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FATIGUE BEHAVIOR OF UNCRACKED MATERIAL SPECIMENS UNDER LOG-NORMAL SPECTRUM LOADING

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1. ABSTRACT

References (1) and (2) presented analytical methods for predicting the fatigue behavior of critical components of helicopter dynamic systems. Miner's theory of cumulative damage was used to estimate the effects of actual flight load spectra.

Laboratory research which provides an experimental evaluation of these methods is now in progress at Ames Research Center. In this research, material specimens are subjected to applied loading spectra which are virtually identical to the ones used in the earlier analyses. The resulting data, in the form of S-N curves under spectrum loading, provides a basis for evaluating analytical methods of cumulative damage prediction prior to crack initiation.

2. NOTATION

C_S	Scatter coefficient, ratio of oscillatory stress at .9999 probability of exceedence to average oscillatory stress
EINF	Asymptote of Weibull formula for matching empirical S-N curve
K	Constant in Weibull formula for matching empirical S-N curve
K_T	Theoretical stress concentration factor
M	Constant in Weibull formula for matching empirical S-N curve
Mc/I	Nominal bending stress at location of notch - lb/in^2
N	Number of cycles to crack initiation
S	Average oscillatory stress - lb/in^2
UTS	Ultimate tensile strength
YS	Yield strength

3. INTRODUCTION

Reference (1) presented S-N curves under log-normal spectrum loading as opposed to constant-amplitude loading, for a variety of materials used in fatigue-critical components of helicopter dynamic systems. The log-normal applied load spectra provide a good analytical representation of the empirical loading spectra for these components. The spectral S-N curves were based upon Miner's theory of cumulative damage in conjunction with S-N curve shapes applicable to constant-amplitude fatigue loading. Excellent correlation was shown with preliminary design charts used by Bell Helicopter for the same materials, as presented in Reference (2).

In order to provide an experimental evaluation of the spectral S-N curve approach of Reference (1), material specimens were tested at Ames Research Center under both constant-amplitude and log-normal spectrum loadings. Using these data, the present paper gives a systematic comparison between the fatigue behavior as predicted by Miner's theory and the actual performance of the specimens under the spectrum loadings. This comparison is of interest because Miner's theory is used extensively in performing the required analyses of the fatigue-critical components during the qualification and certification of rotary wing aircraft, even though the accuracy of the theory is generally considered to be somewhat questionable.

The log-normal applied load spectrum provides the most suitable present basis for evaluating the applicability of Miner's theory and for developing a uniform approach to the characterization of statistical fatigue behavior under spectrum loading during the crack initiation stage, pending the development of a practical materials science approach to the analysis of cumulative fatigue damage prior to crack initiation. The present paper describes the experimental methods used at Ames Research Center to obtain a family of spectral S-N curves, and outlines the planned program continuation to further characterize materials fatigue behavior under spectrum loading.

4. SPECIMENS AND MATERIALS

The presently reported series of tests employed notched three-point bending specimens with $K_T \approx 5.$ as illustrated in Figure 1. The materials tested were as follows:

First series: Annealed Al-4V titanium alloy, YS 120,000 lb/in^2, UTS 130,000 lb/in^2, machined from 1/2 inch rolled plate.

Second series: 2014-T6 aluminum alloy, YS 55000 lb/in^2, UTS 65000 lb/in^2, machined after heat treatment from 1 1/2 inch thick forged billet.

All specimens were electrical discharge machined to the finished dimensions, except that the notches were finished by grinding after heat treatment.

5. TEST METHOD

Tests were conducted in an MTS electro-hydraulic test machine with the servo valve computer-controlled to provide a varying schedule of oscillatory loading at 50 cycles/second, superposed on the mean steady load. As can be seen from Figure 2, the test setup is not amenable to load reversal. For each of the materials, the mean steady load was maintained at a constant value which was selected so as to avoid reversal throughout the range of the tests. The notch opening deflection was monitored throughout the tests by means of a clip gauge.

6. LOADING SEQUENCE

The log-normal spectrum provides the best analytical representation of flight measured loads on helicopter dynamic systems. As noted in Reference (1), the log-normal spectrum is completely defined by two parameters, i.e., the average (50% probable) value of the oscillatory load, and the scatter coefficient C_s. The scatter coefficient is defined as the ratio of the oscillatory load at .9999 probability of exceedance to the average. An example spectrum based upon flight measured data for the XV-15 rotor hub was taken from Reference (3) and is shown in Figure 3.

