CP140 (P3) STRUCTURAL DATA RECORDING SYSTEM

M Oore
IMP Group Limited
Aerospace Division
Halifax, NS B3L 4T1
CANADA

DH Crocker
Department of National Defence
National Defence Headquarters
Ottawa, ON K1A 0K2
CANADA

SUMMARY

Each of the Canadian CP140/CP140A aircraft, variants of the Lockheed P-3C, has been equipped with a Structural Data Recording System (SDRS) to facilitate Individual Aircraft Tracking (IAT). One of the objectives of the system is to provide usage monitoring data that will enable the Canadian Forces (CF) to quantify individual aircraft fatigue usage and crack growth rates from which optimized inspection times can be calculated. Thus inspection frequency and costs can be reduced while the safety of the aircraft is ensured.

This article provides a brief description of the SDRS and related experience acquired during the five years of system usage and data collection. An overview of the parameters recorded by the SDRS is presented as well as examples of data recorded in flight and their significance. Strain sensor recording rise/fall criteria are discussed in the context of minimizing the volume of recorded data while capturing significant data. A rise/fall criteria sensitivity study, conducted to optimize selection of the triggering gate value, is presented.

Since the SDRS zeros strain sensor readings at the beginning of each flight, a strain offset determination method was developed in order to calculate absolute strain values. This method has been substantiated by calibration tests that included validation of a Finite Element (FE) model of the wing and verification of the SDRS strain measuring system. Studies performed to assess the adequacy of the SDRS strain resolution are also presented.

Overall it is demonstrated that SDRS data can be used to generate sufficiently accurate stress spectra for fatigue and crack growth analyses.

1. INTRODUCTION

The CF has an established program for IAT of the CP140/CP140A fleet. This program uses data recorded manually on Flight Engineer Logs and represents tracking methods that are conservative, reactive, and lack timeliness of feedback. The Fatigue Life Index (FLI) and inspection intervals derived are thought to be overly conservative.

In 1993, the CF established a policy to assign airframe punishing training missions to three training aircraft, designated CP140A Arcturus, specifically configured for this role. Such severe usage results in high crack growth rates yielding short inspection intervals for these aircraft when calculated using the methods of the existing IAT program. To address this problem, the CF established an aircraft tracking system based on actual aircraft data. To this end, each of the CP140A aircraft was equipped with a SDRS to record flight parameters and structural loads.

Based on the experience with the SDRS on the three CP140A, the CF decided that it was warranted to have the system installed on all CP140 aircraft. A fleet fit installation of the SDRS on all CP140 Aurora aircraft was completed in 1997.

Support is provided to the CP140/CP140A SDRS program by means of an Aircraft Structural Integrity Program (ASIP) contracted to IMP Group Limited.

2. SDRS OVERVIEW

The heart of the SDRS is the AN/ASH-37A Structural Data Recording Set developed by Systems & Electronics, Inc. (SEI). The AN/ASH-37A is an advanced airborne structural recording system consisting of a twenty channel microprocessor based recorder-converter, a removable memory unit, a Data Entry Keyboard (DEK), a multi-axis motional pickup transducer (accelerometer), temperature compensating strain sensors and a recorder-reproducer for system ground support and data transfer. The SDRS is able to record the following flight information: engine on/off, weight on wheels (WOW) state, flap deployment, centre of gravity acceleration, wing and horizontal stabilizer peak/valley strain, altitude and airspeed.

The AN/ASH-37A system is currently in use by the United States Navy (USN) on the A-6E and E-2C fleets and on the CH-46 and AH-1W helicopter fleets.

The SDRS on the CP140/CP140A is configured to record all significant data for a 30 day period or 100 hours of aircraft operation before download. Details on SDRS recorded parameters are presented in Tables 1 and 2.

3. OPERATIONAL EXPERIENCE WITH SDRS DATA

3.1 Overstress Cases

During the period between 1993 and 1998 there were numerous instances where the vertical acceleration of the centre of gravity of the aircraft (Nz) exceeded the Aircraft Operating Instructions (AOI) limit of 3.0g. During this period, maximum Nz readings ranging from 3.06g to 3.85g were recorded. Such overstresses, when noted by the aircrew, are entered in the aircraft flight log and result in the performance of a costly overstress maintenance check before the aircraft is returned to service. However, the aircrews are often unaware that an overstress has occurred as the cockpit accelerometer indicator reads 0.3g to 0.5g

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below the Nz reading recorded by the SDRS. As a result, it is often not until the aircraft has landed and the SDRS memory module downloaded that there is the first indication of a possible overstress.

3.2 Typical Overstress Incident

A typical flight profile (Figures 1a and 1b) illustrates what appears to be an overstress incident at approximately 2150 seconds. A zoom in on the area where the overstress occurred shows that the vertical acceleration of centre of gravity of the aircraft fluctuated between 2.20g and 3.26g. The following evidence supports the possibility of an overstress. There is a high correlation between, the Nz parameter and the wing root strain recorded by strain sensor 1. Wing root strain is proportional to wing root bending moment, which is in turn related to the magnitude of loading on the wing. However, in the present case, the moderate level of the over-stress (3.26g) coupled with an aircraft weight of only 86,000 lb at the time of the incident indicates that there may be little likelihood that any structural damage resulted from this incident. This type of incident has raised a number of questions:

How should aircrew be alerted of the potential for an overstress? Indication that an overstress incident has occurred may not happen until the SDRS memory module is downloaded and the data examined. From an operational sense this is less than satisfactory. Investigations are currently underway between the CF and SEI to establish a manner of alerting aircrews of possible overstress incidents. One possibility is to modify the DEK to include a cautionary light to indicate when preset levels of centre of gravity acceleration have been exceeded.

What constitutes an overstress? The CF, in consultation with IMP Group Limited, is in the process of defining criteria that will be used to determine whether an overstress has occurred and hence, whether there is a requirement for an overstress inspection.

How can the potential for overstress incidents be reduced? The CP140/CP140A fleet is presently operated to very aggressive limits that are defined by maximum g level. Investigations should be undertaken to examine the effect of redefining fleet operational limits in terms of bank angle. The following example illustrates that such restrictions may be beneficial.

In August 1997, a 2g manoeuvre restriction was imposed at Canadian Forces Base (CFB) Greenwood in an effort to reduce the number of costly aircraft inspections required as a result of overstresses. For the purpose of this study, overstresses were defined as Nz in exceedance of 3g. The CF examined SDRS data for the CP140/CP140A fleet stationed at CFB Greenwood for the period 01 July 1997 to 01 September 1997 to assess whether the operational restriction had any effect on the manoeuvre Nz exceedance distribution. The results of the study are presented in Figure 2, which demonstrates a significant reduction in Nz exceedances in the period after the restriction was imposed when compared to the period before the restriction. While it is premature to draw any definitive conclusions, it appears that the restriction reduced the number of Nz exceedances as well as the number of overstresses experienced.

