PRACTICAL FATIGUE LOADINGS FOR AERONAUTICAL STRUCTURES

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ABSTRACT

Over the past five years, evidence has been accumulating to support the theory that two separate distributions of constant-amplitude fatigue endurances exist at low stress levels. Examples are given to show this grouping in various materials, specimen geometries and loading configurations.

This behaviour renders service fatigue life predictions almost impossible using only constant-amplitude test data and current damage theories. For this reason a 10,000-pound shaker-driven lever-actuated fatigue machine (using random noise) was developed to obtain random-amplitude test data.

This machine has been used to apply Rayleigh and two-degree-of-freedom stationary random loads to unnotched bar specimens, and random-programmed "patches" of stationary Rayleigh loads to aircraft structural components.

INTRODUCTION

Just as the problems associated with rocket lift-off were largely replaced by the equally formidable problems of reentry from space, the difficulties of assessing aircraft structural integrity near the end of its service life now rival, in most conventional structures, those connected with the first flight. It is well known that one does not design aircraft structures for infinite life, yet it is surprising that more intense research is not directed at the protection of the huge investment represented by a modern aircraft. It is usually difficult, for instance, to find out the general service history of a given veteran aircraft in terms of operational role, and only recently have steps been taken to install load-monitoring devices in these structures. The intelligent use and development of such devices, coupled with adequate inspection techniques, will greatly help the manufacturer to monitor and analyse service loads and his structures' ability to withstand them.

In this paper the author first presents some observations concerning the traditional constant-amplitude fatigue test, which is often used for material reliability assessments. He then presents practical methods for fatigue testing vital structural components, using the assumption that service loads are generally the result of a random process acting on concentrated-load elements, after being filtered by intermediate structure. The importance of proper simulation of the variability of service loading has already been pointed out in the previous paper.

TWO-DISTRIBUTION INTERPRETATION OF *S-N* DATA

INTRODUCTION

Ever since the nineteenth century, constant-amplitude fatigue-test results have been presented graphically in the form of "Wohler" or *S-N* curves, in which the endurance is plotted on a logarithmic abscissa, and the alternating stress on a linear ordinate. Other forms of presentation, e.g., catering to the effects of mean stress, often use "constant-life" curves, which tend to obscure the quite formidable problem of scatter which exists in the assessment of mean endurance.

Early in 1960 the author observed that the statistical behaviour of 2024-T4 Aluminium Alloy bar [1] at low stress levels did not appear unimodal or "single-humped" in distribution as previously assumed. The probability of failure could be better represented, in fact, by the interplay of two separate endurance distributions at a given stress level. The distribution usually encountered first was arbitrarily named Short-Term Fatigue (STF) while the second distribution was called Long-Term Fatigue (LTF). It was found that as the stress amplitude was lowered, the STF distribution tended to fade away, while the LTF distribution gradually became predominant.

TWO DISTRIBUTIONS FROM RECENT UNNOTCHED SPECIMEN TESTS

The first intensive study of fatigue behaviour using this approach was recently carried out by Cicci [2]. By plotting the endurance data from about two hundred and fifty rotating-beam tests, i.e., 50 specimens tested at each of five different stress levels near the "knee" of the *S-N* curve, on different types of probability paper, he was able to discern the statistical behaviour shown (schematically only) in Fig. 1.

Cicci also kept records of environmental variables, manufacturing details and test parameters to try to find any correlation of these factors with such grouping. Only relative humidity showed a slight correlation, with comparatively few specimens failing in the STF distribution under dry conditions.

In reliability studies of electron tubes, the Weibull distribution is often used to detect different modes of failure, which manifest themselves as linear segments with different slopes when all results are plotted together. This extreme value distribution was used in Cicci's work to study the degree to which the results would follow such a probability relation. The evaluation of "minimum life" for each of the component distributions was found to be difficult when they exist together, as is the case in the "knee" of the *S-N* curve (Fig. 1). Yet the evaluation of the minimum lives has a significant effect on the goodness of fit for this representation.

Some justification for the Maxwell-Boltzmann distribution was also apparent from goodness of fit, for the component distributions of fatigue lives. A physical argument has been suggested by the author for this model, based on the incoherent births of individual crack-sites over the macrostructure of the metal under the action of fatigue loads. The best fit of the experimental data from Ref. 2 was, nevertheless, the symmetrical log-normal distribution, which is assymmetrical, of course, in its distribution of the endurances themselves.

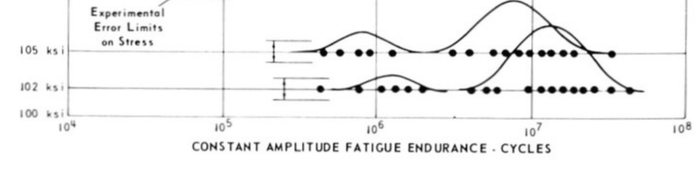


Figure 1. Two-distribution Interpretation. Rotating beam fatigue tests using unnotched 250 ksi yield strength maraging steel specimens (transverse).