For convenience in controlling the test apparatus, a block spectrum of 24 elements is used to approximate a continuously varying spectrum. The sequence of loading is tabulated below for various scatter coefficients, C_s.

Block	No. Cycles	Stress Ratio C_s=.2	Stress Ratio C_s=.4	Stress Ratio C_s=.6
1	4.5	.2287	.4317	.6262
2	26	.2991	.5030	.6818
3	118	.3991	.5860	.7424
4	385	.5114	.6826	.8083
5	765	.6687	.7953	.8801
6	1200	.8745	.9265	.9583
7	1200	1.1435	1.0793	1.043
8	765	1.4954	1.2574	1.136
9	385	1.9554	1.4649	1.237
10	118	2.5571	1.7066	1.347
11	26	3.3439	1.9882	1.467
12	4.5	4.3727	2.3162	1.597
13	4.5	4.3727	2.3162	1.597
14	26	3.3439	1.9882	1.467
15	118	2.5571	1.7066	1.347
16	385	1.9554	1.4649	1.237
17	765	1.4954	1.2574	1.136
18	1200	1.1435	1.0793	1.043
19	1200	.8745	.9265	.9583
20	765	.6687	.7953	.8801
21	385	.5114	.6826	.8083
22	118	.3911	.5860	.7424
23	26	.2991	.5030	.6818
24	4.5	.2287	.4317	.6262

Return to block 1.

Each time through the spectrum, the oscillatory stress level increases in steps from the minimum to the maximum and decreases again to the minimum. This procedure is analogous to a flight profile in which the aircraft takes off, accelerates to maximum speed and decelerates to land, or alternatively progresses through a series of increasingly severe flight conditions and then retraces the pattern in reverse. One time through the spectrum constitutes a total of 10,000 loading cycles, which is roughly equivalent to 20 or 30 minutes of flight in a typical helicopter. The operating life for a limited-life helicopter component might be 10^6 to 10^7 cycles or more, corresponding to 100 to 1000 or more times through the spectrum. Material tests employing the 24-block spectrum are therefore sufficiently fine-grained to model the fatigue behavior of actual components.

7. DEFINITION OF FAILURE

For helicopter safe-life components made from metallic materials, it is customary to define the end of life as the time of crack initiation; i.e., the first occurrence of a detectable crack in a critical area. This definition is somewhat imprecise, since it depends upon the method of crack detection used and its resolution capability. In the present tests, an accurate indication of crack initiation was obtained by measuring the specimen compliance periodically during the tests, based on the clip gauge outputs, and thus detecting the initial change of compliance associated with the initial crack. For the present series of tests, failure was defined as a 10% change of compliance, corresponding to a crack size in the specimens of about .010 inch. A representative plot of compliance versus time is shown in Figure 4.

8. TEST RESULTS - CONSTANT AMPLITUDE LOADING

As a background for the spectrum tests, S-N curves under constant amplitude loading (C_s = 1.0) were developed, as shown in Figure 5.

The ordinates of these curves are in terms of nominal Mc/I stress on the net section at the base of the dovetail. Curve match formulas were developed for the two materials, as follows:

Titanium: (Steady stress = 49980 lb/in^2)

K = 17375.

M = 1.68

EINF = 6033. lb/in^2

Aluminum: (Steady stress = 17778 lb/in^2)

K = 112502.

M = 1.53

EINF = 1896.3 lb/in^2

Where $N=K/\left[(S/EINF) - 1\right]^M$

except that if S >7407.5, then;

$\log (N) = (38618. - S)/7187.$

9. TEST RESULTS - SPECTRUM LOADING

Test results in the form of S-N data under spectrum loading are shown in Figures 6(a) through 7(c). The figures show the reduced S-N curves under spectrum loading which would be predicted by Miner's theory, along with the S-N data under spectrum loading as obtained from the tests. A direct evaluation of Miner's theory is thus presented for each case.

10. EVALUATION OF MINER'S THEORY

In the present series of tests, the test lifetimes were found to coincide with the Miner's theory predictions in some cases, while in other cases the lifetimes differed by factors of the order of 2.5. Errors of this order of magnitude are usually accepted as normal for life predictions based upon Miner's theory.

