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A COMPARISON OF FATIGUE LIFE PREDICTION METHODOLOGIES FOR ROTORCRAFT

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SUMMARY

Because of the current U.S. Army requirement that all new rotorcraft be designed to a "six nines" reliability on fatigue life, this study was undertaken to assess the accuracy of the current safe life philosophy using the nominal stress Palmgrem-Miner linear cumulative damage rule to predict the fatigue life of rotorcraft dynamic components. It has been shown in the past that this methodology can predict fatigue lives that differ from test lives by more than two orders of magnitude. A further objective of this work was to compare the accuracy of this methodology to another safe life method called the local strain approach as well as to a method which predicts fatigue life based solely on crack growth data. Spectrum fatigue tests were run on notched(K_T=3.2) specimens made of 4340 steel using the Felix/28 variable amplitude spectrum (a shortened form of a standard loading sequence for 'fixed' or semi-rigid helicopter rotors). Two other spectra which resulted from a simple rainflow reconstruction of Felix/28 were also tested.

Both linear cumulative damage methods predicted the fatigue lives of the Felix/28 tests fairly well, being slightly on the unconservative side of the test data. The crack growth method, which is based on "small-crack" crack growth data and a crack-closure model, also predicted the fatigue lives very well with the predicted lives being slightly longer than the mean test lives but within the experimental scatter band. The crack growth model was also able to predict the change in test lives produced by the rainflow reconstructed spectra.

Introduction

One of two principle philosophies is currently used for the fatigue design of flight vehicles. These two philosophies are usually identified as safe life and damage tolerance. The safe life philosophy dates back to 1924 when Palmgren(ref. 1) published his work on linear cumulative damage in the life evaluation of ball bearings. In 1945, in an independent study by Miner (ref. 2), the same concept was applied to the design of aircraft components. The damage tolerance philosophy was introduced in the 1960's by the U.S. Air Force(ref. 3) in an attempt to prevent catastrophic accidents resulting from a less than perfect manufacturing process. In the damage tolerance philosophy, new structures are assumed to contain small cracks. Up to the current time the damage tolerance philosophy has been used exclusively on fixed-wing aircraft while all current rotorcraft have been designed using a safe life approach.

Because of two studies(ref. 4 and 5) done about a decade apart, the safe life approach using the Palmgren-Miner(P/M) linear cumulative damage rule has been questioned as being the most reliable approach to predicting fatigue life. In the work in reference 4 by Jacoby, the predicted lives of one-third of about 300 tests on all types of structures and materials were considered to be on the unconservative side. The work in reference 5 , the hypothetical pitch link problem formulated by the American Helicopter Society, showed variations in predicted fatigue life from 9 to 2,594 hours. The current round-robin on fatigue life prediction in the American Helicopter Society(AHS) using a statistical reliability analysis is an effort aimed, in part, at investigating the adequacy of the safe life methodology. The AHS round-robin was instituted to increase future fleet readiness and flight safety which strongly depend on the degree of reliability and maintainability that can be designed into rotorcraft flight critical components. The current U.S. Army fatigue-life specification for new rotorcraft is the so-called "six-nine" reliability, or probability of failure of one in a million. The work reported in this study is a parallel effort to the AHS round-robin but focuses more on the actual methodologies used to predict fatigue life rather than the reliability aspect of the problem.

To make an assessment of the several methods that are used to predict fatigue life, a test program was designed to evaluate the several methodologies. The test spectrum chosen for the tests was the standardized rotorcraft spectrum called Felix/28(ref. 6). This spectrum will be described in a later section in the paper. This spectrum was chosen since very little experience exists in the rotorcraft community in synthesizing load histories from actual flight records as reported in a recent study by Berens et. al. in their report on helicopter fatigue methodology(ref. 7). Two other forms of Felix/28 were also used in the spectrum tests. Both of these spectra were developed using the results of a rainflow counting analysis on the Felix/28 spectrum.

The three analysis methods that were used to calculate fatigue life were the nominal stress P/M, the local strain P/M, and a total-life fracture mechanics analysis developed by Newman(ref. 8). The nominal stress P/M method was chosen since it is the primary method currently used by the rotorcraft community. The local strain method was recommended in a recent study on helicopter fatigue methodology(ref. 7), since it assesses the stress(strain) state at discontinuities such as holes where the fatigue damage process occurs. The total-life analysis was chosen since it is a method that calculates fatigue life based solely on fatigue crack growth from "small" initial cracks(10 to 20 microns in length).

Test Program

Both spectrum-fatigue and constant-amplitude-fatigue test data were needed for this study. The spectrum fatigue tests were needed as a point of reference to assess the ability of the several methodologies in predicting fatigue life. Constant amplitude test data were also needed for fatigue life calculations using the P-M nominal stress linear cumulative damage rule. This section describes the test specimen used for these tests and explains how the fatigue tests were performed.

Material and Specimen Configuration

The material selected for this study was AISI 4340 steel since it is often used in making dynamic components of rotorcraft. The material was supplied in the annealed condition with a plate thickness of 3/8 inch. All specimens were heat treated to Rockwell C scale values between 43 and 45 by a one hour soak at 840 C then tempering in a vacuum at 440 C for two hours followed by furnace cooling in nitrogen gas. The resulting tensile strength was 212 ksi which was calculated from an average of five tests.

The test specimens were machined to the configuration shown in Figure 1 before they were heat treated. The specimens were machined from the plate leaving a surface finish of 32 rms with the longitudinal axis of the specimen being aligned in the rolling direction of the plate. The hole diameter of 0.25 inches was machined using several progressively larger drill sizes with the last drill removing only 0.002 inches maximum to minimize residual stresses. The surface finish of the hole after machine polishing was 8 rms.

The elastic stress concentration factor (based on net section stress) as determined from the boundary force method (ref. 9) is 2.42. The same value is given by Peterson in his book on stress concentration factors(ref. 10).

Constant Amplitude Tests

All constant amplitude fatigue tests were run in servo-hydraulic, electronically controlled test stands. All tests were run at a stress ratio, R, of zero with cyclic frequencies between 10 and 20 hertz. Loads signals were controlled to within one percent. All fatigue lives reported herein were to specimen failure. Maximum net-section stress values ranged from 50 to 170 ksi.

Table 1 presents data for all constant amplitude tests. Figure 2 shows the constant amplitude fatigue tests plotted on a typical stress versus life cycle (S/N) curve. The endurance limit for these tests was estimated to be about 55 ksi.

Spectrum Tests

The spectrum fatigue tests were also performed using servo-hydraulic, electronically controlled test stands. For these tests a computer that was used to input the sequence of peak and trough commands to the testing machine also checked to assure that each commanded peak or trough was attained (to within 0.5% of range) before proceeding with the remainder of the sequence.

The load spectrum chosen for these tests was a helicopter load sequence developed in a collaborative effort by three European countries(ref. 6). Two standardized spectra were developed by this effort. One spectrum, called Helix, is a loading sequence representative of hinged or articulated rotors. The other spectrum, called Felix, represents a load sequence for fixed or semi-rigid rotors. A shortened version of Felix called Felix/28 was chosen for these tests. The full Felix sequence has slightly more than two million load cycles through one pass of the spectrum while Felix/28 has only 161034 cycles.

As with all fatigue test load spectra many modifications are made to the recorded flight loads before the final version of the test load sequence is established(ref. 11). A Westland Helicopter Ltd. Lynx and a MBB-BO-105 were the two helicopters whose load sequences were used in developing Felix. The Felix spectrum is scaled in Felix units with the maximum load in the sequence being 100. In arriving at the final version of Felix all alternating loads below 16 Felix units were omitted. The ground load at landing is -28 Felix units. The Felix/28 spectrum was developed by further omitting all alternating loads that were below 28 Felix units. The full Felix version contained 22 unique maneuvers. In creating Felix/28 if any of these 22 maneuvers were eliminated because of the further load omissions, these maneuvers were retained by redefining these maneuvers to have only one load cycle of the highest load at or below 28 Felix units.