3.3 Relationship Between Damage Severity and Flap Over speed

CP140A data from two sources were combined and analyzed to investigate the hypothesis that a relationship existed between the severity of flap overspeeds as recorded by the SDRS and flap damage severity as recorded by the CF maintenance database system. The method used to test this hypothesis was to rate the damage incidence according to an increasing scale of severity, where the highest damage severity was given the highest rating. There was a high correlation coefficient (0.99) between the mean flap overspeed value and the mean flap damage severity for the three CP140A aircraft. Statistical analysis indicates that there is a 0.087 probability that the relationship between the amount of flap overspeed and the severity of flap damage as reported in maintenance data for CP140A aircraft is due only to chance. Hence, there is a reasonable probability that a causal link exists between the two parameters. This link will be difficult to establish with a high degree of certainty given the small size of the fleet (three aircraft) being monitored. However, there is enough evidence from other sources to conclude that flap deployments outside the operational envelope are costly and should be avoided whenever possible. The focus given to the flap overspeed problem through this discovery was enough to cause operators to monitor the situation resulting in a decreased incidence of flap overspeed damage.

4. SDRS BASED FATIGUE AND DAMAGE TOLERANCE ANALYSIS

4.1 Scope and Objective

At present, each of the eighteen CP140 and the three CP140A aircraft is equipped with a SDRS to facilitate IAT. One of the objectives of the SDRS program is to provide usage monitoring data that will enable to quantify individual aircraft fatigue usage and crack growth rates from which optimized inspection times can be calculated. The goal is to reduce inspection frequency and maintenance costs while ensuring the safety of the aircraft.

Fulfilling these objectives in a practical/economical fashion required several steps. Of primary importance is verification of the SDRS recorded data. While this is crucial for any subsequent fatigue, damage tolerance and inspection interval calculations, it also impacts the confidence in conclusions obtained using SDRS data during the 5 years of experience with the system.

4.2. Calibration and Verification

4.2.1 Calibration Tests

The SDRS is configured such that the strain sensors are zeroed at the beginning of each flight. This "zero reading" is used by the system as a reference for any sensor reading recorded during that flight. This is an effective way to avoid the problem of the sensor zero position drifting over time. However such a system configuration necessitates a suitable method for strain offset determination before each flight in order to obtain correct values of absolute strain.

This implies that the actual level of strain of the fueled aircraft on the ground (before flight) need be known very accurately at each sensor location. The appropriate value of offset strain is then added to the SDRS recorded strain readings to obtain the corresponding value of absolute strain. A NASTRAN Finite Element (FE) model of the wing has been developed at IMP Group Limited to accurately determine these offset strains (see Figure 3). However, due to the complexity of the structural configuration, bending near inflection points (see Figure 4), tires stiffness and questions regarding fueling sequence and fuel distribution inside the wing and in the fuselage, it was decided to conduct strain sensor calibration testing. The steepness of the bending moment slope in Figure 4 implies that small changes in modeling or mass distribution can greatly change the bending moment in the areas near the inflection point. Calibration testing would serve to validate recorded strain data generated by the SDRS and verify the analytical tools (FE model) used in the follow up analysis.

During the installation of the SDRS two identical strain sensors, a primary and a secondary, are installed at each sensor location. Such an arrangement serves to provide an alternate sensor (the secondary) should the primary sensor fail and also facilitates SDRS calibration. By connecting a calibrated, external strain measurement system to the secondary sensors and comparing these readings to the corresponding primary sensor readings recorded by the SDRS, strain sensor readings can be validated.

Three aircraft were subjected to calibration tests. Calibration testing of each aircraft consisted of two phases. Phase I testing involved the application of measured upward and downward point loads near the wingtips. Phase II testing involved the measurement of wing strain at sensors locations for various fuel loadings.

4.2.2 Summary Of Results From Calibration Tests

Phase I results established the linear bending moment/strain relationship at strain sensor locations and verified the analytical FE model. Figures 5a and 5b illustrate this linear relationship. Figure 5b demonstrates the close correlation between the test results and the analytical model.

Phase II results are presented in Figures 6a, 6b and 6c which illustrate the complexity of this structural loading case. Figures 6b and 6c demonstrate the ability of the analytical model to provide acceptable results within the scatter band of the test data. Note that the SDRS readings can change only in 50 microstrain ($\mu\varepsilon$) increments due to the resolution of the system.

4.3 Spectrum Generation

As part of the SDRS program, the development effort also focused on software for generation of stress spectra at critical aircraft locations. Such spectra are required for fatigue and crack growth analysis from which inspection intervals are calculated. The spectra generation software includes algorithms, which use the analytical FE element model verified by calibration test data, to convert the recorded SDRS data into stress at critical aircraft locations. The software also incorporates a rainflow cycle counting algorithm to provide the proper counts of cycles. The final output is in a format that lends itself to fatigue and damage tolerance analysis using both proprietary software developed at IMP Group Limited and commercially available software packages. Damage tolerance analysis (DTA) results, based on generated spectra, provide the basis for inspection intervals and maintenance times determination.

As part of the SDRS program assessment, this spectra generation software was used in combination with the fatigue and crack growth software, to provide SDRS system data evaluation by means of sensitivity/parametric studies. These studies are described in the following sections.

4.4 Rational for Rise/Fall Criteria and Their Determination

The recording of peak/valley strain readings is governed by the rise/fall criteria of the SDRS.

The rise/fall criteria are the amount of change in strain necessary to validate the recording of a peak or a valley strain recording. The SDRS allows for specification of the rise/fall criteria value in its software configuration. The selection of a small rise/fall criteria (gate) value will ensure that small cycle amplitudes are recorded resulting in a very accurate and comprehensive database. However, this results in an overwhelming amount of data, much of which may be insignificant "noise", and may cause memory module overflow leading to loss of substantial data blocks. Optimized rise/fall criteria need to be established to ensure the recording of all significant data but without excessive data storage requirements.

To establish the optimized triggering gate, the SDRS rise/fall criteria were first set to record a very wide field including very small cycle ranges (95 $\mu\varepsilon$). The resulting data were run through software that simulates the SDRS rise/fall triggering criteria. Multiple software runs were performed each corresponding to a specified triggering gate (see Figures 7a through 7f). The resulting files were used to generate stress spectra at a wing lower front spar root fitting. These spectra were then used to conduct the fatigue crack growth analysis presented in Figure 8. The intent was to establish the rise/fall criteria value beyond which reducing the triggering gate had no significant effect on the fatigue crack growth results. It is observed from Figure 8 that there is no significant difference in crack growth results between the 142 $\mu\varepsilon$ and the 95 $\mu\varepsilon$ values of the rise/fall criteria. Spectra generated using the optimized rise/fall criteria value and the next highest value were subjected to fatigue crack growth testing using a centre cracked tension (CCT) test specimens (see Figure 9). This analysis and testing sequence reduced the number of tests normally required in spectrum truncation tests. The tests presented in Figure 9 confirmed that including cycles with rise/fall differences below the analytically determined optimum triggering point had no significant effect on the crack growth test results.

This study also allowed an assessment of the savings in data storage. Summaries of the rise/fall criteria sensitivity crack growth life analysis results and the corresponding number of strain pairs are presented in Figures 10 and 11.