On reviewing the test results, no systematic relationship is apparent which can be used to correlate the spectrum test results with S-N curves previously obtained using Miner's theory. In general, the test lifetimes exceed the Miner's theory predictions, but a notable exception occurs at $C_s = .6$ for titanium (Figure 6(c)).

Contrary to Miner's theory, the spectrum-loaded S-N curves for $C_s = .2$ cross the constant-amplitude curves, so that for the more highly-loaded specimens, the spectrum loading actually increases the specimen life, even though the spectra contain load components which approach five times the average.

11. CONCLUSIONS

This paper presents a method of incorporating a family of standardized applied load spectra in the materials characterization fatigue tests. Providing that the spectra are representative of those encountered in operation or required for certification, this method reduces or eliminates the need for reliance on a theoretical cumulative damage rule such as Miner's theory.

12. PLANNED CONTINUATION

In the planned continuation of the present research, the specimens and test setup will be modified to accommodate load reversal, and the testing will be extended to encompass other K_T values, other steady stress levels, and other materials, including composites. Theories of cumulative fatigue damage such as Miner's will be evaluated. The resulting data and conclusions will provide a basis for an improved methodology for the design of helicopter components subjected to spectrum loading.

13. REFERENCES

1) David P. Chappell: Monitoring of Fatigue Loading on Rotor Systems and Related Components.
Paper No. 64 presented at the Fourth European Rotorcraft and Powered Lift Forum, Stresa, Italy, September 1978; and Journal of American Helicopter Society, April 1979.

2) G. L. Graham and M. J. McGuigan: A Simplified Empirical Method for Rotor Component Fatigue Design.
American Helicopter Society Paper No. 372, May 1979.

3) Jerry P. Barrack: Measurement and Analysis of Structural Fatigue Spectra of the XV-15 Tilt Rotor Research Aircraft.
Presented at the Ninth European Rotorcraft Forum in Stresa, Italy, September 1983.

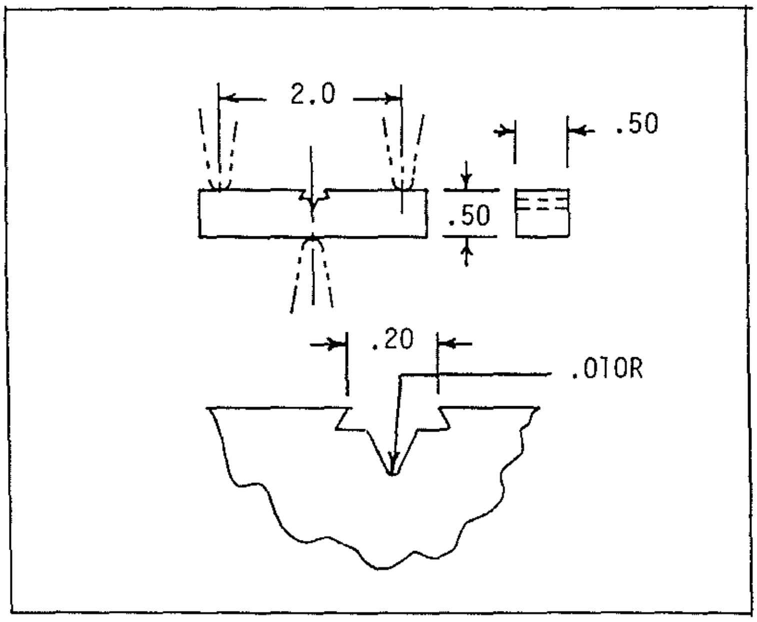

Figure 1. Specimen.

