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FATIGUE LIFE ESTIMATES FOR HELICOPTER LOADING SPECTRA

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Fatigue Life Estimates for Helicopter Loading Spectra

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Abstract

Helicopter loading histories applied to notched metal samples are used as examples, and their fatigue lives are calculated by using a simplified version of the local strain approach. This simplified method has the advantage that it requires knowing the loading history in only the reduced form of ranges and means and number of cycles from the rain-flow cycle counting method. The calculated lives compare favorably with test data.



Introduction

The Palmgren-Miner (P-M) theory of damage has long been used to predict the time to crack initiation in metals. This rule states that the fatigue failure occurs when the summation of life fractions reaches unity. The successful use of this rule requires proper handling of cycle counting, overstrain effects, and local notch mean stress effects. In this paper, the P-M rule is used, and the above three complexities are included by using the rain-flow cycle counting method, by basing the life calculations on data for specimens that have been prestrained [1-3], and by using the local strain approach [4-6], respectively. The local strain approach focuses attention on the stresses and strains that occur locally at a stress raiser of interest, and the S-N curve used is a strain versus life curve.

The rain-flow cycle counting method is a procedure for interpreting an irregular load versus time history as a collection of events (called cycles) to which fatigue damage can be assigned. In this method [7], cycles are counted depending on the comparison of two adjacent ranges as illustrated in Fig. 1, which also defines the range and mean of a cycle. If the first range is less than or equal to the second, a cycle is counted and the corresponding peak and valley are discarded for the purposes of further cycle counting.

Figure 2 illustrates this process for a simple loading history. First, the history is reordered to start with the highest peak or lowest valley as in (b). Cycle counting then proceeds by moving forward in the history. If a cycle is counted, as in (c), its range and mean are recorded and its peak and valley are removed from the history. This procedure, as described in detail in Ref. [7], always yields a major cycle between the highest peak and lowest valley, and smaller cycles temporarily interrupt larger ones.

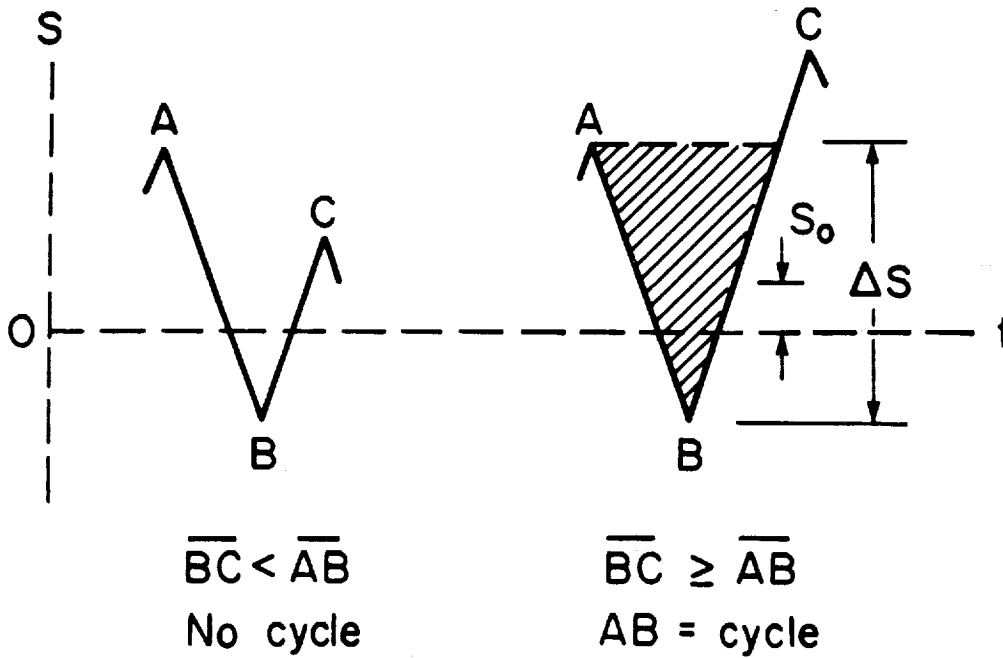
By using the rain-flow cycle counting method, a service loading history can be reduced to a convenient compact form. The compact description is in the form of a matrix giving range, and

mean, and numbers of rain-flow cycle. Table 1 illustrates such a matrix for the loading history of Fig. 2. As a second example, a portion (about one-third) of an actual helicopter loading history is shown in Fig. 3, and the resulting rain-flow matrix in Fig. 4.

As noted above, an area of importance in predicting fatigue life is the overstrain effect. This effect, which is caused by the higher stress levels, needs to be considered since it increases the damage done by the lower stress levels [1,2]. Figure 5 illustrates this effect for titanium 6Al-4V. The lower curve represents test data for specimens which have been plastically strained, but only to a life fraction of a few percent. There is nevertheless a large effect on the life for subsequent testing at a lower level due to the prestrain causing damage to the material at the microstructural level.

A known load versus time history is necessary for analysis of fatigue life using the local strain approach. But the history may be lengthy, and there are no restrictions on the degree of irregularity of the time variation. The local strain approach predicts crack initiation life and assumes that fatigue life is controlled primarily by the local notch surface strain and mean stress, not the nominal (average) stress. Emphasis on local notch behavior is crucial as this permits rational analysis of local notch yielding and its effect on the local notch mean stress. This method in its complete form requires knowing the loading history in full length.

A simplified method for calculating fatigue crack initiation life based on the local strain approach can be used [5,8]. This method has two very distinct advantages. First, only a rain-flow matrix in the compact form of range-mean values is required as the input information. Although some detail is lost, such a matrix can be used with the local strain approach to place upper and lower bounds on the life that would result from the analysis of the original, unsummarized history. This principle is explained in detail in Refs. [3,9]. Note that this compact form is much easier to handle and store than the full history in the form of a time sequence of peaks and valleys. Secondly, the life calculations are simpler and more economical.



For cycle A - B

Peak = S_A

Valley = S_B

Range = $\Delta S = S_A - S_B$

Mean = $S_0 = (S_A + S_B)/2$

Figure 1. Condition for recording an event during rain-flow cycle counting

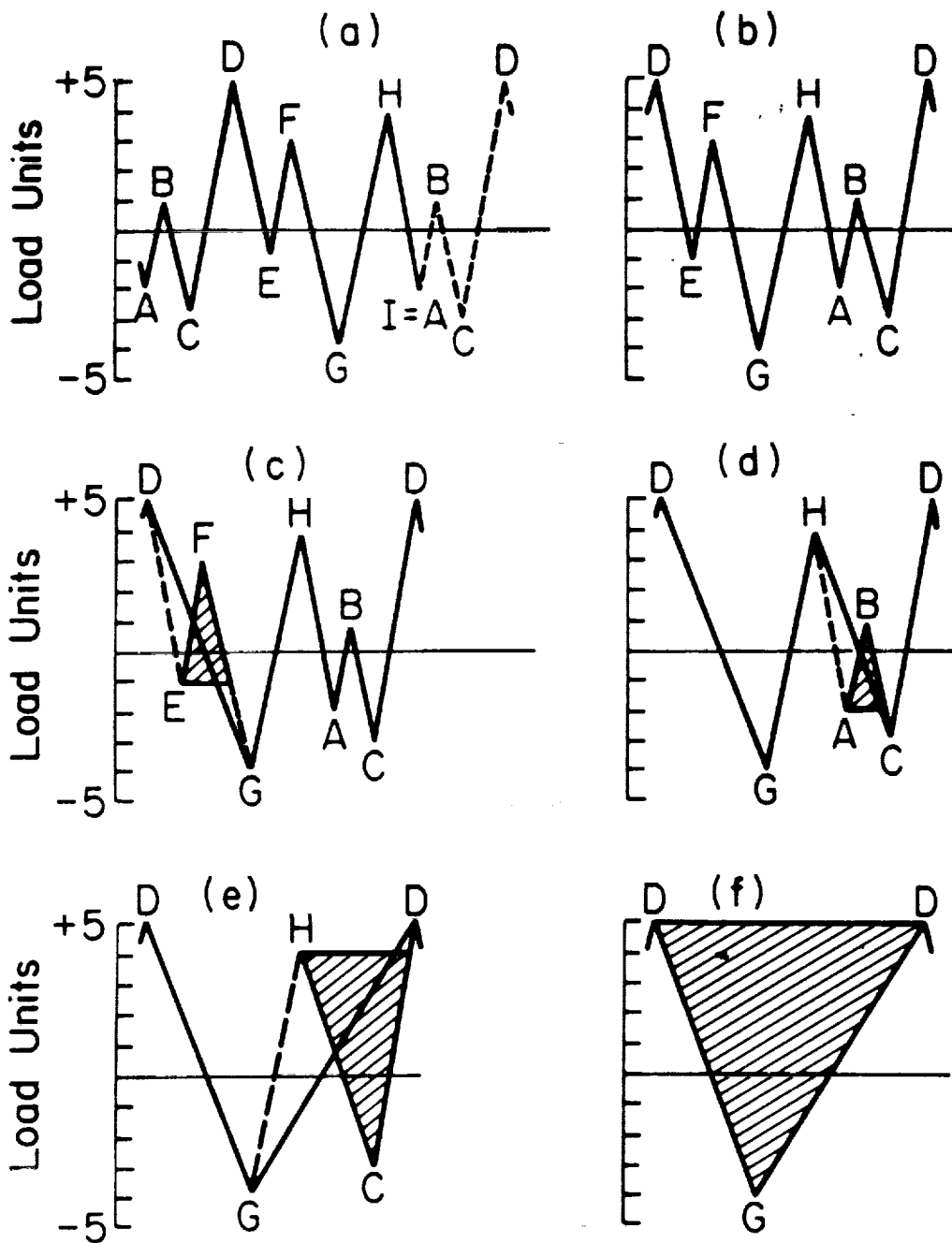


Figure 2. Example of rain-flow cycle counting from the ASTM standards [7]: Before the cycle counting begins, the most extreme point in the history should be located, and the history arranged to start and finish at this point as shown in (b).

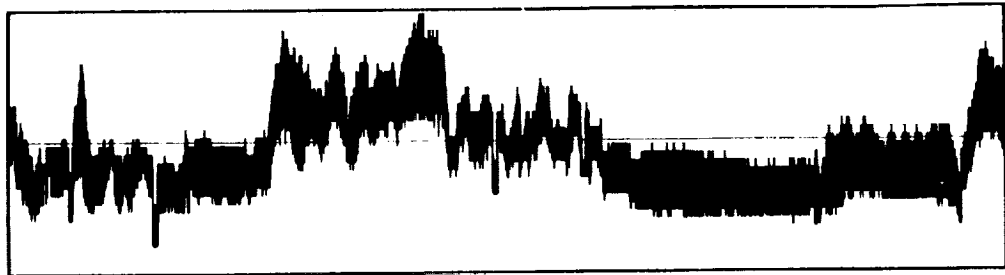


Figure 3. Portion of the modified maneuver history

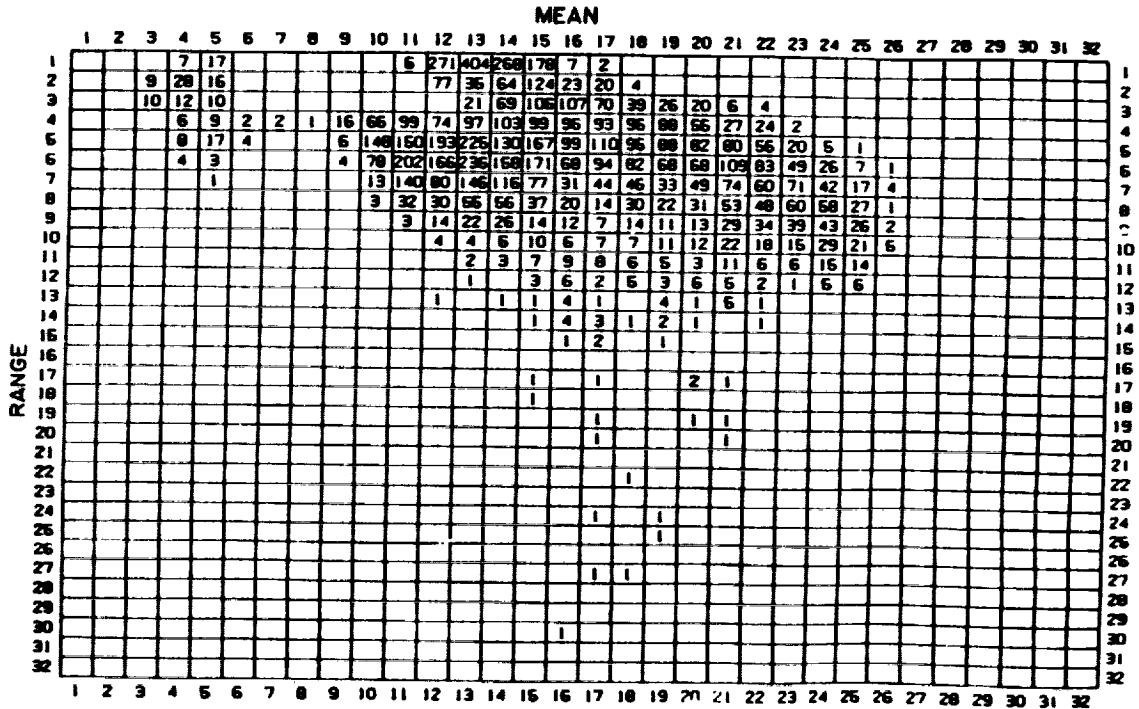


Figure 4. Range-mean matrix from rain-flow cycle counting of the modified maneuver history

Table 1. Rain-flow matrix for the loading history of Fig. 2 [7]

Event	Range (units)	Mean (units)							
		-1.5	-1.0	-0.5	0	0.5	1.0	1.5	All
--	0.5	-	-	-	-	-	-	-	-
--	1.0	-	-	-	-	-	-	-	-
--	1.5	-	-	-	-	-	-	-	-
--	2.0	-	-	-	-	-	-	-	-
--	2.5	-	-	-	-	-	-	-	-
AB	3.0	-	-	1	-	-	-	-	1
--	3.5	-	-	-	-	-	-	-	-
EF	4.0	-	-	-	-	-	1	-	1
--	4.5	-	-	-	-	-	-	-	-
--	5.0	-	-	-	-	-	-	-	-
--	5.5	-	-	-	-	-	-	-	-
--	6.0	-	-	-	-	-	-	-	-
--	6.5	-	-	-	-	-	-	-	-
HC	7.0	-	-	-	-	1	-	-	1
--	7.5	-	-	-	-	-	-	-	-
--	8.0	-	-	-	-	-	-	-	-
--	8.5	-	-	-	-	-	-	-	-
DG	9.0	-	-	-	-	1	-	-	1
--	9.5	-	-	-	-	-	-	-	-
--	10.0	-	-	-	-	-	-	-	-

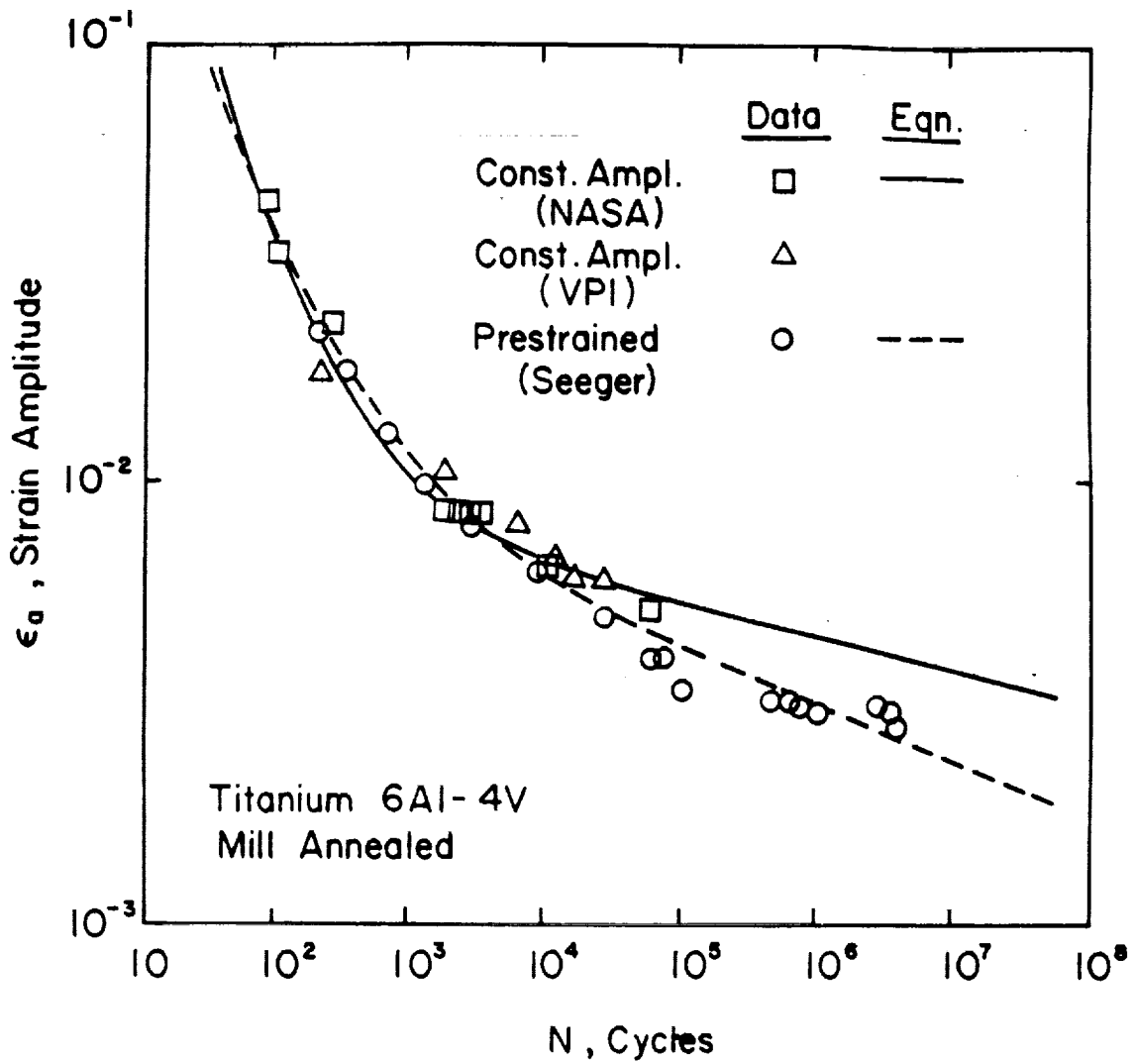


Figure 5. Strain vs. life test data and curves for Ti-6Al-4V

In this paper, two helicopters loading histories are chosen for analysis, and their fatigue lives are calculated using the simplified method. Also, the calculated lives are compared with test data. All life calculations are based on a strain-life curve, which represents failure of small unnotched axial test specimens. Lives so predicted for notched members correspond to initiation of an easily detectable crack. In general, the remaining life for crack growth also needs to be calculated, but this was relatively short and so was neglected for the particular specimens analyzed here.

Life Calculation Methodology

The simplified version of the local strain approach used assumes that fatigue life is controlled primarily by the notch surface strain, and it considers plasticity and mean stress effects in a fairly complete manner. Note that the traditional S-N approach crudely handles plasticity, and also neglects the special mean stress effects which arise from loading sequence. Life calculations by the local strain approach consists of two steps. First, the local notch stress and strain histories must be predicted, and second the life corresponding to the local stress and strain histories must be estimated.

Local Strain Approach

Figure 6 illustrates the initial and most difficult step of estimating the strain-stress history. This step is difficult because it requires specific handling of the complex nonlinearity relating load, strain, and stress. In order to achieve the above task, a cyclic stress curve [10] for the material is needed:

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{A} \right)^{\frac{1}{s}} \quad (1)$$

where ε_a , σ_a are amplitudes of strain and stress, respectively, E is the elastic modulus, and A and s are material constants. Next, by employing Eq.1 and with the aid of Neuber's rule, a curve relating nominal stress, S, and the local notch stress and strain is obtained:

$$\sigma_a \varepsilon_a = \frac{(k_t S_a)^2}{E} \quad (2)$$

where k_t is the elastic stress concentration factor.

Figure 6(b) shows these two curves. These curves are then used to estimate the local stress-strain response at the notch by following the loading history while modeling the hysteresis looping behavior of the material. For the example of Fig. 6, the irregular loading history of (c) results in S versus ε and σ versus ε as shown in (d) and (e). Note that there is a set of closed hysteresis loops, such as 2-3-2', 6-7-6', 5-8-5', and 1-4-1' for this example. Each such loop is identified as a cycle, and the cycles so defined are the same as would be obtained from applying rain-flow cycle counting to the load (S) versus time history.

Each cycle now has a known strain range, $\Delta\varepsilon = 2\varepsilon_a$, and mean stress, σ_0 , as shown for cycle 6-7-6' in Fig. 6 (e). The life, N, corresponding to each combination of ε_a , σ_0 can be obtained from a strain-life curve [10]:

$$\varepsilon_a = \frac{\sigma_f'}{E} (2N')^b + \varepsilon_f' (2N')^c \quad (3)$$

where ε_a is the strain amplitude corresponding to a closed loop, N' is the life in cycles for zero mean stress, and σ_f' , b, ε_f' and c are additional constants for the material. If the rule of Morrow [11] is used to account for mean stress effects, the fatigue life as adjusted for mean stress σ_0 can be estimated by:

$$N = N' \left(1 - \frac{\sigma_o}{\sigma_f} \right)^{-\frac{1}{b}} \quad (4)$$

where N is the final adjusted life.

The final step is then to apply the P-M rule. For a loading history that is assumed to repeat until failure occurs, the rule takes the form:

$$B \left[\sum_{\text{per block}} \frac{n_i}{N_i} \right] = 1 \quad (5)$$

where n_i is the number of occurrences per block of a cycle corresponding to life N_i , and B is the unknown number of blocks (repetitions) to failure for the irregular history.

Simplified Method

As mentioned earlier, the local strain approach generally requires a knowledge of the full sequence of the loading history. However, in the simplified method, the loading history may be used in concise matrix form. The first step is then to determine the rain-flow matrix that contains the information on range and mean loads of rain-flow cycles. Using this information, upper and lower bounds on life can be calculated [3,9]. As long as these bounds are reasonably tight, which will be the case in most practical situations, the more detailed simulations as in Fig. 6 are unnecessary.