4.5 Study of Resolution Effects

4.5.1 Background

The strain resolution limit of the SDRS is inherent in the system design. To facilitate practical memory requirement, all measured values of strain that fall within the same resolution limit of 50 $\mu\varepsilon$ are assigned the same strain value. For example all strain values between 75 $\mu\varepsilon$ and 125 $\mu\varepsilon$ are recorded as 100 $\mu\varepsilon$; all strain values between 125 $\mu\varepsilon$ and 175 $\mu\varepsilon$ are recorded as 150 $\mu\varepsilon$ and so on. Thus all measured strain values are rounded within a 50 $\mu\varepsilon$ range (25 $\mu\varepsilon$ amplitude). The question arises as to the effect of the resolution limit on fatigue and crack growth results. Since the resolution parameter is built into the system and cannot be reduced for the sake of a parametric sensitivity study (as with the rise/fall criteria), a Monte Carlo simulation approach was used to assess the effect of the system resolution on fatigue and crack growth results.

4.5.2 Analysis and Results and Conclusions

SDRS generated data were used to generate a stress spectrum for a critical front lower spar cap and web location. This spectrum was then used to conduct analytical fatigue and crack growth analyses. Because any monitoring system has inherent measurement errors associated with its resolution and rounding errors, a random error analysis was conducted to establish the effect of the resolution error on fatigue and crack growth life predictions. The strain readings resolution errors were simulated with computer generated random numbers within the bounds of the resolution specification of the system. The simulated errors were superimposed on the basic spectrum derived from the SDRS recorded data.

This revised spectrum, which incorporates resolution error effects, was then used to repeat the fatigue and crack growth analyses. The results were used to quantify the potential effect of the resolution random errors on the fatigue life predictions as elaborated in the following. Figure 12 presents a comparison of several fatigue analyses with results normalized by the basic fatigue result. Series 1 in Figure 12 presents fatigue life results for a conservatively adjusted spectrum in which the maximum resolution limit is added to each peak strain and subtracted from each valley strain in the recorded data. It shows that for a resolution range of 50 $\mu\varepsilon$, this conservative approach gives fatigue life that is 35% shorter than the life obtained with the basic spectrum. Hence, this approach may be too conservative for practical evaluation of the error effect. Another approach, using a spectrum that incorporate uniform random error simulation of the resolution, gave the fatigue life results shown by series 2 in Figure 12. It is observed that for resolution errors within 50 $\mu\varepsilon$ the fatigue life result decreased by only by 4%, whereas for resolution of 100 $\mu\varepsilon$ the resulting life is 12% below the basic fatigue life. Additional scenarios are presented in Figure 12 to demonstrate various simulations of the resolution effects. Series 2 is deemed to be the most realistic as the resolution error is expected to be of uniform random distribution within the resolution limits. Since the analysis generating series 2 represents a random effect, fatigue analysis was repeated with several sets of uniform random numbers (Monte Carlo simulation) in order to establish confidence bands. The results for these repetitions displayed a small variation within each resolution range group. The frequency distribution of the results for the 50 $\mu\varepsilon$ cases gave a histogram that rationalized confidence intervals calculation using a t- distribution. Very high confidence (99.99%) bounds were established that the mean population of the fatigue life is between 25,000 to 26,000 hours whereas the basic fatigue calculation gave 26,500 hours. This demonstrates that the 50 $\mu\varepsilon$ resolution effect on the basic fatigue life results could be at most a 6% reduction in fatigue life. Larger resolution error ranges will have a greater effect on fatigue life (series 2) while a 25 $\mu\varepsilon$ resolution will have an effect of significantly less than 6%. Series 3 in Figure 12 presents the effect of increasing the mean strain on fatigue life. The strong effect observed confirms the requirement for the offset strain determination and the calibration testing described in Section 4.2.

The potential effect of the resolution error on crack growth was assessed in a similar manner to that described above for fatigue life. The basic spectrum derived from SDRS generated data was used also to conduct crack growth analysis for multiple crack growth paths at a critical lower spar web location on the wing. Initial crack lengths of 0.05" and 0.25" were considered. To assess the effect of resolution errors on crack growth life predictions, the resolution effect was simulated as before with uniform distribution random errors within ±50 $\mu\varepsilon$. These were superimposed on the basic spectrum derived from the recorded data in the same manner as for the fatigue analysis. This superposition was repeated for 12 sets of random numbers simulating resolution errors of 50 $\mu\varepsilon$ and the resulting 12 spectra were used in crack growth analyses. Results of these analyses show only small variations, due to resolution error, from the basic crack life results. A statistical confidence analysis was conducted which demonstrated that resolution errors within 50 $\mu\varepsilon$ could reduce the crack growth life results at most by 5% when compared to the results using the basic spectra.

It was concluded from the above that the 50 $\mu\varepsilon$ resolution limit of the SDRS is satisfactory. The system resolution limit does not have a significant effect on fatigue and crack growth analyses using SDRS derived data.

Acknowledgements

The authors wish to thank BK MacLeod of IMP Group Limited for his outstanding technical support in the preparation of this paper.

Parameter	Units	Sampling Rate	Range	Resolution	Filter
Elapsed Time	seconds (s)	n/a	167,772	10^{-1}	n/a
Indicated Altitude	feet (ft)	2 Hz	-500 to +40,000	0.0098 psia/count	6 Hz / 3 pole
Indicated Airspeed	knots (kt)	2 Hz	0 to 400	0.0195 psid/count	6 Hz / 3 pole
Centre of Gravity Acceleration (Nz)	g	64 Hz	-1.5g to 4.0g	0.098g	12 Hz / 5 pole
Strain Sensor 1 (WS 92R)	microstrain (με)	32 Hz	-3500 to +3500	50 με	12 Hz / 5 pole
Strain Sensor 3 (WS 147R)	microstrain (με)	32 Hz	-3500 to +3500	50 με	12 Hz / 5 pole
Strain Sensor 3 (WS 223R)	microstrain (με)	32 Hz	-3500 to +3500	50 με	12 Hz / 5 pole
Strain Sensor 4 (HSS 30R)	microstrain (με)	32 Hz	-3500 to +3500	50 με	12 Hz / 5 pole
Weight on Wheels (WOW)	n/a	per flight	0 or 1	n/a	n/a

Table 1 SDRS Recorded Parameters

Mission Data Entered on SDRS Data Entry Keyboard (DEK)	
Parameter	**Format**
Date	6 digits (ddmmyy)
Time	4 digits (hhmm)
Mission Code	(1, 2, 3 or 4)
Takeoff Fuel Weight	3 digits (000s lb)
Takeoff Gross Weight	3 digits (000s lb)
Airframe Hours	6 digits (hours)
Landing Fuel Weight	3 digits (000s lb)
Landing Gros Weight	3 digits (000s lb)