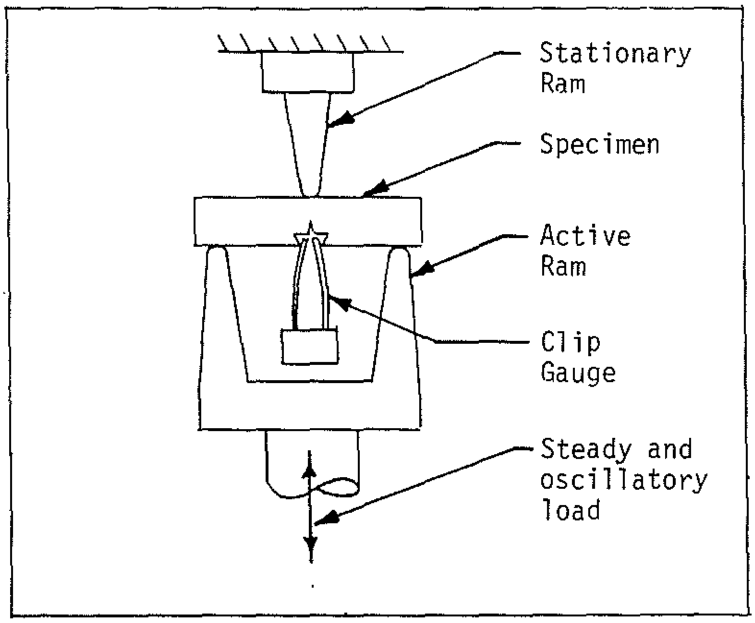

Figure 2. Test Setup.

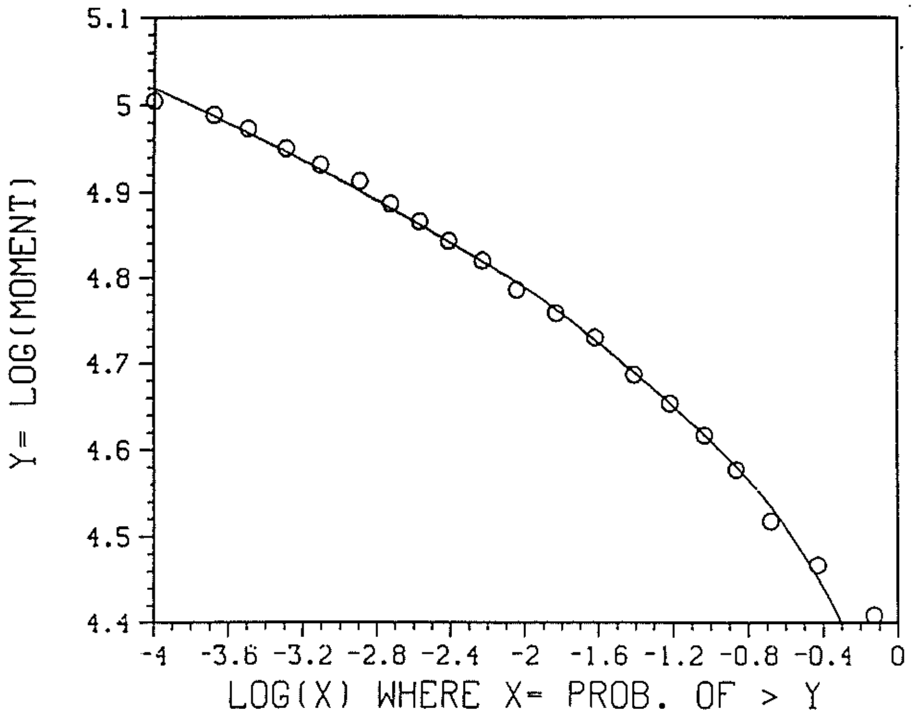

Figure 3. XV-15 hub moment spectrum.
____ Log-normal function.
0000 Empirical flight spectrum.

