the materials of interest. Table 3 identifies the forms of proposed ESEs, as well as the ESE in the baseline version.

LMAero #1 ESE is a modification of Loopin's ESE[4]. One of the many forms of Loopin's equation was used in the crack initiation prediction on a recent aircraft development program. It establishes equivalent strain based on the sign of "A-Ratio", which is a ratio of local mean stress to local stress amplitude. The resulting ESE requires two material dependent parameters.

LMAero #2 ESE is based on Walker's equation[5] which incorporates local strain amplitude and maximum local stress, which implicitly accounts for the stress ratio effects. The resulting ESE requires two material dependent parameters.
LMAero #3 ESE is also a further extension of Walker's equation but addresses R-ratio and fatigue notch factor effects explicitly. The resulting ESE requires three material dependent parameters.

Table 3 Proposed ESE

Equivalent Strain Method (Influence of Mean Stress)	ESE Basis	Equivalent Strain Equation
Morrow's Mean Stress Correction (FAMS)	**Morrow**	$\varepsilon_{eq} = (\varepsilon_a) / [1 + \sigma_{mean}/\sigma_F]$
LMAero #1	**Loopin**	If A>= 0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 + \sigma_{mean}/\sigma_a]^{\beta}$ If A<0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 - \sigma_{mean}/\sigma_a]^{-\alpha/\beta}$
LMAero #2	**Walker**	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha}$
LMAero #3	**Walker**	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha}$ $\times [(1 - R)/(2.46^*K_{fn})]^{\gamma}$

Test Data for Developing ESE Parameters Values

In order to develop material data for the proposed ESEs and their parameters values, constant amplitude coupon tests at varying R-ratio's and with different stress concentration specimens were conducted by DSTO-Australia[6], for 7075-T6 aluminum. The configuration of the test coupons is shown in Figure 9. K_t values in Figure 9 are the K_{tn} based on net cross section at the stress concentration. The DSTO testing was conducted using constant amplitude load control until the failure, with cycling rates limited in inverse proportion to the calculated plastic strain amplitude at the notch. A total of 56 coupons, comprised of 20 coupons for K_{tn} of 3.98, 26 coupons for K_{tn} of 2.73 and 10 coupons for K_{tn} of 1.0, were tested to failure. All the test specimens were tested with tensile mean stress.

The fatigue notch factor, K_{fn} was determined using, $K_{fn} = 1 + 0.6759*(K_{tn} - 1)$. The exact values of K_{tn} was determined from the geometry presented in Figure 9, and using the equation:

$$K_t n = \frac{1 - 0.08\left(\frac{D}{W}\right) + 0.325\left(\frac{D}{W}\right)^2}{\sqrt{1 - \frac{D}{W}}}\left(1 + \sqrt{\frac{2D}{r}}\right)$$

The notch sensitivity factor, "q" (=0.6759) was determined from the NLR coupon test results as shown earlier. The initial values of applicable ESE parameters such as: α, β, γ, and δ, were obtained using multiple linear regression analysis with expected equivalent strain to correlate with coupon test life. For each of the proposed ESE, the DSTO coupon test results were interpreted in terms of cycles to failure and respective equivalent strain for the net section maximum and minimum stress, and K_{fn} for the specimen configurations.

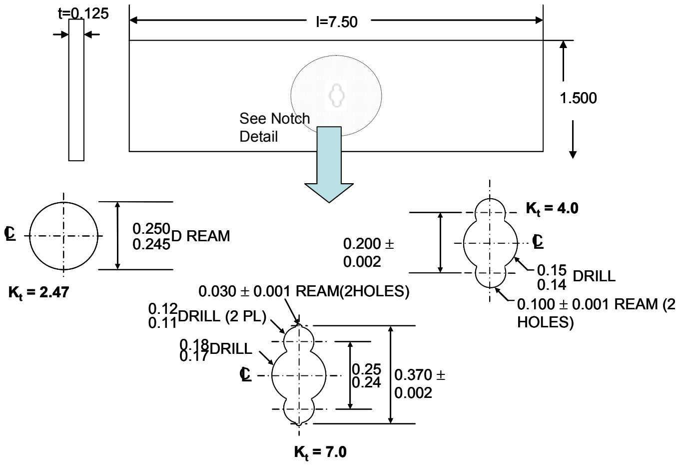

Figure 9 - Notched Coupon Test Specimen Configurations – DSTO Test Program

For each prospective ESE the optimization process sought to maximize the coefficient of correlation value ($r^2 \rightarrow 1.0$) for each of the log-linear strain life equations. Figures 10 through 12 shows the optimized equivalent strain vs. failure cycles relationship. These figures for the proposed ESEs also shows the empirically derived ESE parameters values and established relationship between failure cycles and equivalent strain.