Table 2 Manually Entered SDRS Parameters

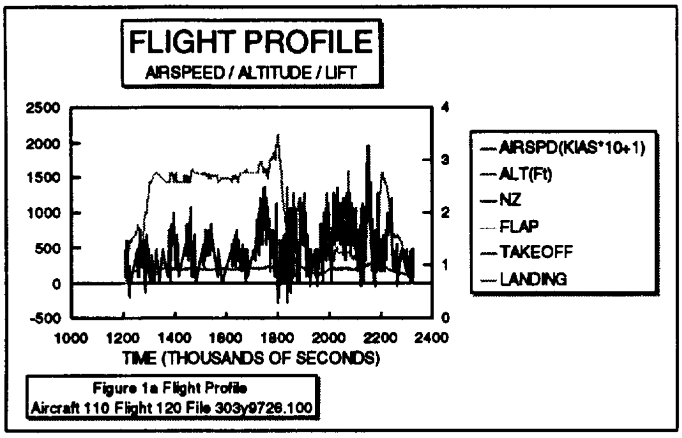

Figure 1a Flight Profile of an Overstress Incident

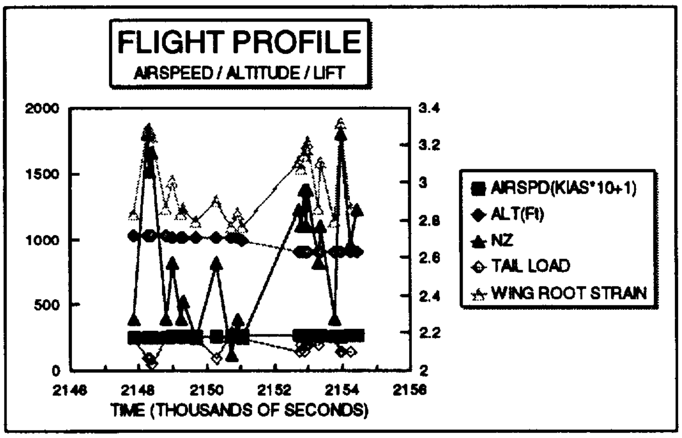

Figure 1b Zoom on Figure 1a Overstress Incident

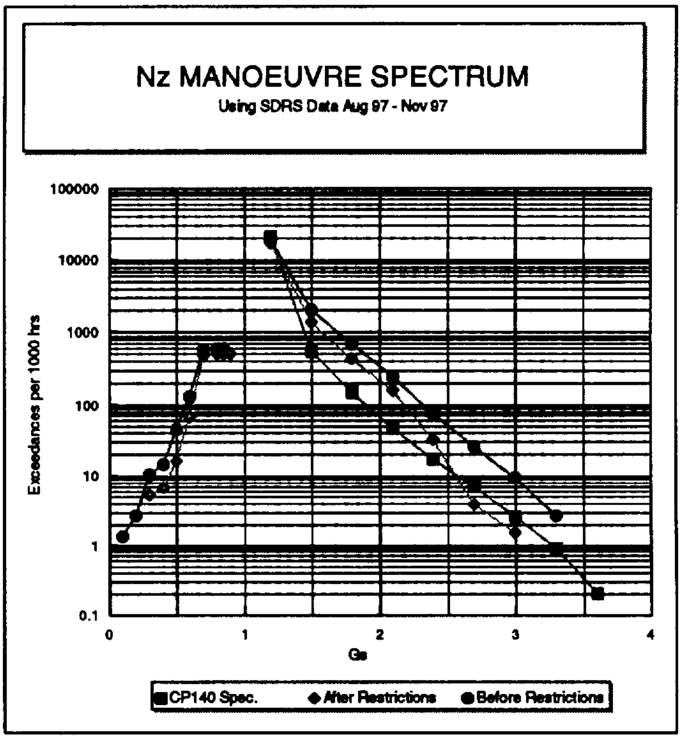

Figure 2 Vertical Acceleration Manoeuvre Spectrum

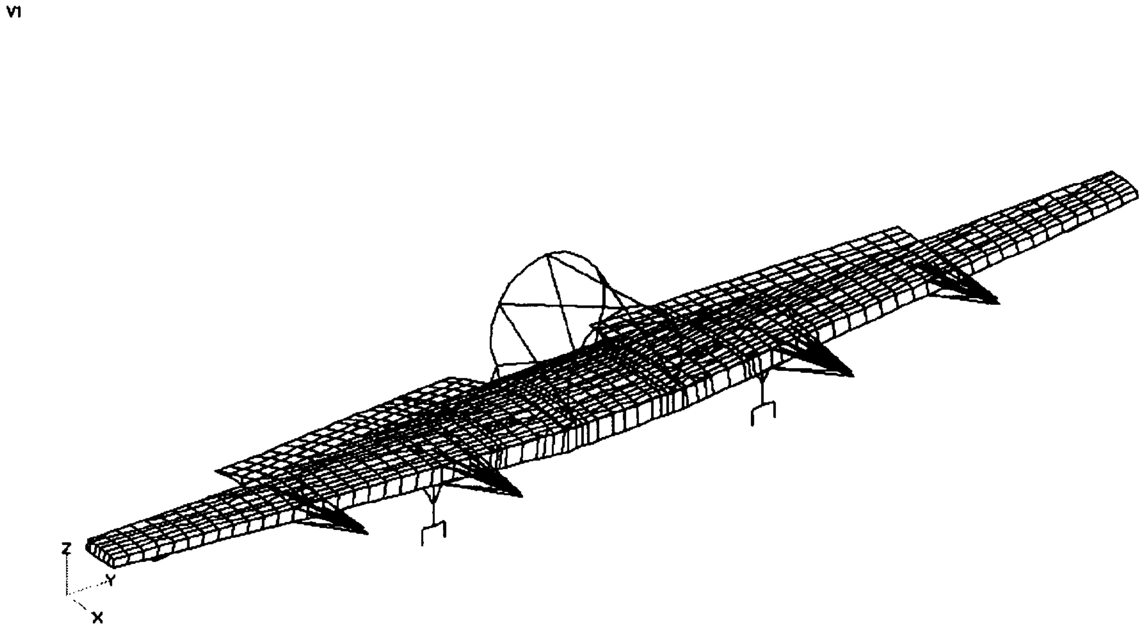

