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EFFECT OF LOADING SEQUENCE; NORMAL AND REVERSED SEQUENCE EFFECT

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INTRODUCTION

Extensive published test results are available, which show that change of the loading sequence (without changing other loading parameters) affects the damage sum D_f. In complicated loading spectra, the effect of loading sequence is hard to isolate from those of other factors; for this reason, it is more easily assessed for simple two-stress level spectra. Numerous two-step tests with different loading programmes were reported in the last three decades [1 - 4]. From these tests follow that in case of alternating loading ($R = -1$), the damage sums are mostly larger than 1 in L-H tests and smaller than 1 in H-L tests. The values for D_f in block tests lie mostly between those obtained in the corresponding simple two-step tests. Different results for increasing and decreasing sequences were also observed in multi-step tests. Marco and Starkey [5] carried out rotating-bending tests with a number of equal loading steps (2 to 20) continuously increasing or decreasing to failure. For two different materials (7075-T6 and AISI4340), they found that the damage sums were always smaller than 1 for the decreasing and larger than 1 for the increasing sequences.

NORMAL AND REVERSED SEQUENCE EFFECT

The phenomenon of lower damage sums for the decreasing sequence - $(\Sigma n/N)_{H-L} < (\Sigma n/N)_{L-H}$ - first observed in rotating-bending tests, may be regarded as a normal sequence effect attributable to the nonlinear, stress-dependent character of damage cumulation [5]. However, there are cases where a reversed sequence effect can be observed [4, 6, 7], e.g., in the case of pulsating tension often $(\Sigma n/N)_{H-L} \geq (\Sigma n/N)_{L-H}$.

Since the damage sum D_f is dependent on the prestress cycle ratio n_1/N_1, the D_f values for the H-L and L-H two-step sequences should be compared at the same ratio n_1/N_1. Table 1 gives such a comparison for a case where the number of cycles applied in the first loading step equalled 50% of the corresponding fatigue life. As can be seen, the sequence effect was normal for alternating loading ($R = -1$) and reversed for pulsating-tension ($R = 0$).

In the author's tests on notched specimens the crack initiation period was about 50% of the total fatigue life. For unnotched specimens ($k_t = 1$) it is about 90%. The table contains results for specimens with and without stress concentration. It is seen that, irrespective of whether or not the visible crack appeared in the first loading step, the sequence effect was normal for $R = -1$ and reversed for $R = 0$.

The fact that damage sum is higher for the H-L than for the L-H sequence in the reversed sequence effect is explained by the beneficial effect of compressive residual stresses formed at the root of the notch under high tensile loadings.

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Plantema's [7] two-step pulsating-tension tests show a reversed sequence effect both for notched and for unnotched specimens, indicating that these beneficial residual stresses may also be expected in smooth specimens near internal defects (e.g., nonmetallic inclusions).

TWO-STEP BLOCK TEST RESULTS FOR VARIOUS TYPES OF LOADING

The author carried out two-step block tests on notched aircraft material specimens, with a view to investigating the damage sums as related to the type of loading. The tested specimens were round or flat, with a central hole. The types of loading used in a two-step stress block were alternating (rotating-bending or tension-compression), pulsating-tension, and combined pulsating-tension and tension-compression. Results are presented in Table 2. In the rotating-bending tests the average damage sum was 0.8 to 1.1 for the smaller and 0.5 to 0.6 for the larger life ratio N_L/H_N, with the deviation from Miner's rule accordingly larger in the second case. The change of frequency of the higher stress amplitudes (for $n_H/n_L \leq 1/10$) had little effect on the damage sum in both cases. In the tension-compression tests, with flat specimens and stress patterns n_H = 3Kc and n_L = 15Kc, the average damage sum exceeded unity only slightly (1.28), while in the pulsating-tension tests the excess was more substantial, the damage sum being 1.89 for similar flat specimens and 1.52 for lug specimens. In the tests with combined loading the damage sums were close to unity (0.9 to 1.3). For the investigated range of the life ratio N_L/N_H (between 2 and 7) the effect of the stress pattern in a block was slight.

