The Effect on Fatigue Crack Growth Under Spectrum Loading of an Imposed Placard “G” Limit

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ABSTRACT

Fatigue cracking problems in the main spar of the Mirage Aircraft operated by the Royal Australian Air Force prompted engineers to impose flight loading limitations on certain aircraft to slow down the crack growth rate. This paper presents the results of experimental and computer prediction studies to determine the effect on fatigue crack growth behavior under spectrum loading of such limits.

KEYWORDS

fatigue, crack, spectrum loading, life prediction

INTRODUCTION

Driven by a requirement to extend the life-of-type of the Mirage 111 aircraft operated by the Royal Australian Force (RAAF), several fatigue life improvement techniques were developed. These techniques, which are detailed in Reference 1, apply to a front flange bolt hole on the lower surface of the wing main spar and involve cold expansion of the bolt holes, the use of interference fit steel bushes in bolt holes and a combination of the two. As reported in Reference 2, a basic criterion of these life extension procedures was that existing fatigue cracks should be completely removed. Due to the variability in the size of cracks which existed in operational aircraft, some could not be completely removed. Additionally, due to the large cracks found in certain aircraft, flight loading limits were imposed to reduce the risk of in flight structural failure and to reduce the crack growth rate. These limits were in the form of a g limit, also referred to as a placard limit. Their effect was to truncate the maximum positive load levels in the spectrum. Limits were imposed at +6.5g and +5g levels. Reference 3 details the g exceedences observed during the placarding and Reference 4 provides a rationale for operating the Mirages with known cracks in the primary structure. The premise of the g limitations was that an increase in fatigue life would result from a reduction in crack growth rate.

Removing certain peak loads however has the potential of decreasing the life due to the loss of beneficial fatigue crack retardation effects. Fatigue crack growth retardation is a well known and documented phenomenon in which crack growth is retarded due to the inclusion of overloads on a structure which is being subjected to cyclic stresses. References 5 and 6 demonstrate the delay effect on fatigue crack growth from a single peak tensile overload and multiple overloads respectively. From Reference 5, the greater the magnitude of the overload, the greater the delay effect on fatigue crack growth to the point where a sufficiently large overload will cause a crack arrest condition where the crack will not propagate under further cyclic loading. Reference 7 demonstrates that the delay effect applies to a spectrum load sequence also.

Fatigue crack growth retardation has been explained as being due to the crack closure phenomenon. Elber showed (Reference 8) that fatigue cracks are closed for a significant portion of the tensile load cycle, leaving this portion of the cycle ineffective in propagating the crack. Elber concluded that the crack closure is due to a wake of plastically deformed material behind the crack tip. This wake transmits compressive stresses across the crack face which keeps the crack closed for a significant portion of the load cycle. An overload increases the closure effect, thus reducing the subsequent fatigue crack growth rate.

This paper summarizes the results of experimental and analytical studies to determine the effect on fatigue crack growth behavior of modifying peak loads in the applied load spectrum. The Mirage aircraft spectrum was used, and experiments were conducted using centre cracked panel specimens of 7075- T651 Aluminium alloy. Fatigue crack growth calculations with the software packages CRACKS84 (References 10 to 12) and CGLIFE (Reference 13) were compared with the experimental results. Additional details of the work are given in Reference 9.

EXPERIMENTAL WORK

Experiments were conducted using a computer controlled, electro-hydraulic MTS fatigue test machine. Four separate spectra were used - the unmodified Mirage spectrum, the spectrum truncated at the 6.5g level, the spectrum truncated at the 5g level and the spectrum with the 7.5g peak increased to 8.5g. Crack growth behavior could then be compared to determine the effect of spectrum modification on crack growth behavior. AMSPEC software (References 14 and 15) was used to conduct the testing. All loading variables other than the spectrum itself were kept constant throughout the tests in order to isolate the effect of spectrum modification. The spectrum was available in Reference 1 in a form suitable for use with AMSPEC. The spectrum was defined as a block of 100 flights of four types; A, A', B, and C. Figure 1 shows a representative segment out of the block (flights 39 to 42) for the unmodified and 6.5g limit spectra. The 100 flights represented 1989 cycles of loading equivalent to 66.6 hours of flight.