The principle behind this bounding is shown in Fig. 7 for one cycle, namely 6-7 from Fig. 6. The guiding principle is that both load-strain loop 6-7 and stress-strain loop 6-7 must lie within the corresponding loop for the largest cycle in the history, namely 1-4. The load limits S_6 and S_7 are known; therefore limits can be placed on the mean strain of cycle 6-7. As shown in Fig.

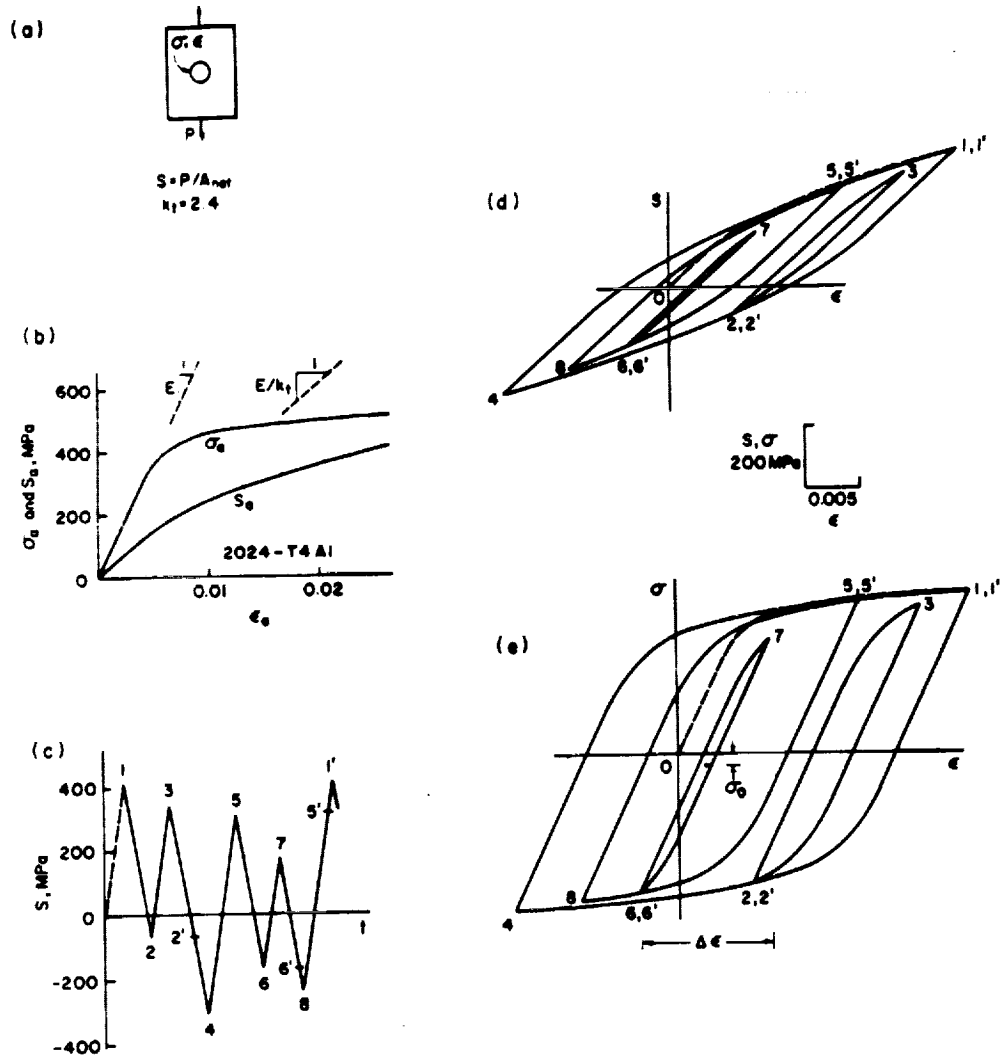


Figure 6. Illustration of local-strain approach for an irregular history: Notched member (a), having cyclic stress-strain and load-strain curves as in (b), is subjected to load history (c). The resulting load-strain response is shown in (d), and (e) is the local-notch stress strain response [6].

7(a), loop 6-7 can be so far to the right that it is attached at A, or so far to the left that it is attached at B. Similarly, the same line of reasoning can be applied to a load-stress loop as in Fig. 7(c), where loop 6-7 could be so low that it is attached at A, or so high that it is attached at B. Figure 7(b) shows the extreme stress-strain loops which satisfy both sets of constraints, so that these correspond to the upper and lower bounds on local notch mean stresses for cycle 6-7, σ_{0B} and σ_{0A} .

Knowing the upper and lower bounds on the mean stress for cycle 6-7 of the example allows bounds to be placed on the life, N , from Eq. 4. The upper bound on N is similarly obtained for all cycles in the history, and these are used with the P-M rule in the following form of Eq. 5 to obtain the upper bound on life for the irregular history. The same procedure, but using the lower bound N 's for each cycle, can be used to obtain the lower bound on life for the irregular history. The above procedure is explained in detail in Refs. [3,9].

If the local notch plastic strains are small during the history, the stress-strain loop for the major cycle, such as 1-4 in the example, is reduced to a straight line, and therefore the upper and lower bounds on life are then identical. Also, at high load levels, the cycles causing most of the damage may not have significant mean stresses due to the large plastic strains, and the bounds will then be close. Hence, the widest separation between the bounds is expected at intermediate load levels. Note that if most of the damage is done by low-level cycles, then the degree of separation of the bounds will be greatest. Also, if all but a negligible fraction of the damage is done by the major cycle, then the two bounds are again identical [3,9].

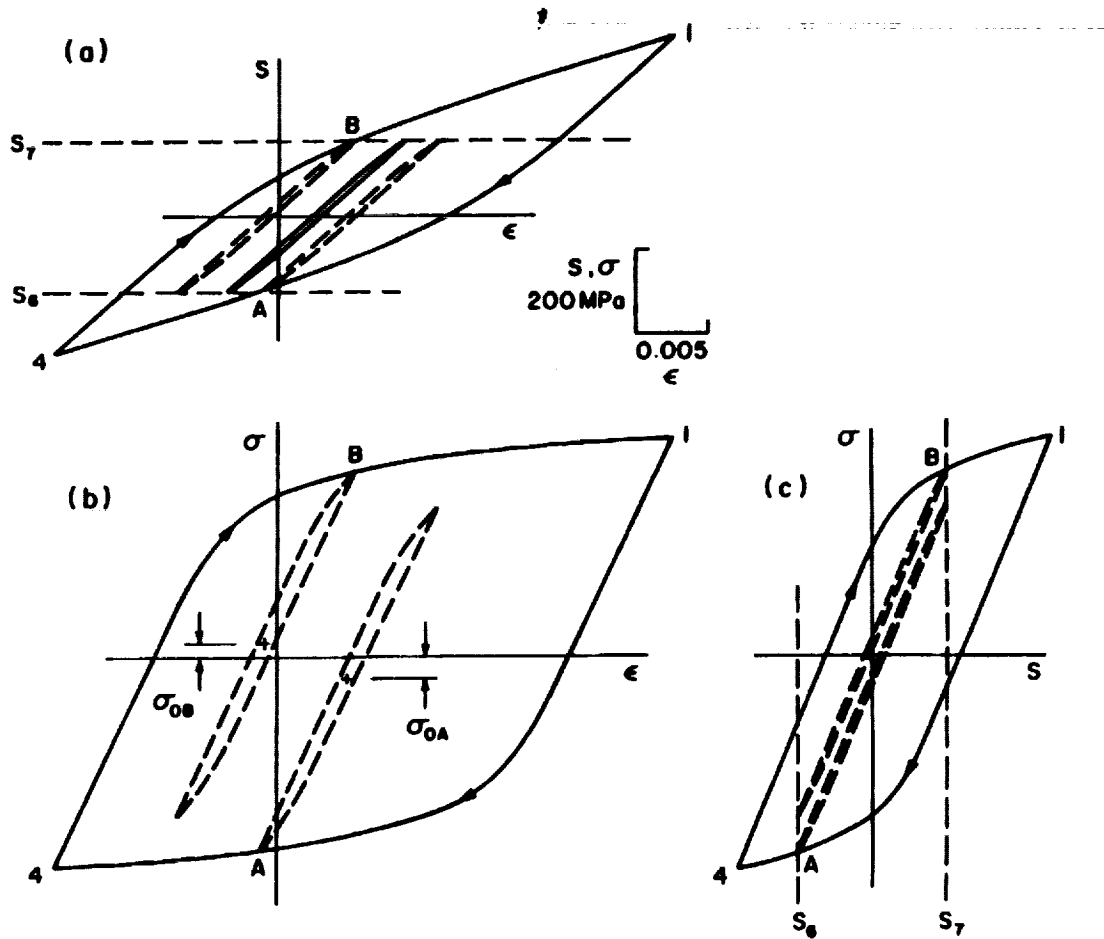


Figure 7. Illustration of placing bounds on the mean stress of a subcycle: This illustration is based on Fig. 6. Note that the sequence of the applied loads is not known, and the mean stress for 6-7 must lie between the σ_{0A} and σ_{0B} values shown.

Material, Specimens and Loading Histories Analyzed

Two helicopter loading histories are analyzed. Fatigue life data for both Helix and a severe maneuver history, applied to plate-with-hole specimens having elastic stress concentration factors between 2.4 and 3.92, are available in Ref. [12] and from tests done at the University of Dayton Research Institute (UDRI). These data include several levels of maximum nominal stress, S_{max} , for titanium 6Al-4V.

Two loading histories, Helix and maneuver, are used in fatigue life calculations. Helix is a standard helicopter loading spectrum obtained from Ref. [12], and the maneuver history was obtained by the University of Dayton Research Institute (UDRI). These two histories are further explained below.

Materials Properties Used

Figures 5 and 8 show strain vs. life and cyclic stress vs. strain data for the titanium 6Al-4V material used, and also curves corresponding to Eqs. 1 or 3 fitted to the data. Constants corresponding to these curves are given in Table 2 for constant amplitude tests and also for tests on prestrained material. Some constant amplitude tests were done at Virginia Tech on the same material. These data are also shown in Figs. 5 and 8, and they agree well with the data obtained from Ref. [13] and also with the fitted constants. In the case of the prestrained material, the data and constants were obtained from Ref. [14].

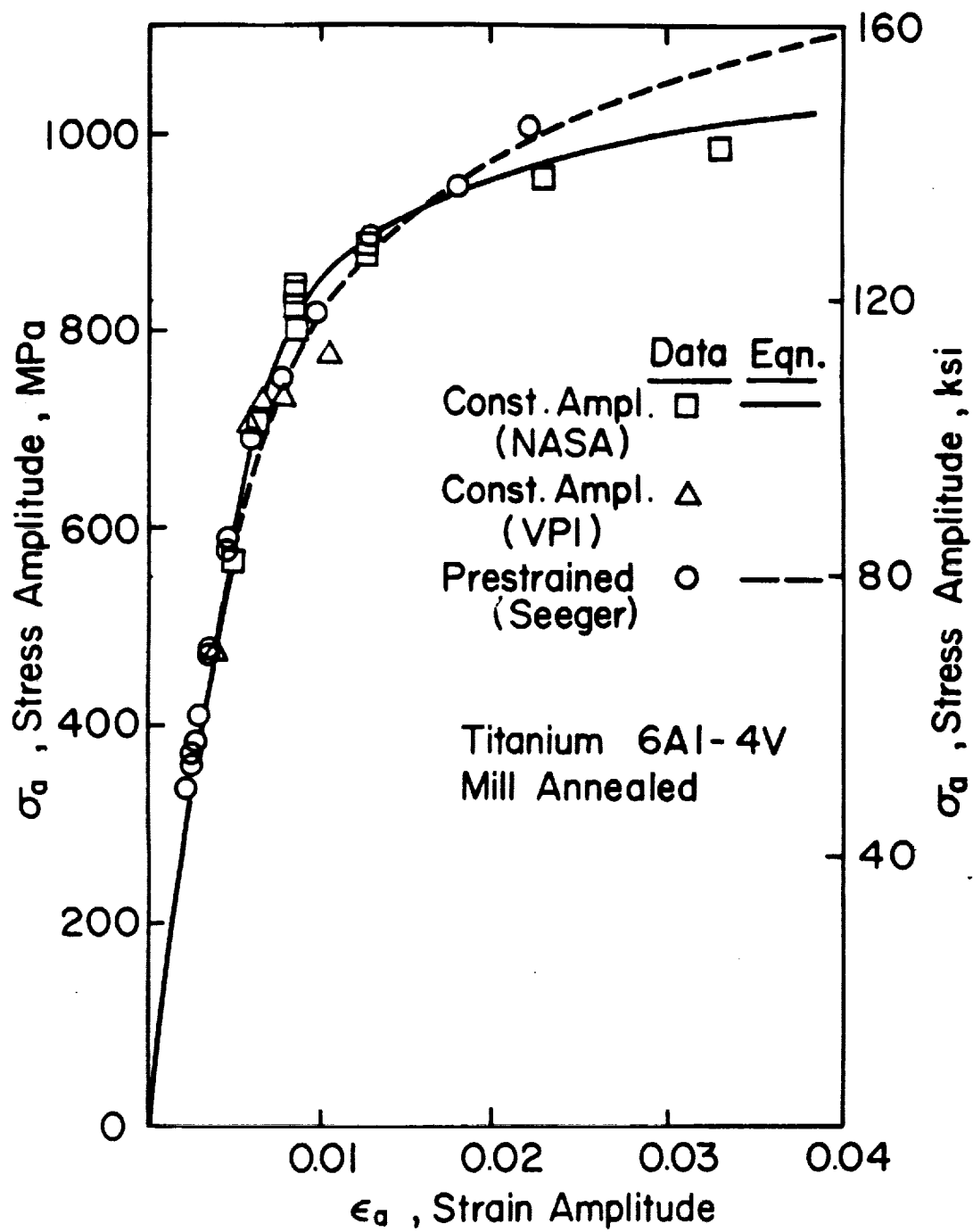


Figure 8. Cyclic stress-strain test data and curves for Ti-6Al-4V

Table 2. Cyclic stress-strain and strain-life constants for Ti 6Al-4V

Symbols, Units	Titanium 6Al-4V	
	Const. Ampl.	Prestrained
E, GPa (ksi)	113.8 (16500)	113.8(16500)
A, MPa (ksi)	1327 (192.4)	1702 (246.9)
s	0.0755	0.127
ϵ'_f	6.22	2.802
c	-1.01	-0.860
σ'_f , MPa (ksi)	1523 (220.9)	2207 (320.0)
b	-0.0763	-0.126

General Description of Helix

Helix [12] is a standard loading sequence for the main rotors of helicopters with articulated rotors. Helix represents a loading history for a 190.5-hour (2,132,024 cycle) sequence of 140 flights. Each flight in the sequence represents one of either training, transport, antisubmarine warfare, or search and rescue. Each of these appears in the sequence in three different lengths of 0.75 hour, 2.25 hours, and 3.75 hours. There are twelve unique flights, which are applied in a specific number of repetitions and sequence to obtain the total 140 flights. Figure 9 shows the load vs. time history for portions of a transport flight in Helix.

Helix is composed of 24 unique maneuvers, which are repeated in various sequences and numbers of repetitions to compose the various flights. The maneuvers such as take off, forward flight of various load levels, turns, etc. each consists of a mean level and a relatively small number of cycles. These cycles occur at one or more stress amplitudes, with the number of cycles being between 1 and 40.

Helix has a relatively high mean levels for the various maneuvers, these mostly ranging from 60 % to 68 % of the maximum nominal stress in the spectrum, S_{max} . Helix reaches 100 % of the S_{max} level at least once in each flight and returns to -20 % at the end of each flight. Hence, Helix has a large ground-air-ground cycle and a large number of cycles at relatively high mean levels. Table 3 gives the range-mean matrix for Helix from rain-flow cycle counting. The matrix entries in Table 3 were obtained from all of Helix by dividing each by 140, the number of flights. These range and mean values correspond to the history scaled so that $S_{max} = 100$ units.

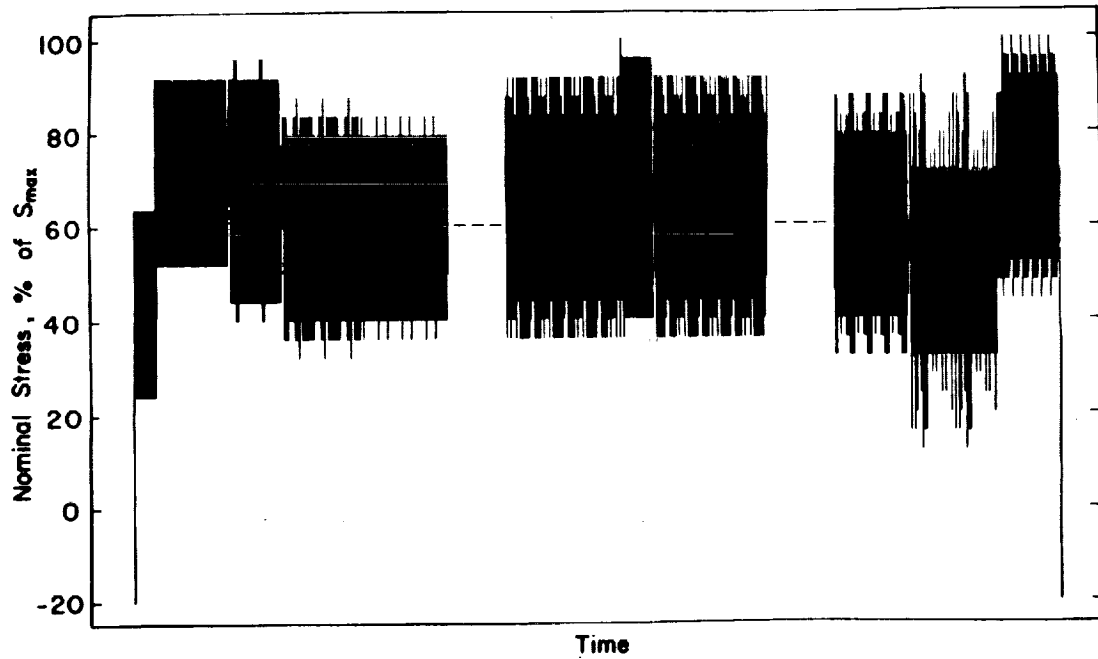


Figure 9. Example of the loading history for portions of a transport flight in Helix [12]

Table 3. Range-mean matrix for Helix from rain-flow cycle counting

Range	Mean									
	40	44	48	52	56	60	64	68	72	ALL
4	0	0	0	1	0	2	16	2	0	21
8	0	0	0	0	1	0	4	0	0	5
12	0	0	0	0	0	0	2	0	0	2
16	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	1	0	0	0	1
24	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	2	0	0	2
32	0	0	0	0	0	0	0	0	0	0
36	0	0	0	1	0	0	0	1	0	2
40	0	12	0	43	30	1742	1348	27	223	3425
44	0	0	0	1	0	1	0	1	0	3
48	0	0	0	14	5	453	2613	155	12	3252
52	0	0	0	0	0	5	20	1	0	26
56	0	0	0	24	6	65	7785	460	4	8344
60	0	0	0	0	1	0	15	0	0	16
64	0	0	0	6	8	30	6	24	0	74
68	0	0	0	1	1	0	0	0	0	2
72	0	0	0	10	4	28	0	0	0	42
76	0	0	0	1	1	1	0	0	0	3
80	0	0	0	1	1	5	0	0	0	7
84	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	1	0	0	0	0	1
92	0	0	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0
120	1	0	0	0	0	0	0	0	0	1
ALL	1	12	0	103	59	2333	11811	671	239	15229

General Description of Maneuver History

A loading history for the tail rotor pitch beam of an AUH-76 helicopter was selected as representative, and loading histories from each of 30 distinct severe maneuvers were assumed to occur once each in a specific sequence. This produced a loading history containing 33,470 cycles, which was then modified by UDRI to eliminate minor events, shortening it to 8777 cycles, that is, 8777 peaks and 8777 valleys. This new history is called the modified maneuver history. Figure 3 shows about one third of the modified maneuver history. Figure 4 shows the complete range and mean matrix from the rain-flow cycle counting. Note that the maneuver history is scaled so that the highest load is 1 unit, which results in the lowest load being -0.516 units; therefore, the overall range is 1.516 units.

Fatigue life calculations were done for both the original and modified histories for titanium 6Al-4V. It was found that the differences are small, and the two histories appear to cause the same damage; therefore, all further testing and analysis is based on the modified history.

Upper-Lower Bound Analysis of Helix

Fatigue lives for the plate-with-hole specimens of titanium 6Al-4V subjected to Helix were calculated using the simplified (upper-lower bound) version of the local strain approach. As already discussed, only the rain-flow matrix of the history is required as input information for fatigue life analysis.

Rather than analyzing all of Helix as a single loading history, it is expedient to analyze each of the twelve unique flights separately. Therefore, the first step is to determine the rain-flow matrix of each unique flight. Then, by using these matrices, upper and lower bounds can be

determined for each unique flight. These lives then combine to obtain overall bounds by considering the number of times each unique flight is repeated in Helix. Note that this combining of flights works because all of the flights return to the -20% level. This gives a common minimum stresses and strains locally at the notch for each flight, which results in no sequence effects from one flight affecting another.

Another option is also available for predicting the lives. In this option only one matrix is used which is derived from all of Helix. Comparison between these two options shows no significant difference; therefore, the simpler one of a single matrix was adopted. Hence, the rain-flow matrix for an average flight in the form of Table 3 is used for the purpose of calculating the upper and lower bounds on life.

The resulting calculated lives are plotted in Fig. 10 and are given in Table 4. Note that one curve is based on constant amplitude strain-life data, and the other on prestrained data. Figure 10 plots $k_t S_{max}$ so that the data for various k_t can be shown on the same plot. This is expected to be valid based on Neuber's rule, Eq. 2, as long as net section yielding does not occur, in which case Eq. 2 is not valid.

The data obtained from RAE scatter over a broad range, and the lives tend to be longer than those obtained from UDRI. Also, from Fig. 10, general agreement is obtained between data and analysis.