Four unique flights each at three different flight lengths make up the 140 flights which represent one pass through the spectrum. The three different flight lengths are 0.75, 2.25, and 3.75 hours. All 140 flights combined represent 190.5 flight hours. The four unique flight types are made up of loading sequences that represent training, transport, anti-submarine warfare, and search and rescue missions. Figure 3 shows a typical load sequence for the transport mission.

Three forms of the Felix/28 spectrum were run during this test program. Each spectrum was run at several different maximum stress levels. Besides the actual Felix/28 sequence, the other two test spectra were load sequences developed from a rainflow cycle counting of the Felix/28 spectrum. Tests were run on these spectra to assess how important load interaction effects are on fatigue life in the Felix/28 spectrum. In one load sequence, called the low-high sequence in this study, the loads were applied in the order from the lowest load range, as determined by the rainflow counting method, to the highest load range. This load sequence is given in Table 2 and shown schematically in Figure 4. The other loading sequence was the reverse order of the low-high sequence and was called the high-low sequence. Since the low-high sequence gave fatigue lives that were slightly longer than the Felix/28 spectrum, the high-low sequence was run to see if shorter lives would result.

Fatigue Life Prediction Methodologies

In this next section, an explanation of the three techniques used in this study to predict fatigue life is presented. The two safe-life methods calculate a total fatigue life without explicitly considering crack growth in the analysis. As opposed to these methods, the Total-Life Analysis uses only crack growth data to predict total fatigue life with the initial crack length, a_i, being determined from a microscopic examination of crack initiation sites($2a_i$= 0.0006 in.).

Palmgrem-Miner Nominal Stress Approach

The rotorcraft industry mostly uses the nominal stress, Palmgren-Miner linear damage accumulation rule(P/M) to calculate the design fatigue life of rotorcraft dynamic components. The linear cumulative damage rule states that fatigue failure occurs when the summation of the so-called cycle ratios (n/N) is equal to one. In the nominal stress approach, the nominal applied stress is used with a cycle counting technique to group the flight loads into discrete load levels so the numerators (n) of the cycle ratios can be defined. In the design of rotorcraft the denominator(N) is determined from fatigue tests on the actual part being designed. Usually six tests are run at different stress levels and a curve is faired through each point to define the endurance limit(ref. 12). The curve shape used in fairing through the test points is usually established from coupon S/N test data. The design endurance limit is the lowest of several "statistical" reductions taken on the mean endurance limit. The statistical reductions often considered are eighty percent of the mean, one standard deviation from the mean, and three standard deviations from the mean. Usually the lowest of the several reductions considered is taken as the design endurance limit. In this report the denominator of the cycle ratio(N) was determined from coupon S/N data at a stress ratio of zero.

Since the fatigue load cycles from the flight loads data are at many different R ratios, these loads(stresses) are "corrected" to stress values that give the equivalent damage as the flight load stresses but at the R ratio of the S/N data. Some form of the Goodman diagram is normally used for this "correction". In this study a linear Goodman correction was used. The fatigue life is then calculated by summing all the cycle ratios for the different stress levels determined from the counting technique and this sum is inverted and multiplied by the number of cycles per pass in the load spectrum to calculate fatigue life. In equation form this becomes

$$\text{Fatigue Life} = (1 / \Sigma\, n/N) * \text{cycle per pass} \quad (1)$$

In using the nominal stress P-M analysis for fatigue life prediction there are at least three parts of the analysis where different approaches can be used. First, a counting technique must be used to group the flight stresses into discrete stress levels to form the cycle ratios. In this study a rainflow counting technique has been used which has been programmed as a computer algorithm(ref. 13). The rainflow count of Felix28 is given in Table 2. Second, an S-N curve is needed for the denominator of the cycle ratios. In this study as stated previously, constant amplitude tests were run at a stress ratio of zero to provide this information(see Fig. 2 and Table 1). In the computer algorithm that was written for the nominal stress P-M analysis, the S-N data were put in an equation which is linear on a log-log plot as shown in figure 5. The horizontal line shown in figure 5 represents the endurance limit which was determined from the three tests that were runouts(see Table 1). The stress levels of these three tests were averaged to define the endurance limit at 55.83 ksi. All tests were used to calculate the log-linear line shown in figure 5 except for the three runout tests and tests that were below the endurance limit. Third, the flight stresses were corrected by a linear Goodman correction to give a set of stresses that gave an equivalent damage as the actual spectrum stresses but at the stress ratio used in the constant amplitude tests.

Local Strain Approach

The local strain approach uses the P/M linear cumulative damage rule, but seeks to define the fatigue damage in a more rigorous manner by relating the fatigue life to the local strain and local mean stress. This approach also is able to account for load interaction effects since the strain for a current load cycle depends on the prior load cycles deformation(ref. 14). Instead of using a S-N curve to determine the denominator of the cycle ratios, a local strain life relationship is used which relates the local strain amplitude, ϵ_a to the cycles to failure, N*. This relationship is usually developed from constant amplitude fatigue tests on unnotched specimens.

For a mean local stress of zero this relationship can be expressed as

$$\epsilon_a = \frac{\sigma_f'}{E}(2N^*)^b + \epsilon_f'(2N^*)^c \qquad (2)$$

fit parameters. These curve fit parameters are often called the fatigue strength coefficient, fatigue strength exponent, fatigue ductility coefficient, and fatigue ductility exponent, respectively. An equation which corrects the above calculated life for a nonzero local mean stress is

$$N = N^* \left(1 - \sigma_o / \sigma_f' \right)^{-1/b} \qquad (3)$$

where σ_o is the local mean stress.

The numerators in the cycle ratios, n, are determined by taking the flight load peaks and valleys and turning them into a sequence of local stress-strain hysteresis loops. These local stress-strain hysteresis loops are then grouped into similar strain ranges to form the cycle ratios (n/N) used to calculate the fatigue life. It is the forming of the stress-strain hysteresis loops where the load interaction effects of the flight loads are taken into account.

The local stress and strains corresponding to each flight load peak and valley can be determined experimentally or estimated through approximate equations(ref. 15). If the equation method is used the flight loads(or stress, S) are often related to the local stress and strain using Neuber's rule in the form

$$\sigma \epsilon = \frac{(K_T S)^2}{E} \qquad (4)$$

where σ and ϵ are the local stress and strain, and K_T is the elastic stress concentration factor. A cyclic stress-strain relationship such as

$$\epsilon = \sigma/E + (\sigma/A)^{1/s} \qquad (5)$$

where A is the cyclic strength coefficient and s is the cyclic strain hardening exponent, is then combined with the Neuber rule to determine the local strain for each flight load peak and valley in the load sequence. The corresponding local stress can then be determined from Neuber's rule and the local stress-strain hysteresis loops are formed.

A rainflow counting of a given flight load sequence will give the same cycle counting results in terms of the the number of cycles(n) at a given nominal stress as the method for generating the hysteresis loops stated above(ref. 15). These nominal stresses can then be converted to local stresses using Neuber's rule as previously stated. Computer algorithms have been developed for performing this type of rainflow counting(ref. 13). A computer program has also been developed for predicting fatigue life from a simplified version of the local strain approach. In this approach upper and lower bounds are placed on the mean stress of each load cycle and fatigue lives are calculated using equations 2 through 5 to determine upper and lower bound values of fatigue life(ref. 13). This approach was used in this study in determining the fatigue life from the local strain methodology.

A computer algorithm, called UPLO, developed by Khosrovaneh and Dowling (ref. 13) was used for calculating the upper and lower bounds on fatigue life. The curve fit parameters needed in equations 2, 3, and 5 are given in Table 4. The range and mean stress values for Felix28 needed by UPLO were determined by a rainflow computer algorithm(ref. 13).