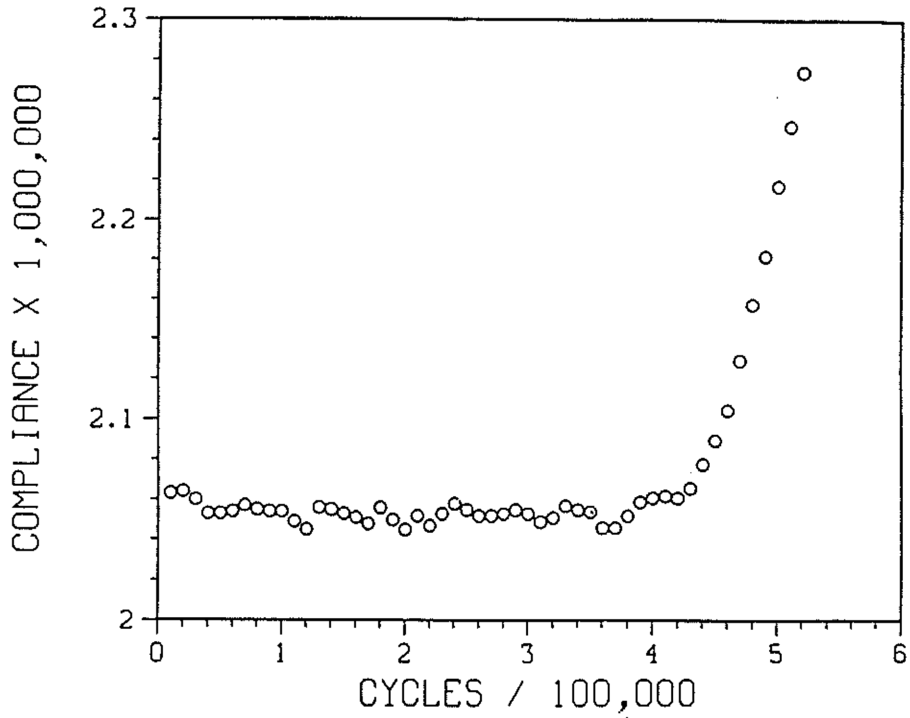

Figure 4. Compliance vs. time.
Titanium specimen No. 17.

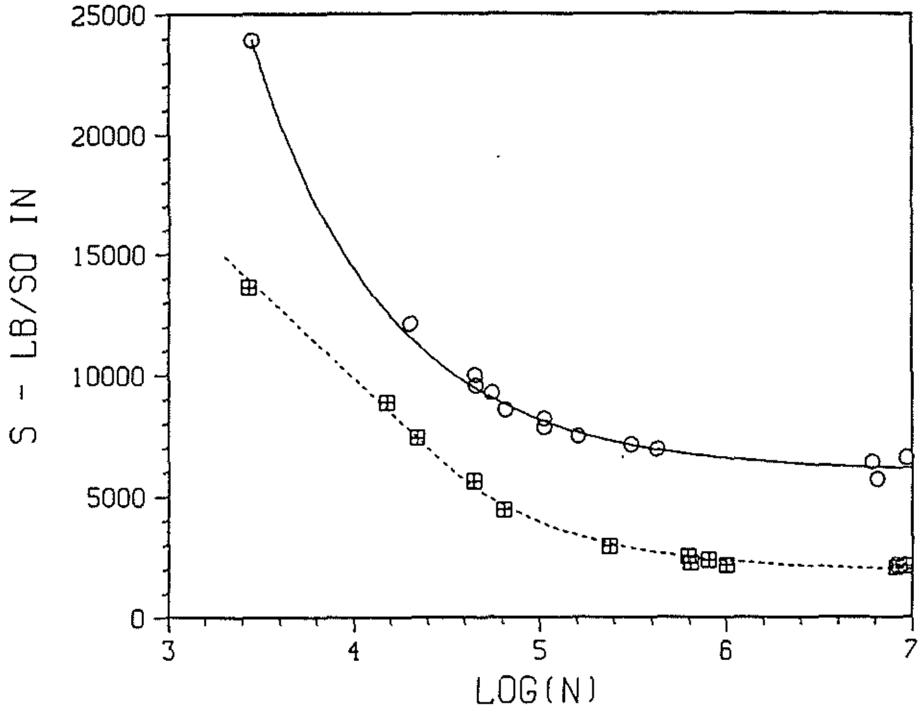

Figure 5. Test results for constant amplitude loading.