The author investigated also the relative remaining fatigue life of specimens with V-notch or central hole after a certain number of stress blocks, when the change of the damage increment was directly proportional to the number of prestress blocks. As can be seen from Table 3, the damage sum and the relative remaining life were considerably higher for the high control stress level than for the low one (normal sequence effect). This can be quantitatively explained by the nonlinear, stress dependent character of the damage cumulation [3, 8]. In the case of a small prestress damage increment (small number of blocks), the relative remaining life was often larger than 1 for the higher control stress level, and substantially smaller than 1 for the lower level. This phenomenon observed for a small number of prestress blocks and a higher control stress level, indicates a beneficial effect comparable to the coaxing effect of low stress amplitudes [3, 4].

For the round grooved specimens the relative crack initiation period was about 0.4 at k_t = 2 and 0.2 at k_t = 4 [11]. The rotating-bending tests with low control stresses showed a considerable drop in the remaining fatigue life well before the prestress damage increment reached the crack initiation point. Similarly, for the flat specimens, where the relative crack initiation period was above 0.9, a considerable drop in the remaining life in pulsating tension was reached before the crack initiation point, when the control stress level was low.

According to Henry's nonlinear damage cummulation rule [8, 3], the respective decrement and increment relative to 1 of the D_f value in an L-H and an H-L sequence should be symmetrical. Table 3 shows, however, that this is not in agreement with test results. In some cases the damage sums actually exceeded 1 for both sequences (e.g., in the pulsating-tension tests). In other cases (k_t = 4, R.B.) both damage sums were lower than 1.

The following conclusions may be relevant for spectra more complex than the present simple two-block version - provided (as in our own tests) all stress levels lie well above the fatigue limit:

1) in pulsating tension, the damage sum does not fall below 1;

2) in combined pulsating tension and tension-compression (with a small number of not very high amplitudes in the second case), the damage sum often exceeds 1;

3) in alternating loading (rotating-bending or tension-compression) with not very different stress levels, the deviations from Miner's rule are not large;

4) in alternating loading with markedly different stress levels, the damage sum is well below 1 (but mostly above 0.3);

5) a beneficial effect of the coaxing type may be observed with some loading sequences in case of a high control stress level.

ROTATING BENDING FRACTURE ANALYSIS

V-notched specimens tested in rotating-bending (Table 3) were subjected to microscopic analysis of the final fracture areas obtained at instantaneous failure. The aim of this analysis was to investigate the effect of the notch geometry (SCF), of the stress level, and of the number of prestress blocks on the final fracture area. The effect of the stress level is presented in Table 4. The final fracture area was always larger for the higher stress level for both investigated aircraft materials and stress concentrations. It should be mentioned here that in Kiddle's [12] pulsating-tension tests with internally-notched flat aircraft material specimens, the final total fracture area was nearly independent of the stress level σ_{max} for k_t = 2.3 (in case of levels between 120 and 240 MN/m^2) and decreased with σ_{max} for the higher stress concentration k_t = 3.4. Table 5 presents the effect of stress concentration for specimens of the same type (V-notch) and notch cross-section, tested under the same bending moment. The final fracture area was evidently smaller for the higher SCF both in constant-load and in block tests. The same conclusion can be drawn by comparing Kiddle's [12] constant load pulsating-tension test results at the same σ_{max} for specimens k_t = 2.3 and 3.4. Table 6 presents results for 7075-T6 specimens, which, after a certain number of prestress blocks, were tested to failure at a high or low stress level. When the failure occurred at the lower stress level the final fracture area was independent of the number of prestress blocks and equal to the fracture area in the constant-load test (Table 4). When the failure occurred at the higher stress level, the final fracture area was larger than in the constant-load tests for specimens subjected to 2 or 4 prestress blocks. Recalling that these specimens had a larger relative remaining fatigue life (Table 3), it can be concluded that the smaller crack propagation rate resulted in a larger final fracture area. A similar explanation can be given for the larger final fracture area of the specimens with k_t = 2, compared with those with k_t = 4, where the crack propagation rate is evidently smaller for the lower stress concentration factor and larger notch radius (Table 5).