Damage Tolerance Approach

In the damage tolerance approach to structural integrity, a safe inspection interval or safe operating life is calculated from crack growth considerations. A safe inspection interval is determined for structures where the structure can be inspected and a safe operation life is determined for structures that can not be inspected. Concepts from fracture mechanics which relate crack growth rates to the stress intensity factor range are used to calculate the safe operating interval or life. In this approach, life is calculated by integrating a crack growth rate versus stress intensity factor relationship like

$$da/dN = C(\Delta K)^{m} \qquad (6)$$

where da/dN is the crack growth rate and ΔK is the stress intensity factor. To calculate a safe inspection interval the initial crack size used in the integration is 0.05 inches(ref. 3). To calculate a safe operation life the initial crack size used in the integration is 0.005 inches. In the calculation of the safe operating life the crack growth life must be greater than the design life of the structure.

In this study, a modified damage tolerance approach was used to predict the total fatigue life of the test specimen. The main difference between the total life analysis(TLA) and the more widely accepted approach, explained above, is that crack-closure concepts(ref. 8) are used to define an effective ΔK and the initial crack length was determined from a previous "small" crack study on 4340 steel(ref. 16). From crack-closure considerations, ΔK in equation 6 is replaced by ΔK effective. In this work the effective stress intensity factor is defined as

$$\Delta K_{eff} = (S_{max} - S_{o})(\pi a)^{1/2} F \qquad (7)$$

where S_o is the crack-opening stress as calculated from the analytical closure model developed by Newman(ref. 8) and F is the boundary correction factor which accounts for the effects of structural configuration on the stress intensity factors. To
calculate the crack growth rate, equation 6 becomes

$$da/dN = C[(S_{max} - S_{o})(\pi a)^{1/2} F]^{m} \qquad (8)$$

Total life is calculated by numerically integrating equation 8 from the initial crack length to failure as

$$N = \sum_{a_i}^{a_f} \frac{\Delta a}{C[(S_{max} - S_o)(\pi a)^{1/2} F]^m} \quad (9)$$

where a_i is the initial crack length as determined from the small crack studies and a_f is the final crack length at failure. Cycles are summed as the crack grows until $K_{max} = K_c$, where K_c is the fracture toughness. When $K_{max} = K_c$, the summation of the load cycles, N, becomes the total fatigue life.

The total fatigue life as determined by the TLA method was calculated from a computer algorithm developed by Newman. For this study the initial crack length used to predict the fatigue life was 0.0006 inches . This value was taken from a small crack study on 4340 steel(ref. 16) in which initial defect sizes at 34 crack initiation sites were evaluated by scanning electron microscopy of the fracture surfaces. The largest value was about 0.002 inches, the median value was about 0.0006 inches, and the smallest was about 0.00008 inches.

Comparisons of Predicted and Test Lives

Figure 6 shows the results for the Felix/28 spectrum tests and the rainflow counted sequence tests. The data are plotted as the maximum stress in the spectrum versus the load cycles to failure. Table 3 shows these test results in tabular form at the several different maximum stress values. Figure 6 shows that at the higher stress levels the low-high sequence gave fatigue lives that were slightly longer than the Felix/28 lives, while the high-low sequence gave slightly shorter lives than the Felix/28 lives. The test results also show that as the maximum stress level in the spectrum is reduced the lives for the three different test spectra appear to converge. In reference 6 it was noted that Felix/28 test lives should be viewed with caution at the higher stress levels, whereas, the lives near the endurance limit simulated the full Felix spectrum test results fairly well. The current tests also show that for this material and hole configuration a maximum stress in the spectrum of 100 ksi will give test lives at about one pass through the spectrum while a runout is at about a maximum stress of 65 ksi in the spectrum.

In figure 7 the Felix28 spectrum test results are shown as well as the analytical life predictions from the nominal stress P-M analysis, local strain P-M, and the TLA analysis as explained above. The P-M analysis life predictions follow the trend of the Felix28 test data very well, although the predictions are slightly on the unconservative side. It should be noted that these lives were based on a <u>mean</u> regression line through the S-N data of figure 2. The mean regression line is shown in figure 5. In general, rotorcraft fatigue lives are based on a reduction from this mean curve. This will be discussed in more detail later.

The local strain P-M life predictions as calculated by the UPLO program also follows the trend of the Felix28 data very well. Similarly to the nominal stress P-M analysis, the local strain predicted lives are slightly unconservative when compared to the test data where the maximum stress in the test spectrum is at the higher values. However, at the lower stress values the local strain predicted lives fall within the scatter of the test results.

The life predictions from the TLA analysis also follows the trend of the test data very well. These predicted lives are also slightly longer than the mean test lives but are within the experimental scatter.

Since the nominal stress P-M method cannot account for any load interaction effects, it will predict the same fatigue lifes for all three spectrums. As stated previously, the local strain P-M method does account for load interaction effects . However, in this study since the bounded analysis of the UPLO computer program was used to predict fatigue lives, it is not clear how successful the local strain analysis would be in predicting the load interaction effects of these spectra. As can be seen in figure 8, the maximum difference in lives that could be produced by the local strain method due to load sequence effects was similar to the difference in lives observed for the two reconstructed sequence tests.

The TLA analysis, like most analyses that calculate crack-growth rates, accounts for load interaction effects. As can be seen in figure 8, different fatigue lives are predicted for the lo-hi and hi-lo load spectra by the TLA method. For the lo-hi spectrum the lives predicted by the TLA fall within the scatter of the test data. For the hi-lo spectrum, the TLA predicts lives that approximate the upper bound of the test life scatter. It must be recalled that these life predictions made with the TLA were done using the median value(0.0006 inches) of the initial defect size determined from a previous test program on the same batch of 4340 steel(ref. 16).

If any of the three methods used in this study were used for predicting the design fatigue life of an aircraft, some type of reduction would be taken from the mean life curves shown previously. Figure 9 shows such possible reductions as well as a life prediction curve using the initial crack size most often used in damage tolerance analysis(0.05 inches, ref. 3). If the nominal stress P-M analysis were used for design, one possible reduction would be to reduce the mean S-N curve to 80% of the mean stresses and calculate fatigue lives based on the 80% S-N curve(ref 12). Fatigue lives predicted by this procedure are shown in Figure 9. Since this "design" life curve falls on the conservative side for practically all test data this would appear to be an acceptable design life curve.

Figure 9 also shows a life prediction "design" curve as calculated by the TLA method(a_i= 0.002 inches). These lives were calculated using the largest inclusion particle dimensions found in reference 16. While this "design" curve also predicts lives on the conservative side of the test data, it predicts an endurance limit between 40 and 45 ksi which is nominally 10 ksi less than the 80% P-M prediction and about 20 ksi less than the one runout test.

To place in perspective the effect of using the current damage tolerance initial crack size(0.05 inches) on predicting total fatigue life, a curve from these calculations is also shown on figure 9. Very conservative lives would be predicted using the 0.05 inch initial crack size.

Conclusions

The following conclusions have been reached from this study on 4340 alloy steel, quenched and tempered to 45 R_c:

1. Both the nominal stress and the local strain Palmgren-Miner linear cumulative damage rules predicted the fatigue lives under the Felix/28 standardized helicopter spectrum with reasonable accuracy.

2. Two simple load sequences(low-high and high-low) from rainflow counting of Felix28 showed different lives than the actual Felix/28. The nominal stress P-M linear cumulative damage rule produces the same life prediction for both reconstructed sequences. The maximum difference in lives that could be produced by the local strain method due to load sequence effects was similar to the difference in lives observed for the two reconstructed sequence tests.

3. The Total Life Analysis(TLA) which uses crack-closure concepts in predicting total fatigue life using crack-growth data alone (initial crack size of 0.0006 inches) also predicted the Felix28 test data very well. Since this analysis can take into account load interaction effects, it also predicted the total fatigue lives of the simple rainflow reconstructed spectra with reasonable accuracy.

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Table 1. Constant amplitude fatigue test data for R = 0.