____ Titanium. ---- Aluminum.

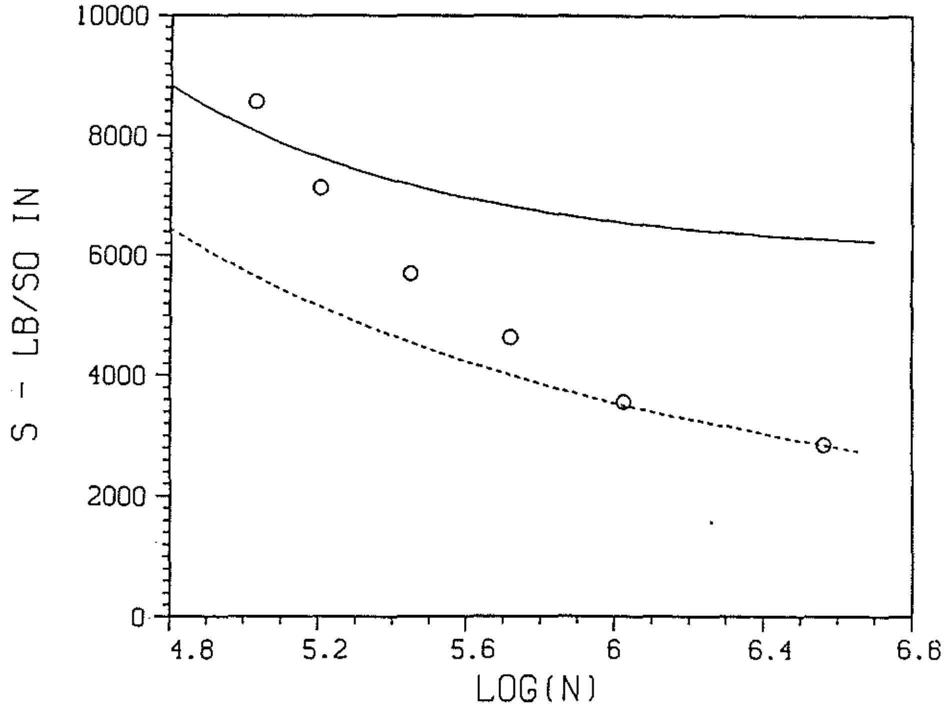

Figure 6(a). Titanium, C_S = .2

____ Constant amplitude test.

---- Miner's theory. oooo Spectrum test.

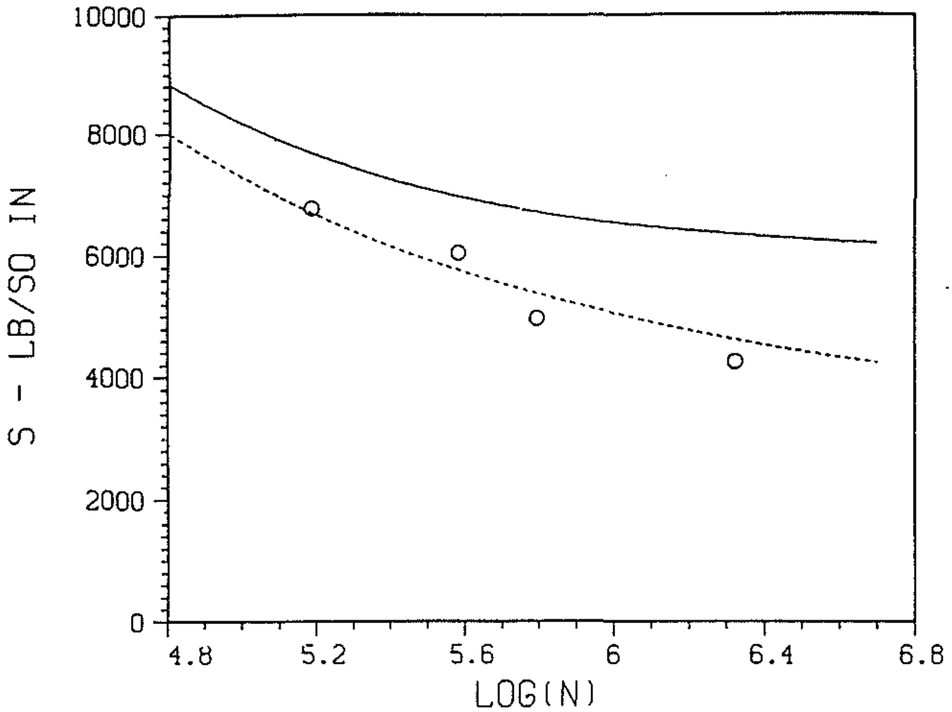

Figure 6(b). Titanium, C_S = .4
____ Constant amplitude test.
---- Miner's theory. oooo Spectrum test.