Figure 3 Wing Finite Element Model

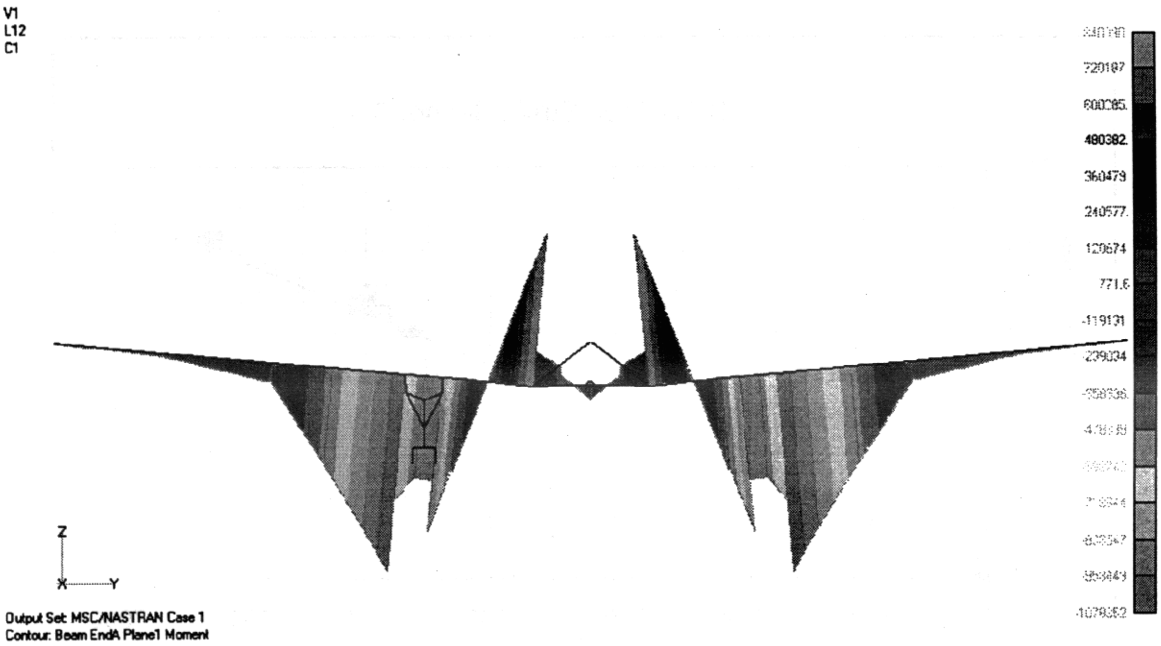

Figure 4 Wing Bending Moments

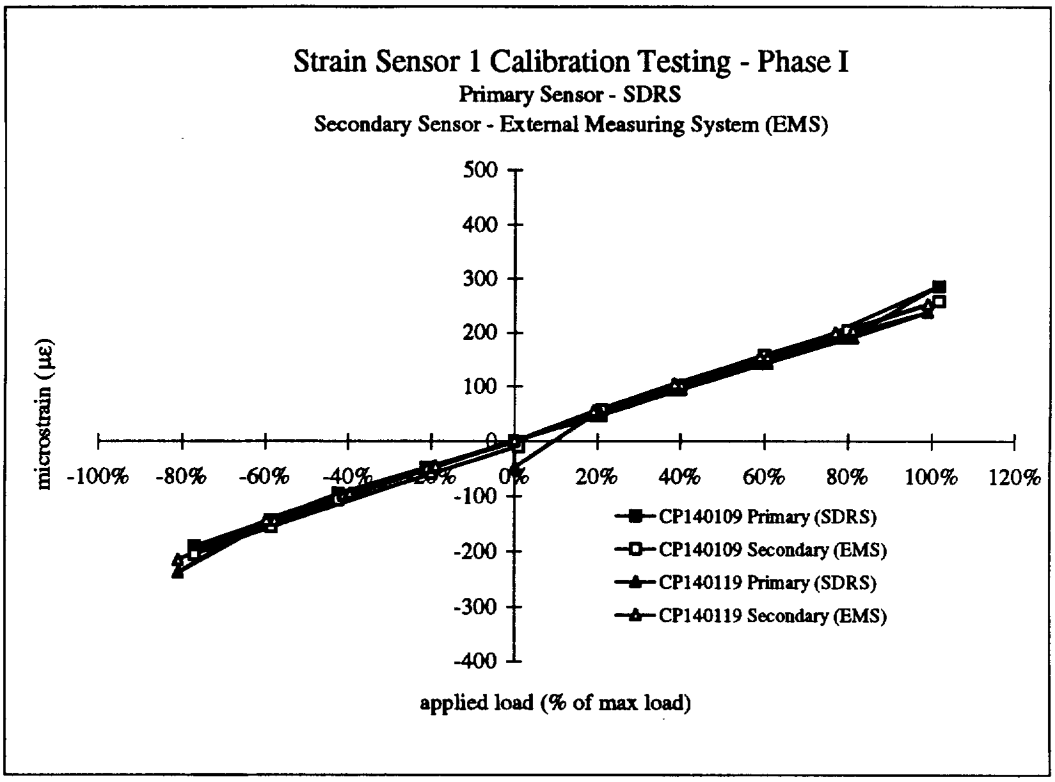

Figure 5a SDRS Calibration Phase I Test Results

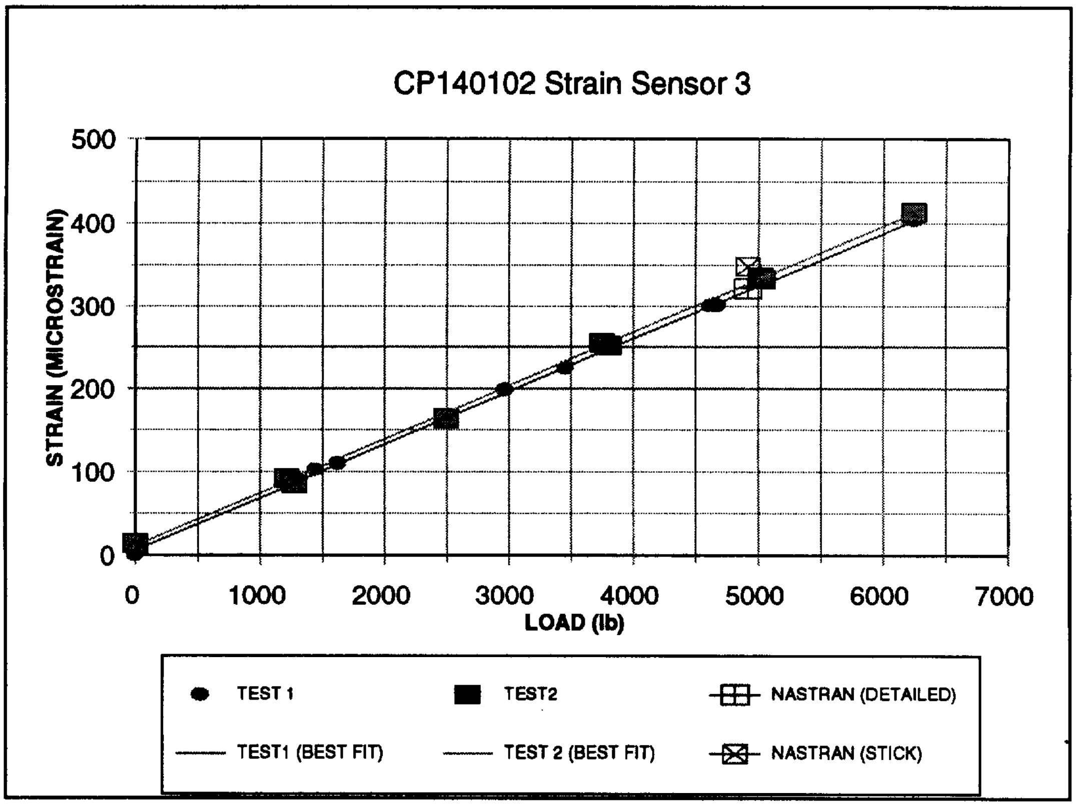

Figure 5b SDRS Calibration Phase I
Test Results and Analytical Model

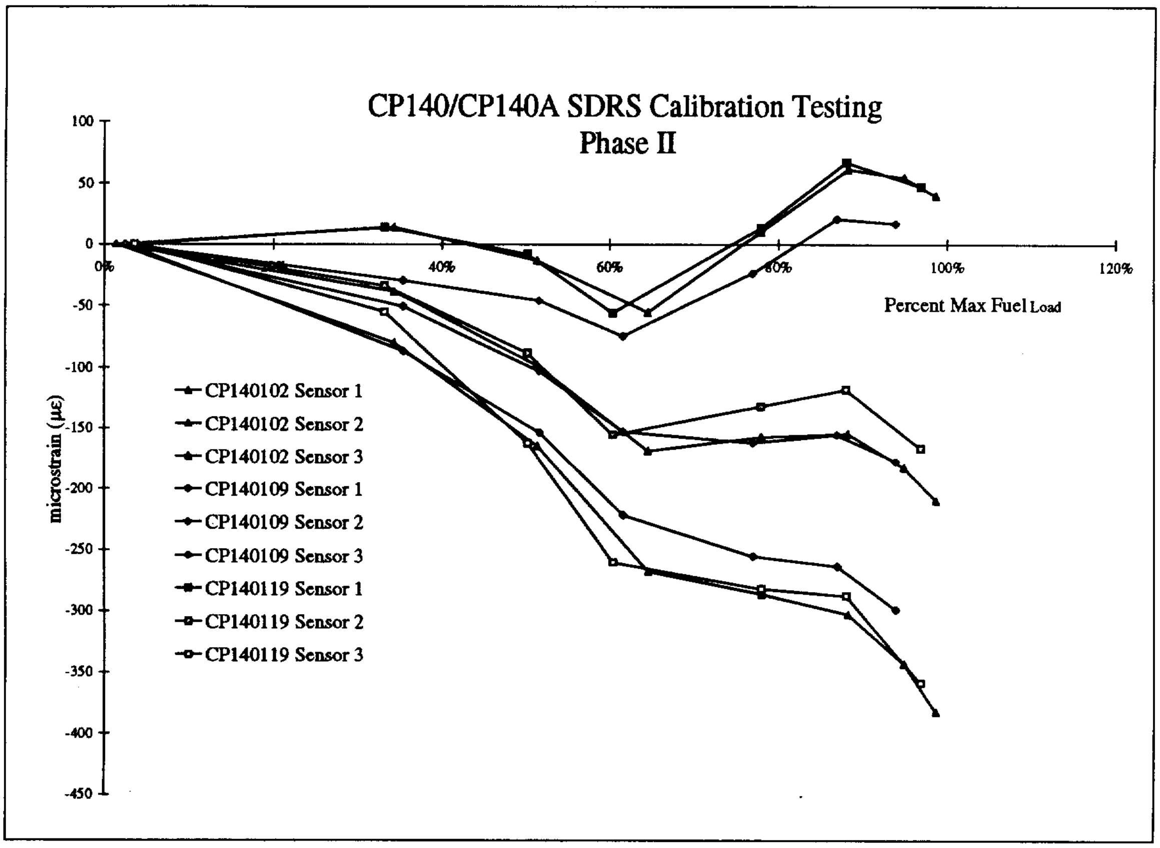