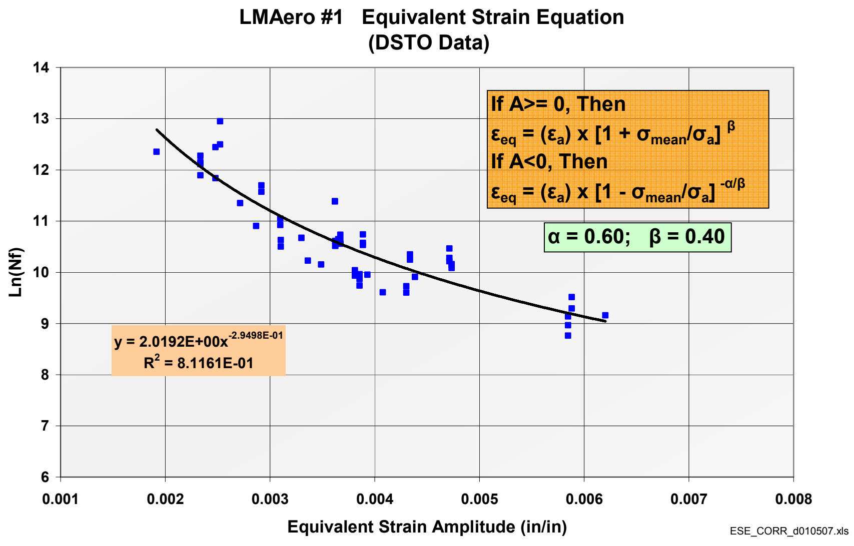

Figure 10 - LM Aero # 1 ESE – Strain vs. Cycles (DSTO)

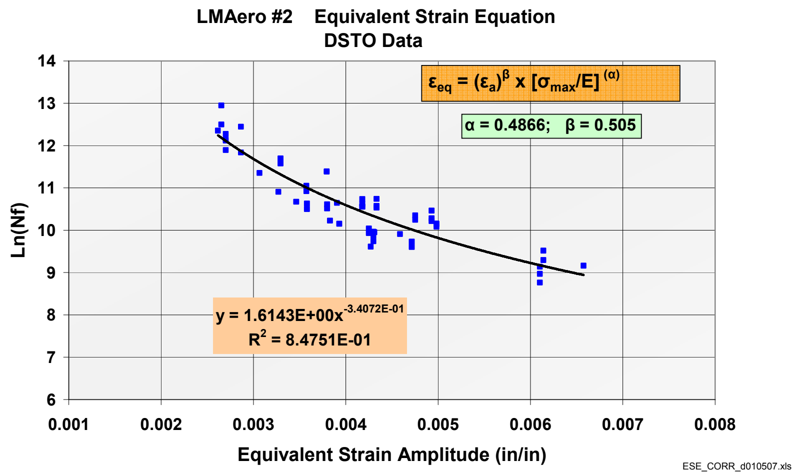

Figure 11 - LM Aero # 2 ESE – Strain vs. Cycles (DSTO)