Two types of specimens were used; ASTM compact tension (CT) specimens for constant amplitude testing and centre crack (CC) specimens with fixed ends for the spectrum testing. The constant amplitude tests were conducted to verify the crack growth properties of the material. As reported in Reference 9, the results of these tests compared well with handbook results for the constant amplitude tests.

A total of nine spectrum loading tests were performed under the four different spectra. The cracks were grown from an initial flaw size of 0.15 inch (2a=0.3 inch) which was achieved by pre cracking in accordance with ASTM guidelines from a 0.1 inch (2a=0.2 inch) notch. The results are plotted in Figure 2.

NUMERICAL WORK

The numerical analyses were performed with the CRACKS84 (References 10 to 12) and CGLIFE (Reference 13) software packages. Both of these packages were written to perform fatigue crack growth analysis on a cycle by cycle basis. The CRACKS84 code includes stress intensity factor solutions for various geometries as well as various crack growth rate models and several load interaction predictive models. In general, the user provides inputs for material properties, geometry, load interaction and the loading spectrum.

CRACKS84 offers three alternative models to account for load interaction effects; the Basic Willenborg Model, the Generalized Willenborg Model and the Willenborg/Chang Model. CGLIFE utilizes the Contact Stress Model. All these models account for retardation by reducing the applied stress intensity range to an effective level. If the current plastic zone measured from the current crack tip is less than the length of the maximum extent of the plastic zone for all previous loads, then load interaction effects are taken into account.

Prior to any spectrum analysis, it was decided to check the performance of CRACKS84 against the experimental results for constant amplitude crack growth. As reported in Reference 9, this check proved satisfactory and CRACKS84 was then run firstly with the unmodified spectrum, and then with the modified spectra. The results comparing experiment and prediction are plotted in Figures 3 to 6. The experimental results are given by unconnected symbols, while the various predictions are represented by the symbols connected with solid lines. The trends observed here in terms of crack growth behavior following spectrum modification echo those observed with the experiments.

Figure 7 compares the performance of the CRACKS84 and CGLIFE predictions for all four spectra and with all the load interaction models. CGLIFE uses the contact stress model exclusively to account for load interaction. Figure 7 plots maximum g load in the spectrum on the vertical axis and the ratio of predicted to experimental life (Np/Ne) on the horizontal axis. A value of Np/Ne=1.0 indicates that the predicted and experimental lives are equal. This plot shows the following:

i. CRACKS84 and CGLIFE may predict the fatigue crack propagation life accurately using a particular load interaction model and for a particular spectrum, but if the spectrum is altered, the accuracy may also change.

ii. The spectra containing higher loads produced conservative life estimates, whilst truncating the spectrum caused less conservative estimates.

iii. The introduction of load interaction models made the predictions less conservative (ie. a shift to the right on Figure 7).

DISCUSSION AND CONCLUSIONS

Several tests were performed to determine the effect of spectrum modification on fatigue crack growth behavior. Figure 2 demonstrates the dramatic effect on crack growth of altering the peak spectrum loads. Truncating the spectrum resulted in an increase in crack growth rate and a decrease in life. Increasing the magnitude of a rarely occuring high positive load had the effect of decreasing the crack growth rate and increasing life. These results highlight the importance of the fatigue crack retardation phenomenon on fatigue crack growth under spectrum loading. Significant retardation effects were lost when the peak loads were reduced, and the effects became more noticeable when the peak loads were increased.

Reference 16 presents the results of a study comparing experimental and predicted fatigue crack growth behavior in 2219-T851 aluminum. The analytical predictions were made using the Walker equation to predict crack growth rate, and the Generalized Willenborg or Vroman/Chang model to predict load interaction effects. The Vroman/Chang model was shown to provide better predictions, especially for loading cycles containing compressive stresses. That report concludes that the Vroman/Chang model adequately predicted fatigue crack growth behavior and fatigue crack growth lives for most of the testing conditions to within +30 percent. The results obtained here with CRACKS84 and CGLIFE had approximately the same accuracy for most cases, as can be seen in Figure 7.