Upper and Lower Bound Analysis of Maneuver History

Figure 11 shows the calculated results as well as test data. Table 5 gives the calculated lives for notched specimens ($k_t = 2.5$). Reasonable agreement is obtained by comparing the test

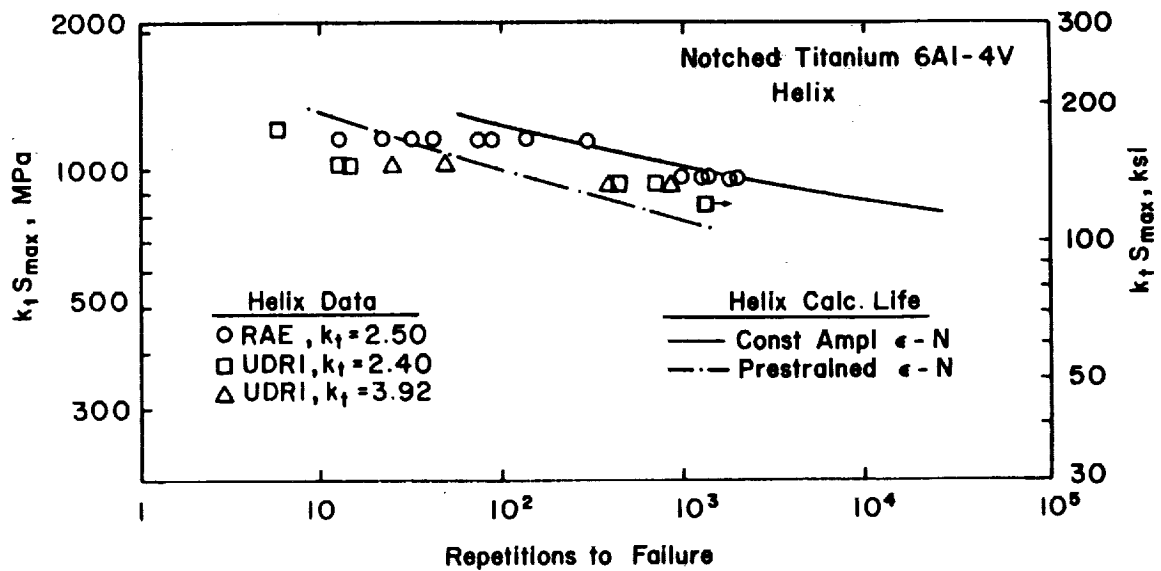


Figure 10. Analysis of Helix compared to test data for Ti 6Al-4V: The lines shown are middles of bounds.

Table 4. Calculated flights to failure for Helix for notched specimens ($k_t = 2.5$)

S_{max} MPa (ksi) (net area)	Helix	
	Lower Bd.	Upper Bd.
(a) Ti 6Al-4V, Const. Ampl. Strain-Life Curve		
317 (46)	26193	26213
358 (52)	4415	4433
407 (59)	857	876
455 (66)	221	240
517 (75)	46.9	62.8
(b) Ti 6Al-4V, Prestrained Strain-Life Curve		
317 (46)	681	687
455 (66)	32.7	36.0
517 (75)	11.8	13.9
530 (77)	9.59	11.5

data and the calculated values, especially when prestrained data are used. An exception is at the lowest stresses where these calculations are conservative.

Figure 12 shows the distribution of numbers of cycles vs. ranges. During the determination of the fatigue lives, it was noted that most of the fatigue damage was done by the higher range levels, and none by the lower levels. In this regard, it was also noted that a potentially large saving of test time can be realized by eliminating lower level non-damaging stress cycles from the load history. Therefore, a rain-flow filtering was done on the maneuver history.

The basis of this filtering was the fatigue "damage", more properly called the usage fraction, which is obtained from the P-M rule calculation. Usage fraction is defined as:

$$\text{usage fraction} = \frac{\frac{n_i}{N_i}}{\sum_{i=1}^I \frac{n_i}{N_i}} \quad (6)$$

where n_i is the number of cycle applied at a stress level corresponding to life N_i , and I is the number of different discrete stress levels. Figure 13 shows the usage fraction at each level vs. range for the modified history.

As is evident from Figs 12 and 13, most cycles occur at the lower ranges, whereas most damage is estimated to be done at higher ranges. Therefore the modified history was shortened by filtering all the ranges less than 0.45 units, that is, 30 % of the largest rain-flow range of 1.516 units. This filtered history contains 510 cycles, that is, 510 peaks and 510 valleys. Figure 14 shows the filtered history. By filtering the lowest stress levels of the modified history, the usage fraction is decreased only slightly, specifically by about 1 %.

Note that both modified and filtered histories produce similar fatigue lives, since most of the damage is done at higher levels that are not filtered out in the latter. Also, from Fig. 11 com-

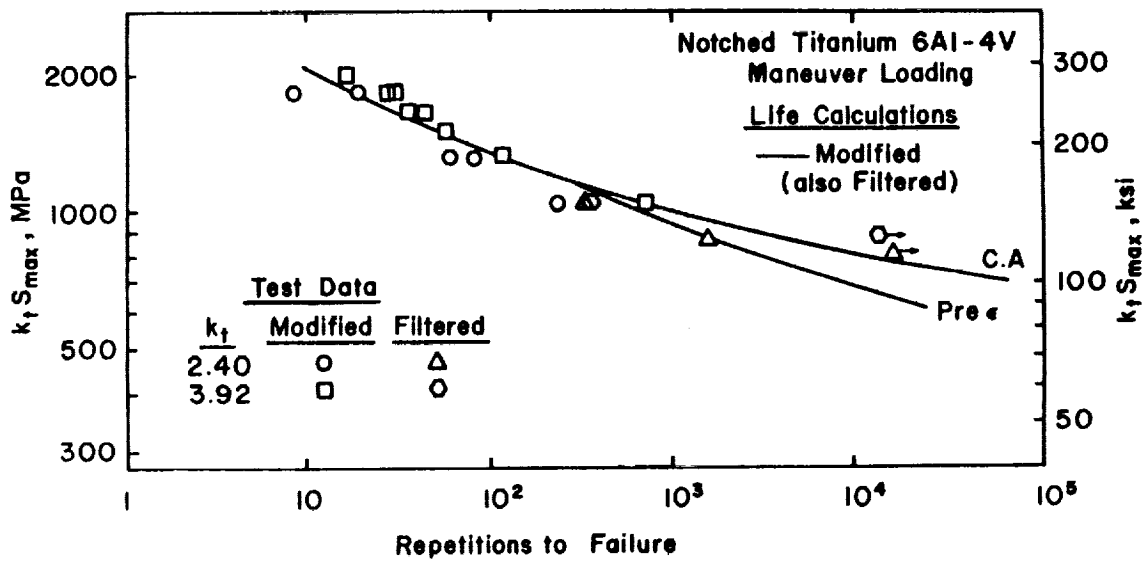


Figure 11. Analysis of maneuver history compared to test data for TI 6Al-4V: The lines shown are middles of bounds.

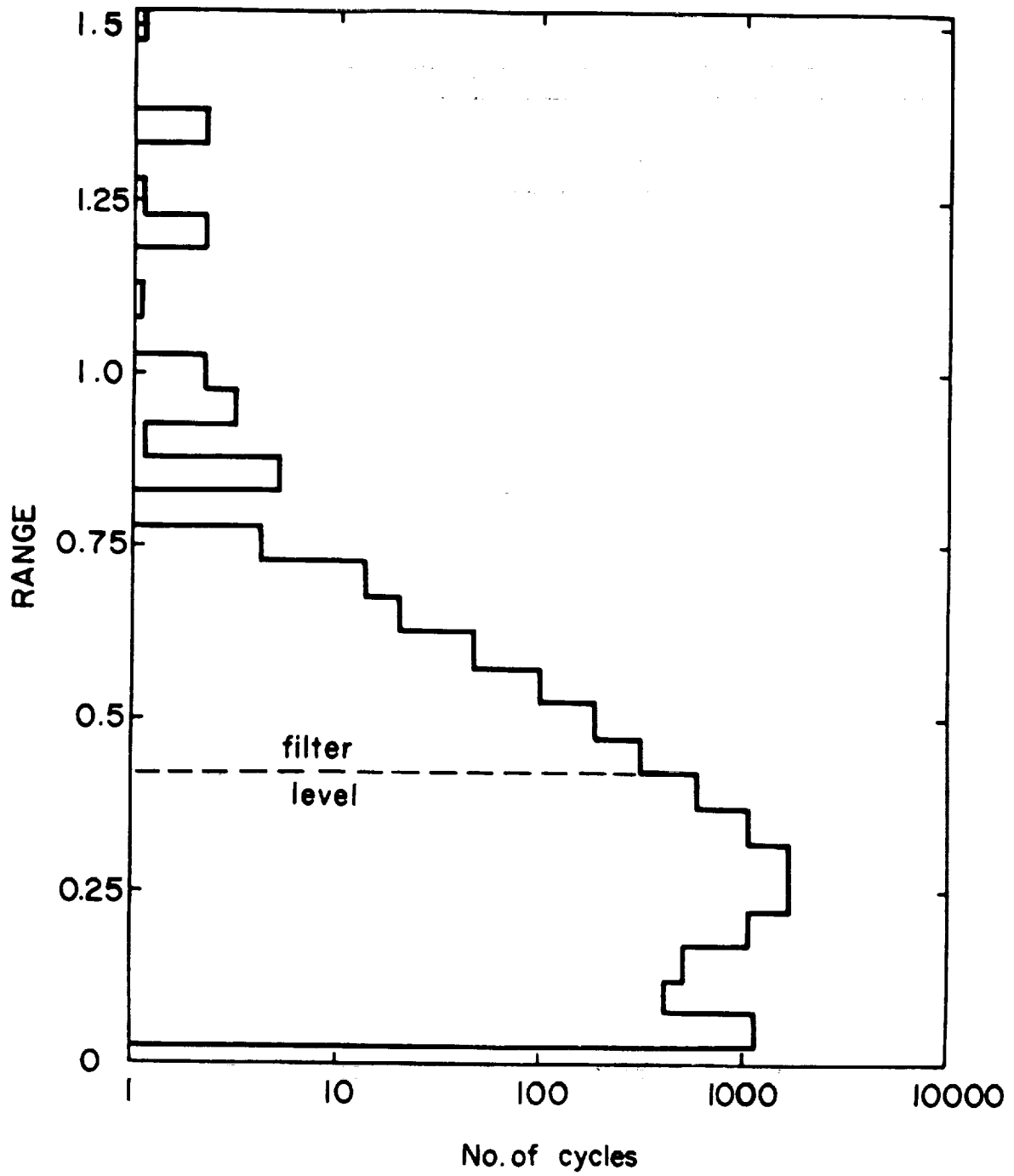


Figure 12. Number of rain-flow cycles vs. range for the modified maneuver history

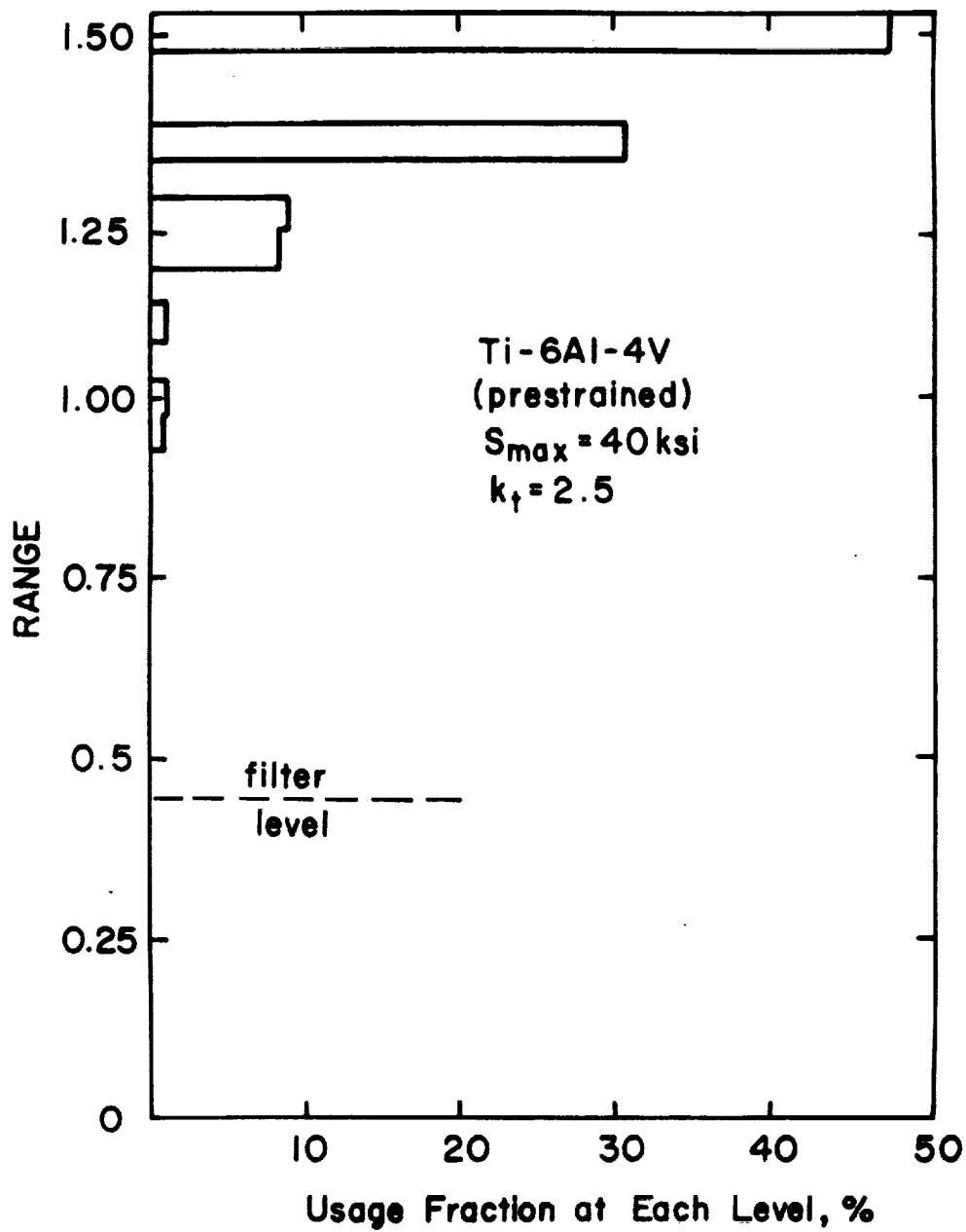


Figure 13. Usage fraction vs. range of rain-flow cycles for the modified maneuver history

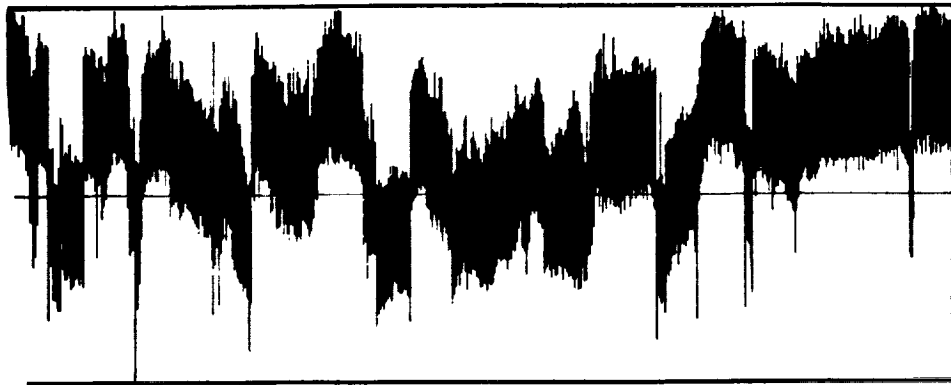


Figure 14. The filtered maneuver loading history

parison of the test data for modified and filtered history at one stress level, where both were tested, shows quite good agreement, which indicates that the filtering was a success.

Discussion

The Helix spectra is typical of a case where the bounds would tend to be relatively widely separated. This is due to most of damage being done at a relatively low level within the spectrum. However, even in this unfavorable situation, the bounds are reasonably tight for both Helix and maneuver history. For real irregular loading histories, wide separation of bounds is not likely to very often be a difficulty with this approach.

From Figs. 10 and 11, it is seen that the calculated lives and the test data are in good agreement when the prestrained data are used. The only exceptions are in the lowest levels, where the data approach or even exceed the calculation based on the constant amplitude strain-life data. The reason for this trend appears to be that these stress levels are so low that even the highest stress level (ground-air-ground) is approaching the endurance limit, and no prestrain effect due to this highest level occurs. The interpretation is made that when the major cycle is sufficiently low, an endurance limit is expected for the spectrum loading. Based on the above discussion, small cycles with amplitudes below the endurance limit can cause fatigue damage if preceded by a major cycle substantially above the endurance limit.

The calculated lives tend to be reasonably accurate at high stress levels, although there is considerable scatter. For Helix on titanium, the highest stress levels used were limited due to static failure, even though the most damaging level was still relatively low. This contrasts with the situation for the maneuver history, where the most damaging levels were calculated to be those near the maximum rain-flow range in the history. (see Fig. 13)

Table 5. Calculated repetitions to failure for maneuver history for notched specimens ($k_t = 2.5$)

S_{max} MPa (ksi) (net area)	Modified Sequence	
	Lower Bd.	Upper Bd.
(a) Ti 6Al-4V, Const. Ampl. Strain-Life Curve		
276 (40)	67700	67700
327 (47)	7940	7940
379 (55)	1410	1410
455 (66)	291	315
586 (85)	59.3	68.9
827 (120)	6.14	13.8
(b) Ti 6Al-4V, Prestrained Strain-Life Curve		
276 (40)	8770	8930
379 (55)	888	934
827 (127)	7.89	14.1

Similar comparisons from previous work [3] for Helix applied to notch specimens of an aluminum alloy are shown in Fig. 15. The trends are the same as for titanium, reinforcing the comments just made.

The above discussion and comparisons between test data and calculated lives suggest that the upper and lower bound approach represents a useful method with distinct advantages for predicting fatigue crack initiation.

Conclusions and Recommendations

The following conclusions and recommendations are drawn based on the above analysis and discussion:

1. Overstrain effects caused by the higher stress levels in a load spectrum need to be considered since these increase damage at the lower stress levels. This is especially true for cycles below the endurance limit where some cycles in the load spectrum are above the endurance limit.
2. The simplified version of the local strain approach (upper and lower bounds) should be used more widely, since only a rain-flow matrix is required as input information, and since it is easy to program on a digital computer. This approach is more economical than analysis of the large amount of data involved in full time sequence load histories. Based on the comparison of test data and calculated lives, the accuracy of the simplified method was either reasonably accurate or conservative depending on the S_{max} level.

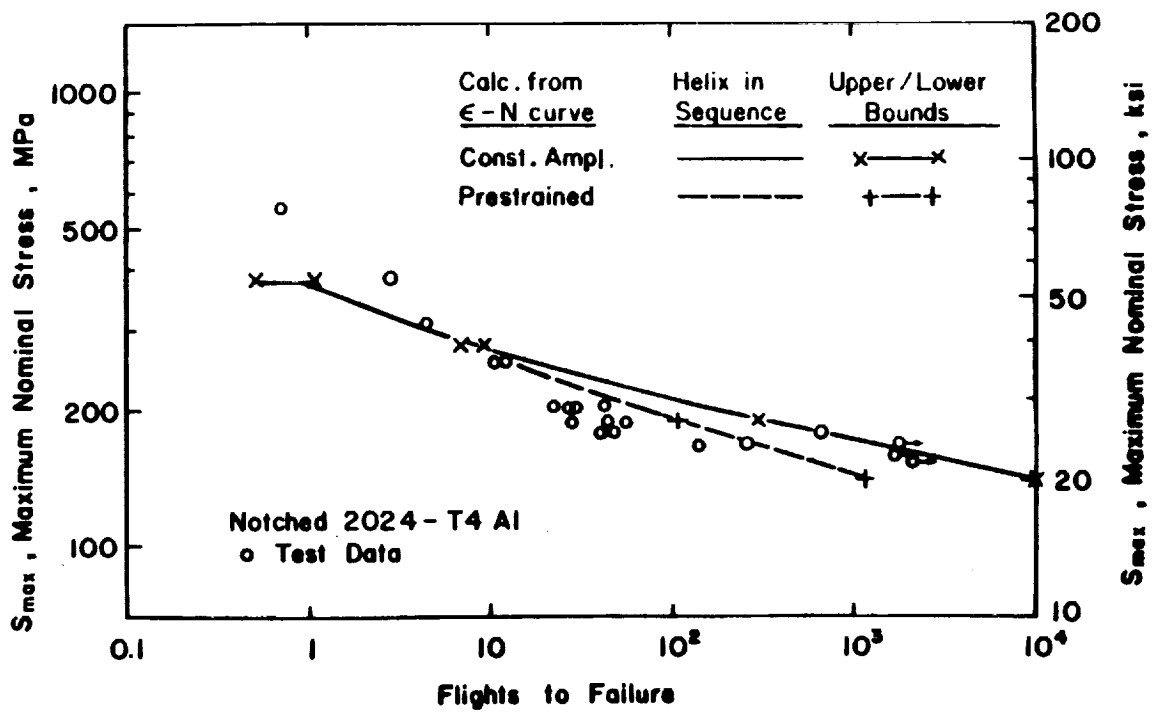


Figure 15. Analysis [3] of Helix compared to test data [12] for 2024-T4 aluminum notched specimens with $k_t = 2.5$: The curves represent full analysis based on local strains, and the bounds from the simplified method are also shown.

Acknowledgements

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APPENDIX A
COMPUTER PROGRAM FOR UPPER/LOWER
BOUNDS ON LIFE ANALYSIS

- USER'S MANUAL FOR UPLO -

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ABSTRACT

A computer program (UPL0) for predicting upper/lower bounds on life is provided. The program takes the result of rainflow counting in the form of a matrix, that is, given numbers of cycles at each combination of range and mean values, and then uses this information by applying a local strain approach method to place upper and lower bounds on life. The input values are defined, and one example problem is attached.