TWO DISTRIBUTIONS WITH NOTCHED SPECIMENS

In Ref. 3 it was noticed that the two-distribution grouping occurred in Weibull's test data for threaded bolts. Recently a series of notched ($K_T=2$) rotating-beam tests was performed, using the same material and test equipment (i.e., four R. R. Moore Rotating Beam Machines) as in Ref. 2. The test results were:

Alternating Stress Amplitude

65 ksi	70 ksi	75 ksi	80 ksi
Endurance (kilocycles) (Machine number in parentheses)			
336 (4)	104 (3)	86 (3)	40 (3)
3,555 (1)	327 (4)	112 (3)	46 (4)
3,730 (3)	1,218 (3)	130 (2)	77 (2)
21,925 (1)	4,978 (3)	145 (4)	82 (4)
22,594 (2)	6,003 (4)	168 (1)	84 (4)
38,481 (4)	8,410 (1)	197 (1)	93 (1)
47,860 (2)	13,045 (2)	471 (3)	100 (4)
69,951 (1)	20,262 (4)	1,814 (4)	115 (4)
96,717 (4)	22,026 (4)	2,337 (4)	512 (3)
110,128 (2)	28,678 (2)	4,721 (1)	684 (1)
253,208 (3)	30,124 (1)	13,442 (2)	1,062 (2)
586,935 (3)	37,490 (2)	14,596 (2)	1,163 (3)
	51,987 (1)		12,167 (1)
			15,667 (2)

These tests are plotted in Fig. 2, and show rather plausible grouping into two distributions. Since these tests would indicate that the two-distribution

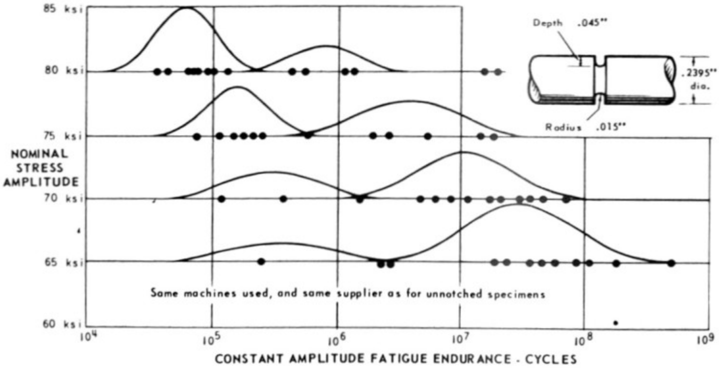


Figure 2. Two-distribution interpretation. Rotating beam fatigue tests using groove-notched ($K_T = 2$) 250 ksi Y.S. maraging steel specimens (longitudinal).

grouping occurs regardless of specimen geometry, the next step was to see if the type of fatigue loading would influence this phenomenon.

TWO DISTRIBUTIONS WITH OTHER TYPES OF FATIGUE LOADS

A series of tests was then performed with the same material in sheet form (0.050 in. thick) using constant-deflection repeated-flexure test equipment, and zero mean stress. The endurances in kilocycles were:

Alternating Stress Amplitude

100 ksi	105 ksi	110 ksi	115 ksi	120 ksi	125 ksi	130 ksi
Endurance (kilocycles) (Machine number in parentheses)						
1,225 (2)	3,614 (1)	228 (2)	186 (1)	235 (1)	108 (1)	131 (2)
8,971 (2)	16,685 (1)	554 (1)	225 (1)	276 (1)	117 (1)	137 (2)
9,183 (1)	22,124*(2)	762 (2)	440 (2)	376 (2)	141 (1)	198 (1)
22,311*(2)	32,719*(2)	6,486 (1)	540 (1)	586 (2)	198 (2)	207 (2)
26,298 (1)		10,319 (2)	8,172 (2)	688 (1)	213 (2)	340 (1)
37,004 (1)		63,441 (2)		699 (1)	272 (1)	
				7,418 (1)		
				8,363 (2)		

* Runouts.

These results are plotted in Fig. 3. Despite the small number of specimens involved, the two-distribution grouping is generally quite evident.

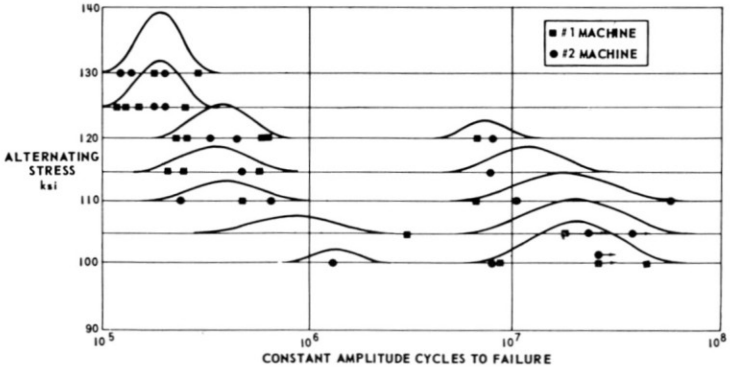


Figure 3. Two-distribution interpretation. Unnotched 250 ksi Y.S. maraging steel sheet-repeated flexure (longitudinal).

