FATIGUE TESTING
AND
ANALYSIS OF RESULTS

by

W. WEIBULL

BOCKAMÖLLAN
BRÖARPS STATION
SWEDEN

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FOREWORD

In dedicating this volume to Deryck C. Smith, the Advisory Group for Aeronautical Research and Development wishes to commemorate the services of an outstanding member of its staff.

Mr. Smith was called to the organization to formulate a new section within the framework of AGARD. By his original ideas, his forceful personality, and his untiring devotion, he brought together a dynamic group of members for his Panel, and imbued them with his own enthusiasm for the work to be accomplished.

This volume is but one of the several publications which indicate the importance and scope of the work which was undertaken by the Panel under his guidance.

Officially AGARD has suffered a severe loss in the death of an executive who had the vision and the ability to see and to carry out an ever expanding program to increase the value of AGARD to the NATO nations.

Personally, the staff will long remember a congenial associate, a helpful and stimulating co-worker, a cherished friend.

THEODORE VON KÁRMÁN
Chairman—AGARD
CHAPTER I
SYMBOLS AND NOMENCLATURE

SECTION 10. GENERAL

There is a wide variety of symbols and nomenclature used in different countries, not to say within each country, and with few exceptions no internationally accepted standards exist. The choice of symbols to be used in the present book was not, therefore, easily taken and a definite and unobjectionable list cannot, for the time being, be established.

Under these circumstances, it was decided to follow mainly the nomenclature and symbols—some of them tentative—proposed by the ASTM Committee E-9 on Fatigue, although some modifications, chosen from the references listed below or obtained as a result of personal discussions with several experts, have been introduced.

There is one question which seems to deserve particular mention, and that is the ambiguous significance of the symbol for "stress", $S$, and its various subscripts. In fact, there are two quite different concepts of "stress" which are both denoted by $S$ and which have to be kept strictly apart in order to avoid confusion. One of them is "the stress applied to the test piece", resulting from the given load; the other is "the stress at which something happens to an individual test piece", i.e. a strength value.

Into the first category fall the quantities mentioned in Section 11 such as $S_{\max}$, $S_a$, $S_{m}$, $K_0$, etc. which are factors defining the test conditions and having a magnitude which can be specified by a definite number, for example, an applied stress amplitude $S_a = 10$ kg/mm². Into the second category fall the quantities mentioned in Section 12 such as $S_\alpha$, $S_N$, $S_\sigma$, $K_\sigma$, etc. which indicate some property of the material and accordingly take a value varying from specimen to specimen; in other words these quantities are random variables with a magnitude which cannot be specified by a definite number but require for their definition a distribution function or, less completely, one or more statistics; for example, the fatigue strength $S_N$ at a given fatigue life, say $N = 10^7$, which may be specified by its arithmetic mean $\overline{S}_N$ or median $\tilde{S}_N$ and its lower bound $S_{N_0}$ or variance $\sigma_S^2$ as a substitute for the distribution function.

Strictly speaking, quantities of the first category are non-random variables only in so far as the nominal stress applied—i.e. the stress aimed at—is concerned, which differs from the stress actually applied because of systematic or accidental errors in the calibration of the testing machine or variations in the dimensions and shape of the test piece.

The stress actually applied is evidently a random variable and thus of a character quite different from the nominal stress. Its scatter adds to the
scatter due to the material. In most cases the actual stresses are unknown and only the nominal stresses are given. Consequently, no distinction between the two sources of scatter can be made and the total scatter is frequently attributed to the test piece alone. It is obvious that in cases where such a distinction is required, different symbols for nominal and actual stresses must be introduced.

REFERENCES

International Unions:

France:

Germany:

Italy:

Netherlands:
(1) Nationaal Luchtvaartlaboratorium, Amsterdam (1954), “A proposal for fatigue symbols and nomenclature to be used in reports in the English language”.

Sweden:

United Kingdom:

United States:

SYMBOLS AND NOMENCLATURE

SECTION II. APPLIED STRESS CYCLES

A stress cycle is the smallest section of the stress-time function which is repeated periodically and identically as shown in Figs. 11.1, 11.2 and 11.3. The stress cycle is defined by: (a) the stress components, (b) the shape and (c) the frequency, i.e. the number of cycles per minute or per second. The simplest shape of the cycle is the harmonic wave in which the profile is a sine or cosine curve (Fig. 11.1). The varying stress of this cycle has one maximum and one minimum value. Its damaging effect is defined by one pair of stress components. This appears to be the case also when the wave is non-harmonic with one maximum and one minimum value as demonstrated in Fig. 11.2. A stress varying according to Fig. 11.3 requires two pairs of stress components for its definition. The pair—or pairs—of stress or strain components necessary to define the applied cycle.

Stress Level.

\[ S = \text{Nominal Stress} \]

\[ S_{\text{max}} = \text{Maximum Stress} \]

The highest algebraic value of the stress in the stress cycle, tensile stress being considered positive and compressive stress negative.
SECTION 12. STRENGTHS AND FATIGUE LIMITS

**S**<sub>n</sub> = Minimum Stress.

**S**<sub>r</sub> = Range of Stress. The algebraic difference between the maximum and the minimum stress in one cycle: \( S_r = S_{max} - S_{min} \).