Quantitative correlation of the value of final fracture area with a critical stress intensity formula is difficult, as the test results partially conflict with some basic assumptions of fracture mechanics.

The stress intensity formula of Harris [13] modified for specimens in bending with an eccentric crack front [14] has the following form:

$$K_I = \frac{2.257\ M}{r^3 + 4r\ e^2}\left[\frac{0.8}{t} + \frac{7.12}{r}\right]^{1/2}$$

where r - is the radius of the final fracture area, e - the eccentricity of this area with respect to the geometric centre of the cross-section with diameter D, t = 1/2(D - 2r) - the average crack depth and M - the bending moment. This formula makes it possible to compare the ratio $\sigma_1/\sigma_2 = M_1/M_2$ computed from microscopic observation data with the test stress ratio. As can be seen from Table 4, the theory is approximately in agreement with the experimental results when k_t = const, but the stress intensity formula does not explain the results in Tables 5 and 6.

CONCLUSIONS

1) There exist a normal and a reversed loading sequence effect:

Normal $\left[\Sigma\frac{n}{N}\right]_{H \to L} < \left[\Sigma\frac{n}{N}\right]_{L \to H}$ in the case of alternating loading two-step tests.

Reversed $\left[\Sigma\frac{n}{N}\right]_{H \to L} > \left[\Sigma\frac{n}{N}\right]_{L \to H}$ in the case of pulsating tension two-step tests, when the step H is sufficiently high.

2) The relative remaining life after a number of stress blocks is higher for the higher control stress level than for the lower one, as in simple two-step tests with a normal sequence effect. This can be although not quantitatively, qualitatively explained by a nonlinear, stress-dependent damage cummulation rule.

3) The formula for K_I accounts, in the case of k_t = const and small e, for the relationship between the stress ratio σ_1/σ_2 on the one hand and the ratios A_1/A_2 and e_1/e_2 on the other. However, the notch radius and the stress history seem to affect the final fracture area (i.e., the parameters A and e).

REFERENCES

1. FORREST, P. G., "Fatigue of Metals", Pergamon Press, Oxford, 1972.
2. BUCH, A. and WEINSTEIN, F., Isr. J. Techn., 5, 1974, 403.
3. BUCH, A., Technion - Haifa TAE Report 231, 1974, 281, 1976.
4. BUCH, A., Materialpruf., 9, 1975, 307.
5. MARCO, S. M. and STARKEY, W. L., Trans. ASME, 76, 1954, 627.
6. SMITH, J., HOWARD, D. M. and SMITH, F. C., NACA TN, 3293, 1955.
7. PLANTEMA, F. Y., in Coll. on Fatigue, Springer, Berlin, 1956, 218.
8. HENRY, D. L., Trans. ASME, 54-A77, 1955, 913.
9. WEBER, D. and LEVY, J. C., R.A.E. Tech. Memo 15/58, 1958.
10. GEDEON, J., ICAS - PAPER, 70-35, 1970.
11. GOLOD, A., Dissertation Technion - Haifa, 1975.
12. KIDDLE, F. E., R.A.E. Tech. Rep. 72107-ARC C.P., 1259, 1972.
13. HARRIS, D. O., Trans. ASME, 1, 89-D, 1967, 49.
14. EISENSTADT, R. and RAJAN, K. M., J. Eng. Mat. Tech., 4, 1974, 81.