Axial-load tests at zero mean stress were also carried out using the same material in the form of bar specimens and using the constant-load machine shown in Fig. 14. The test results were:

		Alternating Stress Amplitude		
102 ksi	105 ksi	108 ksi	116 ksi	125 ksi
		Life, kilocycles		
257.6	201.7	208.9	73.4	61.8
394.0	228.4	331.6	93.0	63.3
950.5	294.5	344.2	186.7	69.5
2,089.6	295.0	1,066.7	191.8	91.2
2,866.0	618.0		200.1	142.9
	781.4			

A composite plot of the grouping indicated by all these test results is given in Fig. 4. This figure also contains a result obtained using about fifty specimens of maraging steel cut from blanks taken longitudinal to the direction of the grain (Ref. 2). A distinct break in the test data occurred at virtually the same per cent of all the data, as occurred with the 50 transverse (to grain direction) specimens for the same stress level [2], indicating that this grouping is insensitive to grain direction as well.

As might be expected, the axial tests result in comparatively lower fatigue strengths for a given per cent STF.

ASSESSING NOTCH SENSITIVITY BY ENDURANCE GROUPING

The quantity "per cent STF" forms a very interesting parameter for assessing the notch factor for specimens without knowledge of their

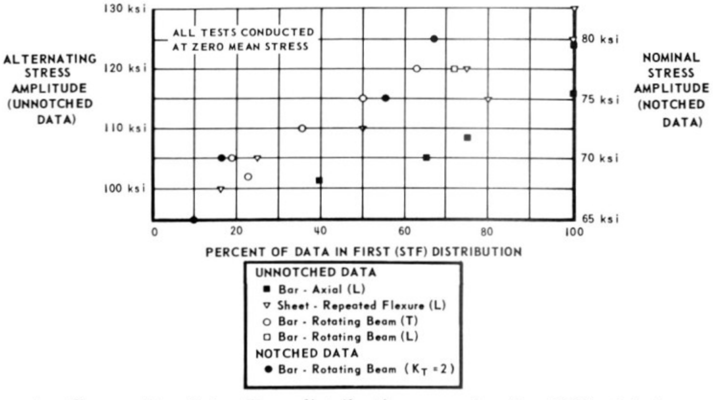


Figure 4. Composite plot. Two distribution grouping for 18% nickel maraging steel from different tests.

geometry. This technique is illustrated in Fig. 5, and is based on the assumption that the operative maximum stress in the notch will govern the failure distribution for the specimens. Consider the test data shown in Fig. 2:

		Estimated Equivalent (Unnotched)	
Nominal stress amplitude, ksi	STF, per cent	Stress amplitude for same per cent STF^{2}, ksi	Notch factor
80	67	121.7	1.52
75	55	117.0	1.56
70	17	105.0	1.50
65	10	100.0	1.54

Considering that the theoretical notch factor was two, it is possible that compressive stresses due to machining the groove may be responsible for the reduction in notch factor to 1.5.

TWO-DISTRIBUTION BEHAVIOUR MANIFESTED AS A "DISCONTINUITY"

Recently a discontinuity has been observed by various researchers, in the aluminium alloy *S-N* curve. This phenomenon is quite consistent with the two-distribution interpretation, as discussed in Ref. 4. Further discussion on this point, and a discussion of analogous behaviour found in the stress-rupture curves from creep experiments is given by the author in Ref. 5.

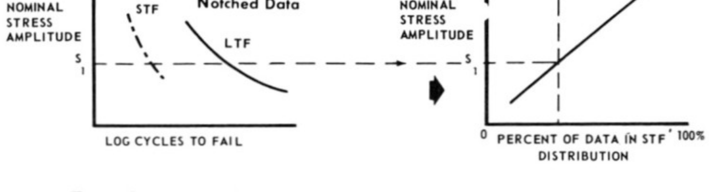


Figure 5. Procedure to evaluate notch factor in fatigue using constant amplitude loading.

TWO-DISTRIBUTION BEHAVIOUR AT ELEVATED TEMPERATURES

Very distinct grouping of test endurances into two distributions has also been observed over a wide temperature range (—196° C to 500° C) [15]. Panseri and Mori's test results at room temperature and —196° C are represented by single curves by the authors, but the test points indicate two-distribution grouping as an equally plausible representation. For the elevated temperatures investigated (300° C, 400° C, 500° C) there is no question in the authors' minds that such bimodal grouping occurs, and they have represented their mean results in a manner similar to Cicci's results (Fig. 1).

ASSESSING FATIGUE LIFE WITH TWO DISTRIBUTIONS

The two-distribution interpretation has considerable relevance in cases where reliance is placed on single-level constant amplitude test data to assess the life of a structure [6]. In such cases, the correct evaluation of low probabilities of failure is of paramount importance. Large variations in the endurance values for a given failure probability may occur, depending on the assumptions made regarding the underlying distribution(s) for the population of test data.