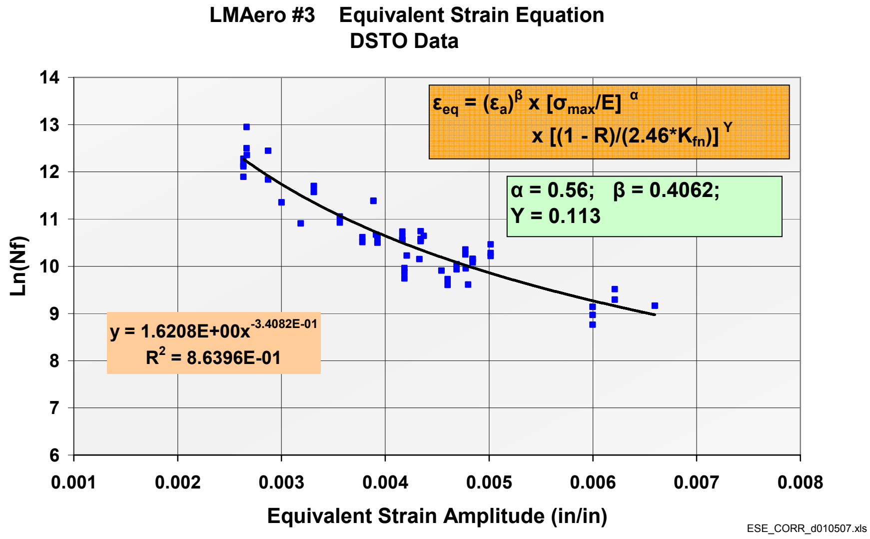

Figure 12 - LM Aero # 3 ESE – Strain vs. Cycles (DSTO)

Table 4 summarizes the ESE parameters values and strain vs. life equation constants (P1, P2), based on FAMS material database for Al 7075-T6 material.

Table 5 summarizes the ESE parameters values and strain vs. life equation constants (P1, P2), based on DSTO test results which were generated under the regime of: loads control, variable fatigue notch factor, variable R- ratios, and constant amplitude. The optimized values for ESE parameters shown in Table 5 are for Al 7075-T6 material.

Table 4 Values of ESE Parameters and Strain vs. Life Equation Constants (FAMS)

ESE -Option	Equivalent Strain Equation (FAMS Strain-Life Data)	K_f	Equation Constants				$Ln(Nf) = P1^*(Eq. Strn)^{P2}$	
			α	β	Y	σ_F (ksi)	P1	P2
FAMS	$\varepsilon_{eq} = (\varepsilon_a) / [1 + \sigma_{mean}/\sigma_F]$	3.67				110	0.39182	-0.59011
LMAero #1	If A>= 0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 + \sigma_{mean}/\sigma_a]^{\beta}$ If A<0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 - \sigma_{mean}/\sigma_a]^{-\alpha/\beta}$	3.66	0.18	0.489			0.39182	-0.59011
LMAero #2	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha}$	3.89	0.58168	0.42974			0.39182	-0.59011
LMAero #3	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha} \times [(1 - R)/(2.46^*K_{fn})]^{Y}$	4.1	0.6396	0.3578	0.0732		0.39182	-0.59011

Table 5 Values of ESE Parameters and Strain vs. Life Equation Constants (DSTO Tests)

ESE -Option	Equivalent Strain Equation (DSTO Test based Strain-Life Data)	K_f	Equation Constants				$Ln(Nf) = P1^*(Eq. Strn)^{P2}$	
			α	β	Y	σ_F (ksi)	P1	P2
FAMS	$\varepsilon_{eq} = (\varepsilon_a) / [1 + \sigma_{mean}/\sigma_F]$	3.67				110	0.39182	-0.59011
LMAero #1	If A>= 0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 + \sigma_{mean}/\sigma_a]^{\beta}$ If A<0, $\varepsilon_{eq} = (\varepsilon_a) \times [1 - \sigma_{mean}/\sigma_a]^{-\alpha/\beta}$	3.41	0.6	0.4			2.01920	-0.29500
LMAero #2	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha}$	3.45	0.4866	0.505			1.61430	-0.34070
LMAero #3	$\varepsilon_{eq} = (\varepsilon_a)^{\beta} \times [\sigma_{max}/E]^{\alpha} \times [(1 - R)/(2.46^*K_{fn})]^{Y}$	3.57	0.56	0.4062	0.113		1.62080	-0.34080

Verification of Modified ESE

The verification of the improvement in life predictions was accomplished using the original NLR coupon test results for the eight flight-by-flight spectra. Since, the same configuration of test coupon was used in testing the NLR spectra, K_{fg} for all the coupon test ought to be the same. The K_{fg} was determined using average test results of Spectra-A at FCA301 as the basis for each ESE. For example, K_{fg} of 3.67 was determined for the *original* ESE iteratively by equating damage of 1.0 at 33,772 average test hours of FCA301 and Spectra A. The analysis for the remainder of Spectra-B through -D at FCA301 and for all the Spectra-A through -D at FCA361 then used the test demonstrated K_{fg} values for each proposed ESE option. The corresponding strain-life curves for each modified ESE were also developed from the results of DSTO coupon tests, and were incorporated into a modified version of FAMS used in conjunction with the related ESE option. This strain-life relationship for each modified ESE is expressed in equation form as:

$$Ln(Nf) = P_1^*(\varepsilon_{eq})^\wedge P_2,$$ where P_1 and P_2 are defined in Table 4.