Figure 6a SDRS Calibration Phase II Test Results

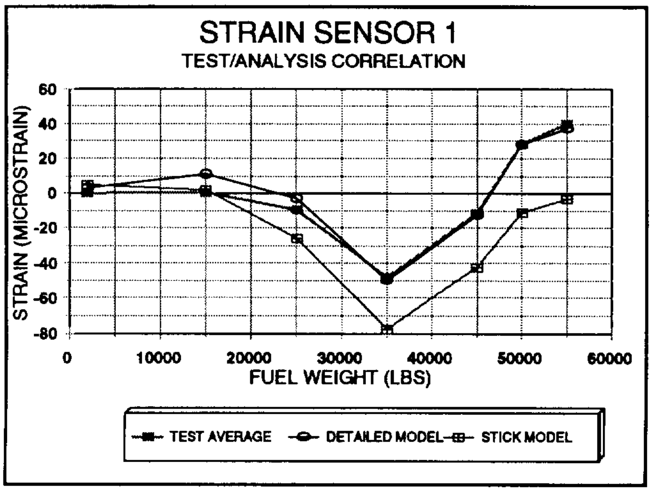

Figure 6b SDRS Calibration Phase II Test Results and Analytical Model

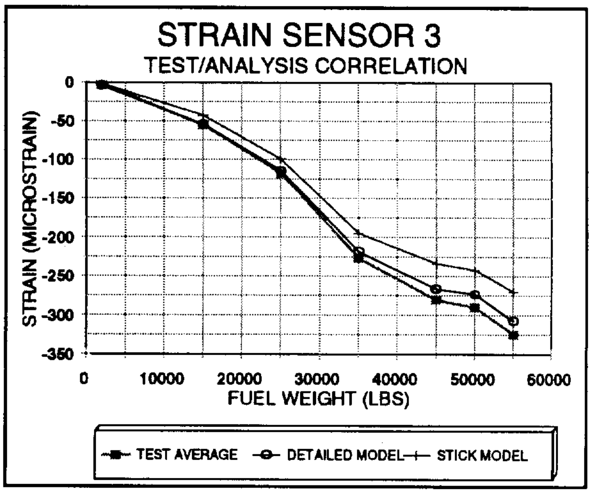

Figure 6c SDRS Calibration Phase II Test Results and Analytical

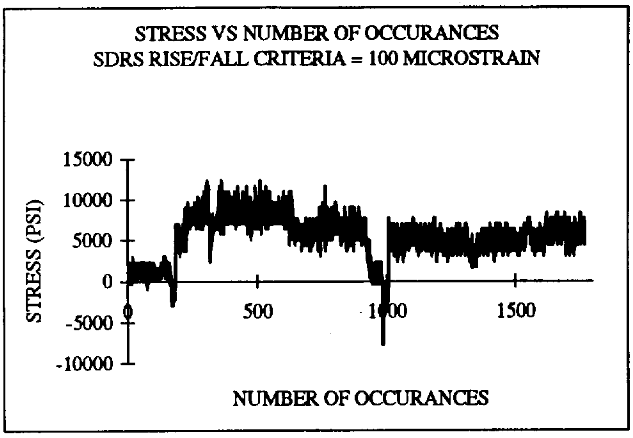

Figure 7a

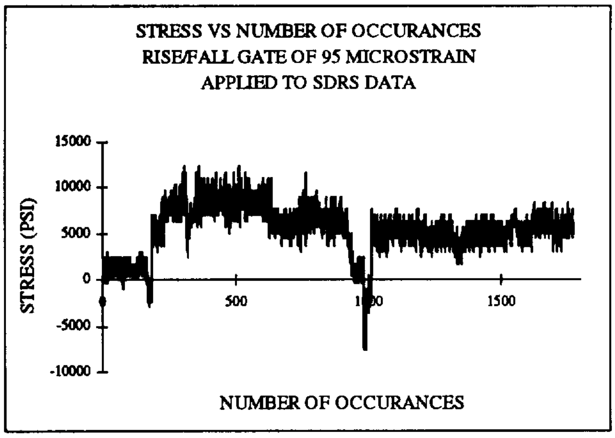