S_{max} (ksi)	Cycles-to-failure			
50	5993030			
52.5	3757353,	10000000(run-out)		
55	2577077,	10000000(run-out)		
60	206790,	116768,	10000000(run-out)	
65	97278,	81773		
70	308435,	61361,	58233	
80	80827,	49277,	37095,	34059
	28099			
120	7434,	7306,	7056	
175	1531,	1336,	1325	

Table 2. Rainflow Low-High Load Sequence Derived From Felix28

NOMINAL STRESS RANGE (KSI)	NOMINAL STRESS MEAN (KSI)	NUMBER OF CYCLES
2.80	25.59	354
2.80	32.83	334
6.42	29.21	416
10.04	29.21	609
10.04	36.45	1228
10.04	40.07	810
13.66	36.45	2
17.28	18.35	140
17.28	32.83	78
20.91	32.83	2061
20.91	36.45	90
24.53	-7.00	140
24.53	18.35	140
24.53	36.45	2040
28.15	29.21	833
31.77	25.59	346
35.39	25.59	7904
35.39	29.21	56
35.39	32.83	71072
35.39	43.69	2529
39.01	21.97	3014
39.01	25.59	42825
39.01	29.21	6393
39.01	43.69	252
42.63	25.59	480
42.63	29.21	207
42.63	36.45	1274
46.25	21.97	274
46.25	25.59	6239
46.25	29.21	4274
46.25	40.07	604
49.87	3.86	268
49.87	25.59	956
49.87	29.21	2179
53.49	25.59	2
53.49	29.21	116
57.12	25.59	5
57.12	29.21	185
60.74	29.21	25
64.36	25.59	7
64.36	29.21	8
64.36	32.83	75
67.98	29.21	9
71.60	29.21	16
75.22	25.59	7
78.84	18.35	5
78.84	25.59	1
82.46	21.97	128
82.46	29.21	16
89.70	25.59	8

Table 3. Spectra Fatigue Test Data

a) Felix/28 Spectrum

S_{max} (ksi)	Cycles-to-failure			
65	41000000(run-out)			
70	11031000			
73.3	4396500			
80	3128200,	2898600,	2095100,	1177900
	1032500,	841860,	552600,	404510
85	121080			
86.7	176308			
90	227510,	179180		
93.3	279190			
100	187490,	175650,	107580	
120	52079,	41228		

b) Rainflow Low-High Spectrum (of Felix/28)

70	42290000(run-out)		
80	2116500		
90	4112834,	3176269,	629160
100	577140,	219872,	214420
120	206495,	65124,	49055

c) Rainflow High-Low Spectrum (of Felix/28)

80	592808,	422226,	2440630	
90	551120,	532280,	484260,	325150
100	49790,	230500,	62559	
120	34915,	33825		

Table 4. Local Strain Curve Fit Parameters

σ_f'	fatigue strength coefficient	290 ksi
b	fatigue strength exponent	-0.091
ϵ_f'	fatigue ductility coefficient	0.48
c	fatigue ductility exponent	-0.60
A	cyclic strength coefficient	305 ksi
s	cyclic strain hardening exponent	0.15