CONTENTS

	<u>Page</u>
INTRODUCTION (WITH FIGURES).....	A-4
DETAILS OF EQUATIONS	A-7
PROGRAM PROCEDURE OF UPPER/LOWER BOUND CALCULATIONS	A-9
DEFINITION OF INPUT DATA	A-13
REFERENCES	A-14
EXAMPLE PROBLEM	A-15
TABLES	A-16 thru 25

INTRODUCTION

Consider a notch member as in Figure A-1a, subjected to an irregular variation of nominal stress, S , with time. The goal is to predict the upper and lower bounds on life. A simplified version of local strain approach described in Reference A-1 was used to predict the upper and lower bounds on life. The first step is to summarize a lengthy history, using the rain-flow counting method, into a compact form of a matrix giving combinations of range and mean values. This step must be done using a rain-flow computer (RAINFL) program which feeds its output to the upper and lower bounds program as data. The above matrix is then used with the local strain approach to place upper and lower bounds on life that would result from the analysis of the original unsummarized history. The principle behind this bounding is illustrated by Figure A-2 with the aid of Figure A-1.

The computer program explained in this manual is the same program that was previously used in Reference A-2.

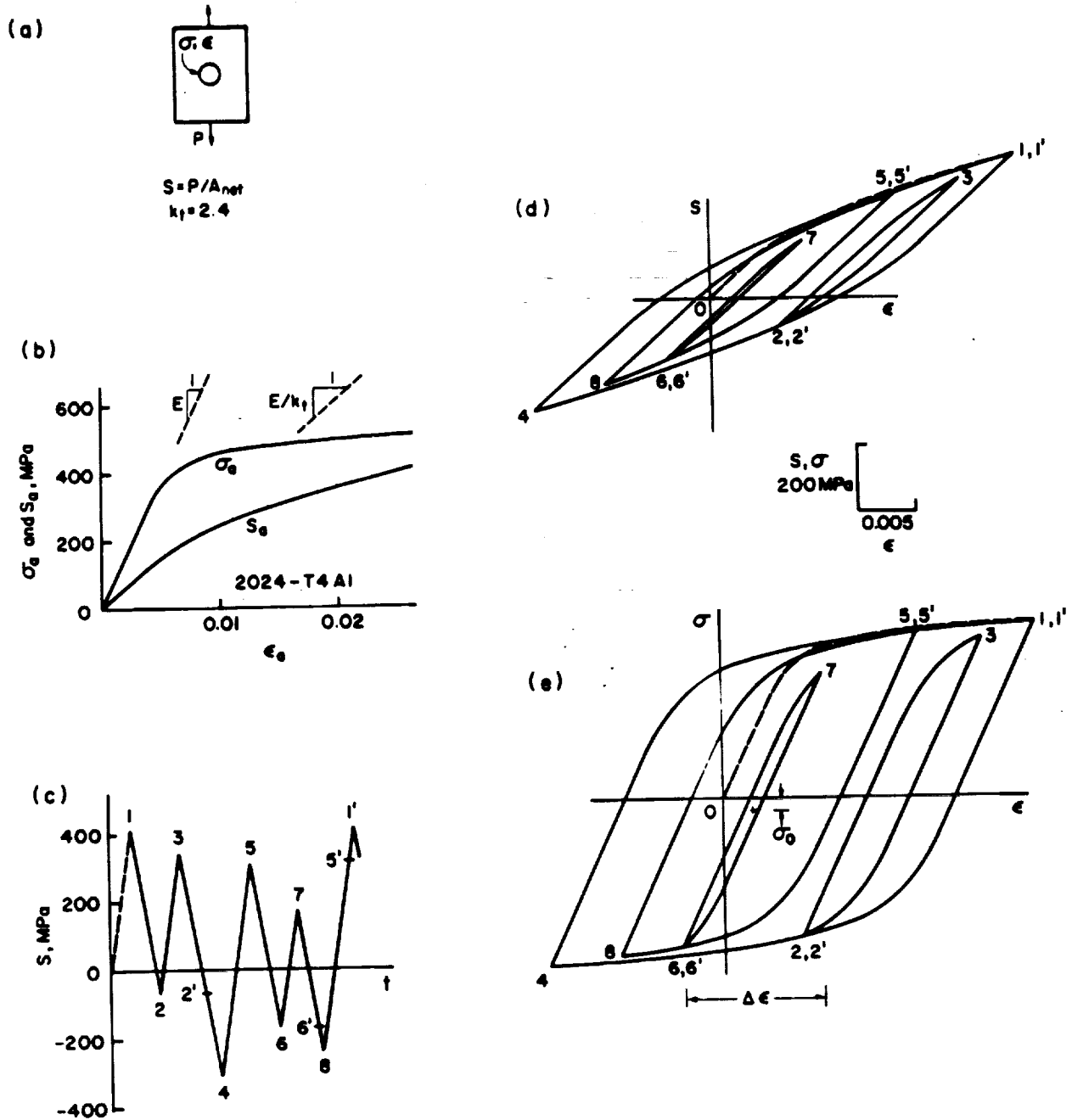


Figure A-1 - Illustration of local strain approach for an irregular load vs. time history. Notched member (a), having cyclic stress-strain and load-strain curves as in (b), is subjected to load history (c). The resulting load-strain response is shown in (d) and the local notch stress-strain response in (e).

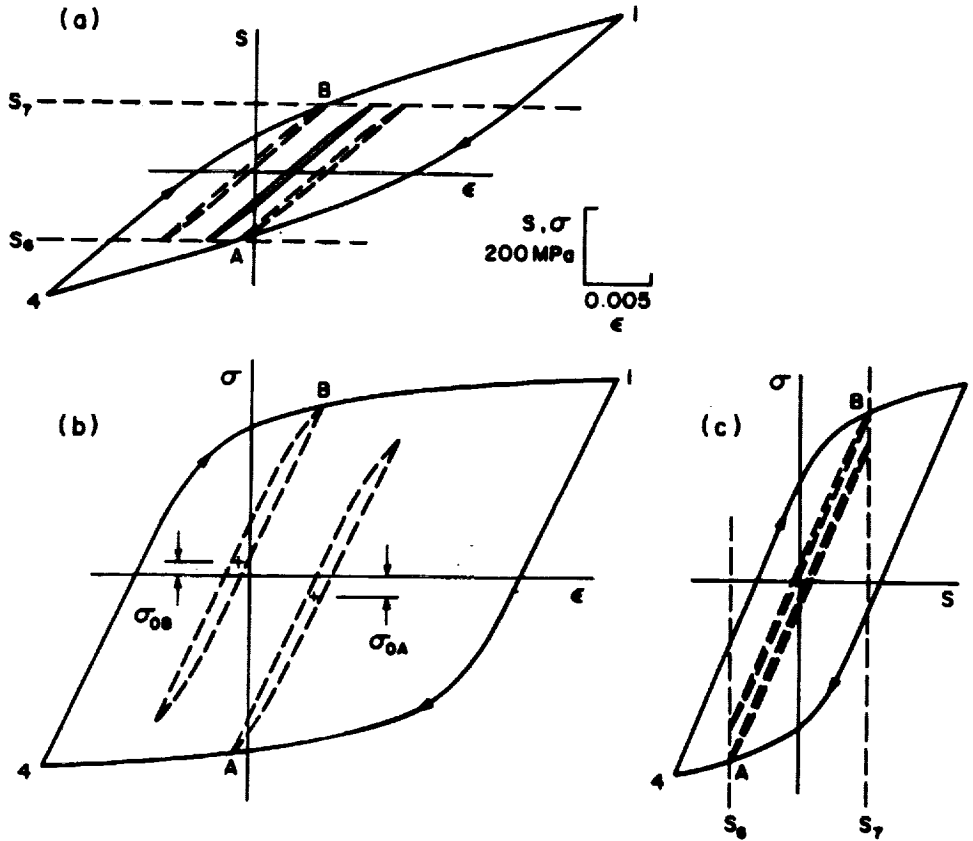


Figure A-2 - Illustration based on Fig. 1 of placing bounds on the mean stress of a subcycle when the sequence of the applied loads is not known. The mean stress for cycle 6-7 must lie between the values of σ_{0A} and σ_{0B} .

DETAILS OF EQUATIONS

The equations associated with the program are listed below to provide necessary information for the user.

1. Cyclic stress-strain curve:

$$\epsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{A}\right)^{1/s} \quad (1)$$

where

σ_a = stress amplitude

ϵ_a = strain amplitude

E = elastic modulus

A = cyclic strength coefficient

s = cyclic strain hardening exponent

2. General strain-life curve:

$$\epsilon_a = \frac{\sigma'_f}{E} (2N^*)^b + \epsilon'_f (2N^*)^c \quad (2)$$

where

σ'_f = fatigue strength coefficient

b = fatigue strength exponent

ϵ'_f = fatigue ductility coefficient

c = fatigue ductility exponent

N^* = life in cycles for zero mean stress

3. Life equation due to Morrow, considering the effect of mean stress:

$$N = N^* \left(1 - \frac{\sigma_0}{\sigma'_f}\right)^{-1/b} \quad (3)$$

where

N = final life

σ_0 = mean stress

4. Palmgren-Miner rule:

$$B \sum_{\text{per block}} \frac{n_i}{N_i} = 1 \quad (4)$$

where

n_i = number of occurrences of a cycle corresponding to life N_i

B = unknown number of blocks to failure

5. Neuber's rule:

$$\sigma_a \epsilon_a = \frac{(k_t S_a)^2}{E} \quad (5)$$

where

k_t = stress concentration factor

S_a = nominal stress amplitude

PROGRAM PROCEDURE OF UPPER/LOWER BOUND CALCULATIONS

The detailed procedure of the upper/lower program is given below. The example of cycle 6-7-6' of Figure A-1 is further employed as an example with the aid of Figure A-2.

It is convenient to write Equations 1 and 5 in general form without subscripts:

$$\epsilon = \sigma/E = (\sigma/A)^{1/s} \quad (6)$$

$$\sigma \epsilon = \frac{(k_t S)^2}{E} \quad (7)$$

The values of the constants E, A, s and k_t are of course unchanged.

Combining Equations 6 and 7 gives a relationship involving only strain, ϵ , and nominal stress, S.

$$\epsilon = \left[\frac{k_t S}{E} \right]^2 \frac{1}{\epsilon} + \left[\frac{(k_t S)^2}{E \epsilon A} \right]^{1/s} \quad (8)$$

Considering Figure A-2, the goal is to determine the bounds on mean stress, such as σ_{0A} and σ_{0B} . Point 1 corresponds to the maximum load in the history and 4 to the minimum load in the history. As a convenience, it is assumed that the largest absolute value of load is positive. If not, then what follows will need to be modified with appropriate sign changes. Note that the load history is known, which implies that S values are known for all calculations, so that the unknowns are the σ and ϵ values. These calculations take advantage of the fact that various loop curves in either Figure A-2a or b have the same shape, which is that of the corresponding curve from Figure A-1 expanded with a scale factor of two.

To obtain the unknowns for point 1 let

$$S = S_1 \quad (9a)$$

$$\epsilon = \epsilon_1 \quad (9b)$$

$$\sigma = \sigma_1 \quad (9c)$$

Substitute Equation 9 into Equation 6 and 8, and solve for ϵ_1 from Equation 8. Then using Equation 6, solve for σ_1 . Equations 6 and 8 are solved by Newton's method, as direct solutions are not possible. To analyze the range of major cycle 1-4-1', let

$$S = \frac{\Delta S_{1-4}}{2} \quad (10a)$$

$$\epsilon = \frac{\Delta \epsilon_{1-4}}{2} \quad (10b)$$

$$\sigma = \frac{\Delta \sigma_{1-4}}{2} \quad (10c)$$

Using a parallel procedure to that just described, $\Delta \epsilon_{1-4}$ and $\Delta \sigma_{1-4}$ are obtained. Then the stress and strain at point 4 are

$$\epsilon_4 = \epsilon_1 - \Delta \epsilon_{1-4} \quad (11a)$$

$$\sigma_4 = \sigma_1 - \Delta \sigma_{1-4} \quad (11b)$$

To analyze the range of minor cycles, such as 6-7, let

$$S = \frac{\Delta S_{6-7}}{2} \quad (12a)$$

$$\epsilon = \frac{\Delta\epsilon_{6-7}}{2} \quad (12b)$$

$$\sigma = \frac{\Delta\sigma_{6-7}}{2} \quad (12c)$$

Using the same procedure, $\Delta\epsilon_{6-7}$ and $\Delta\sigma_{6-7}$ are determined.

Once the stress and strain at points 1 and 4 are obtained, the points of attachment of loops A and B in Figure A-2 must be determined. In order to determine point of attachment of loop A, let

$$S = \frac{S_1 - S_A}{2} \quad (13a)$$

$$\epsilon = \frac{\epsilon_1 - \epsilon_A}{2} \quad (13b)$$

$$\sigma = \frac{\sigma_1 - \sigma_A}{2} \quad (13c)$$

Then substitute Equation 13 into Equations 6 and 8 and obtain ϵ_A and σ_A . Then to find the point of attachment of loop B, let

$$S = \frac{S_B - S_4}{2} \quad (14a)$$

$$\epsilon = \frac{\epsilon_B - \epsilon_4}{2} \quad (14b)$$

$$\sigma = \frac{\sigma_B - \sigma_4}{2} \quad (14c)$$

Again substituting into Equations 6 and 8, obtain ϵ_B and σ_B .

The bounds on mean stresses are then

$$\sigma_{oB} = \sigma_B - \frac{\Delta\sigma_{6-7}}{2} \quad (15a)$$

$$\sigma_{oA} = \sigma_A + \frac{\Delta\sigma_{6-7}}{2} \quad (15b)$$

Next, into Eq. 2 substitute

$$\epsilon_a = \frac{\Delta\epsilon_{6-7}}{2} \quad (16)$$

and obtain N , the life for zero mean stress. Finally, substitute this N^* and σ_{oB} into Equation 3 to obtain the lower bound in life, N , for cycle 6-7-6'. Similarly, substitute N^* and σ_{oA} to get the upper bound on N .

Following a similar procedure for all cycles smaller than the major one then allows the P-M rule, Equation 4, to be employed once with all of the lower bound N values, and a second time with all of the upper bound N values, to obtain bounds on the calculated number of blocks (repetitions) to failure, B .

DEFINITION OF INPUT DATA

Line No. Of Read Statement	Variable Name	Explanation	Comment
3	L	(Number of columns)x(number of rows) in the range/mean matrix	
4	KT	Stress concentration factor, k_t	
5	AMAX	Load scale factor	Factor which multiplies by the range and mean values from the matrix to give nominal stresses, S in ksi, defined consistently with k_t .
6	RMMIN LEVLN XIM RMIN LEVLN XIR	Lowest mean value in the matrix Number of columns (mean values) in the range/mean matrix Constant increment between mean values Lowest range value in the matrix Number of rows (range values) in the range/mean matrix Constant increment between range values	All these values should be the same as the values in the range/mean rainflow matrix used as input.
7	EM A SH SFP BS EFP CS	E A s σ'_f b ϵ'_f c	ksi ksi ksi
9	MM ()	Elements of the matrix in one dimensional form	For Example: If a matrix has 10 columns, then MM(1) = A(1,1) MM(2) = A(1,2) MM(10) = A(1,10) MM(11) = A(2,1), etc.

Note: Other consistent stress units may replace ksi for E, A, σ'_f , and AMAX. All other inputs are dimensionless.

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EXAMPLE PROBLEM

A rainflow matrix of combinations of range and mean values for the standard helicopter load spectrum Helix [A-3] is used to determine the upper and lower bounds on life. Table A-1 shows this matrix which contains 30 rows and 9 columns. Table A-2 shows the input for this example. The entire program listing and output are also attached as Table A-3. The output lists the upper bound mean stresses, such as σ_{OB} in Figure A-2b and also the lower bound mean stresses, such as σ_{OA} in Figure A-2b. It also gives the percentage of the total "damage," that is, the Palmgren-Miner usage factor, corresponding to the upper and lower bound mean stress cases for each particular combination of nominal stress range and mean.

The load scale factor AMAX is selected to scale the load history to any desired magnitude. To select a value, it is necessary to know how the original rainflow matrix used as input is scaled. AMAX is specifically the constant which the values in the input matrix are multiplied by to obtain the desired nominal stresses, S. For this example, the largest cycle has a mean value from the matrix of 0.40 and a range of 1.20. Hence, its maximum is 1.00 and its minimum is -0.20. If a load scale factor of AMAX = 59 is chosen, this causes the analysis to be done for $S_{max} = 59 \times 1.00 = 59.0$ ksi, which corresponds to the largest range in the load history being $\Delta S = 59 \times 1.20 = 70.8$ ksi.

Table A-1. Range-Mean Matrix for Helix from Rain-Flow Cycle Counting
(Cycles per Flight, Average)*

Range	Mean									
	.40	.44	.48	.52	.56	.60	.64	.68	.72	ALL
.04	0	0	0	1	0	2	16	2	0	21
.08	0	0	0	0	1	0	4	0	0	5
.12	0	0	0	0	0	0	2	0	0	2
.16	0	0	0	0	0	0	0	0	0	0
.20	0	0	0	0	0	1	0	0	0	1
.24	0	0	0	0	0	0	0	0	0	0
.28	0	0	0	0	0	0	2	0	0	2
.32	0	0	0	0	0	0	0	0	0	0
.36	0	0	0	1	0	0	0	1	0	2
.40	0	12	0	43	30	1742	1348	27	223	3425
.44	0	0	0	1	0	1	0	1	0	3
.48	0	0	0	14	5	453	2613	155	12	3252
.52	0	0	0	0	0	5	20	1	0	26
.56	0	0	0	24	6	65	7785	460	4	8344
.60	0	0	0	0	1	0	15	0	0	16
.64	0	0	0	6	8	30	6	24	0	74
.68	0	0	0	1	1	0	0	0	0	2
.72	0	0	0	10	4	28	0	0	0	42
.76	0	0	0	1	1	1	0	0	0	3
.80	0	0	0	1	1	5	0	0	0	7
.84	0	0	0	0	0	0	0	0	0	0
.88	0	0	0	0	1	0	0	0	0	1
.92	0	0	0	0	0	0	0	0	0	0
.96	0	0	0	0	0	0	0	0	0	0
.100	0	0	0	0	0	0	0	0	0	0
1.04	0	0	0	0	0	0	0	0	0	0
1.08	0	0	0	0	0	0	0	0	0	0
1.12	0	0	0	0	0	0	0	0	0	0
1.16	0	0	0	0	0	0	0	0	0	0
1.20	1	0	0	0	0	0	0	0	0	1
ALL	1	12	0	103	59	2333	11811	671	239	15229

*The matrix entries were obtained from those for all of Helix by dividing each by 140, the number of flights.

Table A-2. Input for Example Problem

270
2.5
59.
0.4,9,0.04,0.04,30,0.04
15838.,192.4,.0755,220.9,-.0763,6.216,-1.0101
0,0,0,1,0,2,16,2,0,
0,0,0,0,1,0,4,2,0,
0,0,0,0,0,0,2,0,0,
0,0,0,0,0,0,0,0,0,
0,0,0,0,0,1,0,0,0,
0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,2,0,0,
0,0,0,0,0,0,0,0,0,
0,0,0,1,0,0,0,1,0,
0,12,0,43,30,1742,1348,27,223,
0,0,0,1,0,1,0,1,0,
0,0,0,14,5,453,2613,155,12,
0,0,0,0,0,5,20,1,0,
0,0,0,24,6,65,7785,460,4,
0,0,0,0,1,0,15,0,0,
0,0,0,6,8,30,6,24,0,
0,0,0,1,1,0,0,0,0,
0,0,0,10,4,28,0,0,0,
0,0,0,1,1,1,0,0,0,
0,0,0,1,1,5,0,0,0,
0,0,0,0,0,0,0,0,0,
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0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,
1,0,0,0,0,0,0,0,0,

Table A-3. Program Listing and Output for Example

```

C*JOB
                                A1336,P=100
                                UPPER/LOWER LIFE PREDICTION PROGRAM (UPLO)

INPUT
DATA LINE 1.      L=NO OF COLUMNS*NO OF ROWS IN THE RANGE/
                   MEAN MATRIX.
DATA LINE 2.      KT=STRESS CONCENTRATION FACTOR.
DATA LINE 3.      AMAX=LOAD SCALE FACTOR (KSI)
DATA LINE 4.      RMMIN=LOWEST MEAN VALUE IN THE MATRIX.
                   LEVLM=NO OF COLUMNS(MEAN VALUES) IN THE
                   RANGE/MEAN MATRIX.
                   XIM=CONSTANT INCREMENT BETWEEN MEAN VALUES.
                   RMIN=LOWEST RANGE VALUE IN THE MATRIX.
                   LEVLR=NO OF ROWS(RANGE VALUES)IN THE RANGE/
                   MEAN MATRIX.
                   XIR=CONSTANT INCREMENT BETWEEN RANGE VALUES.
                   THE ABOVE VALUES SHOULD BE THE SAME AS THE VALUES
                   IN THE RANGE/MEAN RAINFLOW MATRIX USED AS INPUT.
DATA LINE 4.      EM=ELASTIC MODULUS(KSI)
                   A=CYCLIC STRENGTH COEFF(KSI)
                   SH=CYCLIC STRAIN HARDENING EXPONENT
                   SFP=FATIGUE STRENGTH COEFF(KSI)
                   BS=FATIGUE STRENGTH EXPONENT
                   EFP=FATIGUE DUCTILITY COEFF
                   CS=FATIGUE DUCTILITY EXPONENT
DATA LINE 5.      MM( )=ELEMENTS OF MATRIX IN ONE DIMEN-
                   SIONAL FORM.
                   FOR EXAMPLE IF A MATRIX HAS 10
                   COLUMNS THEN MM(1)=A(1,1)
                   MM(2)=A(1,2),MM(11)=A(2,1), ETC.

1  DIMENSION VV(300),SLL(300),XNF(300),XNNU(300),XNNL(300),
   *SIGL(300),SIGU(300),UU(300),STRN1(300),STRN2(300),STMEN1(300
   *),STMEN2(300),RQ(300),RM(300)
   *,SMAX1(300),SMIN1(300),SMXMN(2)
   *,MM(900),RA(32),CMM(32),X2(900),Y2(900),BU(900),BL(90
   *0),X3(1999),Y3(1999),MMM(1999),X4(1999),Y4(1999),SD(300)
   *,STRS1(300),STRS2(300),DMU(300),DML(300)

2  REAL KT,KT1
3  READ(5,*)L
4  READ(5,*)KT
5  READ(5,*)AMAX
6  READ(5,*)RMMIN,LEVLM,XIM,RMIN,LEVLR,XIR
7  READ(5,*)EM,A,SH,SFP,BS,EFP,CS
8  WRITE(6,300)EM,SFP,BS,EFP,CS,A,SH,AMAX
9  READ(5,*)(MMM(I),I=1,L)
10 CMM(1)=RMMIN
11 DO 904 L=2,LEVLM
12 LL=L-1
13 CMM(L)=CMM(LL)+XIM
14 904 CONTINUE
15 RA(1)=RMIN
16 DO 905 L=2,LEVLR
17 LL=L-1
18 905 RA(L)=RA(LL)+XIR
19 R=1/SH
20 IKK=1
21 DO 907 I=1,LEVLR