Figure 7b

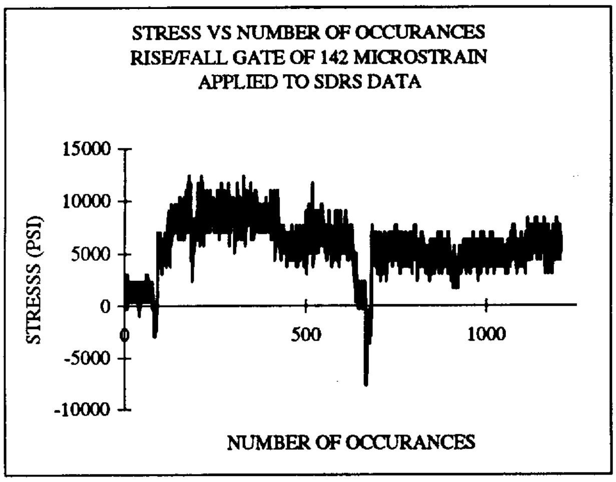

Figure 7c

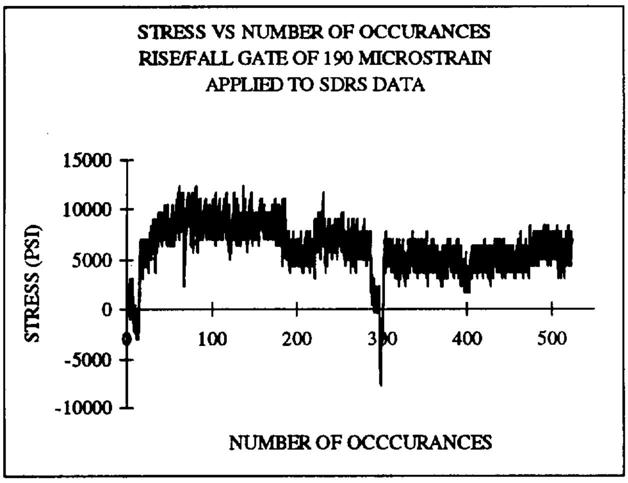

Figure 7d

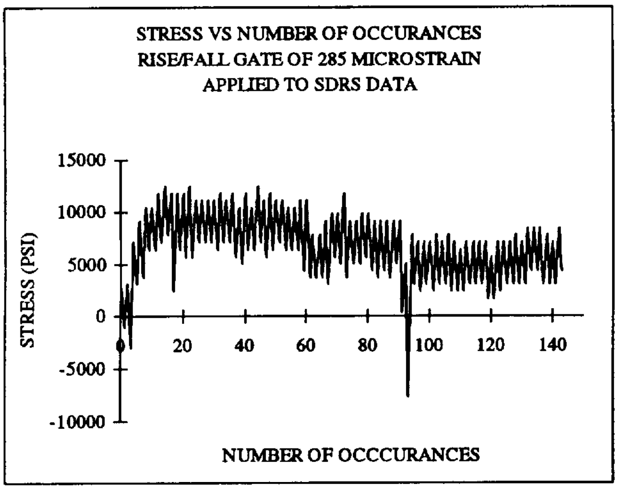

Figure 7e

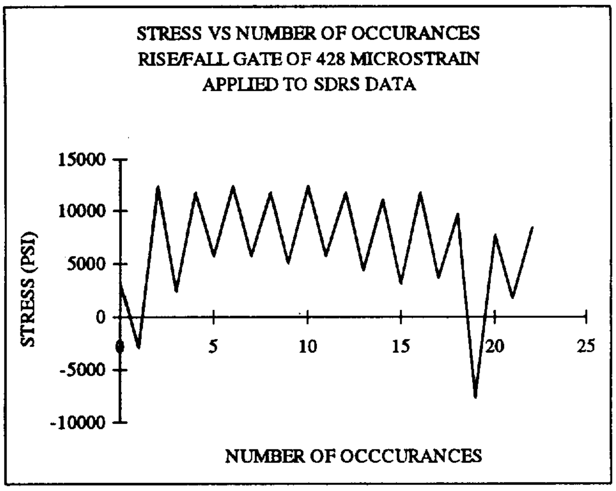

Figure 7f

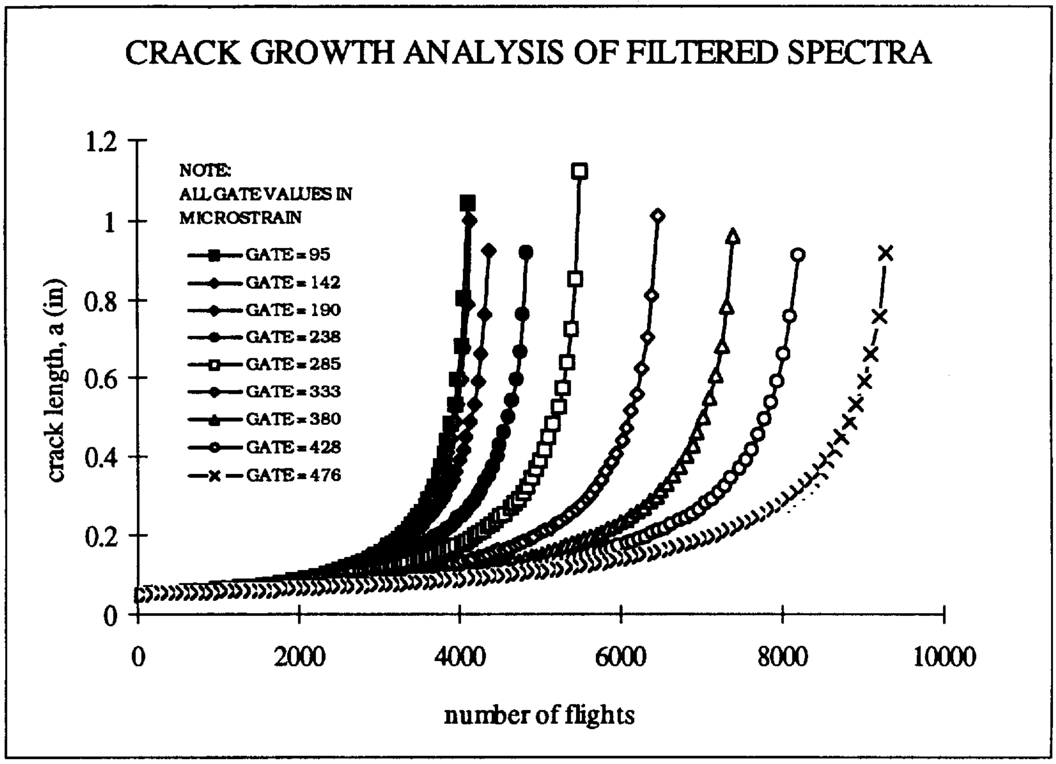

Figure 8 Rise/Fall Gate Effect on Fatigue Crack Growth

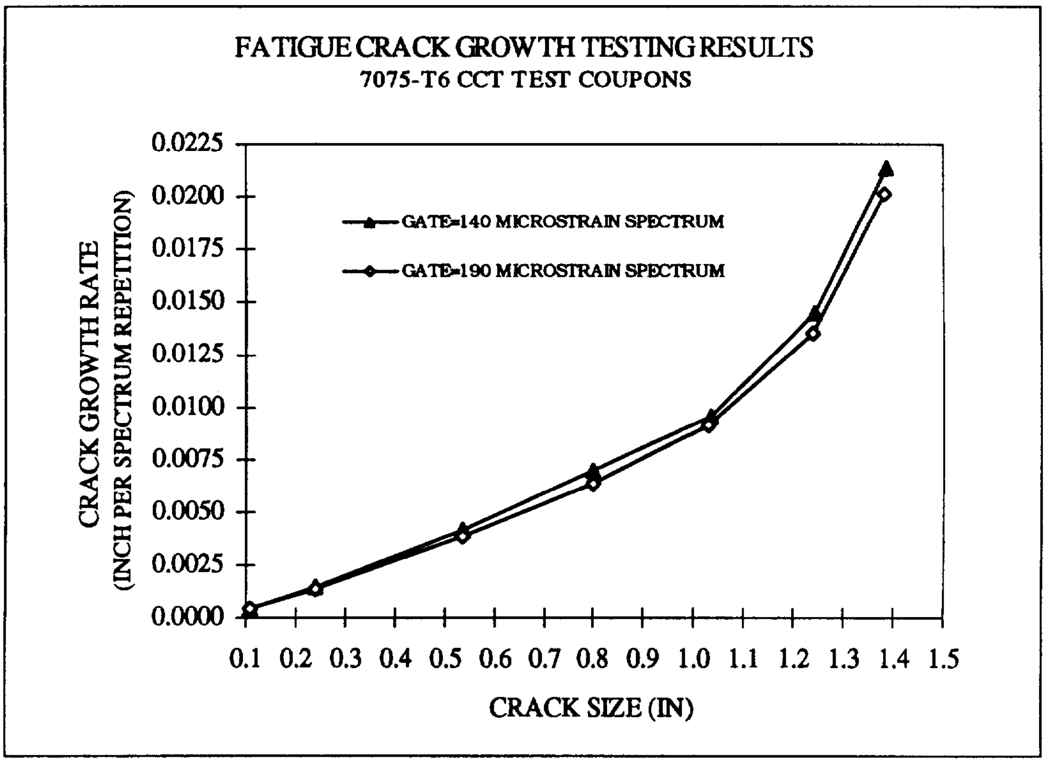