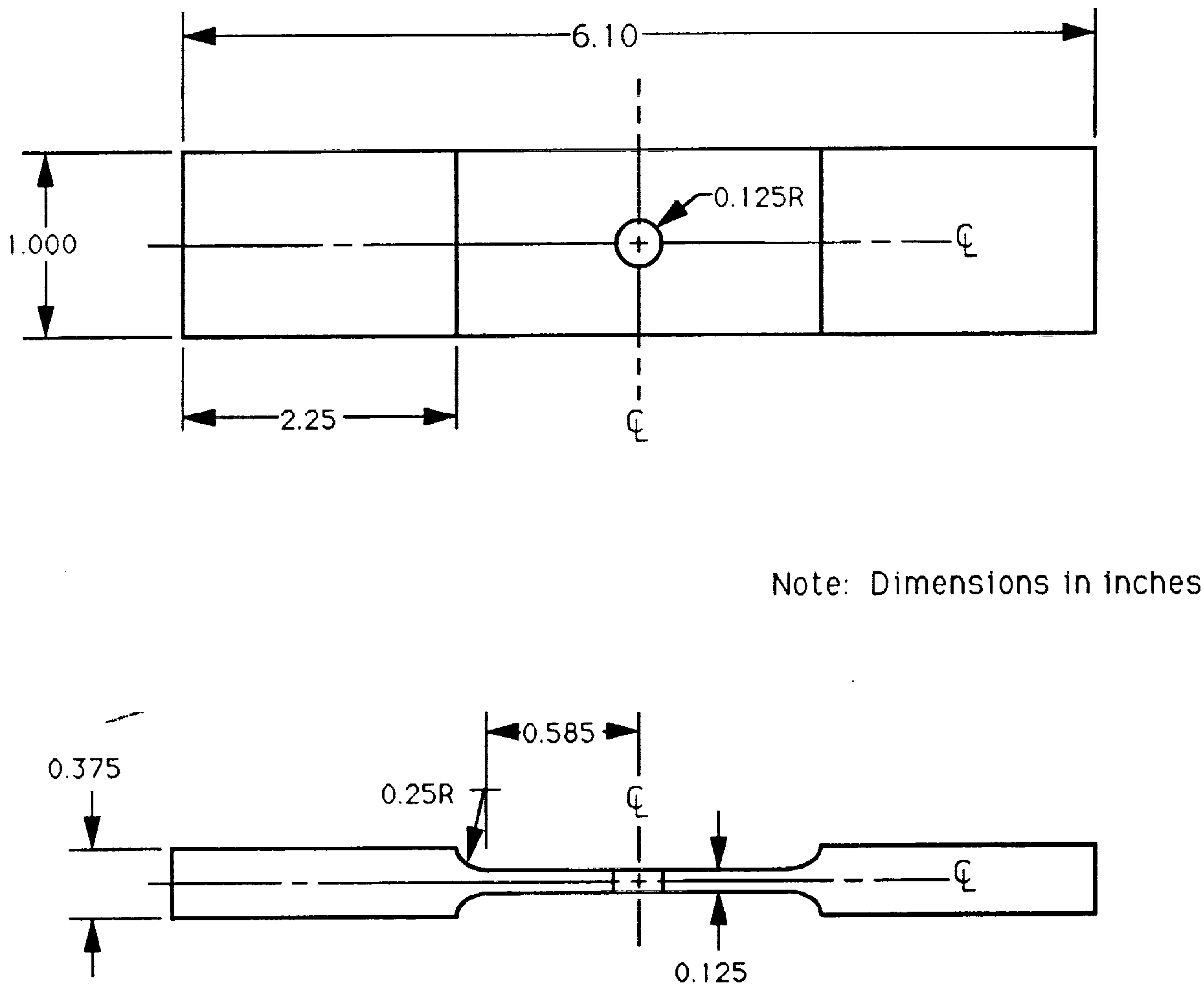

Fig. 1. Fatigue test specimen configuration

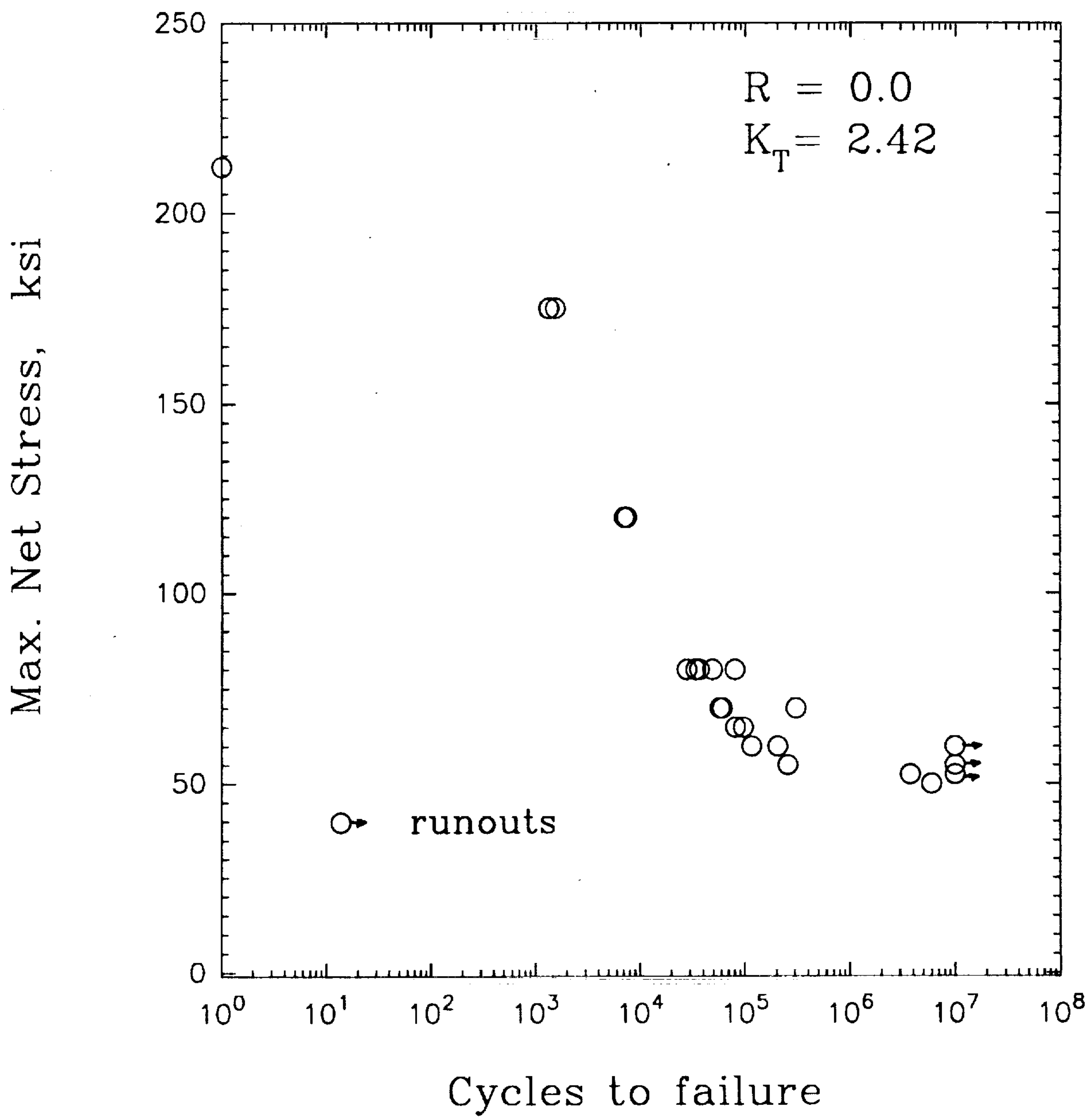

Fig. 2 Constant amplitude test data.

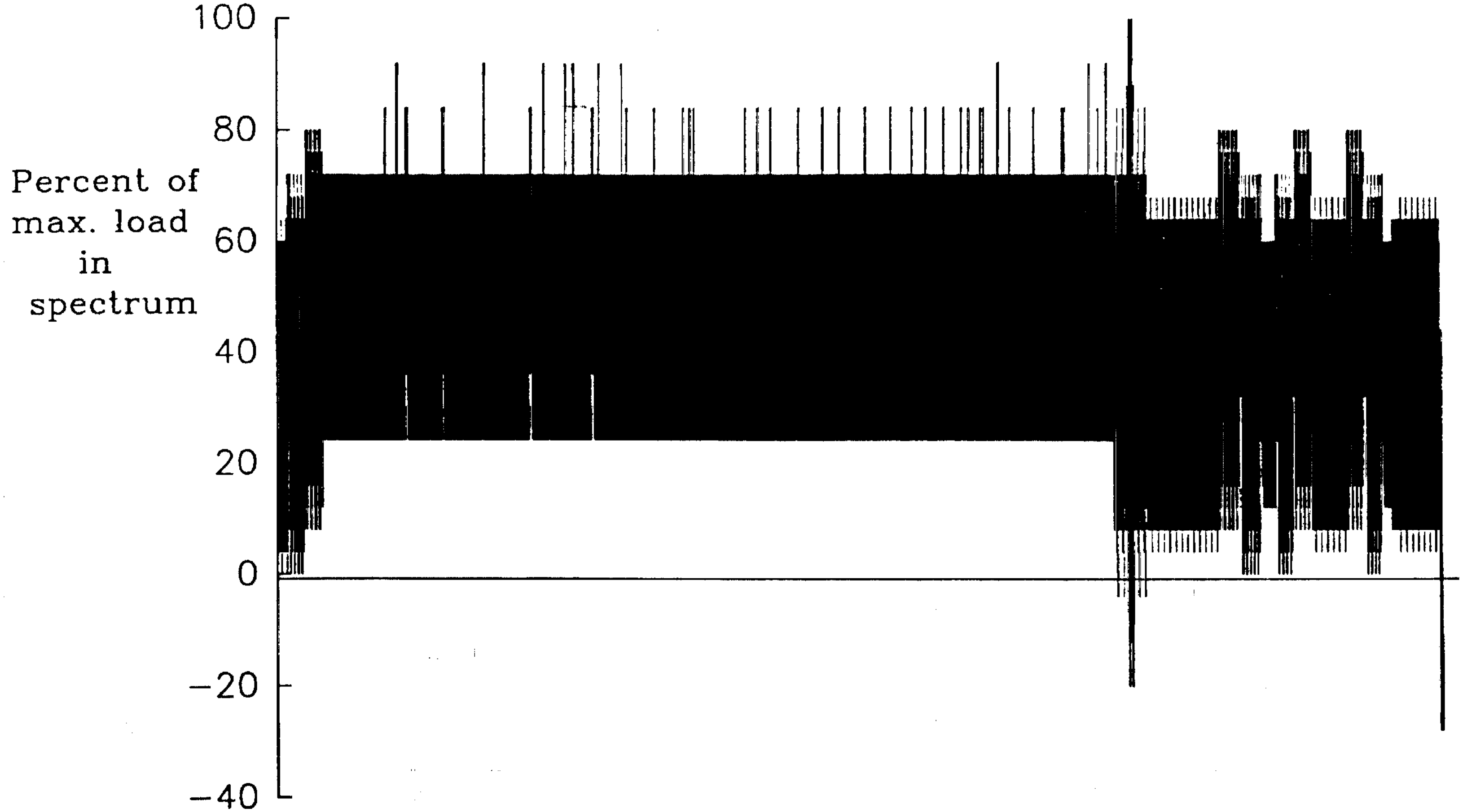

Fig. 3 Felix28 long transport flight (3.75 hrs).