Table 6 and Figure 13 show predicted fatigue initiation life for each test Spectra-B through -D for FCA301, in terms of life ratio with respect to the average coupon test life from Table 2. It shows the life ratios for each spectra using the original ESE and the modified

ESEs, using strain-life data from the FAMS material database, as well as, DSTO test derived strain-life data. For FCA301 and Spectra-A through -D, modified ESEs shows a better correlation with the NLR test results. The modified ESEs predictions using DSTO test derived strain-life data shows even better predictions, for Spectra-B through Spectra-D, than the prediction using FAMS strain-life data.

Table 6 - Correlation of Test Results vs. Predicted Life w/Proposed ESE – FCA301

Strain-Life Basis	Analysis Approach	Kfg Based on FCA 301-Spec. A.	Spectra A		Spectra B		Spectra C		Spectra D	
			Spectra	33772	Test Life	43901	Test Life	22339	Test Life	32056
			Ana.	Ana/Test	Ana.	Anal/Test	Ana.	Anal/Test	Ana.	Anal/Tes
FAMS	FAMS (Morrow's Eq.)	3.67	33,499	0.99	59,209	1.35	23,442	1.05	50,561	1.58
FAMS	LMAero Mod #1 (β=0.489/ α=0.18)	3.66	34,185	1.01	54,146	1.23	23,490	1.05	52,183	1.63
	LMAero Mod #2 (β=0.4297/ α=0.5817)	3.89	33,912	1.00	50,166	1.14	30,703	1.37	52,938	1.65
	LMAero Mod #3 (β=.6578/ α=.6396 / Y=.0732)	4.10	33,903	1.00	44,909	1.02	28,780	1.29	48,391	1.51
LMAero (DSTO Test Data)	LMAero Mod #1 (β=0.4/ α=0.6)	3.41	33,866	1.00	36,727	0.84	24,199	1.08	44,283	1.38
	LMAero Mod #2 (β=0.505/ α=0.4866)	3.45	33,886	1.00	44,096	1.00	29,155	1.31	49,406	1.54
	LMAero Mod #3 (β=.4062/ α=0.56 / Y=0.113)	3.57	33,977	1.01	43,410	0.99	25,359	1.14	47,816	1.49

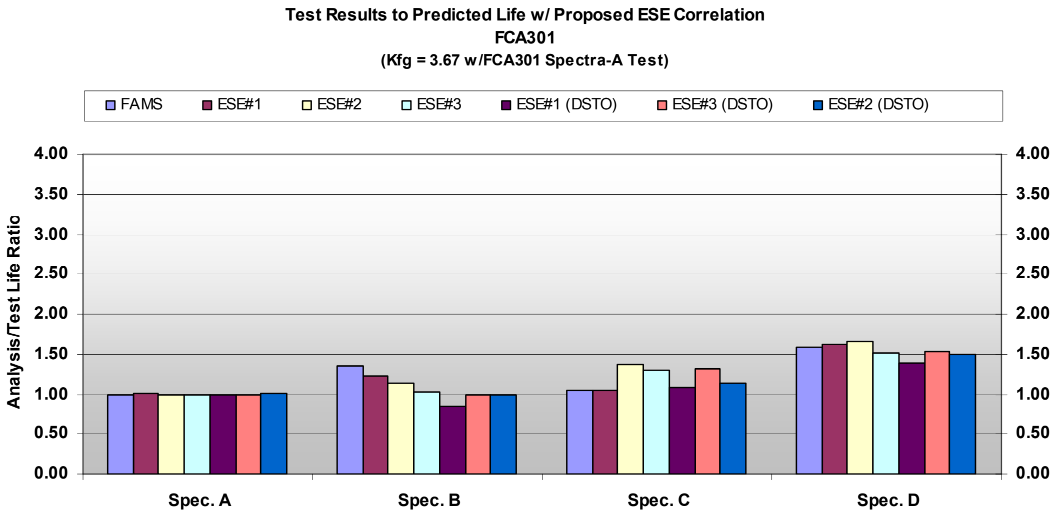

Figure 13 – Test to Analysis w/ Proposed ESE Correlation for FCA 301

Table 7 and Figure 14 show the similar predictions for FCA361. The modified ESE shows significant improvement in fatigue life prediction, for all the spectra, using either FAMS strain-life data or DSTO test derived strain-life data. For each ESEs, DSTO derived strain-life data shows much improved life prediction than the FAMS strain-life data. The life ratio range of 1.95- 2.87 with the original equivalent strain equation in FAMS is reduced to 1.05-1.30 with LMAero # 2 ESE. This is a significant improvement in fatigue life prediction for FCA361. Overall, all the ESE options show significant improvement in life predictions for Spectra-A through -D.