```

Table A-3 (2nd page)

```

22      DO 908 J=1,LEVLN
23      X4(IKK)=((2.*CMM(J))+RA(I))/2.
24      Y4(IKK)=(2.*CMM(J))-X4(IKK)
25      X3(IKK)=X4(IKK)*AMAX
26      Y3(IKK)=Y4(IKK)*AMAX
27      IKK=IKK+1
28      908 CONTINUE
29      907 CONTINUE
30      IKK=IKK-1
31      IK=1
32      DO 960 I=1,IKK
33      IF(MMM(I).EQ.0) GO TO 960
34      X2(IK)=X3(I)
35      Y2(IK)=Y3(I)
36      MM(IK)=MMM(I)
37      IK=IK+1
38      960 CONTINUE
39      IK=IK-1
40      SMAX=X2(IK)
41      SMIN=Y2(IK)
42      DO 909 I=1,IK
43      909 SLL(I)=(X2(I)-Y2(I))/2.
44      NLOAD=IK
45      DO 911 I=1,IK
46      SMAX1(I)=X2(I)
47      IF(SMAX1(I).GT.Y2(I)) GO TO 912
48      SMAX1(I)=Y2(I)
49      SMIN1(I)=X2(I)
50      GO TO 911
51      912 SMIN1(I)=Y2(I)
52      911 CONTINUE
C*****
C      DETERMINING MAX,MIN LOCAL STRAIN AND STRESS
53      IF(ABS(SMIN).LT.ABS(SMAX))THEN
54      C=((SMAX*KT)**2)/EM
55      CALL NEUBER(C,R,A,V,U,EM)
56      FMAX=U
57      STMAX=V
58      SSS=SLL(IK)
59      C=((SSS*KT)**2)/EM
60      CALL NEUBER(C,R,A,V,U,EM)
61      FMIN=FMAX-(2.*U)
62      STMIN=STMAX-(2.*V)
63      ELSE
64      C=((SMIN*KT)**2)/EM
65      CALL NEUBER(C,R,A,V,U,EM)
66      FMIN=U
67      STMIN=V
68      SSS=SLL(IK)
69      C=((SSS*KT)**2)/EM
70      CALL NEUBER(C,R,A,V,U,EM)
71      WRITE(6,*)V,U
72      FMAX=FMIN+(2.*U)
73      STMAX=STMIN+(2.*V)
74      END IF
75      WRITE(6,310)FMAX,STMAX
76      WRITE(6,320)FMIN,STMIN
C*****
C      DETERMINING UPPER AND LOWER BOUNDS ON MEAN STRESS
77      DO 1100 I=1,NLOAD

```

Table A-3 (3rd page)

```

78      SPRM1=(SMAX1(I)-SMIN)/2.
79      C=((SPRM1*KT)**2)/EM
80      CALL NEUBER (C,R,A,V,U,EM)
81      STRN1(I)=(2.*V)+STMIN
82      STRS1(I)=(2.*U)+FMIN
83      SPRM2=(SMAX-SMIN1(I))/2.
84      C=((SPRM2*KT)**2)/EM
85      CALL NEUBER (C,R,A,V,U,EM)
86      STRN2(I)=STMAX-(2.*V)
87      STRS2(I)=FMAX-(2.*U)
88      SL=SLL(I)
89      C=((SL*KT)**2)/EM
90      CALL NEUBER(C,R,A,V,U,EM)
91      VV(I)=V
92      STMEN1(I)=STRN1(I)-VV(I)
93      STMEN2(I)=STRN2(I)+VV(I)
94      1100 CONTINUE
95      DO 1310 I=1,NLOAD
96      SIGU(I)=STRS1(I)-UU(I)
97      SIGL(I)=STRS2(I)+UU(I)
98      1310 CONTINUE
99      DO 1099 I=1,IK
100     SD(I)=2.*SLL(I)
101     1099 SD(I)=2.*SLL(I)
102     WRITE(6,330)
103     DO 1400 I=1,NLOAD
104     ER=VV(I)
C*****
C      UPPER/LOWER LIFE PREDICTION
105     CALL LIFE (ER,SFP,BS,EFP,CS,EM,XNFF)
106     XNF(I)=XNFF
107     1400 CONTINUE
108     DO 1500 I=1,NLOAD
109     XNNU(I)=(XNF(I))/((1-(SIGL(I)/SFP)))*(1/BS))
110     XNNL(I)=(XNF(I))/((1-(SIGU(I)/SFP)))*(1/BS))
111     1500 CONTINUE
112     DO 1600 I=1,IK
113     BU(I)=MM(I)/XNNL(I)
114     BL(I)=MM(I)/XNNU(I)
115     1600 CONTINUE
116     BUU=0.
117     BLL=0.
118     DO 1800 I=1,IK
119     BUU=BU(I)+BUU
120     BLL=BL(I)+BLL
121     1800 CONTINUE
122     BLLL=1./BLL
123     BUUU=1./BUU
124     DO 2001 I=1,IK
125     DML(I)=(BL(I)/BLL)*100.
126     IF(DML(I).LT.0.01)DML(I)=0.
127     2001 CONTINUE
128     DO 2200 I=1,IK
129     DMU(I)=(BU(I)/BUU)*100.
130     IF(DMU(I).LT.0.01)DMU(I)=0.
131     2200 CONTINUE
132     DO 1700 I=1,IK
133     RQ(I)=ABS(X2(I)-Y2(I))
134     RM(I)=(X2(I)+Y2(I))/2.
135     WRITE(6,34)RQ(I),RM(I),VV(I),MM(I),SIGL(I),SIGU(I),DML(I),DMU(I)

```

Table A-3 (4th page)

```

136 1700 CONTINUE
137 WRITE(6,350)BUUU
138 WRITE(6,360)BLLL
139 300 FORMAT('1',/12X,'ELASTIC MODULUS(KSI)=' ,F7.0//12X,
*'FATIGUE STRENGTH COEFFICIENT(KSI) =' ,F6.1//12X,
*'FATIGUE STRENGTH EXPONENT =' ,F7.4//12X,
*'FATIGUE DUCTILITY COEFFICIENT =' ,F8.4//12X,
*'FATIGUE DUCTILITY EXPONENT =' ,F7.4//12X,
*'CYCLIC STRENGTH COEFFICIENT(KSI) =' ,F6.1//12X,
*'CYCLIC STRAIN HARDENING EXPONENT =' ,F6.3//12X,
*'LOAD SCALE FACTOR =' ,F6.3)
140 310 FORMAT('1',//,12X,'MAX LOCAL STRESS(KSI)=' ,F9.3,//,12X,
*'MAX LOCAL STRAIN=' ,F9.5)
141 320 FORMAT(//,12X,'MIN LOCAL STRESS(KSI)=' ,F9.3,//,12X,
*'MIN LOCAL STRAIN' ,F9.5)
142 330 FORMAT(/12X,'NOMINAL' ,3X,'NOMINAL' ,21X,'LOWER' ,4X,'UPPER' ,3X,
*'PERCENT' ,3X,'PERCENT' ,
*/13X,'STRESS' ,4X,'STRESS' ,21X,'MEAN' ,5X,'MEAN' ,4X,'OF TOTAL' ,
*2X,'OF TOTAL' ,
*/14X,'RANGE' ,5X,'MEAN' ,4X,'STRAIN' ,4X,'NO OF' ,3X,'STRESS' ,3X,
*'STRESS' ,2X,'LOWER' ,5X,'UPPER' ,
*/14X,'(KSI)' ,5X,'(KSI)' ,2X,'AMPLITUDE' ,2X,'CYCLES' ,2X,'(KSI)' ,
*4X,'(KSI)' ,3X,'DAMAGE' ,4X,'DAMAGE' )
143 34 FORMAT(12X,F7.2,3X,F7.2,3X,F8.5,2X,I5,2X,F7.3,2X,F7.3,3X,F5.2,
*5X,F5.2)
144 350 FORMAT(//,12X,'LOWER LIFE BOUND=' ,E11.3)
145 360 FORMAT(//,12X,'UPPER LIFE BOUND=' ,E11.3)
146 STOP
147 END
C*****

148 SUBROUTINE NEUBER(C,R,A,V,U,EM)
149 DIMENSION E(100)
150 S1=(EM/A**R)**(1/(1-R))
151 EP1=(S1/A)**R
152 C1=S1*EP1
153 IF(C.GT.C1) GO TO 10
154 E(1)=(C/EM)**.5
155 GO TO 20
156 10 E(1)=(C/A)*(R/(1+R))
157 20 DO 1 I=1,100
158 P=C/EM/E(I)
159 Q=(C/A/E(I))**R
160 E(I+1)=E(I)-(E(I)-P-Q)/(1+P/E(I)+R*Q/E(I))
161 X=E(I+1)/E(I)
162 IF(X.GT.0.999.AND.X.LT.1.001) GO TO 30
163 1 CONTINUE
164 30 V=E(I+1)
165 U=C/V
166 RETURN
167 END
C*****

168 SUBROUTINE LIFE(ER,SFP,BS,EFP,CS,EM,XNFF)
169 DIMENSION XN(100)
170 XNT=.5*(SFP/EM/EFP)**(1/(CS-BS))
171 EPT=EFP*(2*XNT)**CS
172 IF(ER.GT.EPT)GO TO 40
173 XN(1)=.5*(EM*ER/SFP)**(1/BS)
174 GO TO 50

```

Table A-3 (5th page)

```

175 40 XN(1)=.5*(ER/EFP)**(1/CS)
176 50 DO 210 K=1,100
177 G=SFP/EM**2**BS
178 H=EFP**2**CS
179 XN(K+1)=XN(K)-(G*XN(K)**BS+H*XN(K)**CS-ER)/(G*BS*XN(K)**(BS-1)+H
&*CS*XN(K)**(CS-1))
180 Z=XN(K+1)/XN(K)
181 IF(Z.GT.0.999.AND.Z.LT.1.0010) GO TO 60
182 210 CONTINUE
183 60 XNFF=XN(K+1)
184 RETURN
185 END

```

C*ENTRY

Table A-3 (6th page)

ELASTIC MODULUS(KSI)	= 15838.
FATIGUE STRENGTH COEFFICIENT(KSI)	= 220.9
FATIGUE STRENGTH EXPONENT	= -0.0763
FATIGUE DUCTILITY COEFFICIENT	= 6.2160
FATIGUE DUCTILITY EXPONENT	= -1.0101
CYCLIC STRENGTH COEFFICIENT(KSI)	= 192.4
CYCLIC STRAIN HARDENING EXPONENT	= 0.076
LOAD SCALE FACTOR	= 59.000

Table A-3 (7th page)

MAX LOCAL STRESS(KSI)= 124.578

MAX LOCAL STRAIN= 0.01103

MIN LOCAL STRESS(KSI)= -51.903

MIN LOCAL STRAIN -0.00018

NOMINAL STRESS RANGE (KSI)	NOMINAL STRESS MEAN (KSI)	STRAIN AMPLITUDE	NO OF CYCLES	LOWER MEAN STRESS (KSI)	UPPER MEAN STRESS (KSI)	PERCENT OF TOTAL LOWER DAMAGE	PERCENT OF TOTAL UPPER DAMAGE
2.36	30.68	0.00019	1	53.778	54.296	0.00	0.00
2.36	35.40	0.00019	2	65.578	66.093	0.00	0.00
2.36	37.76	0.00019	16	71.478	71.990	0.00	0.00
2.36	40.12	0.00019	2	77.378	77.885	0.00	0.00
4.72	33.04	0.00037	1	59.678	60.194	0.00	0.00
4.72	37.76	0.00037	4	71.478	71.988	0.00	0.00
4.72	40.12	0.00037	2	77.378	77.881	0.00	0.00
7.08	37.76	0.00056	2	71.478	71.985	0.00	0.00
11.80	35.40	0.00093	1	65.578	66.085	0.00	0.00
16.52	37.76	0.00130	2	71.478	71.960	0.00	0.00
21.24	30.68	0.00168	1	53.778	54.285	0.00	0.00
21.24	40.12	0.00168	1	77.378	77.793	0.00	0.00
23.60	25.96	0.00186	12	41.979	42.492	0.00	0.00
23.60	30.68	0.00186	43	53.778	54.281	0.00	0.00
23.60	33.04	0.00186	30	59.678	60.169	0.00	0.00
23.60	35.40	0.00186	1742	65.578	66.049	0.11	0.11
23.60	37.76	0.00186	1348	71.478	71.916	0.14	0.14
23.60	40.12	0.00186	27	77.378	77.765	0.00	0.00
23.60	42.48	0.00186	223	83.278	83.584	0.07	0.07
25.96	30.68	0.00205	1	53.778	54.276	0.00	0.00
25.96	35.40	0.00205	1	65.578	66.034	0.00	0.00
25.96	40.12	0.00205	1	77.378	77.729	0.00	0.00
28.32	30.68	0.00224	14	53.779	54.269	0.00	0.00
28.32	33.04	0.00224	5	59.678	60.149	0.00	0.00
28.32	35.40	0.00224	453	65.578	66.016	0.30	0.31
28.32	37.76	0.00224	2613	71.478	71.865	2.89	2.92
28.32	40.12	0.00224	155	77.378	77.684	0.29	0.29
28.32	42.48	0.00224	12	83.278	83.461	0.04	0.04
30.68	35.40	0.00242	5	65.578	65.993	0.00	0.00
30.68	37.76	0.00242	20	71.478	71.829	0.06	0.06
30.68	40.12	0.00242	1	77.378	77.629	0.00	0.00
33.04	30.68	0.00261	24	53.779	54.249	0.05	0.05
33.04	33.04	0.00261	6	59.679	60.116	0.02	0.02
33.04	35.40	0.00261	65	65.578	65.965	0.33	0.33
33.04	37.76	0.00261	7785	71.478	71.784	64.88	65.23
33.04	40.12	0.00261	460	77.378	77.561	6.50	6.47
33.04	42.48	0.00261	4	83.278	83.278	0.10	0.10
35.40	33.04	0.00279	1	59.679	60.093	0.00	0.00
35.40	37.76	0.00279	15	71.478	71.729	0.31	0.31
37.76	30.68	0.00298	6	53.780	54.216	0.07	0.07
37.76	33.04	0.00298	8	59.679	60.065	0.14	0.14
37.76	35.40	0.00298	30	65.578	65.884	0.87	0.87
37.76	37.76	0.00298	6	71.478	71.661	0.29	0.29
37.76	40.12	0.00298	24	77.378	77.378	1.95	1.91
40.12	30.68	0.00317	1	53.781	54.194	0.02	0.02

Table A-3 (8th page)

40.12	33.04	0.00317	1	59.680	60.029	0.04	0.04
42.48	30.68	0.00335	10	53.782	54.165	0.52	0.52
42.48	33.04	0.00335	4	59.680	59.984	0.33	0.33
42.48	35.40	0.00335	28	65.579	65.762	3.78	3.76
44.84	30.68	0.00354	1	53.784	54.129	0.11	0.11
44.84	33.04	0.00354	1	59.681	59.930	0.17	0.17
44.84	35.40	0.00354	1	65.579	65.679	0.27	0.27
47.20	30.68	0.00373	1	53.785	54.085	0.21	0.21
47.20	33.04	0.00373	1	59.681	59.863	0.33	0.33
47.20	35.40	0.00373	5	65.579	65.579	2.69	2.63
51.92	33.04	0.00410	1	59.682	59.682	1.15	1.13
70.80	23.60	0.00560	1	36.337	36.337	10.96	10.73

LOWER LIFE BOUND= 0.851E 03

UPPER LIFE BOUND= 0.869E 03

APPENDIX B
COMPUTER PROGRAM FOR RAIN-FLOW CYCLE COUNTING ANALYSIS
- USER'S MANUAL FOR RAINF -

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ABSTRACT

A computer program (RAINP) for rain-flow cycle counting analysis is provided. The program can take a lengthy load history and reduce it to the compact form of a matrix giving combinations of range and mean or peak and valley values. This information can be used for fatigue analysis. The input values are defined and five examples using different options of the program are provided.

CONTENTS

	Page
INTRODUCTION (WITH FIGURE).....	B-4
PROGRAM LOGIC.....	B-6
DEFINITION OF INPUT DATA.....	B-7
REFERENCES.....	B-8
EXAMPLE 1.....	B-9
TABLES B-1 and B-2.....	B-10 thru 17
EXAMPLE 2.....	B-18
TABLES B-3 and B-4.....	B-19 and 20
EXAMPLE 3.....	B-21
TABLES B-5 and B-6.....	B-23 thru 29
EXAMPLE 4.....	B-30
TABLES B-7 and B-8.....	B-31 thru 38
EXAMPLE 5.....	B-39
TABLES B-9 and B-10.....	B-40 thru 45

INTRODUCTION

Rain-flow cycle counting is a method that exists for reducing service load history records to a compact description so that the information can be used in analysis for fatigue. The compact description is in the form of a matrix giving combinations of range and mean, or peak and valley values. This method is widely accepted as the most accurate cycle counting method for predicting fatigue life based on a cumulative damage type of approach. The rain-flow method cannot be misled by any synthetic load sequences and will always count the cycles correctly, based on the fact that closed hysteresis loops are most representative of a fatigue damage event.

Figure B-1 illustrates rain-flow cycle counting. As shown in this example, the rain-flow method has the important characteristic that it counts the major load excursions as cycles, while also counting the minor events. This feature allows it to realistically handle real service loading where there are low level vibratory loads, etc., superimposed on major cycles associated with the usage of the machine, vehicle or structure, such as ground-air-ground cycles in aircraft.

The computer program explained in this manual is the same program that was previously used in Reference B-1.

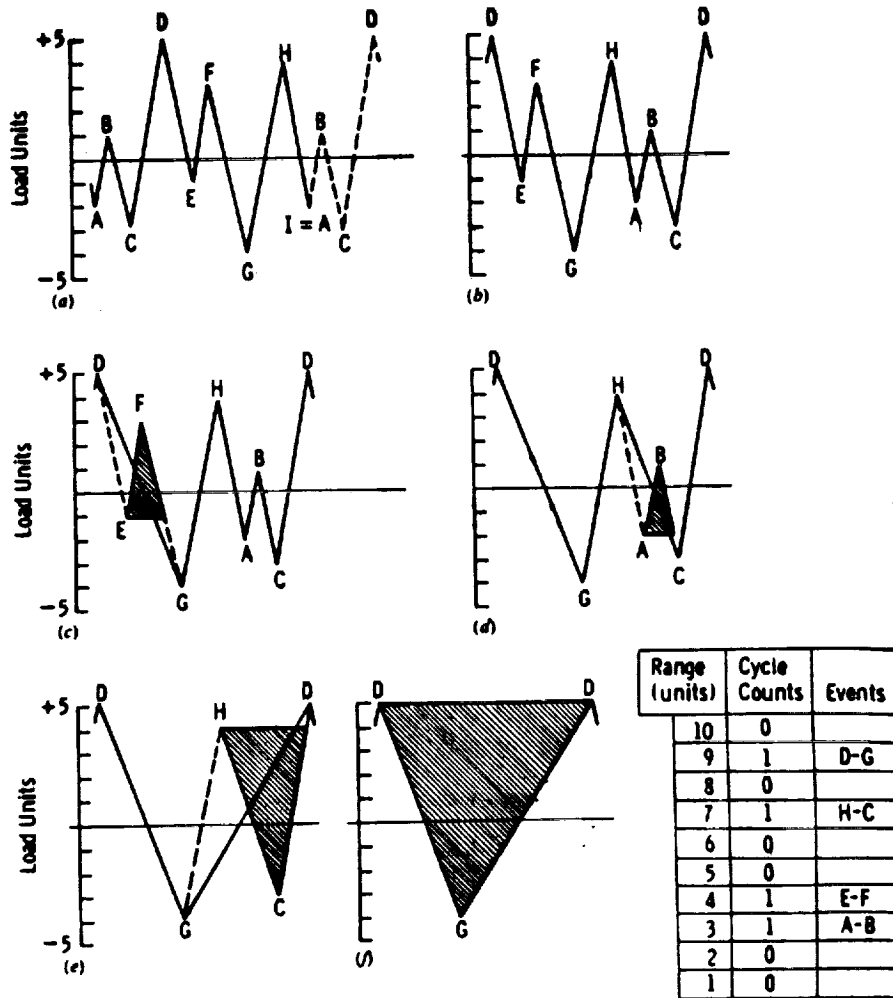


FIG. 7 Example of Simplified Rainflow Counting for a Repeating History

TABLE X1.4 Simplified Rainflow Counting for Repeating Histories (Fig. 7)

Range Units	Mean Units								
	-2.0	-1.5	-1.0	-0.5	0	+0.5	+1.0	+1.5	+2.0
10	1	...	...	...
9	1	...	...	...
8	1	...	...	...
7	1	...	...	...
6	1	...	...	...
5	1	...	...	...
4	1	...	...	...
3	1	...	...	...
2	1	...	...	...
1	1	...	...	...

Figure B-1. Illustration of rain-flow cycle counting from the ASTM Standards [B-2].

PROGRAM LOGIC

The following logic is used consistent with the ASTM standard [B-2]: Let x denote the absolute value of the range under consideration, and y previous absolute range adjacent to x .

Step 1: Determine the maximum absolute value in the history. (Note that this value can be either a peak or a valley.)

Step 2: Arrange the history to start with the maximum absolute value. Move all peaks and valleys which occur prior to the maximum to the end as illustrated in Figure B-1a.

Step 3: Read the next value. If out of data, go to step 9.

Step 4: Three points are needed to define x and y . If there are less than three points, go back to step 3. Define x and y using the three most recent peaks and valleys that have not been discarded.