The possibility of large errors is especially evident if the test level chosen is the so-called "most damaging stress level" as evaluated using the Palmgren-Miner rule of cumulative damage, since it almost invariably will fall in the stress regime where two-distribution behaviour occurs. Figure 6 presents some aspects of life assessment using the two-distribution approach. The creation of confidence limits for two coexisting log-normal distributions is discussed in Ref. 1. Note that significant economies in test time can result from merely identifying specimens as "LTF" in assessing low-failure-probability endurance. Using the present practice of assuming a single distribution, the occurrence of "runouts" presents a problem in evaluating dispersion and hence low failure probabilities, and special techniques such as illustrated in Ref. 7 must be used to obtain approximations.

METALLURGICAL ASPECTS

In spite of Wood's fundamental observations on different crack mechanisms existing in fatigue at different stress levels, very little progress has been made in the correlation of the two-distribution grouping of test data with metallurgical (especially fractographic) studies. Work described in

Ref. 8 would lead one to believe that, while both groups probably have Stage 1 crack growth in common [9], STF might be identified with Stage 2 (ductile) growth, with the characteristic occurrence of regular striations, and LTF identified with Stage 2 (brittle) growth, with the "river" marks characteristic of this type of fatigue crack. The slight correlation of STF with relative humidity mentioned earlier may point to a corrosive mechanism.

RANDOM LOAD FATIGUE TESTING

INTRODUCTION

Structural fatigue loads are generally the result of random processes, for example, the action of atmospheric turbulence on a wing, the contours of an unimproved road acting on an automobile frame, and the state of the sea affecting the hull of a ship or the foil of a hydrofoil craft. It is highly unlikely that any formula for life assessment for such structures will be proven adequate until such loadings are properly analysed and simulated under laboratory conditions. Certainly methods based on constant-amplitude fatigue alone, with little or no allowance for stress interaction, have little hope in finding general applicability.

A more direct approach to life-assessment testing which appears to be quite fruitful, is to accept the necessity of complex equipment and to apply random-process-generated (RPG) loads to structures to simulate service conditions. This approach was initiated in 1956 by Head and Hooke in

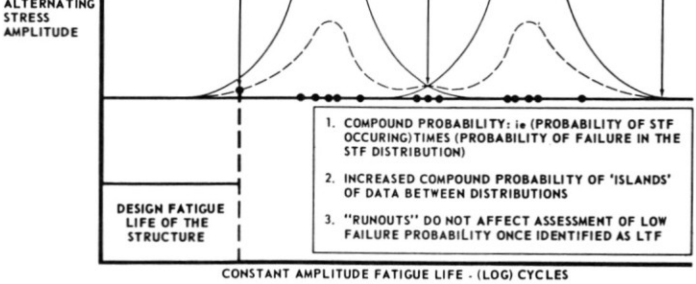


Figure 6. Assessing low probabilities of failure with the two-distribution interpretation.

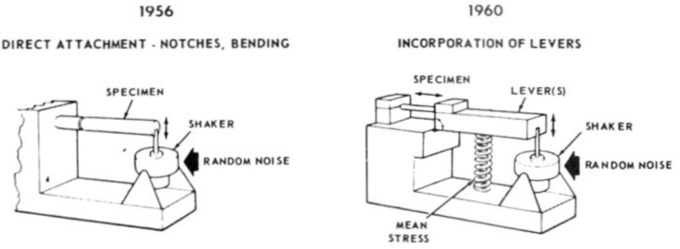
Australia, who employed direct attachment of the specimen (Fig. 7) to the electromagnetic shaker. For most specimens, direct coupling to the shaker usually requires severe notching to induce failure with the power available, and also makes the establishment of the operative maximum stress fairly difficult.

SHAKER-LEVER MACHINES

By placing a simple intermediate structure (having essentially the same response characteristics as the practical structure under study) between the specimen and the random process, one obtains the advantages listed in the figure. Using such a machine (shown in Fig. 14) a series of tests was performed holding the root-mean-square (RMS) stress amplitude constant throughout the test to specimen failure. These tests, called stationary Rayleigh fatigue tests, are described in Ref. 4. The analysis of such test histories is shown schematically in Fig. 8. Note that a *rigid* lever system is implied. Any input random process will therefore be carried through in instantaneous amplitude since the system is linear.

The scatter obtained in such tests was very similar to that which occurs at high stress levels in constant amplitude tests, as also mentioned in Ref. 6. It appears that the two-distribution behaviour just described disappears with random amplitude testing; indeed, it was found that two-level "single-jump" constant amplitude testing is sufficient to remove bimodal behaviour [1].