Table 7 - Correlation of Test Results vs. Predicted Life w/Proposed ESE – FCA361

Strain-Life Basis	Analysis Approach	Kfg Based on FCA 301-Spec. A.	Spectra A		Spectra B		Spectra C		Spectra D	
			Test Life	18,316	Test Life	41789	Test Life	25114	Test Life	22956
			Ana.	Anal/Test	Ana.	Anal/Test	Ana.	Anal/Test	Ana.	Anal/Tes
FAMS	FAMS (Morrow's Eq.)	3.67	39,642	2.16	117,762	2.82	49,040	1.95	65,822	2.87
FAMS	LMAero Mod #1 (β=0.489/ α=0.18)	3.66	32,419	1.77	88,494	2.12	39,152	1.56	47,089	2.05
	LMAero Mod #2 (β=0.4297/ α=0.5817)	3.89	28,898	1.58	85,384	2.04	40,177	1.60	42,281	1.84
	LMAero Mod #3 (β=.6578/ α=.6396 / Y=.0732)	4.10	28,677	1.57	87,447	2.09	35,668	1.42	46,199	2.01
LMAero (DSTO Test Data)	LMAero Mod #1 (β=0.4/ α=0.6)	3.41	28,221	1.54	51,137	1.22	32,080	1.28	33,480	1.46
	LMAero Mod #2 (β=0.505/ α=0.4866)	3.45	23,878	1.30	47,891	1.15	26,327	1.05	26,217	1.14
	LMAero Mod #3 (β=.4062/ α=0.56 / Y=0.113)	3.57	28,482	1.56	58,203	1.39	31,058	1.24	30,854	1.34

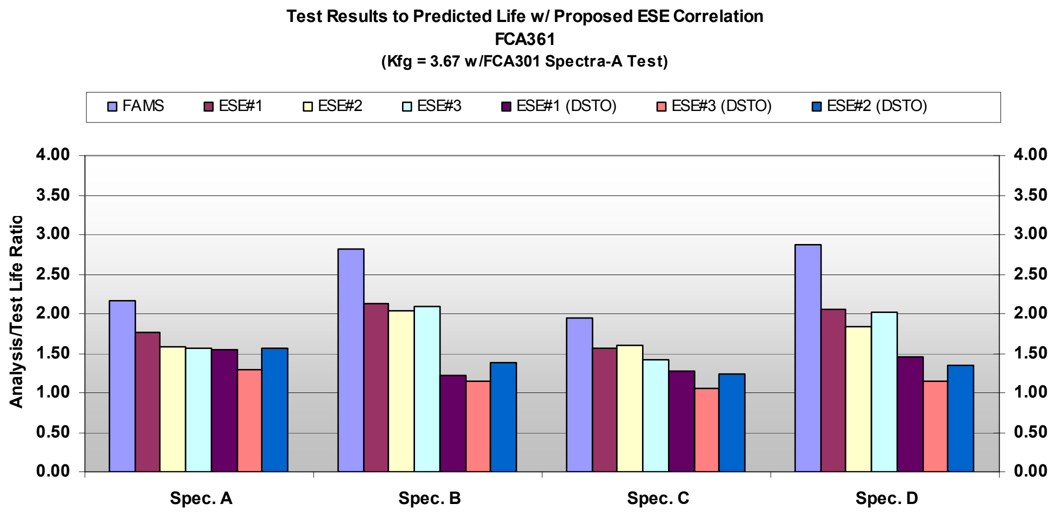

Figure 14 – Test to Analysis w/ Proposed ESE Correlation for FCA 361

Having demonstrated the effectiveness of modified ESE#2 on improving the fatigue initiation life prediction, it is note worthy to visulize the changes in the damage distribution as a function of R-ratio ranges. Figure 13 shows the comparison of original FAMS and ESE #2 modified damage distribution at FCA361 for all four spectra. It shows the shift in equivalent strain computation for tensile and compressive mean stresses in the right direction and shows the effeciveness in fatigue initiation life prediction with modified ESE. Analysis to test life ratios for original equivalent strain transfer function and for modified equivalent strain function (LMA #2) are also shown in Figure 13 for each of the four spectra at FCA361.