The following conclusions are made:

i. The imposition of a placarded g limit on a fighter type aircraft such as the Mirage may result in an increase in the crack growth rate for a mode I crack subjected to tensile loads associated with positive g manuevers. The amount of crack growth rate increase will depend on the amount of retardation present from the initial spectrum and the level of the imposed limit.

ii. When determining the severity, from a fatigue crack propagation viewpoint, of an anticipated fighter aircraft load spectrum, account must be taken of the beneficial retardation effects resulting from rarely occurring, high positive loads. Omission of these loads will result in a spectrum with a lower maximum peak, but with increased fatigue crack propagation severity.

iii. Care must be taken when evaluating the results of a prediction using the methodology of programs such as CRACKS84 and CGLIFE. These programs use a combination of many empirically based models to predict fatigue crack growth behavior under complex variable amplitude loading. The prediction may match experiment closely for a particular load history, but retaining the same parameters and adjusting the load history will affect the accuracy. Additionally, it appears from this study that the greater the amount of retardation present, the more conservative the prediction.

REFERENCES

[1] Mann, J.Y., A.S. Machin, W. F. Lupson, and R. A. Pell, "The use of interference fit bolts or bushes and hole cold expansion for increasing the fatigue life of thick section aluminium alloy bolted joints", Structures Note 490, Defence Sciences and Technology Organization, Aeronautical Research Laboratories, Melbourne Australia, 1983.

[2] Mann, J.Y., A.S. Machin, and R.A.Pell, "Fatigue crack propagation in Mirage 111 wing main spar specimens and the effects of spectrum truncation on life", Structures Report 405, Defence Sciences and Technology Organization, Aeronautical Research Laboratories, Melbourne Australia, 1983.

[3] "Damage and g exceedences during Mirage aircraft placarding", Report No.AA619, Commonwealth Aircraft Corporation, Melbourne Australia, 1983.

[4] Grandage, J.M., "A rationale for the safe operation of an aircraft fleet having known cracks in the primary structure", The proceedings of the International Committee on Aeronautical Fatigue, Pisa, Italy, 22-24 May 1985, pp 495-509.

[5] Probst, E.P. and B. M. Hillberry, "Fatigue crack delay and arrest due to single peak tensile overloads", AIAA Journal, Volume 12, No 3, March 1974, pp 330-335.

[6] Trebules, V.W.,Jr., R. Roberts and R.W. Hertzberg, "Effect of multiple overloads on fatigue crack propagation in 2024-T3 aluminium alloy", Progress in flaw growth and fracture testing, ASTM STP 536, American Society for Testing and Materials, 1973. pp 115-146.

[7] Dean, M.A., "The effect of periodic overloads on flight by flight fatigue crack growth rates", AFWAL-TR-83-3069, Structural Integrity Branch, Structures and Dynamics Division, 1983.

[8] Elber, W., "The significance of Fatigue Crack Closure", Damage Tolerance in Aircraft Structures, ASTM STP 486, American Society for Testing and Materials, 1971, pp 230-242.

[9] Walker, K.F., "The effect on fatigue crack growth under spectrum loading of an imposed placard "g" limit", MS Thesis, School of Aeronautics and Astronautics, Purdue University, December 1987.

[10] Dawicke, D.S. and D.A. Skinn, "CRACKS84 Volume 1 Users Guide", University of Dayton Research Institute, Dayton Ohio, 1984.

[11] Dawicke, D.S. and D.A. Skinn, "CRACKS84 Volume 2 Programming Guide", University of Dayton Research Institute, Dayton Ohio,1985.

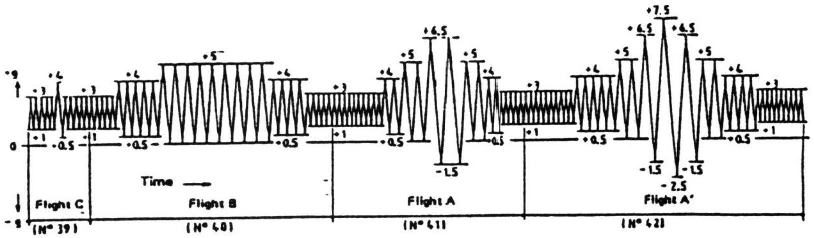
[12] Dawicke, D.S. and D.A. Skinn, "CRACKS84 Volume 3 Technical Guide", University of Dayton Research Institute, Dayton Ohio, 1984.