Table 1 Damage Sums $D_f = \Sigma n/N$ in Case of Two-Step Loading with Various Loading Sequences and the Same Cycle Ratio $n_1/N_1 = 0.5$ in the First Step

Material and SCF	Kind of Loading	Stress Levels MN/m²		Fatigue Lives Kc		Loading Sequence	D_f	Reference
		High	Low	N_H	N_L			
NiCrMo-steel $k_t = 1$ 7075-T alloy $k_t = 1$	R.B.	840 350	560 175	15 10	200 5000	H-L L-H H-L L-H	0.73 1.14 0.63 1.45	[5]
2024-T alloy $k_t = 2$	T.C.	140	110	32.8	172	H-L L-H	1.08 1.62	[3]
2024-T alloy $k_t = 1$ 2024-T alloy $k_t = 2.85$	P.T. R=0	230 105	160 65	196 185	1290 1168	H-L L-H H-L L-H	2.36 0.85 1.67 1.15	[7]
PMMA $k_t = 3.6$	P.T. R=0	27.8	24.5	15.7	128	H-L L-H	2.42 0.84	[4]
2024T lugs $k_t = 2.65$ $k_t = 3.7$	P.T. R=0	100±98 40±38	100±58 40±25	216 345	800 832	H-L* L-H* H-L L-H	2.83 1.83 3.43 2.17	[3]

$*n_1/N_1 = 0.25$

Table 2 Damage Sums D_f in Case of Various Two-Step Block Tests Until Failure. Notched 2024-T Specimens

Kind of Specimen mm	Kind of Loading	Stress Levels MN/m²		Fatigue lives Kc		Life Ratio	Stress Pattern Kc		Damage D_f
		High	Low	N_H	N_L	N_L/N_H	n_H	n_L	
Flat, k_t=2 d=10, W=15.5	T.C.	140	110	33	172	5.2	3	15	1.279
Round, k_t=2 d=2, D=10	R.B.	250	210	79	292	3.7	1 2 3	30 30 30	1.082 0.848 0.828
Round, k_t=2 d=2, D=10	R.B.	250	170	35.5	235	6.6	0.6 1 2	20 20 20	0.512 0.564 0.549
Round*, k_t=2	R.B.	230	200	35.5	123	3.5	1	3	1.003
Flat, k_t=2 d=5, W=10 d=10, W=15.5 d=5, W=10 ** d=7.5, W=15.5	T.C.+ P.T.	±140 ±140 ±140 ±100	+150 +150 +150 +150	41 76 41 179	289 148 289 287	7.0 1.95 7.0 1.6	6 6 2 2	9 9 28 28	1.194 1.300 1.134 0.904
Flat, k_t=2 d=10, W=15.5	P.T.	+220	+170	49	206	4.2	3	12	1.886
Lug, k_t=3.7 d=10, W=30	P.T.	40±3.8 40±2.5		345	832	2.4	30	50	1.52

*7075-T6, V-Notch ** Alclad

Table 3 Damage Sums $D_f = \Sigma n/N$ and Relative Remaining Fatigue Life After a Number of Prestress Blocks

Kind of Specimen mm	Kind of Loading	Stress Levels σ MN/m² Stress Pattern n Kc Fatigue Life N Kc	Damage per Block Δ* and D_f	Relative Remaining Fatigue Life**
Flat, k_t=2 d=10 W=15.5 2024-T3	2 T.C. Blocks + L + H	$\sigma_H = 140$ $\sigma_L = 110$ $n_H = 3$ $n_L = 15$ $N_H = 32.8$ $N_L = 172$	Δ = 0.178 0.961 1.708	 0.604 1.351
	4 T.C. Blocks + L + H		 1.123 2.074	 0.409 1.360
Round, k_t=4 V-Notch 2024-T4	2 R.B. Blocks + L + H	$\sigma_H = 130$ $\sigma_L = 105$ $n_H = 5$ $n_L = 15$ $N_H = 172$ $N_L = 512$	Δ = 0.058 0.630 0.670	 0.514 0.554
	4 R.B. Blocks + L + H		 0.855 0.815	 0.623 0.583
Round, k_t=2 V-Notch 2024-T4	3 R.B. Blocks + L + H	$\sigma_H = 170$ $\sigma_L = 130$ $n_H = 2$ $n_L = 20$ $N_H = 127$ $N_L = 672$	Δ = 0.045 0.840 1.453	 0.705 1.318
	9 R.B. Blocks + L + H		 0.930 1.337	 0.582 0.958
Round, k_t=2 V-Notch 7075-T6	2 R.B. Blocks + L + H	$\sigma_H = 230$ $\sigma_L = 200$ $n_H = 1$ $n_L = 3$ $N_H = 35.3$ $N_L = 123$	Δ = 0.053 0.921 1.002	 0.816 0.896
	4 R.B. Blocks + L + H		 0.534 0.938	 0.324 0.728
	6 R.B. Blocks + L + H		 0.596 1.142	 0.278 0.824
	8 R.B. Blocks + L + H		 0.587 1.172	 0.163 0.748
Flat, k_t=2 d=10 W=15.5 2024-T3	4 P.T. Blocks + L + H	$\sigma_H = +220$ $\sigma_L = +170$ $n_H = 3$ $n_L = 12$ $N_H = 49$ $N_L = 206$	Δ = 0.120 1.454 1.423	 0.976 0.945
	6 P.T. Blocks + L + H		 0.942 1.611	 0.225 0.894
	8 P.T. Blocks + L + H		 1.160 1.462	 0.200 0.506
Flat, k_t=2 d=10 W=15.5 2024-T3	T.C. + P.T. 1 Block + L + H	$\sigma_H = \pm 180$ $\sigma_L = +180$ $n_H = 0.5$ $n_L = 5$ $N_H = 11.4$ $N_L = 103$	Δ = 0.092 0.811 0.874	 0.719 0.782
	3 Blocks + L + H		 0.603 1.173	 0.326 0.896