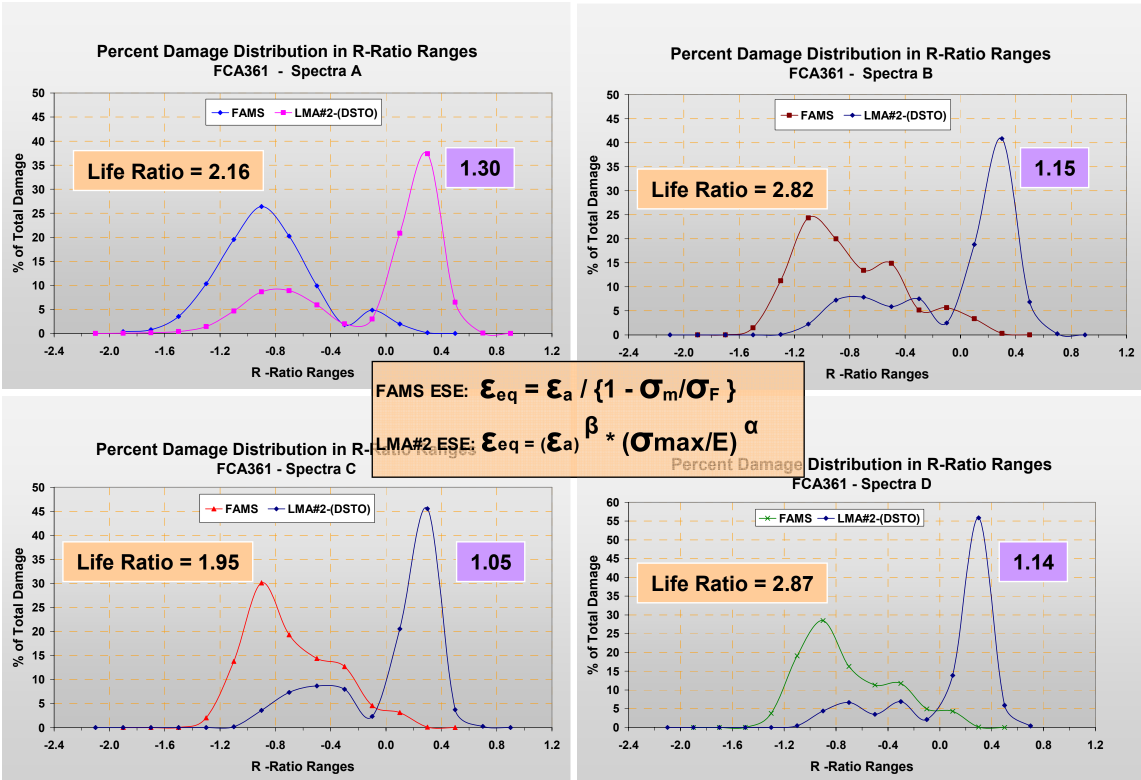

Figure 13 – Comparison of Post-ESE Damage Distribution- FCA361

CONCLUDING REMARKS

The accurate prediction of fatigue lives for a range of complex spectra that vary in spectral content, R-ratios, and peak stress is not an easy task for the current state of the art strain-life based fatigue life prediction model. Nevertheless, such a performance is required if aircraft are firstly to be designed to be structurally efficient, and then effectively managed through their service life. It has been demonstrated that inclusion of alternate equation forms for stress ratio effects improves fatigue initiation life predictions for an existing strain-based model and alleviates conservatism in the life predictions compared with the original mean stress effect correction. Three modified equivalent strain equations are identified and optimized based on coupon data and the resulting new life predictions are correlated to the original variable amplitude flight-by-flight sequences to demonstrate the improvement.

The use of strain-life data obtained from load control constant amplitude fatigue tests conducted at variable R-ratio and variable fatigue notch factor, provides a better fatigue initiation life prediction of complex variable amplitude spectra than did the baseline predictions which used handbook un-notched specimen strain-life data.

The current results are determined for 7075-T6 material. It is recommended to investigate whether the presented modification also gives improved fatigue life results for other aerospace materials like 2024-T3, 7050-T73, or 7075-T73. This requires the availability of similar strain-life data obtained from tests for these materials.

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