Figure 9 Fatigue Crack Growth Testing Results

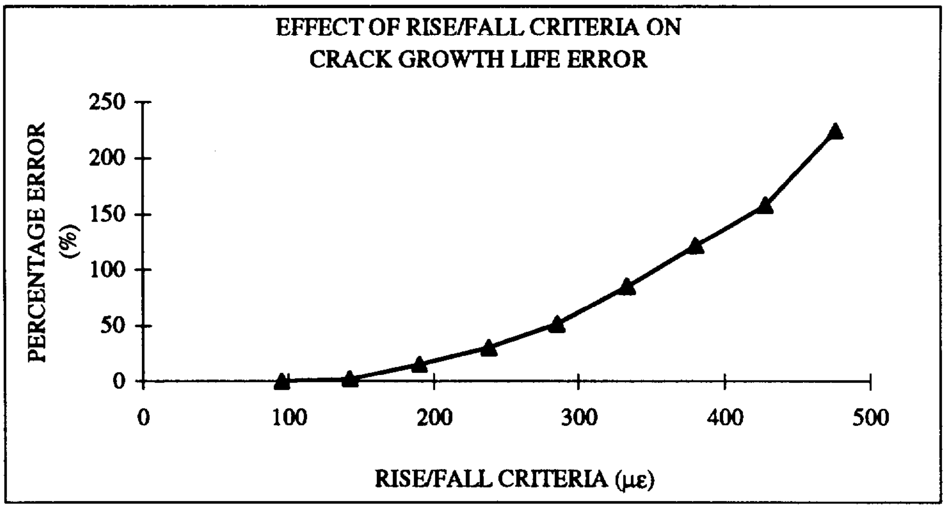

Figure 10 Effect of Rise/Fall Criteria on Grack Growth Life Error

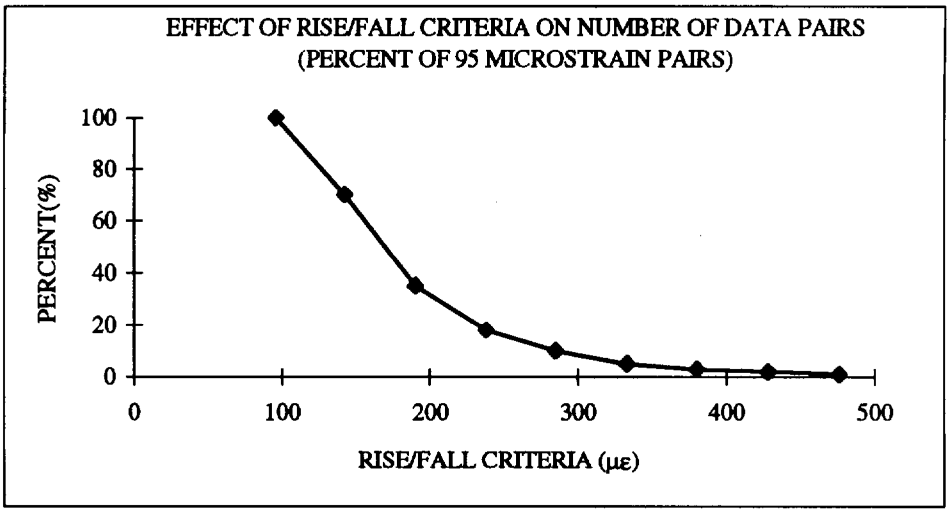

Figure 11 Effect of Rise/Fall Criteria on Number of Data Pairs

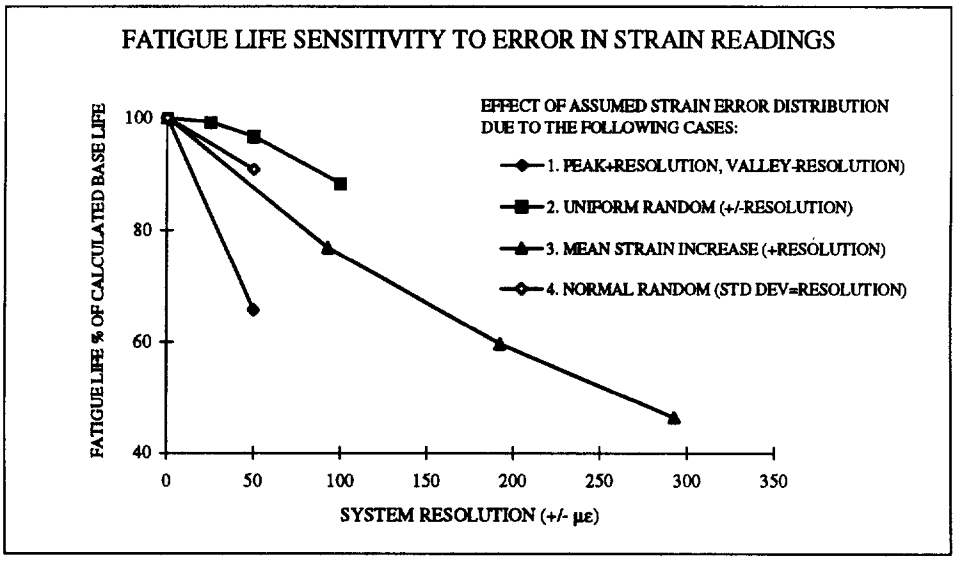

Figure 12 Fatigue Life Sensitivity To Error in Strain Readings