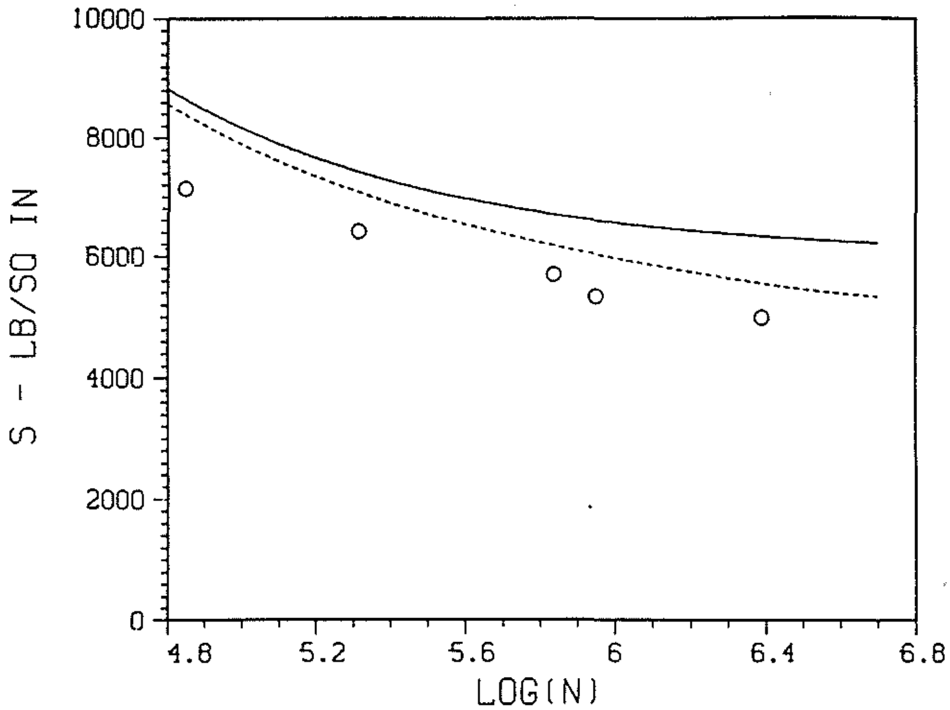

Figure 6(c). Titanium, C_S = .6
____ Constant amplitude test.
---- Miner's theory. oooo Spectrum test.

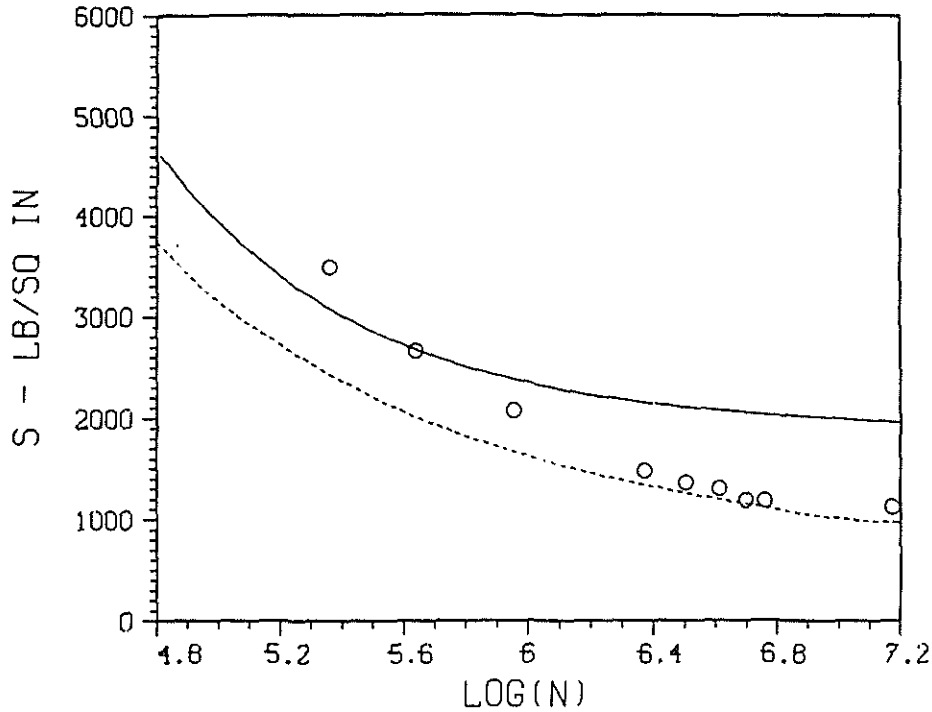

Figure 7(a). Aluminum, C_S = .2
____ Constant amplitude test.
---- Miner's theory. oooo Spectrum test.