Step 5: Compare the two ranges, namely x and y .

- a) If $x < y$, go to step 3.
- b) If $x \geq y$, go to step 6.

Step 6: If a rain-flow filtered history is not desired, go to step 8.

Step 7: If $y \leq$ filter level specified in the program Input, then discard the peak and valley of the range y in the array in memory which is the original history of step 2.

Step 8: Count range y as one cycle, determine the mean value of the peak and valley of y , discard the peak and valley of y in the array set up in step 3, and go to step 4.

Step 9: Stop.

DEFINITION OF INPUT DATA

Line No. of READ Statement	Variable Name	Explanation	Comment
3	OPTION	= 1 List filtered history as peak/valley sequence; also print range/mean matrix of rain-flow cycles for original history. = 2 List range, mean, min, and a max of rain-flow cycles not in matrix form. = 3 Print range/mean matrix of rain-flow cycles. = 4 Print max/min 32x32 matrix of rain-flow cycles.	Integer The history is converted to a min value of 1 and max value of 32.
4	FL	Filter level as a range value	Required only for OPTION = 1.
5	NN	Number of peak/valley points in history	
8	XIM	Constant increment between mean values in the range/mean matrix	Required only for OPTION = 1 or 3.
	XIR	Constant increment between range values in the range/mean matrix	Required only for OPTION = 1 or 3.
9	P()	Input load history as peaks and valleys in sequence	History must start and end with the same value.

REFERENCES

- B-1. Berens, A. P., Gallagher, J. P., Dowling, N. E., Khosrovaneh, A., K., and Thangjitham, S., "Helicopter Fatigue Methodology, Vols. I and II," Report No. USAAVSCOM TR 87-D-13A and 13B, U. S. Army Aviation Applied Technology Directorate, Ft. Eustis, VA, 1987.
- B-2. "Standard Practice for Cycle Counting in Fatigue Analysis," 1986 Annual Book of ASTM Standards, Vol. 03.01, Standard No. 1049, pp. 836-848.
- B-3. Fatigue Under Complex Loading: Analyses and Experiments, R. M. Wetzel, Editor, The Society of Automotive Engineers, Warrendale, PA, Vol. AE-6, 1977.

EXAMPLE 1

The history of Figure B-1 is used for this rain-flow cycle counting example. Option 2 of the program is used; therefore, the result is shown as a list of range, mean, minimum, and maximum values. Table B-1 shows the input for this example. The entire program listing and program output for this example are attached as Table B-2.

Table B-1. Input for Example 1

2
9
-2.,1.,-3.,5.,-1.,3.,-4.,4.,-2.

Table B-2. Program Listing and Output for Example 1

```

C#JOB          NPV1336,P=100
                RAIN-FLOW COUNTING PROGRAM (RAINF)
                NOTE THAT THE HISTORY MUST START AND END WITH THE SAME VALUE.

                INPUT
                DATA LINE 1.  OPTION=1  LIST FILTER HISTORY AS PEAK/VALLEY
                                SEQUENCE.ALSO PRINT RANGE/MEAN
                                MATRIX OF RAINFLOW CYCLES FOR
                                ORIGINAL HISTORY.
                                =2  LIST RANGE,MEAN,MIN,AND MAX OF RAIN-
                                FLOW CYCLES NOT IN MATRIX FORM.
                                =3  PRINT RANGE/MEAN MATRIX OF RAINFLOW
                                CYCLES.
                                =4  PRINT MAX/MIN MATRIX OF RAINFLOW
                                CYCLES.
                DATA LINE 2.  FL=FILTER VALUE AS A RANGE
                DATA LINE 3.  NN=NUMBER OF PEAK/VALLEY POINTS IN HISTORY
                DATA LINE 4.  XIM=CONSTANT INCREMENT BETWEEN MEAN VALUES
                                IN THE RANGE/MEAN MATRIX.
                                XIR=CONSTANT INCREMENT BETWEEN RANGE VALUES
                                IN THE RANGE/MEAN MATRIX.
                NOTE THAT XIM,AND XIR REQUIRED FOR OPTION=1 OR 3
                DATA LINE 5.  P( )=INPUT LOAD HISTORY AS PEAKS AND VALLEYS
                                IN SEQUENCE.

1  REAL P(10000),PE(10000),PP(10000),PC(10000),PCC(10000),MM(64),
2  *RA(64),PI(10000),MEAN(5005),R(5005)
3  INTEGER M(64,64),SUM(64),SUMM,MI(32,32),OPTION
4  READ(5,*)OPTION
5  IF(OPTION.EQ.1)READ(5,*)FL
6  READ(5,*)NN
7  IF(OPTION.EQ.4)GO TO 40
8  IF(OPTION.EQ.2)GO TO 40
9  READ(5,*)XIR,XIM
10 READ(5,*)(P(I),I=1,NN)
    N=NN

C
C
11 DETERMINATION OF LARGEST PEAK OR VALLEY
12 LCOUNT=1
13 DO 100 I=1,N
14 PE(I)=P(I)
15 CONTINUE
16 PMAX=ABS(P(1))
17 DO 200 I=2,N
18 IF(PMAX.GE.PE(I)) GO TO 200
19 PMAX=ABS(P(I))
20 LCOUNT=I
21 CONTINUE
22 IF(OPTION.EQ.4)THEN
23 SMAX=P(1)
24 SMIN=P(1)
25 DO 301 I=2,NN
26 IF(P(I).GT.SMAX)SMAX=P(I)
27 IF(P(I).LT.SMIN)SMIN=P(I)
28 CONTINUE
29 CF1=SMIN
    CF2=SMAX

```

Table B-2 (2nd page)

```

30      CF3=SMAX-SMIN
31      END IF
      C
      C
      C
32      ARRANGE THE PEAK OR VALLEY
33      JK=LCOUNT+1
34      J=N-JK+1
35      KKK=LCOUNT
36      DO 300 I=1,J
37      PP(I)=P(KKK)
38      KKK=KKK+1
39      300 CONTINUE
40      C      JJJ=N-LCOUNT-1
41      J=J+1
42      C      DO 130 I=1,JJJ
43      DO 350 I=1,LCOUNT
44      PP(J)=P(I)
45      J=J+1
46      350 CONTINUE
47      DO 500 I=1,NN
48      PC(I)=PP(I)
49      NNN=N+1
50      IF(OPTION.EQ.2)WRITE(6,210)
      C
      C
      C
51      FINDING THE CYCLE
52      AA=3.1422
53      DO 194 I=1,32
54      DO 195 J=1,32
55      MI(I,J)=0
56      195 CONTINUE
57      194 CONTINUE
58      I=0
59      K=1
60      IF(OPTION.EQ.2)WRITE(6,107)
61      J=1
62      2      I=I+1
63      IF(I.LT.3) GO TO 2
64      J=J+1
65      IF(I.EQ.NNN) GO TO 400
66      50      IF(PP(J).EQ.AA) THEN
67      J=J-1
68      GO TO 50
69      END IF
70      JM1=J-1
71      60      IF(PP(JM1).EQ.AA) THEN
72      JM1=JM1-1
73      GO TO 60
74      END IF
75      70      IF(I.GT.NNN) GO TO 400
76      X=ABS(PP(I)-PP(J))
77      Y=ABS(PP(J)-PP(JM1))
78      XX=(PP(J)+PP(JM1))/2.
79      5      IF(X.GE.Y)THEN
80      IF(OPTION.NE.1)GO TO1600
81      IF(Y.LE.FL) THEN
      PC(J)=AA
      PC(JM1)=AA
      END IF

```

Table B-2 (3rd page)

```

82 1600 IF(OPTION.EQ.2)GO TO 41
83 IF(OPTION.EQ.4)THEN
84 PI(J)=((32.*(-CF1+PP(J)))+CF2-PP(J))/CF3
85 PI(JM1)=((32.*(-CF1+PP(JM1)))+CF2-PP(JM1))/CF3
86 PMAX=PI(J)
87 PMIN=PI(JM1)
88 IF(PMAX.LT.PMIN)THEN
89 PMAX=PI(JM1)
90 PMIN=PI(J)
91 END IF
92 END IF
93 IF(OPTION.EQ.4)THEN
94 EIJ=PMAX+.5
95 EJI=PMIN+.5
96 IJ=INT(EIJ)
97 JI=INT(EJI)
98 MI(IJ,JI)=MI(IJ,JI)+1
99 END IF
100 IF(OPTION.EQ.4)GO TO 42
101 R(K)=Y
102 MEAN(K)=XX
103 K=K+1
104 GO TO 42
105 41 PMAX=PP(J)
106 PMIN=PP(JM1)
107 IF(PMAX.LT.PMIN)THEN
108 PMAX=PP(JM1)
109 PMIN=PP(J)
110 END IF
111 WRITE(6,108)Y,XX,PMAX,PMIN
112 42 PP(J)=AA
113 PP(JM1)=AA
114 J=J-1
115 3 J=J-1
116 IF(J.LT.1) GO TO 11
117 IF(PP(J).EQ.AA) GO TO 3
118 IF(I.EQ.4) THEN
119 I=5
120 J=I-1
121 END IF
122 JM1=J-1
123 IF(JM1.LT.1)THEN
124 JM1=J
125 J=I
126 I=I+1
127 GO TO 70
128 END IF
129 6 IF(PP(JM1).EQ.AA) GO TO 4
130 X=ABS(PP(I)-PP(J))
131 Y=ABS(PP(J)-PP(JM1))
132 XX=(PP(J)+PP(JM1))/2.
133 GO TO 5
134 4 JM1=JM1-1
135 IF(JM1.LT.1)THEN
136 JM1=J
137 J=I
138 I=I+1
139 END IF
140 GO TO 6
141 11 I=I+2

```

Table B-2 (4th page)

```

142      J=I-1
143      JM1=J-1
144      GO TO 70
145      ELSE
146      XX=(PP(J)+PP(JM1))/2.
147      J=I-1
148      END IF
149      GO TO 2

      C
      C
      C
150      400  IF(OPTION.EQ.2) GO TO 999
151          IF(OPTION.EQ.4)GO TO 998
152          K=K-1
153          RMAX=R(1)
154          RMIN=R(1)
155          RMMAX=MEAN(1)
156          RMMIN=MEAN(1)
157          DO 1800 I=2,K
158             IF(R(I).GT.RMAX)RMAX=R(I)
159             IF(R(I).LT.RMIN)RMIN=R(I)
160             IF(MEAN(I).GT.RMMAX)RMMAX=MEAN(I)
161             IF(MEAN(I).LT.RMMIN)RMMIN=MEAN(I)
162      1800  CONTINUE
163             DIFR=RMAX-RMIN
164             DIFM=RMMAX-RMMIN
165             ER=DIFR/XIR
166             EM=DIFM/XIM
167             ER=ER+2
168             EM=EM+2
169             LEVLM=INT(EM)
170             LEVLR=INT(ER)
171             DO 192 L=1,LEVLR
172             DO 193 LL=1,LEVLM
173             M(L,LL)=0
174      193  CONTINUE
175      192  CONTINUE
176             YA=RMIN-XIR
177             XA=RMMIN-XIM
178             WRITE(6,111)RMIN,RMAX,RMMIN,RMMAX
179             XB=.50
180             YB=.50
181             DO 1900 I=1,K
182             EI=((R(I)-YA)/XIR)+YB
183             EJ=((MEAN(I)-XA)/XIM)+XB
184             II=INT(EI)
185             JJ=INT(EJ)
186             IF(II.EQ.0)II=1
187             IF(JJ.EQ.0)JJ=1
188             M(II,JJ)=M(II,JJ)+1
189      1900  CONTINUE

      C
      C
      C
190      FILTERING PROCESS
191      IF(OPTION.NE.1)GO TO 1102
192      KN=1
193      DO 1000 II=1,NM
194      IF(PC(II).EQ.AA) GO TO 1000
195      PCC(KN)=PC(II)
      KN=KN+1

```


Table B-2 (5th page)

```

196 1000 CONTINUE
197     KN=KN-1
198     WRITE(6,112)
199 112  FORMAT('1',//15X,'FILTER HISTIRY-PEAK/VALLEY SEQUENCE')
200     WRITE(6,113)FL
201 113  FORMAT(//15X,'FILTER LEVEL=',F7.3)
202     WRITE(6,1103) KN
203 1103 FORMAT(//15X,'NUMBER OF POINTS IN FILTER HISTORY=',I5,//)
204     WRITE(6,1001)(PCC(I),I=1,KN)
205 1001 FORMAT(1X,8(2X,F6.1))
C
C
C     MATRIX PREPRATION
206     GO TO 1102
207 998  LEVLM=32
208     LEVLR=32
209     XIR=1
210     XIM=1
211     RMMIN=1
212     RMIN=1
213     DO 201 I=1,32
214     DO 202 J=1,32
215     M(I,J)=MI(I,J)
216 202  CONTINUE
217 201  CONTINUE
218 1102 IF(OPTION.EQ.2)GO TO 999
219     MM(1)=RMMIN
220     DO 900 L=2,LEVLM
221     LL=L-1
222     MM(L)=MM(LL)+XIM
223 900  CONTINUE
224     RA(1)=RMIN
225     DO 1100 L=2,LEVLR
226     LL=L-1
227 1100 RA(L)=RA(LL)+XIR
228     I=0
229 99   I=I+1
230     IF(I.GT.LEVLR) GO TO 1153
231     SUM(I)=0.
232     DO 98 J=1,LEVLM
233     SUM(I)=SUM(I)+M(I,J)
234 98   CONTINUE
235     GO TO 99
236 1153 CONTINUE
237 999  IF(OPTION.EQ.2)GO TO 997
238 1151 L=1
239     LB=8
240 1152 IF(OPTION.EQ.1)GO TO 996
241     WRITE(6,116)
242     GO TO 1154
243 996  WRITE(6,114)
244     WRITE(6,115)FL
245 1154 IF(OPTION.EQ.4)GO TO 604
246     GO TO 1150
247 604  WRITE(6,605)
248 605  FORMAT(77X,'TOTAL',/1X,'PEAK /*****VALLEY
*****',4X,'CYCLES',/)
249     GO TO 2100
250 1150 WRITE(6,600)
251 600  FORMAT(77X,'TOTAL',/1X,'RANGE /*****MEA

```

Table B-2 (6th page)

```

*****', 3X, 'CYCLES',/)
252 2100 WRITE(6,101)(MM(LL),LL=L, LB)
253      DO 1300 I=1,LEVL
254      WRITE(6,102)RA(I),SUM(I)
255      WRITE(6,103)(M(I,J),J=L, LB)
256 1300 CONTINUE
257      IF(LB.EQ.LEVLM)GO TO 1400
258      L=L+8
259      LB=LB+8
260      IF(LB.GT.LEVLM)LB=LEVLM
261      GO TO 1152
262 1400 SUMM=0
263      DO 1500 I=1,LEVL
264 1500 SUMM=SUMM+SUM(I)
265      WRITE(6,104)SUMM
266 101  FORMAT(12X,8(F6.1,2X))
267 102  FORMAT(2X,F6.1,69X,I4)
268 103  FORMAT('+',11X,8(I6,2X))
269 104  FORMAT('/',5X,'TOTAL NO OF CYCLES=',3X,I5)
270 997  CONTINUE
271 107  FORMAT(15X,'RANGE',15X,'MEAN',15X,' MAX',15X,' MIN')
272 108  FORMAT(14X,F7.3,12X,F7.3,13X,F7.3,13X,F7.3)
273 111  FORMAT('1',//15X,'MIN RANGE=',F8.3,//15X,'MAX RANGE=',F8.3,
*//15X,'MIN MEAN=',F8.3,//15X,'MAX MEAN=',F8.3)
274 116  FORMAT('1',//35X,'RAINFLOW CYCLES ')
275 114  FORMAT('1',//20X,'RAINFLOW CYCLES FOR ORIGINAL HISTORY')
276 115  FORMAT(/5X,'NO RANGE LESS THAN OR EQUAL TO FILTER LEVEL=',F7.3
*,3X,'OCCUR IN FILTER HISTORY')
277 210  FORMAT('1',//10X,'RANGES COUNTED AS CYCLES BY RAINFLOW CYCLE COUNT
*ING METHOD.')
278      STOP
279      END

```

C\$ENTRY

Table B-2 (7th page)

RANGES COUNTED AS CYCLES BY RAINFLOW CYCLE COUNTING METHOD.

RANGE	MEAN	MAX	MIN
4.000	1.000	3.000	-1.000
3.000	-0.500	1.000	-2.000
7.000	0.500	4.000	-3.000
9.000	0.500	5.000	-4.000

EXAMPLE 2

A history containing 41 peak/valley points is used with Option 2. Tables B-3 and B-4 show the input and output of this program, respectively.

Table B-3. Input for Example 2

2
41
-8.6,1.11,-6.2,-1.71,-2.95,2.10,-6.6,5.43,-2.58,-.4,-2.9,6.51,-1.12,.97,
-1.65,1.88,-4.47,2.01,-2.5,7.3,-1.08,5.36,-5.87,-.18,-3.5,.85,-1.89,
5.3,.1,4.45,-3.82,1.89,-2.04,3.9,-4.97,7.78,-3.99,4.61,-5.52,3.1,-8.6

Table B-4. Output for Example 2

RANGES COUNTED AS CYCLES BY RAINFLOW CYCLE COUNTING METHOD.			
RANGE	MEAN	MAX	MIN
1.240	-2.330	-1.710	-2.950
7.310	-2.545	1.110	-6.200
8.700	-2.250	2.100	-6.600
2.180	-1.490	-0.400	-2.580
8.330	1.265	5.430	-2.900
2.090	-0.075	0.970	-1.120
3.530	0.115	1.880	-1.650
4.510	-0.245	2.010	-2.500
10.980	1.020	6.510	-4.470
6.440	2.140	5.360	-1.080
3.320	-1.840	-0.180	-3.500
2.740	-0.520	0.850	-1.890
4.350	2.275	4.450	0.100
3.930	-0.075	1.890	-2.040
7.720	0.040	3.900	-3.820
10.270	0.165	5.300	-4.970
13.170	0.715	7.300	-5.870
8.600	0.310	4.610	-3.990
8.620	-1.210	3.100	-5.520
16.380	-0.410	7.780	-8.600

EXAMPLE 3

A history containing 1709 peak/valley points, called the SAE Transmission History, is used with Option 3. Therefore, the results are given in the form of a compact matrix containing range and mean values. The results are in agreement with the published values from Reference B-3. Tables B-5 and B-6 show the input and output for this example, respectively.

Note that the size of the matrix is determined by the XIM and XIR increment values, for mean and range, respectively, which are given to the program as input data. The program determines the smallest range and the lowest mean value. The increments are then added by the program a sufficient number of times to include the largest range and highest mean. Hence, the program automatically makes the matrix large enough to include the largest range and highest mean. In this particular case, the matrix size resulting from $XIM = XIR = 50$ is 27×20 . Since the smallest range is 200

$$200 + (27 - 1)50 = 1500$$

which is sufficiently large to include the largest range of 1494. Similarly, since the lowest mean value is -160,

$$-160 + (20 - 1)50 = 790$$

which is sufficiently large to include the highest mean of 753.