Introducing levers between the random process and the specimen permits quite large magnification of loads, since use is made of the resonance phenomenon. The first machine (Fig. 14) has been developed to the point where, in the single-lever configuration, the "600-lb" shaker has been


1956

DIRECT ATTACHMENT - NOTCHES, BENDING

1960

INCORPORATION OF LEVERS

Advantages of Shaker-Lever Arrangement

1. LEVER MAGNIFIES LOAD. (CAN USE LARGE SPECIMENS).
2. UNIFORM STRESS. (AXIAL, UNNOTCHED).
3. CAN INTRODUCE NON-ZERO MEAN STRESSES.

Figure 7. Random load fatigue testing.

proven capable of applying dynamic loads up to 10,000 lb to the specimen. This machine, and one recently developed to test sheet specimens (Fig. 15) are examples of the use of first-class levers; i.e., the fulcrum is situated between the specimen and the shaker. A smaller shaker-lever machine was recently constructed using a second-class lever (i.e., specimen between shaker and fulcrum), which is capable of applying 3,000 lb dynamic load using a 25-lb shaker. Lowcock and Williams [8] have constructed a 350-lb capacity shaker-lever machine employing a third-class lever (i.e., shaker between specimen and fulcrum). Their machine is quite different, however, since it employs a *flexible* lever, excited by a shaker at its midlength (antinode) to vibrate in the fundamental bending mode.

STATIONARY RAYLEIGH FATIGUE USED AS A PRELOAD

In Ref. 4 a series of tests was carried out to construct the constant amplitude *S-N* relation using specimens, all of which had previously experienced equal durations of fixed RMS stress single-degree-of-freedom random loading. The result was the creation of an endurance line (in log stress-log endurance coordinates) parallel to the virgin specimen relation, but uniformly displaced to lower fatigue lives. Such a result on log-log coordinates implies that, using a conventional semilog plot, the two endurance lines would diverge at high stress levels. This finding is contrary to the arguments put forward in Ref. 10. In the discussion following Ref. 10 in the ASTM proceedings, it is clear that the above-cited results would confirm Henry's ideas—that prestressing is essentially prenotching. Certainly the occurrence of secondary cracks in random load tests with

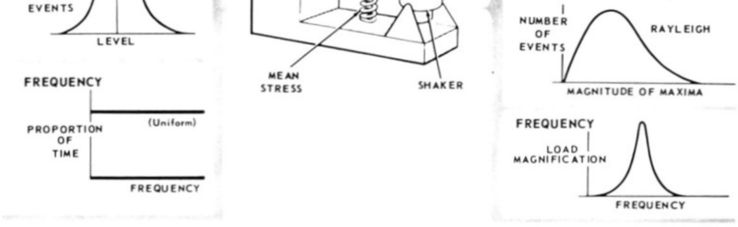


Figure 8. Analysis of random loads (single lever).

unnotched specimens (discussed later in this paper) is consistent with Henry's views.

THE EFFECT OF MEAN STRESS ON RAYLEIGH ENDURANCES

Recently a series of tests was completed using the machine shown in Fig. 14, in which constant-RMS random loads were applied to maraging steel specimens to failure, using both zero and a moderate tensile mean stress. In these tests (to be described in a forthcoming symposium [14]), it was interesting to find that the Modified Goodman rule was a good representation of the variation in random-load fatigue strength with mean stress. Specifically the mean stress parameter "*m*" equalled 1.065 using the notation of Ref. 11, and using the RMS stress in place of Stress Amplitude.

RANDOM LOAD TESTS WITH TWO DEGREES OF FREEDOM

There are many practical cases where fatigue energy enters a structure in essentially two predominant modes of vibration (e.g., an aircraft wing). Such a representation is often sufficient for multimode structures as well, because the energy associated with many natural random processes is sharply attenuated at high frequencies. In the shaker-lever machine one can simulate a second resonance by the addition of a second lever and an interlever spring connection. Such a system is shown in Fig. 9, and was used to obtain stationary random load endurances at the same general RMS levels as were obtained with the single lever. The results, given in Ref. 4,

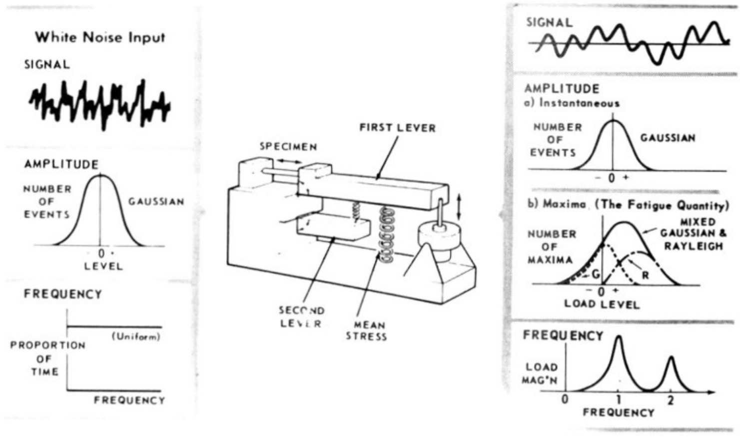


Figure 9. Analysis of random loads (two lever).

showed a significant (but not as large as expected) change in endurance moving from single to dual resonance fatigue. Further studies of the effect on fatigue life of various frequency spectra are contemplated in our laboratory. These two-lever tests demonstrated one great advantage in direct RPG testing with correct simulation of the intermediate structure. The problems associated with the definition of "cycle" are circumvented, since the complex waveform is created under controlled conditions, and does not really have to be analysed in itself, for the practical consideration of life evaluation.