[13] "CGLIFE User's manual for the prediction of crack growth life", McDonnell Aircraft Company, St. Louis, Missouri, September 1984.

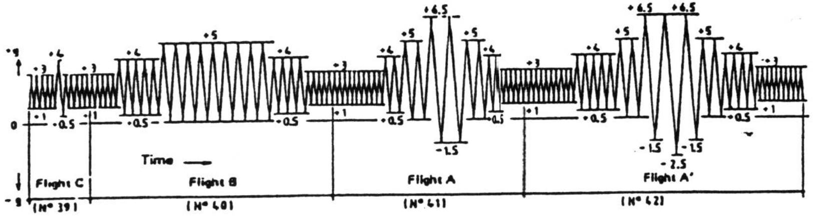
[14] Morrison, A.S., "Development of Software for the control of spectrum loading fatigue tests", MS Thesis, School of Aeronautics and Astronautics, Purdue University, December 1985.

[15] Morrison, A.S., "A user's manual for AMSPEC Software for the control of Spectrum Loading Fatigue Tests", Department of Aeronautics and Astronautics Report No. 1-85, Purdue University, November 1985.

[16] Chang, J.B., R.M. Engle, and J. Stolpestad, "Fatigue Crack Growth Behaviour and life predictions for 2219-T851 Aluminium Subjected to Variable Amplitude Loadings", presented at the 13th National Fracture Mechanics Symposium, Philadelphia, 1980.



UNMODIFIED SPECTRUM



6·5g LIMIT SPECTRUM

Figure 1: Representative segments from the unmodified Mirage spectrum and the spectrum with a 6.5g limit.

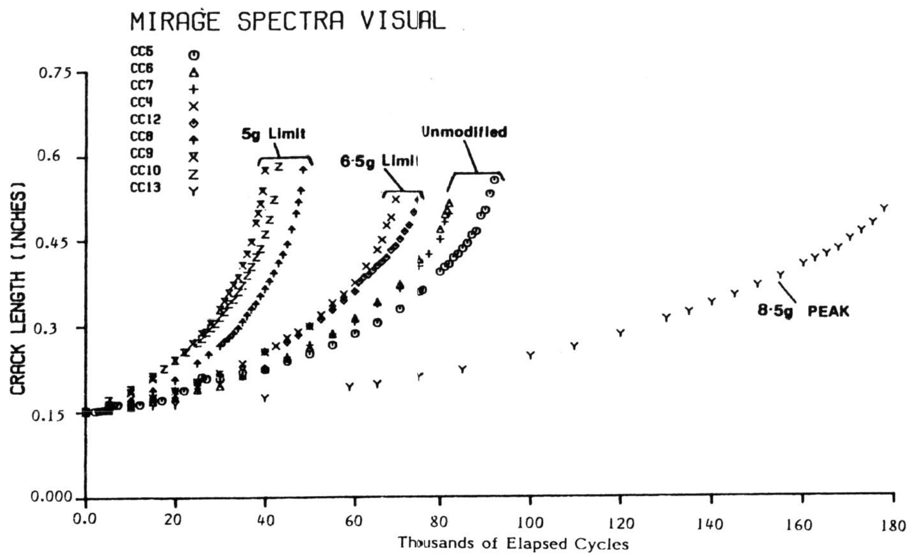


Figure 2: Crack growth curves for all Mirage spectra from visual readings showing effect of spectrum modification on crack growth.