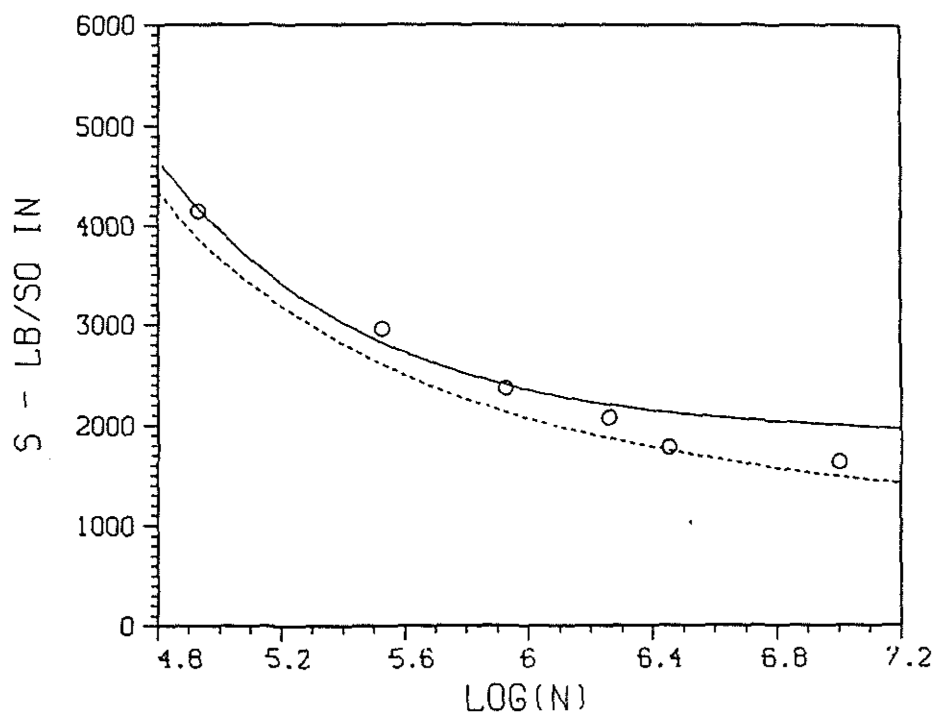

Figure 7(b). Aluminum, C_S = .4
____ Constant amplitude test.
---- Miner's theory. oooo Spectrum test.

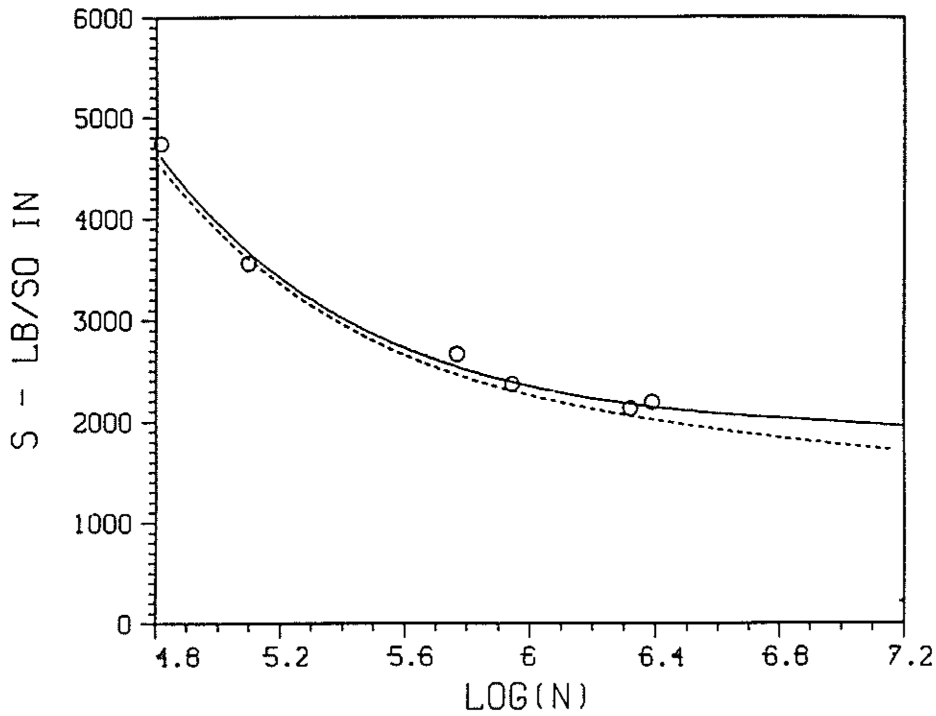

Figure 7(c). Aluminum, C_S = .6
____ Constant amplitude test.
---- Miner's theory. oooo Spectrum test.