The correct assessment of the quantity "cycle" is quite difficult in multimode response, and various counting methods have been introduced to assess this quantity in fatigue. The best solution would appear to be to avoid relating complex wave histories to "cycles" to begin with, and use a consistent "frequency response" approach from first principles. The action of "cycles" in fatigue would then be considered as a special case of the more general spectral approach. Since most counting techniques do not yield information on the sequence of loads in any case, such a spectral approach would not be unreasonable.

ANALYSIS OF SINGLE-LEVER STRESS HISTORIES

When nearly all the fatigue energy enters the system around a single resonant frequency as shown in Fig. 8, the distribution of peaks of the specimen load history simplifies to the Rayleigh probability distribution. It is then possible to construct cumulative Rayleigh distribution paper

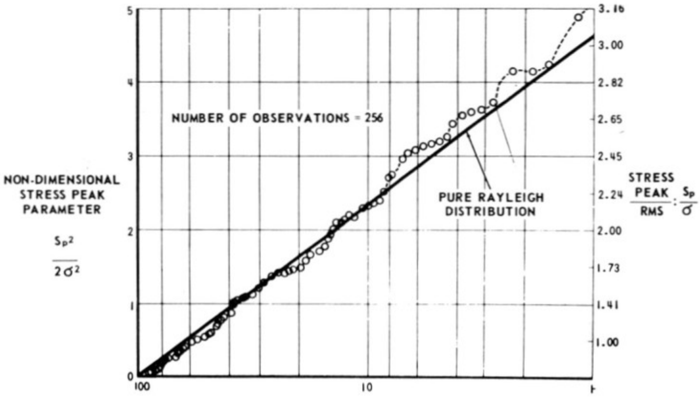


Figure 10. Percent of peaks greater than ordinate stress peak distribution—single level exitation RMS stress = 40 ksi.

using semilogarithmic graph paper, as shown in Fig. 10. Test trace data can be ranked and plotted on such paper to allow one to assess (a) the degree to which the Rayleigh distribution is a good representation, (b) the RMS of the peaks, and (c) the "clipping ratio" for the signal (shown as an upper bound to the occurrences of high loads with decreasing probability). It is important of course to use a sample trace of sufficient length to ensure good statistical accuracy for the evaluation of these parameters.

PROGRAMMED CONSTANT AMPLITUDE FATIGUE TESTS

There are many advocates of the programmed constant-amplitude fatigue test illustrated in Fig. 11. This technique, designed to cater to the problem of stress interaction between various stress levels involves, unfortunately, a number of arbitrary decisions in its construction. These arbitrary features, which result in an unlimited number of possible simulations for a given RMS and frequency spectrum, have prevented the achievement of a unique correlation between random load and programmed constant-amplitude test results [12].

Recent studies of crack propagation in fatigue have shown that one of the main problems associated with fatigue using programmed constant-amplitude loadings has been the creation of rather specialized residual stress fields near the crack tip. Repeated constant-amplitude cycles of the same (high) magnitude can set up artificially strong residual stresses, which can greatly inhibit crack growth in subsequent constant amplitude cycles at a lower stress level. This is intuitively quite unlike the residual stress field developed naturally by RPG loads, with their singular excursions to high stress levels occurring in a random sequence.

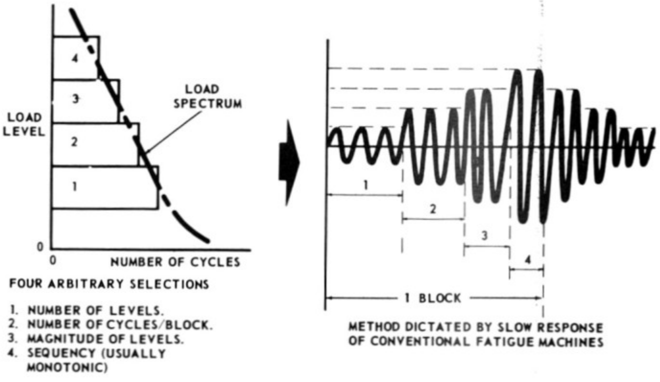


Figure 11. 'Programmed' constant amplitude testing.

THE ELECTRONIC EQUIPMENT NECESSARY FOR RPG TESTS

Figure 12 presents a typical electronic flow diagram for the equipment needed to operate a shaker-lever random load fatigue machine. For most tests, the strain-gauge bridge used to monitor the loads in the specimen is located in the gripping head fixed to the foundation of the machine. For tests with practical structures such as the strut shown in Fig. 14, use is made of a strain-gauge bridge located on the connecting plate situated between the lever and the adjacent gripping head. Calibration of the machine must, in the latter case, be carried out at the frequency of vibration for the practical specimen concerned, since the strain-gauge bridge will be in motion.