Note that the number of cycles counted also appears in the output. This is always related to the number of peak/valley points in the history, NN, as follows:

$$\text{No. of cycles} = \frac{NN - 1}{2}$$

NN is always odd, since the last peak or valley, P(), is a repetition of the first one, in this particular case

$$\text{No. of cycles} = \frac{1709 - 1}{2} = 854$$

Table B-5. Input for Example 3

3													
1709	50.	50.											
0	513	292	562	267	585	314	524	299	513	299	569	272	535
298	523	291	680	444	683	396	678	374	701	276	607	331	542
339	572	274	500	285	565	274	491	237	496	-76	142	-276	71
-309	19	-249	137	-93	658	275	534	240	612	360	690	315	689
306	698	417	666	392	699	374	701	368	659	345	650	403	610
393	637	400	618	285	630	385	616	374	703	-174	136	-331	334
98	510	151	542	84	642	398	651	-197	44	-197	125	-121	228
-17	631	387	657	408	623	218	553	291	640	408	693	453	657
356	642	400	698	330	571	337	689	395	647	377	594	227	631
299	682	411	663	404	629	306	631	306	614	409	648	414	683
374	575	324	691	379	585	368	621	371	610	373	582	-8	240
-227	248	-205	285	-89	470	248	460	136	519	317	517	278	503
179	615	324	559	219	679	421	683	-254	84	-222	243	-19	495
270	629	291	560	351	657	243	608	373	663	269	653	156	663
443	690	249	612	229	602	339	738	231	498	237	614	-167	39
-261	437	192	503	103	682	201	589	226	480	135	561	347	548
149	494	260	661	158	467	-184	161	-105	555	248	449	132	712
276	529	301	524	309	564	195	467	35	378	-294	188	-308	245
-211	607	41	526	205	506	218	513	249	603	261	712	506	727
194	400	-244	173	-276	610	405	615	360	642	403	641	353	556
340	655	433	669	422	662	457	796	403	671	78	549	285	616
376	690	18	731	108	578	282	629	170	748	181	578	342	604
261	585	330	694	349	614	313	521	290	533	266	565	291	645
-228	1	-286	157	-87	725	183	714	393	621	194	426	152	561
235	551	213	691	136	487	164	549	244	598	162	507	249	716
339	733	194	566	-191	120	-179	108	-119	181	-74	722	422	639
303	671	369	715	350	605	153	765	409	762	355	712	398	718
362	679	448	718	446	698	342	605	188	498	276	537	283	522
222	546	345	570	191	500	280	658	269	685	341	551	344	618
303	612	285	666	228	534	303	546	-110	110	-362	88	-199	173
-130	612	333	680	341	603	283	619	30	406	206	470	260	717
218	487	190	573	270	476	265	607	310	784	573	822	496	825
508	887	491	769	486	716	342	594	365	578	254	593	355	561
324	573	153	696	443	651	372	653	-256	39	-173	620	213	560
217	559	274	491	211	571	266	640	169	572	223	496	221	573
264	758	358	743	501	777	-161	57	-146	210	-13	216	-15	373
133	371	151	624	313	628	405	698	-202	146	-92	483	141	551
229	551	207	533	271	554	218	532	210	630	179	489	266	618
408	650	328	599	-211	158	-204	68	-179	256	-108	114	-114	476
228	494	178	658	218	612	245	652	416	658	355	678	428	722
437	747	542	776	-201	405	188	707	408	640	422	648	415	727
393	610	387	722	417	720	476	688	484	691	360	570	-350	528
216	679	475	689	274	562	286	653	233	453	253	573	282	582
356	603	234	871	494	771	511	773	481	727	491	836	566	782
398	659	329	685	387	629	218	604	329	628	-248	274	-206	710
463	663	365	695	406	803	437	739	449	679	452	695	454	703
260	602	-330	34	-350	188	-180	309	-7	648	417	647	439	683
438	699	451	712	382	698	296	625	385	680	405	718	457	673
372	744	414	618	82	597	191	570	211	522	212	517	211	495
232	439	235	616	256	512	270	575	314	791	369	787	502	769
468	785	444	798	501	732	522	723	462	680	-264	68	-154	188
-14	242	13	582	291	618	227	537	285	555	224	545	329	588
374	647	242	561	353	694	433	753	-237	313	-147	226	-163	705
329	636	376	680	383	641	404	712	367	732	290	610	318	629
315	588	353	577	265	612	368	723	-183	267	-208	111	-153	473
271	576	365	618	395	605	-283	235	-172	687	242	521	299	532

Table B-5 (2nd page)

283	596	306	629	392	639	326	583	368	591	360	601	373	632
409	640	272	496	175	470	251	549	301	573	313	517	317	565
322	529	265	586	353	555	-215	251	-133	419	63	535	175	490
164	517	126	560	165	726	408	671	399	662	325	596	331	583
378	744	309	635	417	677	373	650	368	673	-189	242	-17	610
197	548	181	523	296	582	113	560	137	739	366	725	362	717
341	607	317	604	351	567	141	653	452	709	158	404	-280	253
-183	199	-28	425	167	620	400	669	381	706	401	652	382	725
365	812	395	695	416	758	469	671	374	763	514	757	265	519
27	637	212	566	275	526	325	593	141	511	135	693	412	657
281	533	-204	199	-185	136	-86	186	-18	206	-8	739	110	453
253	506	275	511	108	516	169	420	116	383	-8	299	66	292
-259	-22	-242	244	1	222	-17	221	-276	233	-194	226	-11	560
358	567	356	599	361	607	394	652	378	632	342	637	276	557
299	583	190	506	235	570	299	557	334	582	255	544	240	636
270	619	228	583	371	593	373	589	377	626	426	648	250	647
293	717	417	701	320	709	385	701	427	682	286	601	175	559
285	533	310	535	319	555	326	564	-181	138	-219	251	7	443
102	490	263	534	45	693	398	678	329	671	433	696	283	554
189	489	-367	207	-276	-34	-263	149	-86	474	73	363	-419	-17
-240	-18	-219	181	-470	-19	-293	277	-259	292	-145	276	-1	227
1	566	117	516	148	415	-406	-19	-301	205	-330	632	231	433
178	582	331	835	490	748	355	693	475	722	441	742	437	730
419	722	416	769	442	775	501	701	449	685	431	632	425	646
415	683	341	769	485	738	421	762	485	696	374	591	356	639
356	675	426	705	449	688	479	770	251	484	45	282	-251	255
-320	438	222	639	251	647	431	707	469	789	400	669	334	546
342	705	374	684	427	698	368	645	358	625	373	652	409	634
322	624	368	659	392	748	355	675	362	667	447	755	349	683
315	693	330	607	226	744	443	754	503	709	427	703	274	516
258	588	141	457	221	428	-164	78	-251	526	313	725	314	582
212	733	318	629	357	752	458	791	492	717	403	727	369	603
277	636	358	562	229	770	535	840	544	792	318	522	-318	110
-233	288	-100	265	-120	703	14	592	162	530	229	577	217	613
164	593	319	632	398	623	250	789	256	475	-387	232	-347	133
-141	140	-129	544	303	644	358	642	365	673	336	889	365	669
447	813	506	817	537	776	524	749	542	868	545	871	415	690
471	789	487	706	452	669	192	512	-227	93	-189	518	293	594
89	576	362	789	191	449	151	478	238	501	104	786	299	832
610	829	530	734	-318	728	83	441	-7	511	46	895	405	877
609	876	630	888	527	797	-239	163	-102	632	11	811	390	855
271	578	324	675	221	632	362	733	420	803	-495	141	-296	100
-140	510	251	661	366	695	161	453	235	459	117	691	428	764
-247	217	-301	149	-207	157	-74	222	-66	280	-204	561	197	561
153	492	270	607	240	645	202	571	213	695	-448	103	-312	129
-138	508	304	603	67	626	342	601	286	576	221	721	315	636
304	669	337	605	367	567	280	514	-286	94	-133	355	36	458
146	506	294	577	-11	222	-341	94	-227	50	-156	329	19	585
165	398	176	822	561	801	553	776	-258	192	-125	464	211	730
52	834	352	642	285	587	-222	233	-136	251	18	528	33	449
234	626	226	480	35	594	189	518	47	589	63	449	205	645
-229	336	87	798	529	753	51	412	188	999	411	942	486	757
394	830	464	732	330	800	452	689	329	712	421	690	378	870
462	782	116	653	-223	54	-223	130	-237	-33	-254	551	274	549
251	658	192	640	323	578	281	530	294	575	240	478	234	519
296	645	353	664	318	575	178	594	374	598	308	581	330	739
412	615	344	601	328	549	324	645	381	639	393	645	377	592
294	538	297	535	251	503	286	656	427	635	394	640	378	653
392	614	358	608	313	513	244	844	365	607	406	620	387	609
346	572	259	543	269	498	269	570	309	513	151	506	221	582

Table B-5 (3rd page)

347	553	-277	50	-204	109	-256	164	-65	313	49	342	124	365
162	716	34	325	-249	507	-15	322	66	360	-158	83	-281	314
43	511	280	682	292	503	218	705	197	486	221	458	202	608
-325	-20	-242	508	254	478	192	631	408	716	350	567	258	592
367	658	408	623	264	587	371	589	285	632	368	599	318	589
309	512	260	571	346	725	261	487	192	593	293	539	189	554
0													

Table B-6. Output for Example 3

MIN RANGE= 200.000

MAX RANGE=1494.000

MIN MEAN=-160.000

MAX MEAN= 753.000

Table B-6 (2nd page)

RAINFLOW CYCLES									TOTAL
RANGE	/*****MEAN*****/								CYCLES
	-160.0	-110.0	-60.0	-10.0	40.0	90.0	140.0	190.0	
200.0	0	5	5	2	2	5	0	0	173
250.0	2	2	5	8	9	9	5	0	244
300.0	1	0	5	3	2	1	3	5	134
350.0	1	1	3	1	2	3	0	3	91
400.0	0	1	1	1	2	1	0	1	68
450.0	0	0	1	1	5	1	0	0	33
500.0	0	0	1	1	2	1	0	0	21
550.0	0	0	1	1	0	0	0	0	18
600.0	0	1	1	0	0	0	0	0	10
650.0	0	0	0	0	0	0	0	0	3
700.0	0	0	0	0	0	0	0	0	3
750.0	0	0	0	0	0	0	1	0	4
800.0	0	0	0	0	0	0	0	0	0
850.0	0	0	0	0	1	0	1	0	8
900.0	0	0	0	0	0	0	0	2	4
950.0	0	0	0	0	0	1	0	0	7
1000.0	0	0	0	0	0	0	0	3	9
1050.0	0	0	0	0	0	0	0	0	9
1100.0	0	0	0	0	0	0	0	2	9
1150.0	0	0	0	0	0	0	0	0	5
1200.0	0	0	0	0	0	0	1	0	3
1250.0	0	0	0	0	0	0	0	0	3
1300.0	0	0	0	0	0	0	0	0	2
1350.0	0	0	0	0	0	0	0	0	0
1400.0	0	0	0	0	0	0	0	1	0
1450.0	0	0	0	0	0	0	0	0	0
1500.0	0	0	0	0	0	0	0	0	1

Table B-6 (3rd page)

RANGE	RAINFLOW CYCLES								TOTAL CYCLES
	240.0	290.0	340.0	390.0	440.0	490.0	540.0	590.0	
200.0	3	5	11	24	30	33	25	14	173
250.0	3	6	13	32	37	41	39	14	244
300.0	1	4	10	15	24	23	20	11	134
350.0	2	3	6	15	17	11	14	6	91
400.0	0	3	7	10	21	9	7	4	68
450.0	0	2	0	8	9	2	2	2	33
500.0	0	2	2	2	3	2	1	0	21
550.0	0	0	4	2	6	2	0	1	18
600.0	0	0	2	1	3	1	0	0	10
650.0	0	0	2	1	0	0	0	0	3
700.0	0	0	2	0	1	0	0	0	3
750.0	0	0	1	1	1	0	0	0	4
800.0	0	0	0	0	0	0	0	0	0
850.0	3	1	0	0	0	0	0	0	0
900.0	3	1	0	0	0	0	0	0	0
950.0	4	2	0	0	0	0	0	0	0
1000.0	5	1	0	0	0	0	0	0	0
1050.0	3	4	0	0	0	0	0	0	0
1100.0	2	3	0	0	0	0	0	0	0
1150.0	3	0	0	0	0	0	0	0	0
1200.0	1	1	0	0	0	0	0	0	0
1250.0	2	0	0	0	0	0	0	0	0
1300.0	0	0	0	0	0	0	0	0	0
1350.0	0	0	0	0	0	0	0	0	0
1400.0	0	0	0	0	0	0	0	0	0
1450.0	0	0	0	0	0	0	0	0	0
1500.0	1	0	0	0	0	0	0	0	1

Table B-6 (4th page)

RAINFLOW CYCLES					TOTAL CYCLES
RANGE	/*****MEAN*****				
	640.0	690.0	740.0	790.0	
200.0	6	2	1	0	
250.0	10	2	2	0	173
300.0	5	3	0	0	244
350.0	3	0	0	0	134
400.0	0	0	0	0	91
450.0	0	0	0	0	68
500.0	2	0	0	0	33
550.0	0	1	0	0	21
600.0	0	0	0	0	18
650.0	0	0	0	0	10
700.0	0	0	0	0	3
750.0	0	0	0	0	3
800.0	0	0	0	0	4
850.0	0	0	0	0	0
900.0	0	0	0	0	8
950.0	0	0	0	0	4
1000.0	0	0	0	0	7
1050.0	0	0	0	0	9
1100.0	0	0	0	0	9
1150.0	0	0	0	0	5
1200.0	0	0	0	0	3
1250.0	0	0	0	0	3
1300.0	0	0	0	0	2
1350.0	0	0	0	0	0
1400.0	0	0	0	0	1
1450.0	0	0	0	0	0
1500.0	0	0	0	0	1

EXAMPLE 4

The same history as Example 3 is analyzed using Option 1. Tables B-7 and B-8 show the input and output of this program, respectively. The output includes the filtered history as a peak/valley sequence and also the rain-flow cycles for the original history.

In this case, filtering at a range of 400 reduced the length of the history from 1709 peaks and valleys to 361. The listing of the filtered history alternates between peaks and valleys, or valleys and peaks, and starts and ends with the largest absolute value. Note that range/mean matrix printed is the same as for Example 3.

Table B-7. Input for Example 4

1														
400.0														
1709														
50.	50.													
0	513	292	562	267	585	314	524	299	513	299	569	272	535	
298	523	291	680	444	683	396	678	374	701	276	607	331	542	
339	572	274	500	285	565	274	491	237	496	-76	142	-276	71	
-309	19	-249	137	-93	658	275	534	240	612	360	690	315	689	
306	698	417	666	392	699	374	701	368	659	345	650	403	610	
393	637	400	618	285	630	385	616	374	703	-174	136	-331	334	
98	510	151	542	84	642	398	651	-197	44	-197	125	-121	228	
-17	631	387	657	408	623	218	553	291	640	408	693	453	657	
356	642	400	698	330	571	337	689	395	647	377	594	227	631	
299	682	411	663	404	629	306	631	306	614	409	648	414	683	
374	575	324	691	379	585	368	621	371	610	373	582	-8	240	
-227	248	-205	285	-89	470	248	460	136	519	317	517	278	503	
179	615	324	559	219	679	421	683	-254	84	-222	243	-19	495	
270	629	291	560	351	657	243	608	373	663	269	653	156	663	
443	690	249	612	229	602	339	738	231	498	237	614	-167	39	
-261	437	192	503	103	682	201	589	226	480	135	561	347	548	
149	494	260	661	158	467	-184	161	-105	555	248	449	132	712	
276	529	301	524	309	564	195	467	35	378	-294	188	-308	245	
-211	607	41	526	205	506	218	513	249	603	261	712	506	727	
194	400	-244	173	-276	610	405	615	360	642	403	641	353	556	
340	655	433	669	422	662	457	796	403	671	78	549	285	616	
376	690	18	731	108	578	282	629	170	748	181	578	342	604	
261	585	330	694	349	614	313	521	290	533	266	565	291	645	
-228	1	-286	157	-87	725	183	714	393	621	194	426	152	561	
235	551	213	691	136	487	164	549	244	598	162	507	249	716	
339	733	194	566	-191	120	-179	108	-119	181	-74	722	422	639	
303	671	369	715	350	605	153	765	409	762	355	712	398	718	
362	679	448	718	446	698	342	605	188	498	276	537	283	522	
222	546	345	570	191	500	280	658	269	685	341	551	344	618	
303	612	285	666	228	534	303	546	-110	110	-362	88	-199	173	
-130	612	333	680	341	603	283	619	30	406	206	470	260	717	
218	487	190	573	270	476	265	607	310	784	573	822	496	825	
508	887	491	769	486	716	342	594	365	578	254	593	355	561	
324	573	153	696	443	651	372	653	-256	39	-173	620	213	560	
217	559	274	491	211	571	266	640	169	572	223	496	221	573	
264	758	358	743	501	777	-161	57	-146	210	-13	216	-15	373	
133	371	151	624	313	628	405	698	-202	146	-92	483	141	551	
229	551	207	533	271	554	218	532	210	630	179	489	266	618	
408	650	328	599	-211	158	-204	68	-179	256	-108	114	-114	476	
228	494	178	658	218	612	245	652	416	658	355	678	428	722	
437	747	542	776	-201	405	188	707	408	640	422	648	415	727	
393	610	387	722	417	720	476	688	484	691	360	570	-350	528	
216	679	475	689	274	562	286	653	233	453	253	573	282	582	
356	603	234	871	494	771	511	773	481	727	491	836	566	782	
398	659	329	685	387	629	218	604	329	628	-248	274	-206	710	
463	663	365	695	406	803	437	739	449	679	452	695	454	703	
260	602	-330	34	-350	188	-180	309	-7	648	417	647	439	683	
438	699	451	712	382	698	296	625	385	680	405	718	457	673	
372	744	414	618	82	597	191	570	211	522	212	517	211	495	
232	439	235	616	256	512	270	575	314	791	369	787	502	769	
468	785	444	798	501	732	522	723	462	680	-264	68	-154	188	
-14	242	13	582	291	618	227	537	285	555	224	545	329	588	
374	647	242	561	353	694	433	753	-237	313	-147	226	-163	705	
329	636	376	680	383	641	404	712	367	732	290	610	318	629	
315	588	353	577	265	612	368	723	-183	267	-208	111	-153	473	

Table B-7 (2nd page)

271	576	365	618	395	605	-283	235	-172	687	242	521	299	532
283	596	306	629	392	639	326	583	368	591	360	601	373	632
409	640	272	496	175	470	251	549	301	573	313	517	317	565
322	529	265	586	353	555	-215	251	-133	419	63	535	175	490
164	517	126	560	165	726	408	671	399	662	325	596	331	583
378	744	309	635	417	677	373	650	368	673	-189	242	-17	610
197	548	181	523	296	582	113	560	137	739	366	725	362	717
341	607	317	604	351	567	141	653	452	709	158	404	-280	253
-183	199	-28	425	167	620	400	669	381	706	401	652	382	725
365	812	395	695	416	758	469	671	374	763	514	757	265	519
27	637	212	566	275	526	325	593	141	511	135	693	412	657
281	533	-204	199	-185	136	-86	186	-18	206	-8	739	110	453
253	506	275	511	108	516	169	420	116	383	-8	299	66	292
-259	-22	-242	244	1	222	-17	221	-276	233	-194	226	-11	560
358	567	356	599	361	607	394	652	378	632	342	637	276	557
299	583	190	506	235	570	299	557	334	582	255	544	240	636
270	619	228	583	371	593	373	589	377	626	426	648	250	647
293	717	417	701	320	709	385	701	427	682	286	601	175	559
285	533	310	535	319	555	326	564	-181	138	-219	251	7	443
102	490	263	534	45	693	398	678	329	671	433	696	283	554
189	489	-367	207	-276	-34	-263	149	-86	474	73	363	-419	-17
-240	-18	-219	181	-470	-19	-293	277	-259	292	-145	276	-1	227
1	566	117	516	148	415	-406	-19	-301	205	-330	632	231	433
178	582	331	835	490	748	355	693	475	722	441	742	437	730
419	722	416	769	442	775	501	701	449	685	431	632	425	646
415	683	341	769	485	738	421	762	485	696	374	591	356	639
356	675	426	705	449	688	479	770	251	484	45	282	-251	255
-320	438	222	639	251	647	431	707	469	789	400	669	334	546
342	705	374	684	427	698	368	645	358	625	373	652	409	634
322	624	368	659	392	748	355	675	362	667	447	755	349	683
315	693	330	607	226	744	443	754	503	709	427	703	274	516
258	588	141	457	221	428	-164	78	-251	526	313	725	314	582
212	733	318	629	357	752	458	791	492	717	403	727	369	603
277	636	358	562	229	770	535	840	544	792	318	522	-318	110
-233	288	-100	265	-120	703	14	592	162	530	229	577	217	613
164	593	319	632	398	623	250	789	256	475	-387	232	-347	133
-141	140	-129	544	303	644	358	642	365	673	336	889	365	669
447	813	506	817	537	776	524	749	542	868	545	871	415	690
471	789	487	706	452	669	192	512	-227	93	-189	518	293	594
89	576	362	789	191	449	151	478	238	501	104	786	299	832
610	829	530	734	-318	728	83	441	-7	511	46	895	405	877
609	876	630	888	527	797	-239	163	-102	632	11	811	390	855
271	578	324	675	221	632	362	733	420	803	-495	141	-296	100
-140	510	251	661	366	695	161	453	235	459	117	691	428	764
-247	217	-301	149	-207	157	-74	222	-66	280	-204	561	197	561
153	492	270	607	240	645	202	571	213	695	-448	103	-312	129
-138	508	304	603	67	626	342	601	286	576	221	721	315	636
304	669	337	605	367	567	280	514	-286	94	-133	355	36	458
146	506	294	577	-11	222	-341	94	-227	50	-156	329	19	585
165	398	176	822	561	801	553	776	-258	192	-125	464	211	730
152	834	352	642	285	587	-222	233	-136	251	18	528	33	449
234	626	226	480	35	594	189	518	47	589	63	449	205	645
-229	336	87	798	529	753	51	412	188	999	411	942	486	757
394	830	464	732	330	800	452	689	329	712	421	690	378	870
462	782	116	653	-223	54	-223	130	-237	-33	-254	551	274	549
251	658	192	640	323	578	281	530	294	575	240	478	234	519
296	645	353	664	318	575	178	594	374	598	308	581	330	739
412	615	344	601	328	549	324	645	381	639	393	645	377	592
294	538	297	535	251	503	286	656	427	635	394	640	378	653
392	614	358	608	313	513	244	844	365	607	406	620	387	609

Table B-7 (3rd page)

346	572	259	543	269	498	269	570	309	513	151	506	221	582
347	553	-277	50	-204	109	-256	164	-65	313	49	342	124	365
162	716	34	325	-249	507	-15	322	66	360	-158	83	-281	314
43	511	280	682	292	503	218	705	197	486	221	458	202	608
-325	-20	-242	508	254	478	192	631	408	716	350	567	258	592
367	658	408	623	264	587	371	589	285	632	368	599	318	589
309	512	260	571	346	725	261	487	192	593	293	539	189	554
0													

Table B-8. Output for Example 4

MIN RANGE= 200.000

MAX RANGE=1494.000

MIN MEAN=-160.000

MAX MEAN= 753.000

Table B-8 (2nd page)

FILTER HISTORY-PEAK/VALLEY SEQUENCE

FILTER LEVEL=400.000

NUMBER OF POINTS IN FILTER HISTORY= 361

999.0	411.0	942.0	394.0	830.0	330.0	800.0	329.0
870.0	116.0	653.0	-254.0	658.0	192.0	640.0	234.0
664.0	178.0	739.0	251.0	656.0	244.0	844.0	151.0
582.0	-277.0	716.0	-249.0	507.0	-281.0	682.0	218.0
705.0	197.0	608.0	-325.0	716.0	258.0	725.0	192.0
593.0	0.0	701.0	-309.0	658.0	240.0	701.0	285.0
703.0	-331.0	542.0	84.0	651.0	-197.0	657.0	218.0
698.0	227.0	691.0	-227.0	248.0	-205.0	683.0	-254.0
657.0	243.0	663.0	156.0	690.0	229.0	738.0	-261.0
682.0	135.0	561.0	149.0	661.0	-184.0	555.0	132.0
712.0	-294.0	188.0	-308.0	245.0	-211.0	607.0	41.0
727.0	-244.0	173.0	-276.0	796.0	78.0	690.0	18.0
731.0	108.0	629.0	170.0	748.0	181.0	694.0	-286.0
725.0	183.0	714.0	152.0	691.0	136.0	598.0	162.0
733.0	-191.0	722.0	303.0	715.0	153.0	765.0	188.0
685.0	-362.0	680.0	30.0	717.0	190.0	887.0	153.0
696.0	-256.0	620.0	211.0	640.0	169.0	777.0	-161.0
698.0	-202.0	630.0	179.0	650.0	-211.0	658.0	218.0
776.0	-201.0	727.0	-350.0	689.0	233.0	871.0	218.0
628.0	-248.0	274.0	-206.0	803.0	-350.0	712.0	296.0
744.0	82.0	597.0	191.0	791.0	369.0	798.0	-264.0
647.0	242.0	753.0	-237.0	313.0	-163.0	732.0	265.0
723.0	-183.0	267.0	-208.0	618.0	-283.0	235.0	-172.0
687.0	175.0	586.0	-215.0	535.0	126.0	726.0	325.0
744.0	-189.0	610.0	181.0	582.0	113.0	560.0	137.0
739.0	141.0	709.0	-280.0	253.0	-183.0	812.0	27.0
637.0	135.0	693.0	-204.0	739.0	110.0	511.0	108.0
516.0	-259.0	244.0	-276.0	233.0	-194.0	652.0	190.0
636.0	228.0	717.0	-219.0	534.0	45.0	696.0	-367.0
207.0	-276.0	474.0	-419.0	181.0	-470.0	277.0	-259.0
292.0	-145.0	566.0	-406.0	205.0	-330.0	632.0	178.0
835.0	355.0	775.0	341.0	769.0	356.0	770.0	-251.0
255.0	-320.0	789.0	322.0	755.0	226.0	754.0	-251.0
725.0	212.0	733.0	318.0	791.0	229.0	840.0	-318.0
288.0	-120.0	703.0	14.0	592.0	162.0	613.0	164.0
789.0	-387.0	232.0	-347.0	889.0	365.0	871.0	-227.0
594.0	89.0	789.0	104.0	786.0	299.0	832.0	-318.0
728.0	-7.0	511.0	46.0	895.0	405.0	888.0	-239.0
632.0	11.0	811.0	390.0	855.0	271.0	675.0	221.0
803.0	-495.0	141.0	-296.0	695.0	117.0	764.0	-247.0
217.0	-301.0	280.0	-204.0	561.0	153.0	645.0	202.0
695.0	-448.0	103.0	-312.0	603.0	67.0	626.0	221.0
721.0	-286.0	577.0	-341.0	585.0	165.0	822.0	-258.0
730.0	152.0	834.0	-222.0	528.0	33.0	626.0	35.0
594.0	47.0	589.0	63.0	645.0	-229.0	798.0	51.0
999.0							