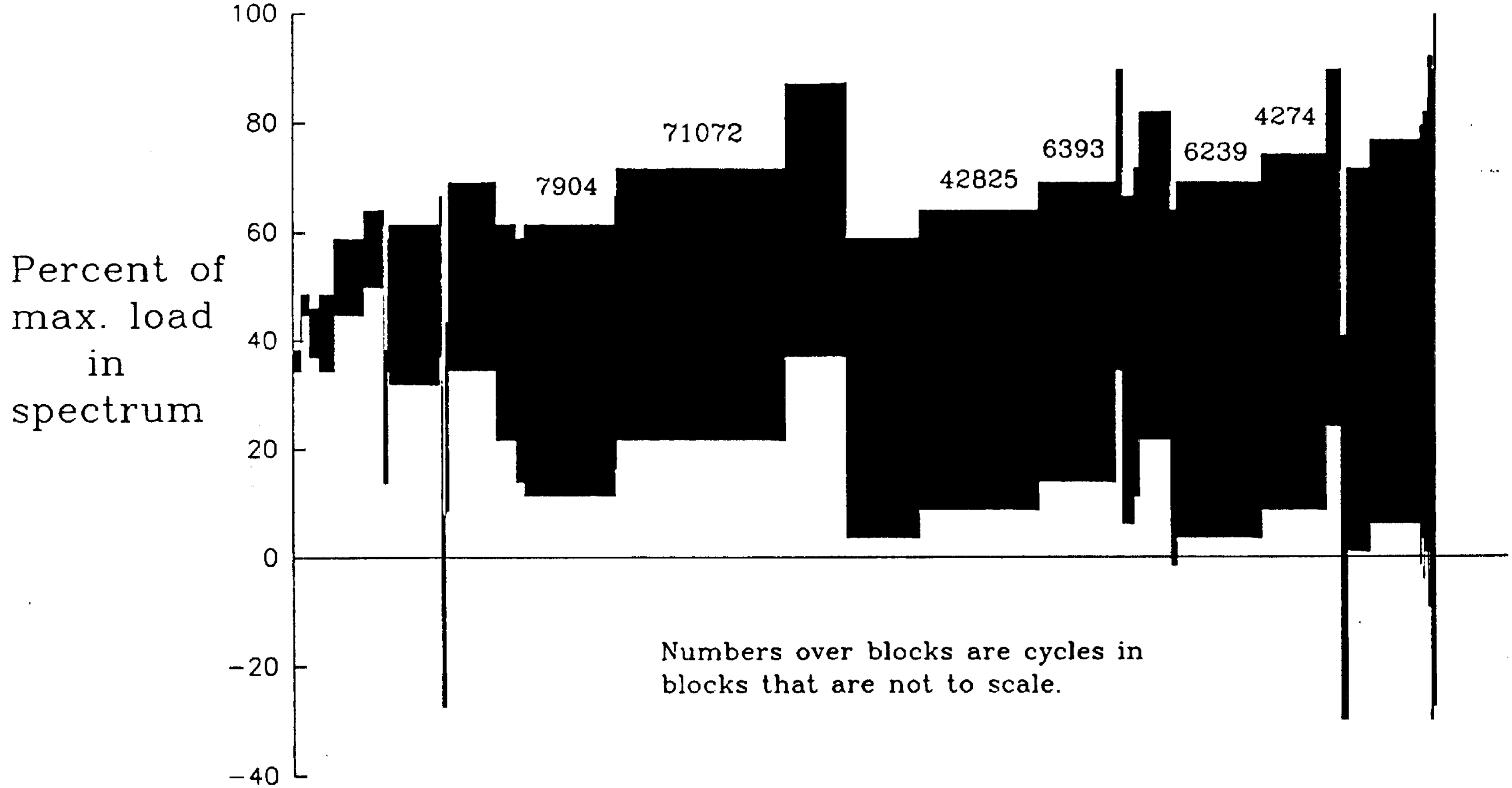

Fig. 4 Rainflow low–high load sequence derived from Felix28

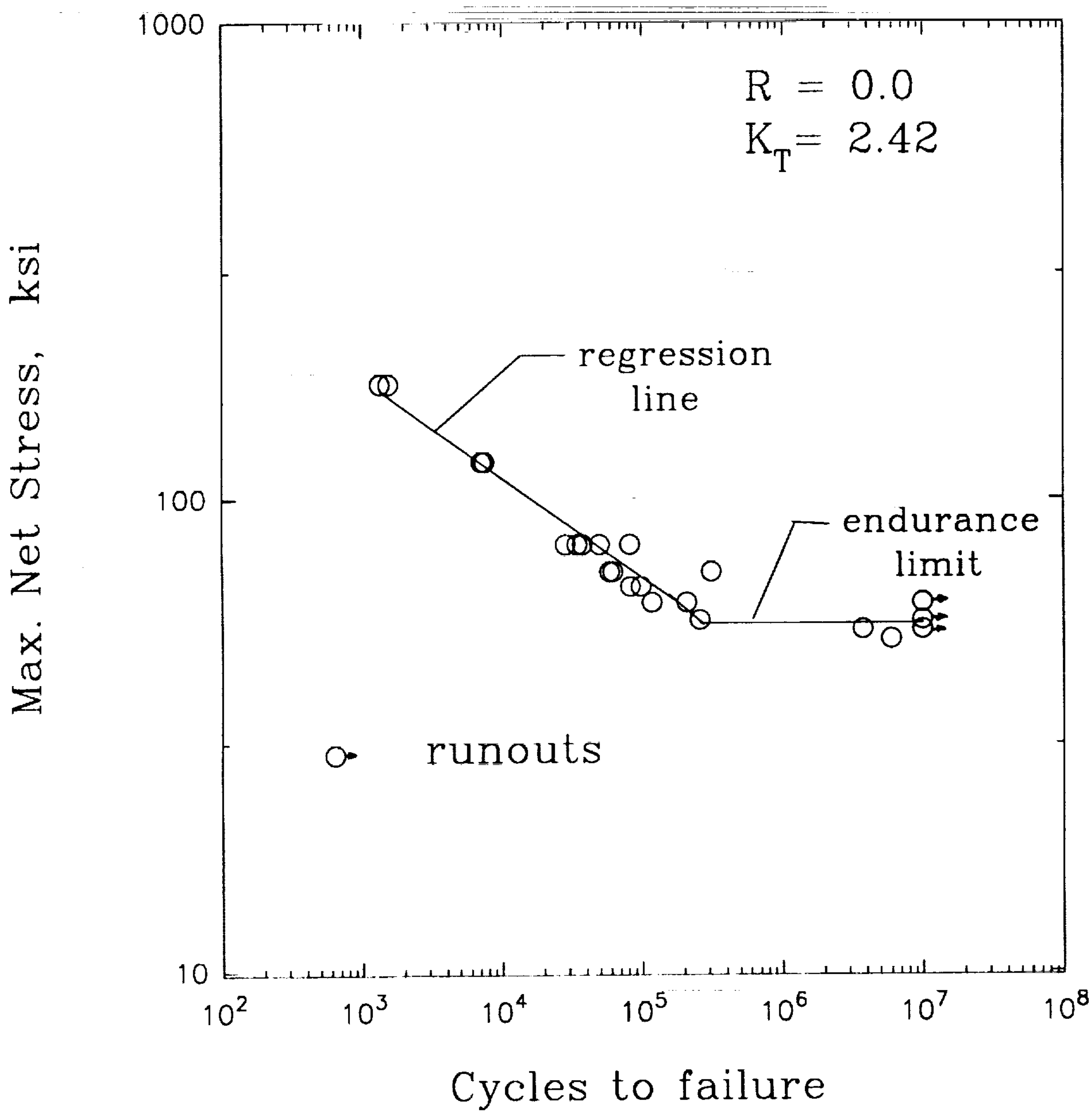

Fig. 5 Regression analysis of constant amplitude data