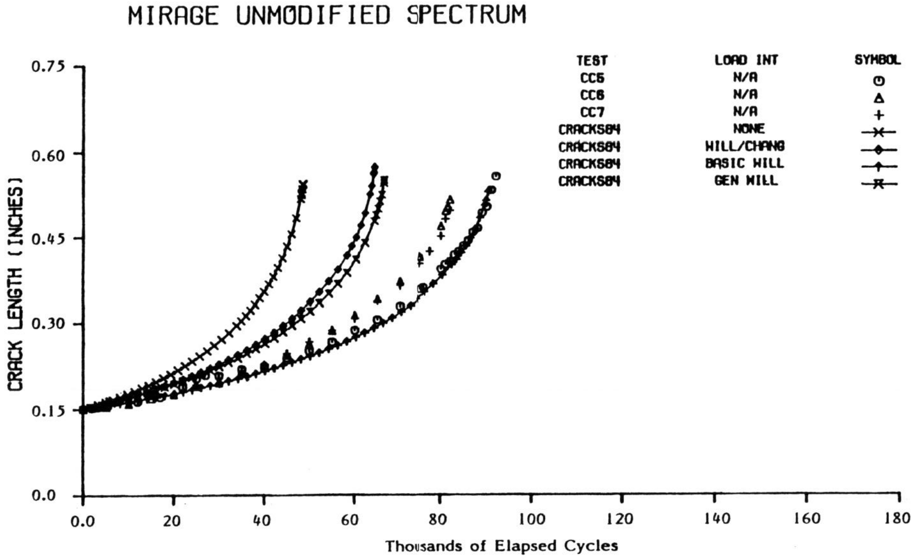


Figure 3: Comparison of experimental crack growth with CRACKS84 predictions for the unmodified spectrum.

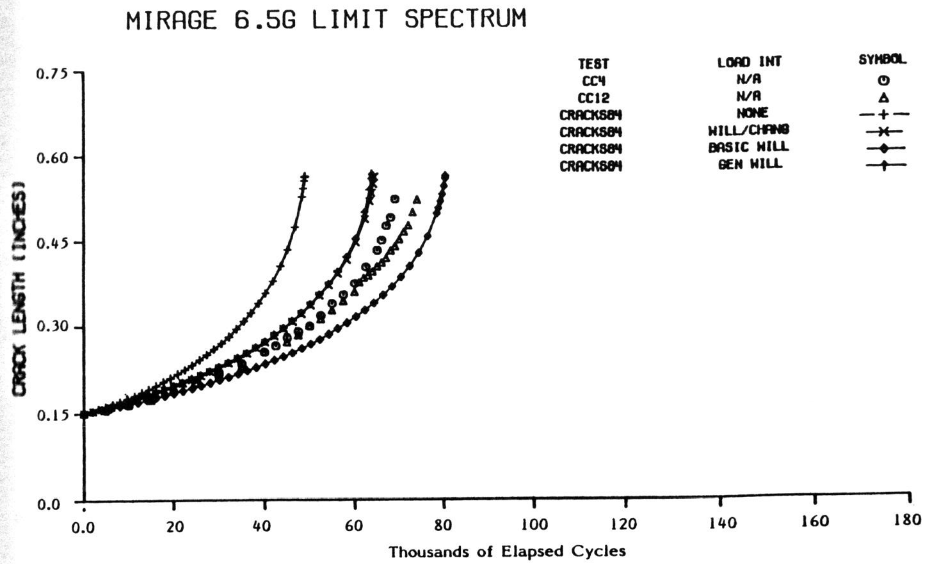


Figure 4: Comparison of experimental crack growth with CRACKS84 predictions for the 6.5g limit spectrum.