Table B-8 (3rd page)

RAINFLOW CYCLES FOR ORIGINAL HISTORY

NO RANGE LESS THAN OR EQUAL TO FILTER LEVEL=400.000 OCCUR IN FILTER HISTORY

RANGE	/*****MEAN*****/								HISTORY TOTAL CYCLES
	-160.0	-110.0	-60.0	-10.0	40.0	90.0	140.0	190.0	
200.0	0	5	5	2	2	5	0	0	173
250.0	2	2	5	8	9	9	5	5	244
300.0	1	0	5	3	2	1	3	3	134
350.0	1	1	3	3	2	3	0	1	91
400.0	0	1	1	1	2	1	0	1	68
450.0	0	0	1	1	5	1	0	0	33
500.0	0	0	1	3	2	1	0	0	21
550.0	0	0	1	1	0	0	0	0	18
600.0	0	1	1	0	0	0	0	0	10
650.0	0	0	0	0	0	0	0	0	3
700.0	0	0	0	0	0	0	0	0	3
750.0	0	0	0	0	0	0	1	0	4
800.0	0	0	0	0	0	0	0	0	0
850.0	0	0	0	0	1	0	1	2	8
900.0	0	0	0	0	0	0	0	0	4
950.0	0	0	0	0	0	1	0	0	7
1000.0	0	0	0	0	0	0	0	3	9
1050.0	0	0	0	0	0	0	0	2	9
1100.0	0	0	0	0	0	0	0	0	5
1150.0	0	0	0	0	0	0	0	0	3
1200.0	0	0	0	0	0	0	1	0	3
1250.0	0	0	0	0	0	0	0	0	2
1300.0	0	0	0	0	0	0	0	0	0
1350.0	0	0	0	0	0	0	0	1	0
1400.0	0	0	0	0	0	0	0	0	0
1450.0	0	0	0	0	0	0	0	0	0
1500.0	0	0	0	0	0	0	0	0	1

C-2

Table B-8 (4th page)

RAINFLOW CYCLES FOR ORIGINAL HISTORY

NO RANGE LESS THAN OR EQUAL TO FILTER LEVEL=400.000 OCCUR IN FILTER HISTORY

RANGE	/*****MEAN*****/								HISTORY TOTAL CYCLES
	240.0	290.0	340.0	390.0	440.0	490.0	540.0	590.0	
200.0	3	5	11	24	30	33	25	14	173
250.0	3	6	13	32	37	41	39	14	244
300.0	1	4	10	15	24	23	20	11	134
350.0	2	3	6	15	17	11	14	6	91
400.0	0	3	7	10	21	9	7	4	68
450.0	0	2	0	8	9	2	2	2	33
500.0	0	2	2	2	3	2	1	0	21
550.0	0	0	4	2	6	2	0	1	18
600.0	0	0	2	2	3	1	0	0	10
650.0	0	0	2	1	0	0	0	0	3
700.0	0	0	2	0	1	0	0	0	3
750.0	0	0	1	1	1	0	0	0	4
800.0	0	0	0	0	0	0	0	0	0
850.0	3	1	0	0	0	0	0	0	0
900.0	3	1	0	0	0	0	0	0	8
950.0	4	2	0	0	0	0	0	0	4
1000.0	5	1	0	0	0	0	0	0	7
1050.0	3	4	0	0	0	0	0	0	9
1100.0	3	3	0	0	0	0	0	0	9
1150.0	2	3	0	0	0	0	0	0	5
1200.0	3	0	0	0	0	0	0	0	3
1250.0	1	1	0	0	0	0	0	0	3
1300.0	2	0	0	0	0	0	0	0	0
1350.0	0	0	0	0	0	0	0	0	2
1400.0	0	0	0	0	0	0	0	0	0
1450.0	0	0	0	0	0	0	0	0	1
1500.0	1	0	0	0	0	0	0	0	0

Table B-8 (5th page)

RAINFLOW CYCLES FOR ORIGINAL HISTORY

NO RANGE LESS THAN OR EQUAL TO FILTER LEVEL=400.000 OCCUR IN FILTER HISTORY

RANGE	/*****MEAN*****/				TOTAL CYCLES
	640.0	690.0	740.0	790.0	
200.0	6	2	1	0	173
250.0	10	2	2	0	244
300.0	5	3	0	0	134
350.0	3	0	0	0	91
400.0	0	0	0	0	68
450.0	0	0	0	0	33
500.0	2	0	0	0	21
550.0	0	1	0	0	18
600.0	0	0	0	0	10
650.0	0	0	0	0	3
700.0	0	0	0	0	3
750.0	0	0	0	0	4
800.0	0	0	0	0	0
850.0	0	0	0	0	8
900.0	0	0	0	0	4
950.0	0	0	0	0	7
1000.0	0	0	0	0	9
1050.0	0	0	0	0	9
1100.0	0	0	0	0	5
1150.0	0	0	0	0	3
1200.0	0	0	0	0	3
1250.0	0	0	0	0	2
1300.0	0	0	0	0	0
1350.0	0	0	0	0	1
1400.0	0	0	0	0	0
1450.0	0	0	0	0	0
1500.0	0	0	0	0	1

EXAMPLE 5

A history containing 1021 peak/valley points is used. This is the Filtered version (filter level = .46) of a simulated helicopter combat maneuver loading history. Option 4 is used, so that the results are given in the form of a compact 32 x 32 matrix containing the maximum and minimum (peak and valley) values of the rain-flow cycles. Tables B-9 and B-10 show the input and output of this program, respectively. Note that the history is converted using linear interpolation to have a minimum value of 1 and a maximum value of 32.

Table B-9. Input for Example 5

4									
1021									
1.000	0.430	0.973	0.457	0.978	0.456	0.939	0.467	0.924	0.409
0.919	0.467	0.925	0.442	0.971	0.426	0.884	0.357	0.887	0.334
0.802	0.135	0.721	0.154	0.641	-0.041	0.749	0.001	0.750	0.127
0.835	0.380	0.896	0.397	0.860	0.369	0.832	0.365	0.849	0.350
0.836	-0.258	0.433	-0.033	0.422	-0.033	0.434	-0.174	0.293	-0.180
0.287	-0.216	0.355	-0.222	0.558	0.059	0.528	-0.055	0.398	-0.096
0.420	-0.092	0.388	-0.067	0.449	-0.134	0.381	-0.121	0.356	-0.095
0.406	-0.084	0.393	-0.067	0.387	-0.114	0.371	-0.087	0.379	-0.124
0.804	0.335	0.841	0.306	0.805	0.340	0.796	0.316	0.835	0.324
0.820	0.264	0.758	-0.010	0.748	0.289	0.797	0.333	0.803	0.149
0.765	0.200	0.697	0.230	0.771	0.321	0.886	0.335	0.874	0.373
0.894	0.423	0.983	0.423	0.909	0.369	0.860	0.383	0.879	0.422
0.932	0.395	0.936	0.380	0.867	0.348	0.806	0.197	0.676	0.002
0.514	0.018	0.511	0.046	0.559	-0.516	0.381	-0.215	0.376	-0.109
0.545	0.073	0.726	0.235	0.733	0.260	0.776	0.294	0.814	0.317
0.866	0.304	0.791	0.324	0.819	0.348	0.800	0.301	0.828	0.303
0.834	0.363	0.857	0.342	0.964	0.350	0.904	0.254	0.863	0.350
0.837	0.334	0.876	0.157	0.710	0.199	0.776	0.209	0.704	0.223
0.727	0.192	0.664	0.141	0.785	0.163	0.775	0.179	0.701	0.216
0.706	0.191	0.712	0.183	0.690	0.165	0.674	0.149	0.631	0.127
0.616	0.116	0.621	0.088	0.627	0.165	0.635	0.122	0.581	0.058
0.598	0.080	0.550	0.073	0.564	0.091	0.625	-0.016	0.596	-0.237
0.860	-0.035	0.510	0.032	0.495	-0.201	0.603	0.009	0.631	0.066
0.696	0.157	0.719	0.059	0.657	0.132	0.727	0.109	0.589	-0.011
0.668	-0.071	0.630	-0.048	0.626	-0.091	0.527	-0.112	0.529	-0.109
0.436	-0.146	0.403	-0.124	0.334	-0.171	0.280	-0.382	0.298	-0.193
0.721	0.254	0.722	0.219	0.828	0.335	0.898	0.365	0.871	0.232
0.799	0.303	0.839	0.296	0.788	0.309	0.780	0.303	0.775	0.275
0.742	0.167	0.747	0.183	0.781	0.259	0.760	0.099	0.692	0.108
0.725	0.116	0.700	0.189	0.692	0.076	0.619	0.128	0.600	0.088
0.731	0.051	0.732	0.124	0.656	0.118	0.755	0.079	0.643	0.053
0.739	0.079	0.711	0.063	0.648	0.153	0.614	0.144	0.681	0.128
0.705	0.109	0.785	0.075	0.561	0.098	0.641	0.146	0.771	0.230
0.708	0.220	0.826	0.361	0.832	0.373	0.832	0.375	0.884	0.369
0.939	0.398	0.882	0.365	0.911	0.442	0.947	0.393	0.901	0.373
0.995	0.365	0.974	0.382	0.976	0.371	0.978	0.412	0.883	0.390
0.872	0.362	0.839	0.381	0.882	0.419	0.889	0.346	0.881	0.348
0.826	0.371	0.839	0.342	0.896	0.337	0.790	0.321	0.885	0.287
0.811	0.039	0.583	0.054	0.535	-0.097	0.555	0.005	0.458	0.001
0.611	0.010	0.542	0.000	0.451	-0.294	0.277	-0.237	0.303	-0.215
0.287	-0.201	0.268	-0.219	0.275	-0.190	0.280	-0.174	0.312	-0.163
0.364	-0.185	0.316	-0.135	0.360	-0.103	0.352	-0.115	0.352	-0.148
0.304	-0.155	0.322	-0.153	0.336	-0.137	0.327	-0.142	0.332	-0.169
0.301	-0.266	0.659	0.182	0.702	0.220	0.733	0.231	0.746	0.237
0.742	0.271	0.776	0.259	0.783	0.279	0.757	0.270	0.729	0.196
0.703	0.190	0.642	0.147	0.630	0.106	0.629	0.165	0.730	0.139
0.624	0.099	0.603	0.147	0.710	0.092	0.711	0.047	0.566	0.115
0.577	0.084	0.541	0.015	0.472	0.021	0.512	-0.199	0.321	-0.158
0.337	-0.124	0.430	-0.081	0.412	-0.125	0.417	-0.074	0.442	-0.026
0.540	-0.066	0.561	-0.141	0.387	-0.072	0.382	-0.082	0.468	-0.054
0.497	-0.060	0.452	-0.089	0.411	-0.094	0.430	-0.131	0.382	-0.131

Table B-9 (2nd page)

0.356	-0.099	0.405	-0.116	0.488	-0.144	0.460	-0.086	0.440	-0.121
0.553	-0.115	0.501	-0.077	0.487	-0.041	0.495	-0.012	0.470	-0.026
0.519	-0.019	0.532	-0.013	0.459	-0.022	0.542	-0.062	0.575	-0.016
0.549	-0.017	0.542	0.024	0.573	0.012	0.681	0.053	0.640	0.108
0.595	0.139	0.602	0.028	0.613	0.015	0.635	-0.079	0.582	0.013
0.530	0.052	0.620	0.161	0.647	0.180	0.635	0.164	0.685	0.180
0.709	0.129	0.701	0.127	0.643	0.104	0.615	-0.075	0.471	-0.049
0.432	-0.032	0.423	-0.060	0.396	-0.095	0.458	-0.055	0.429	-0.083
0.494	-0.080	0.486	-0.040	0.515	-0.047	0.505	-0.101	0.477	-0.049
0.509	-0.065	0.541	-0.087	0.590	-0.084	0.579	0.077	0.595	-0.098
0.654	-0.133	0.612	-0.087	0.618	-0.137	0.572	-0.134	0.490	-0.043
0.435	-0.107	0.366	-0.099	0.536	0.000	0.456	0.005	0.695	0.042
0.648	0.117	0.731	0.238	0.803	0.275	0.811	0.193	0.825	0.248
0.700	0.171	0.887	0.217	0.762	0.185	0.721	0.236	0.701	0.200
0.732	0.227	0.873	0.197	0.800	0.192	0.684	0.221	0.738	0.194
0.742	0.161	0.750	0.223	0.718	0.181	0.742	0.253	0.732	0.241
0.731	0.194	0.730	0.228	0.776	0.265	0.790	0.226	0.795	0.238
0.717	0.244	0.765	0.270	0.768	0.226	0.732	0.256	0.748	0.216
0.755	0.286	0.787	0.272	0.727	0.232	0.738	0.187	0.749	-0.341
0.299	-0.155	0.311	-0.180	0.650	-0.198	0.318	-0.182	0.281	-0.231
0.442	-0.073	0.453	-0.085	0.471	-0.061	0.467	0.000	0.483	0.002
0.531	0.044	0.546	-0.041	0.541	0.010	0.564	0.047	0.594	0.040
0.534	0.033	0.570	0.059	0.556	0.101	0.562	0.097	0.587	0.110
0.601	0.012	0.625	-0.259	0.683	0.220	0.748	0.287	0.849	0.328
0.858	0.401	0.870	0.389	0.892	0.375	0.900	0.446	0.917	0.436
0.948	0.475	0.971	0.403	0.951	0.460	0.951	0.404	0.884	0.365
0.975	0.447	0.950	0.440	0.914	0.449	0.922	0.414	0.926	0.456
0.941	0.450	0.910	0.408	0.880	0.352	0.824	0.342	0.865	0.358
0.864	0.381	0.936	0.346	0.872	-0.213	0.559	0.061	0.513	0.040
0.509	-0.020	0.466	-0.151	0.775	0.305	0.821	0.229	0.788	0.333
0.834	0.333	0.819	0.362	0.829	0.302	0.833	0.324	0.846	0.290
0.802	0.252	0.813	0.309	0.775	0.175	0.797	0.239	0.780	0.273
0.737	0.276	0.789	0.304	0.846	0.291	0.742	0.285	0.767	0.240
0.775	0.211	0.722	0.221	0.698	0.205	0.707	0.174	0.690	0.002
0.673	0.172	0.790	0.225	0.760	0.294	0.795	0.308	0.789	0.334
0.822	0.351	0.811	0.303	0.802	0.289	0.782	0.301	0.784	0.325
0.783	0.299	0.847	0.324	0.822	0.343	0.896	0.373	0.875	0.394
0.943	0.383	0.857	0.350	0.924	0.372	0.894	0.421	0.874	0.383
0.878	0.357	0.846	0.379	0.908	0.377	0.913	0.434	0.887	0.390
0.879	0.379	0.878	0.388	0.839	0.334	0.842	0.381	0.896	0.395
0.901	0.393	0.872	0.374	0.946	0.398	0.881	0.392	0.897	0.338
0.958	0.402	0.912	0.337	0.877	0.398	0.878	0.379	0.838	0.380
0.920	0.389	0.856	0.383	0.858	0.377	0.910	0.398	0.860	0.399
0.881	0.428	0.901	0.362	0.910	0.417	0.928	0.414	0.897	0.394
0.956	0.422	0.943	0.407	0.949	0.425	0.954	0.394	0.922	0.423
0.955	0.337	0.905	0.444	0.934	0.413	0.932	0.405	0.926	0.383
0.907	0.362	0.860	0.004	0.494	-0.016	0.771	0.141	0.900	0.431
0.952	0.406	0.961	0.470	0.952	0.440	0.995	0.401	0.944	0.465
0.972	0.414	0.952	0.485	0.958	0.437	0.987	0.399	0.990	0.414
0.980	0.457	0.981	0.407	0.962	0.452	0.959	0.407	0.910	0.437
0.966	0.440	0.945	0.453	0.932	0.421	0.939	0.438	0.920	0.000
1.000									

Table B-10. Output for Example 5

PEAK	RAINFLOW CYCLES								TOTAL CYCLES
	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	
1.0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0
7.0	0	0	0	0	0	0	0	0	0
8.0	0	0	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0	0	0
10.0	0	0	0	0	0	0	0	0	0
11.0	0	0	0	0	0	0	0	0	0
12.0	0	0	0	0	0	0	0	0	0
13.0	0	0	0	0	0	0	0	0	0
14.0	0	0	0	0	0	0	0	0	0
15.0	0	0	0	0	0	0	0	0	0
16.0	0	0	0	0	0	0	0	0	0
17.0	0	0	0	0	0	0	0	0	0
18.0	0	0	0	0	0	0	3	5	8
19.0	0	0	0	0	0	0	1	10	17
20.0	0	0	0	0	0	1	2	1	18
21.0	0	0	0	0	0	0	1	0	20
22.0	0	0	0	0	0	0	0	0	22
23.0	0	0	0	0	0	0	0	0	27
24.0	0	0	0	0	0	0	0	1	33
25.0	0	0	0	0	0	1	1	0	33
26.0	0	0	0	0	0	0	1	0	24
27.0	0	0	0	0	0	0	1	0	48
28.0	0	0	0	0	0	0	1	0	47
29.0	0	0	0	0	0	0	1	0	51
30.0	0	0	0	0	0	0	1	0	50
31.0	0	0	0	1	0	1	0	0	60
32.0	1	0	0	0	1	1	0	0	41

Table B-10 (3rd page)

PEAK	RAINFLOW CYCLES								TOTAL CYCLES
	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	
1.0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0
7.0	0	0	0	0	0	0	0	0	0
8.0	0	0	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0	0	0
10.0	0	0	0	0	0	0	0	0	0
11.0	0	0	0	0	0	0	0	0	0
12.0	0	0	0	0	0	0	0	0	0
13.0	0	0	0	0	0	0	0	0	0
14.0	0	0	0	0	0	0	0	0	0
15.0	0	0	0	0	0	0	0	0	0
16.0	0	0	0	0	0	0	0	0	0
17.0	0	0	0	0	0	0	0	0	0
18.0	0	0	0	0	0	0	0	0	8
19.0	0	0	0	0	0	0	0	0	17
20.0	0	0	0	0	0	0	0	0	18
21.0	0	0	0	0	0	0	0	0	20
22.0	0	0	0	0	0	0	0	0	22
23.0	0	0	0	0	0	0	0	0	27
24.0	0	0	0	0	0	0	0	0	33
25.0	0	0	0	0	0	0	0	0	33
26.0	5	0	0	0	0	0	0	0	24
27.0	16	7	0	0	0	0	0	0	48
28.0	6	22	9	0	0	0	0	0	47
29.0	1	8	25	10	0	0	0	0	51
30.0	0	2	19	25	11	0	0	0	50
31.0	0	4	16	16	12	0	0	0	60
32.0	0	0	2	4	1	0	0	0	41

Table B-10 (4th page)

PEAK	RAINFLOW CYCLES								TOTAL CYCLES
	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	
1.0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0
7.0	0	0	0	0	0	0	0	0	0
8.0	0	0	0	0	0	0	0	0	0
9.0	0	0	0	0	0	0	0	0	0
10.0	0	0	0	0	0	0	0	0	0
11.0	0	0	0	0	0	0	0	0	0
12.0	0	0	0	0	0	0	0	0	0
13.0	0	0	0	0	0	0	0	0	0
14.0	0	0	0	0	0	0	0	0	0
15.0	0	0	0	0	0	0	0	0	0
16.0	0	0	0	0	0	0	0	0	0
17.0	0	0	0	0	0	0	0	0	8
18.0	0	0	0	0	0	0	0	0	17
19.0	0	0	0	0	0	0	0	0	18
20.0	0	0	0	0	0	0	0	0	20
21.0	0	0	0	0	0	0	0	0	22
22.0	0	0	0	0	0	0	0	0	27
23.0	0	0	0	0	0	0	0	0	33
24.0	0	0	0	0	0	0	0	0	33
25.0	0	0	0	0	0	0	0	0	24
26.0	0	0	0	0	0	0	0	0	48
27.0	0	0	0	0	0	0	0	0	47
28.0	0	0	0	0	0	0	0	0	51
29.0	0	0	0	0	0	0	0	0	50
30.0	0	0	0	0	0	0	0	0	60
31.0	0	0	0	0	0	0	0	0	41
32.0	0	0	0	0	0	0	0	0	11



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16. Abstract Helicopter loading histories applied to notched metal samples are used as examples, and their fatigue lives are calculated by using a simplified version of the local strain approach. This simplified method has the advantage that it requires knowing the loading history in only the reduced form of ranges and means and number of cycles from the rain-flow cycle counting method. The calculated lives compare favorably with test data.			
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