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* Δ = $n_H/N_H + n_L/N_L$ where n_H and n_L are the number of cycles in a stress block.

** N_H'/N_H or N_L'/N_L where N' is the remaining fatigue life at the control stress level (H or L).

Table 4 Final Fracture Area $A = \pi r^2$ at Two Stress Levels

Material and Specimens	Stress σ MN/m²	Final Fracture Area $A = \pi r^2$ mm²	Average Area A mm²	Stress Ratio σ_1/σ_2	
				Test Ratio	K_I Formula
7075-T6 k_t = 2 ρ = 0.63 mm	230 200	2.14 ÷ 2.81 1.75 ÷ 2.46	2.584 2.192	1.150	1.276
2024-T4 k_t = 2 ρ = 0.63 mm	170 130	1.84 ÷ 2.94 1.59 ÷ 2.04	2.223 1.903	1.308	1.260
2024-T4 k_t = 4 ρ = 0.12 mm	130 105	0.82 ÷ 1.69 0.52 ÷ 1.57	1.263 1.220	1.238	1.235
AlZnMgCu k_t = 2 ρ = 0.63 mm	260 230	4.00 ÷ 5.31 2.54 ÷ 3.47	4.502 3.221	1.130	1.123

Table 5 Comparison of Final Fracture Areas for 2024-T4 Specimens with k_t = 4 and k_t = 2 in the Case of the Same Fracture Stress Level σ = 130 MN/m²

Type of Specimen	S.C.F.	k_t = 4		k_t = 2	
		Scatter	Average	Scatter	Average
Fatigue Life	N Kc	127 ÷ 201	172	625 ÷ 735	672
Av. Area for the Constant Load Tests,	A mm²	0.82 ÷ 1.69	1.263	1.59 ÷ 2.04	1.903
Av. Area for the Block Tests	A mm²	0.92 ÷ 1.73	1.286	0.99 ÷ 2.14	1.629

Table 6 Final Fracture Area A after a Certain Number of Stress Blocks and Constant Stress Amplitude Loading (7075-T6, k_t = 2, R.B) at a High (230 MN/m²) or Low (200 MN/m²) Stress Level

Number of Blocks	Stress Level MN/m²	Average Area A mm²	Scatter A mm²
2	230	3.14	2.63 ÷ 3.61
2	200	2.28	1.94 ÷ 2.43
4	230	3.01	2.42 ÷ 3.60
4	200	2.16	1.80 ÷ 2.53
6	230	2.40	2.05 ÷ 2.83
6	200	2.18	2.10 ÷ 2.30
8	230	2.69	2.38 ÷ 2.79
8	200	1.98	1.65 ÷ 2.31