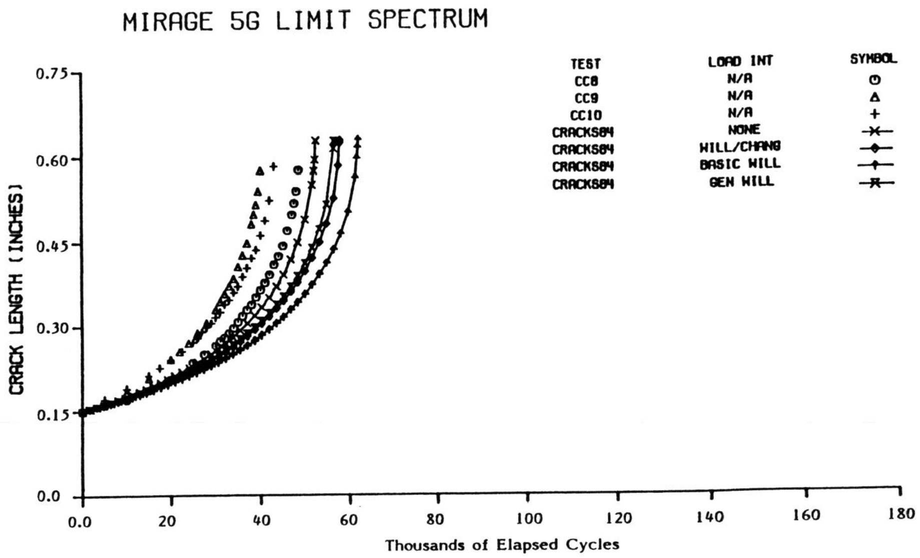


Figure 5: Comparison of experimental crack growth with CRACKS84 predictions for the 5g limit spectrum.

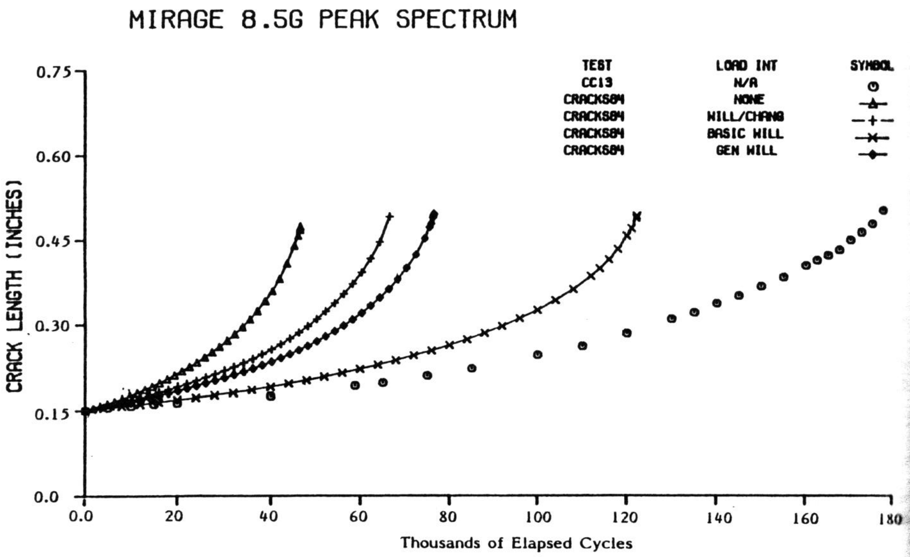


Figure 6: Comparison of experimental crack growth with CRACKS84 predictions for the 8.5g peak spectrum.

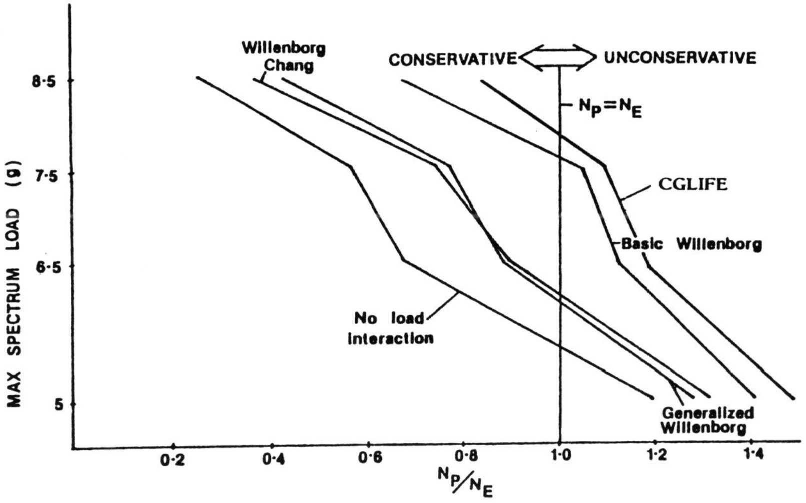


Figure 7: Maximum load in spectrum versus ratio of predicted to experimental life showing performance of various load interaction models.