QUASI-STATIONARY (QS) FATIGUE TESTING

In Ref. 4 the author introduced a completely new type of fatigue test called quasi-stationary (QS) random loading. This technique consists of programming a sequence of discrete levels of RMS (stationary) random loads, where the sequence has been suitably randomized by using a table of random numbers. The frequency of occurrence of given levels is adjusted by a mathematical transformation of the basically "rectangular" probability of ordinary random numbers, to the probability distribution desired. In this way the operator of the machine can, after about the first ten random sequential selections of RMS from the final RMS schedule (holding

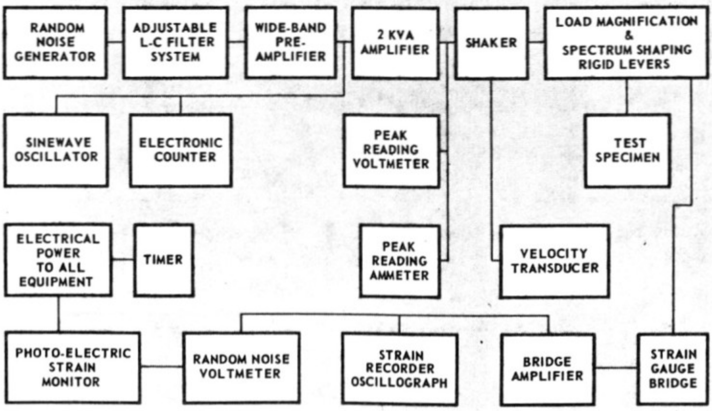


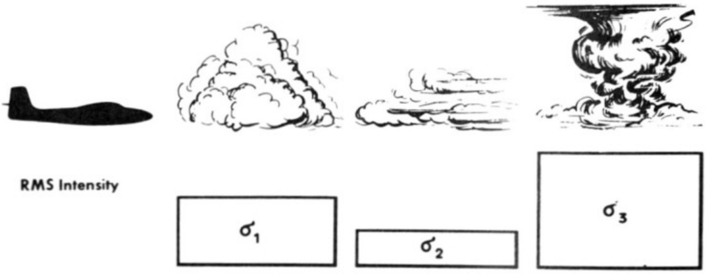
Figure 12. Electronic equipment schematic for the random load fatigue machines.

each level steady for, say 2,000 cycles) approach asymptotically the desired final distribution of stresses required to simulate a service history. The discrete nature of this type of RMS program is not an approximation to a process that is actually continuous (as is the case with the programmed constant amplitude test), but rather, as Fig. 13 shows, a good simulation of what actually occurs in service. This type of test can be set up directly from the relative frequency data obtained from collected load statistics. This procedure, with experimental results, is fully described in Ref. 4.

Many workers advocate the use of tape histories obtained from strain records for a given element in an aircraft structure, to apply the identical stress history to the test specimen. Unless the tape is very long, so that it represents a reasonable sample of the service *life* of the structure, and not just one or two levels of turbulence intensity, many levels of stationary random loads will be omitted. Also the tape will have to be repeatedly used to break a single specimen, introducing a nonrandom effect. Another disadvantage of a tape history test is that, if applied in turn to several specimens, one might assume that the scatter in endurances is typical of service conditions, when in reality it is only representative of identical load sequences applied to identical specimens.

The QS test avoids these problems—it can be run almost indefinitely using inexpensive random-noise generators, it will not leave out statistically significant RMS levels in the overall program, and a group of specimens, even if tested with the identical RMS sequence (which is not necessary) will experience quite different instantaneous load histories.

In the QS tests with unnotched bar specimens and the single degree of freedom configuration described in Ref. 4, the scatter appeared to be quite small, which is encouraging, since it indicates that as long as the relative



IN ITS SERVICE LIFE, AN AIRCRAFT ENCOUNTERS A SUCCESSION OF STATIONARY GAUSSIAN DISTURBANCES (REFERENCE - NASA).

THIS FINAL RMS DISTRIBUTION CAN BE APPLIED WITH THE FATIGUE MACHINE, USING A TABLE OF RANDOM NUMBERS (SUITABLY TRANSFORMED).

Figure 13. Quasi-stationary (QS) fatigue testing.

frequency of RMS levels is properly adjusted, effects of sequence can be largely taken care of by the use of the "short-term stationary random process" as the program unit.

The QS test is currently being applied to a number of aircraft strut end fittings complete with connecting lug (Fig. 14) so that fretting effects (which can vary considerably from constant to random-amplitude loading) are also monitored. In these strut tests, the operator also periodically applies a single Ground-Air-Ground cycle using the motorized mean stress spring. Since the test frequency is over one hundred times the service frequency, it is not necessary to factor the overall RMS stress level, in order to prove a given structure for a specified fatigue life.