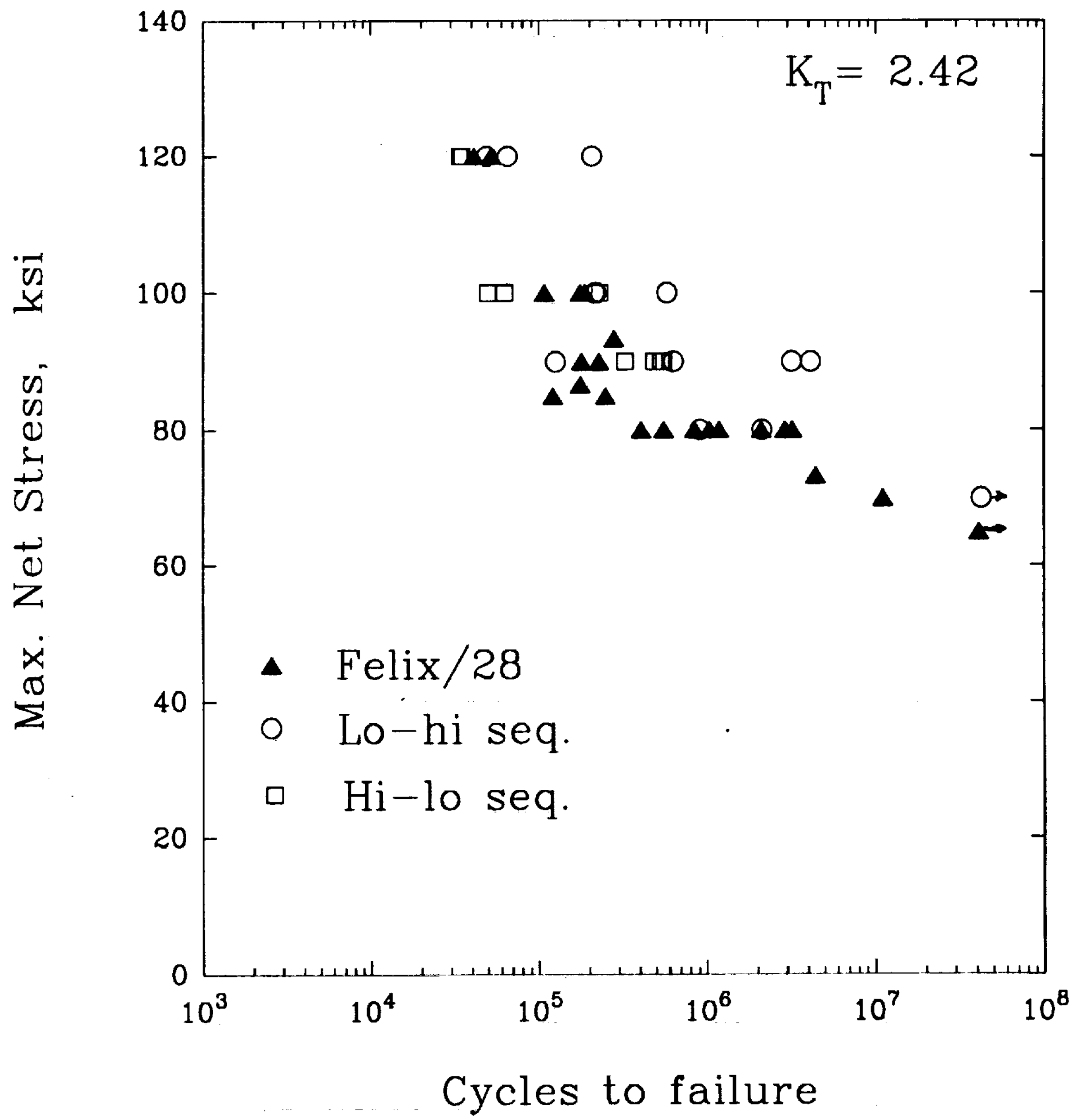

Fig. 6 Spectrum test data.

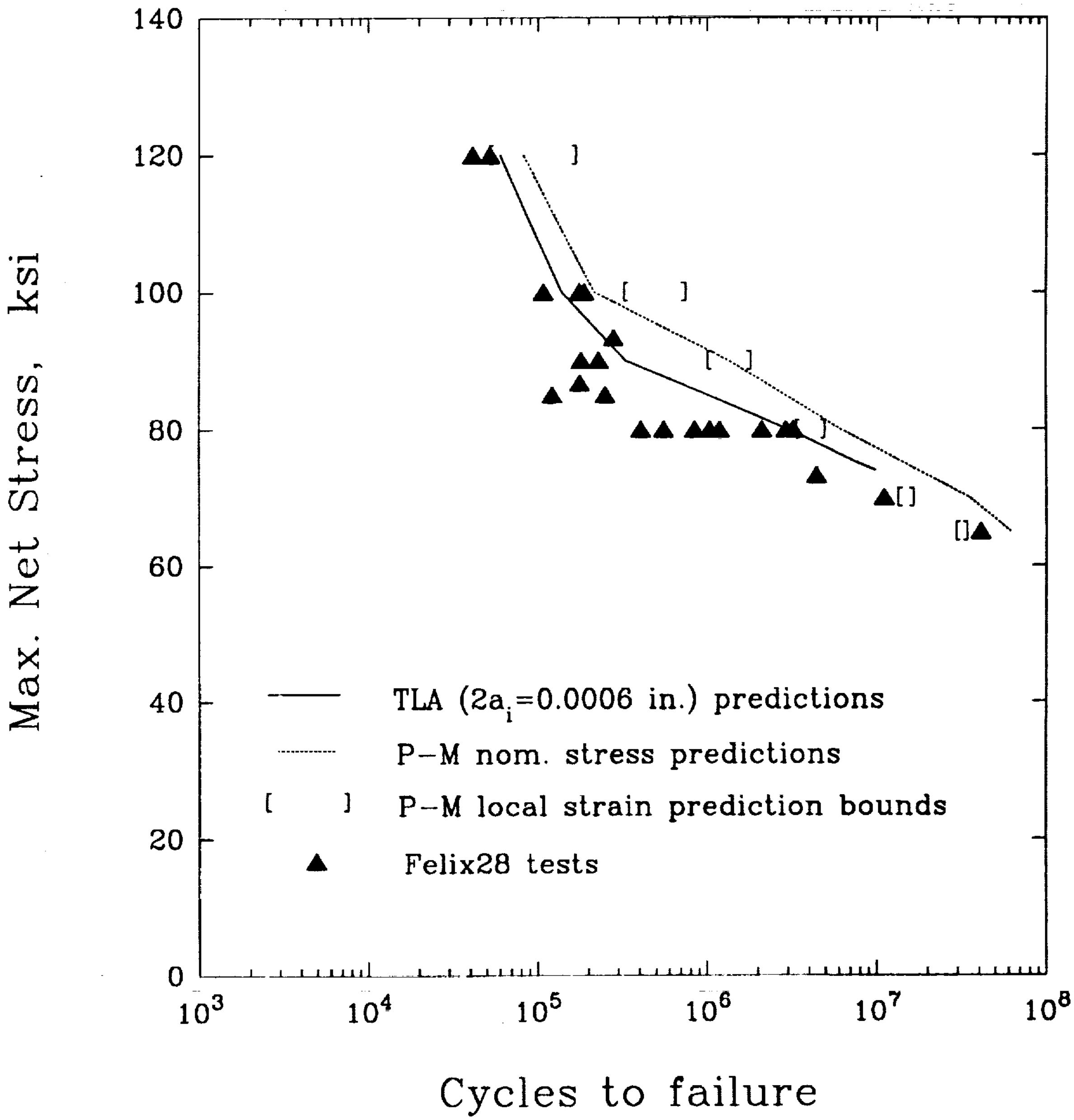

Fig. 7 Fatigue life predictions for Felix28 tests.