Thus far, the QS test has only been used with the single-degree-of-freedom configuration of the shaker-lever machine. Such tests can, of course, be easily extended to two degrees of freedom in the manner shown in Fig. 9, since the QS test is essentially a discrete manipulation of the RMS level of the input disturbance, and not of the intermediate structure.

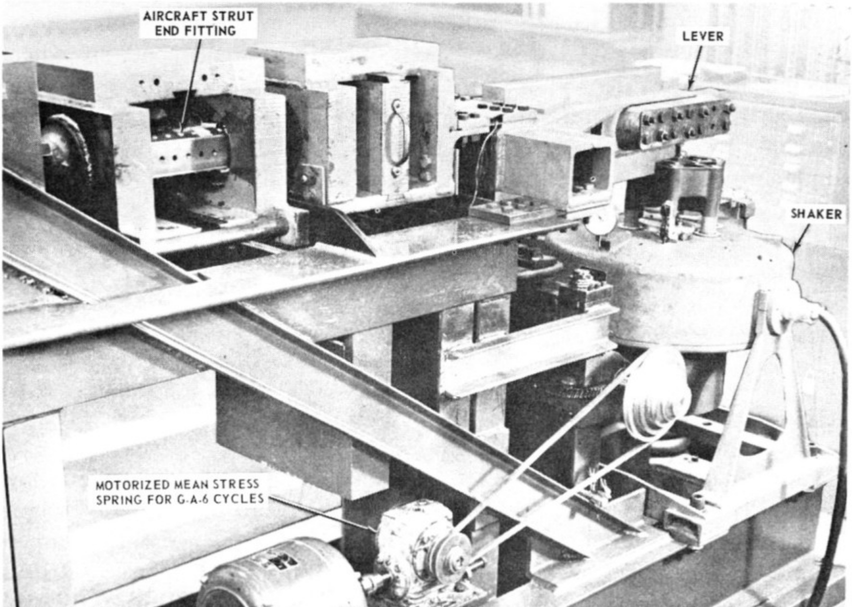


Figure 14. Showing installation of a strut end fitting for QS testing

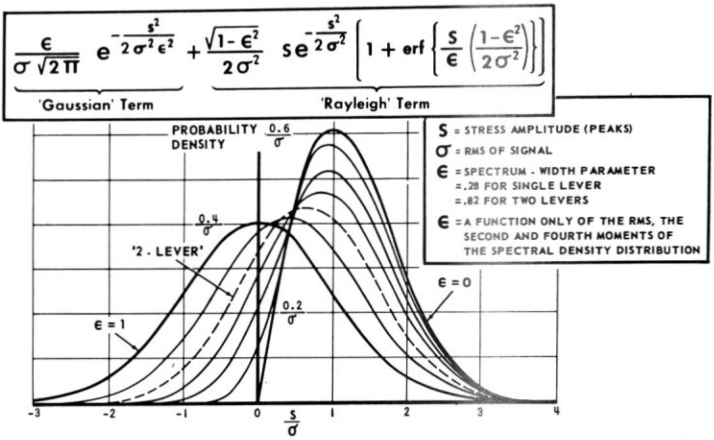


Figure 16. Distribution of maxima for Gaussian disturbance of a linear system.

CONCLUSIONS

The two-distribution grouping of constant amplitude fatigue data has thus far been observed with various aluminium alloys (2024, 7075, etc.), various steels (e.g., B.S.S.6LI), ultrahigh-strength 18 per cent Nickel maraging steel (250,000 psi ultimate tensile strength), phosphor bronze and titanium alloy. It has been observed in axial, repeated flexure and rotating-beam tests in a wide variety of fatigue machines; it has been observed in bar, sheet, and strip specimens, in unnotched specimens with different grain directions, notched bar specimens and bolts; it has been observed over a wide range of test temperatures. These observations would indicate that this behaviour is inherent in the fatigue process itself, with two separate physical mechanisms existing in the development of fatigue damage.

Accounting for this behaviour leads to a more accurate evaluation of the endurances corresponding to low probabilities of failure, and possibly to a new method to assess fatigue notch sensitivity in metal.

The study of cumulative damage in fatigue, if aimed at the accurate prediction of fatigue life under random loading, should begin with random load test observations, rather than form an extrapolation from the rather special constant amplitude type of fatigue containing artificially induced problems of its own. The creation and development of "second generation" fatigue machines capable of either random or constant amplitude testing should be encouraged not only to supply such observations, but to prove existing structures for service conditions, and finally to test fatigue theories based on random-load conditions. Certainly the use of any but the simplest cumulative damage law based on the constant amplitude endurance relation should be reconsidered until the exact nature of the S-N relation is revealed.

The use of random-process-generated fatigue test methods (such as the QS test) should be encouraged, since it has been demonstrated that such tests simulate overall service conditions to a much greater degree than present methods. Such tests can be applied directly to fairly large structural components, and as such represent a truly practical fatigue loading for testing aeronautical structures.

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