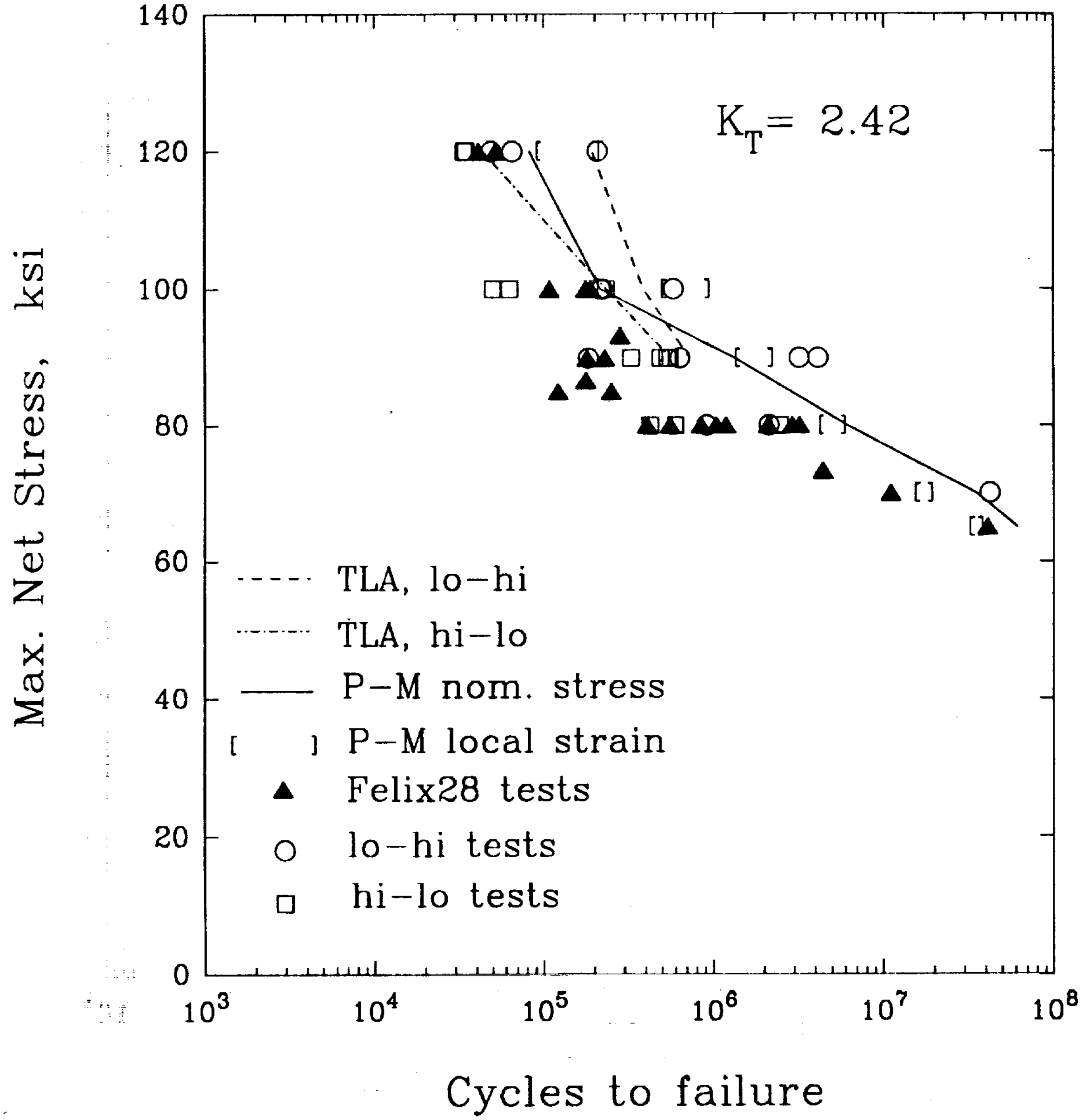

Fig. 8 Fatigue life predictions for lo–hi and hi–lo spectrum tests.

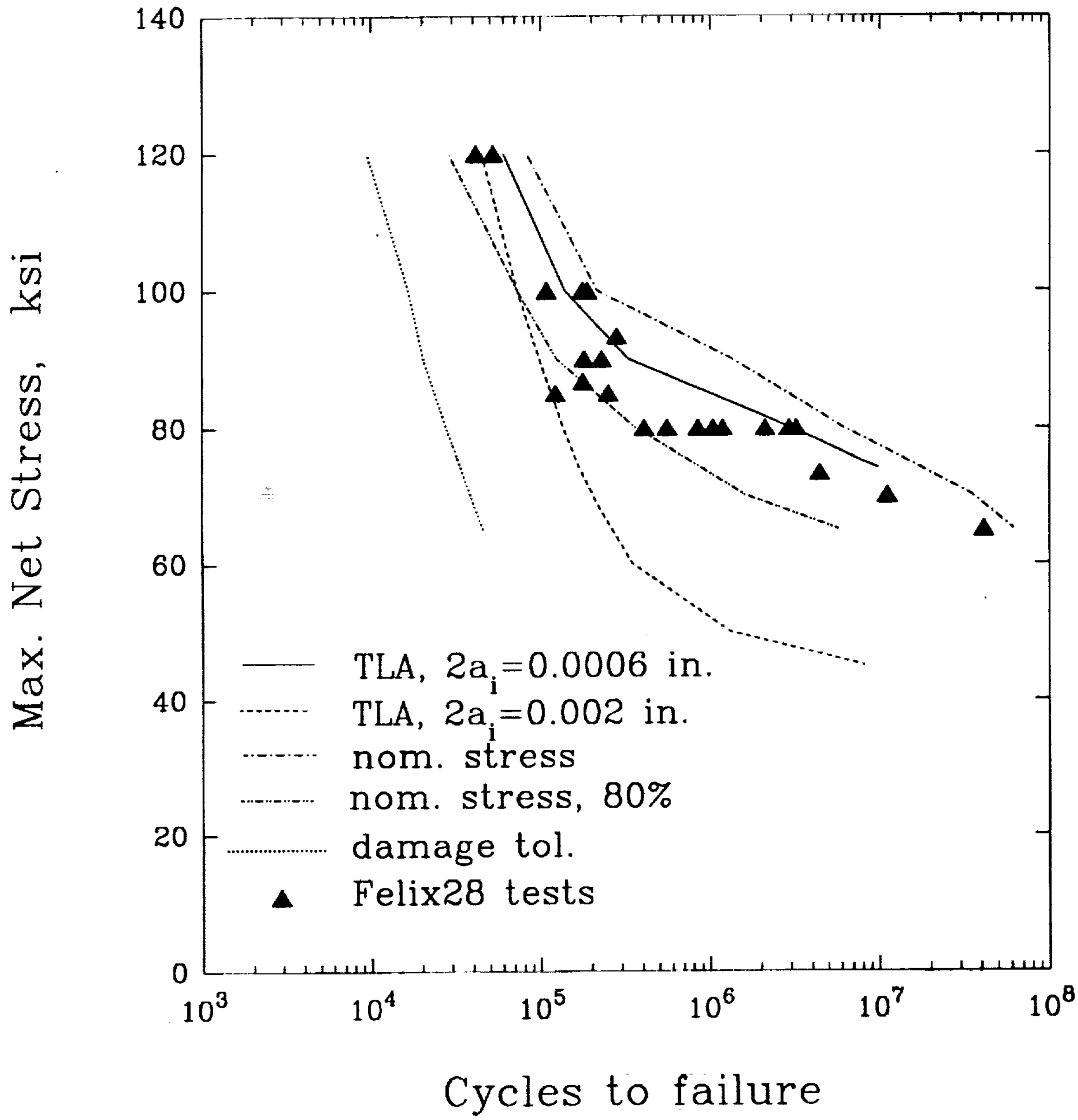

Fig. 9 Effect of conservative assumptions on fatigue life predictions for Felix28 tests.

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15. Supplementary Notes

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16. Abstract

Because of the current U.S. Army requirement that all new rotorcraft be designed to a "six nines" reliability on fatigue life, this study was undertaken to assess the accuracy of the current safe life philosophy using the nominal stress Palmgrem-Miner linear cumulative damage rule to predict the fatigue life of rotorcraft dynamic components. It has been shown in the past that this methodology can predict fatigue lives that differ from test lives by more than two orders of magnitude. A further objective of this work was to compare the accuracy of this methodology to another safe life method called the local strain approach as well as to a method which predicts fatigue life based solely on crack growth data. Spectrum fatigue tests were run on notched ($K_T = 3.2$) specimens made of 4340 steel using the Felix/28 variable amplitude spectrum (a shortened form of a standard loading sequence for "fixed" or semi-rigid helicopter rotors). Two other spectra which resulted from a simple rainflow reconstruction of Felix/28 were also tested.

Both linear cumulative damage methods predicted the fatigue lives of the Felix/28 tests fairly well, being slightly on the unconservative side of the test data. The crack growth method, which is based on "small-crack" crack growth data and a crack-closure model, also predicted the fatigue lives very well with the predicted lives being slightly longer than the mean test lives but within the experimental scatter band. The crack growth model was also able to predict the change in test lives produced by the rainflow reconstructed spectra.

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