**S**<sub>a</sub> = Stress Amplitude. One half the range of stress: \( S_a = \frac{1}{2} S_r \).

**S**<sub>ma</sub> = Mean Stress. The algebraic mean of the maximum and the minimum stress in one cycle: \( S_{ma} = \frac{1}{2} (S_{max} + S_{min}) \).

**R** = Stress Ratio. The algebraic ratio of the minimum stress to the maximum stress in one cycle: \( R = \frac{S_{min}}{S_{max}} \).

**A** = Stress Amplitude Ratio. The ratio of the stress amplitude to the mean stress: \( A = S_a/S_{ma} \).

**K** = Stress Concentration Factor. The ratio of the greatest stress in the region of a notch or other stress raiser as determined by advanced theory, photoelasticity, or direct measurement of elastic strain, to the corresponding nominal stress.

SECTION 13. FATIGUE LIFE AND NUMBERS OF CYCLES

**N** = Fatigue Life. The number of stress cycles at which fatigue failure occurs for a given test condition.

**n** = Run-out Number of Cycles. Number of cycles at which test is discontinued.

**n** = Stress Cycles Imposed. The number of cycles which have been imposed on a specimen without failure at any stage of a fatigue test.

**C** = Cycle Ratio. The ratio of the stress cycles actually applied at a given stress level to the expected fatigue life at that stress level, based on the S-N diagram: \( C = n/N \).

**X** = \( \log N \). In some cases an unspecified random variable.

**D** = Fatigue Damage. Change of fatigue properties of a test piece subjected to cycling stresses.

SYMBOLS AND NOMENCLATURE

**P** = Probability of Failure. The ratio of the number of specimens which have failed to the total number of specimens tested.

**Q** = Probability of Survival. It follows that \( P + Q = 1 \).

**F(x)** = Distribution Function of \( x \). A non-decreasing point function which corresponds to the probability function in such a way that \( F(x) = P(\xi \leq x) \) is the probability that the random variable \( \xi \) takes a value equal to or less than \( x \).

**G(x)** = Inverse Function of \( F(x) \), i.e. \( G[F(x)] = x \).

**f(x)** = Frequency or Density Function of \( x \), i.e. \( df(x)/dx = f(x) \).

**E(x)** = Mathematical Expectation or Mean Value of a random variable \( x \).

\( \sigma_x^2 = D'(x) = \text{var}(x) = \text{Variance of } x \).

\( \sigma_x = \text{Standard Deviation of } x \).

**\tilde{\theta}** = Estimate of \( \theta \) from a sample.

**\text{cov}(x,y)** = Covariance of \( x \) and \( y \).

\( \mu \) and \( \sigma \) = Sample Size — Number of values in a sample.

\( m \) and \( i \) = Order Numbers in a random sample ordered from least to greatest.

\( a, b, B \) = Parameters of an \( S-N \) equations.

\( \alpha \) and \( \beta \) = Parameters of a distribution function.

\( \chi \) = Arithmetic Mean of observed values \( \bar{x} \).

\( \bar{X} \) = Median of observed values \( X_{\bar{X}} \).

\( \Sigma \) = Summation sign.

**t** = Subscript corresponding to \( N = \infty \).

\( o \) = Subscript corresponding to lower bound of a random variable, i.e. to \( P = 0 \).

\( s = \bar{S} - \tilde{S} \) = Deviation of \( b \) from mean.

\( u = \bar{U} - \tilde{U} \) = Deviation of \( U \) from mean.

SECTION 14. STATISTICAL QUANTITIES AND MATHEMATICAL SIGNS

**Axial Loads**

**Fluctuating Tensile Load.** Minimum load and maximum load both tensile.

**Repeated Tensile Load.** Minimum load zero, maximum load tensile. \( (R = 0) \).

**Alternating Axial Load.** Unspecified axial load cycle.

**Load.** Reversed Axial Load. Alternating load with maximum load numerically equal to minimum load. \( (S_{max} = 0) \).

**Repeated Compressive Load.** Maximum load zero, minimum load compressive.

**Load.** Fluctuating Compressive Load. Minimum load and maximum load both compressive.

**Plain Bending Loads**

**Fluctuating, repeated, alternating and reversed bending loads defined analogically with definitions for axial loads.**

**Rotating Bending Loads**

A rotating specimen is subjected to a constant non-rotating bending moment, or a non-rotating specimen is subjected to a rotating constant bending moment.
FATIGUE TESTING AND ANALYSIS OF RESULTS

Torsional Loads
Fluctuating, repeated, alternating and reversed torsional loads defined analogically with definitions for axial loads.

Combined Loads
To be specified for each condition, including any relative phase differences between the components.

SECTION 16. VARIABLE-STRESS LEVEL TESTS

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<th>Description</th>
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<td>Variable-stress Level</td>
<td>Test during which a specimen is subjected to stress cycles differing in stress amplitude and/or mean stress.</td>
</tr>
<tr>
<td>Step</td>
<td>Fixed number of stress cycles of constant amplitude and mean stress.</td>
</tr>
<tr>
<td>Block</td>
<td>An aggregate of steps.</td>
</tr>
<tr>
<td>Shape of Block</td>
<td>The pattern in which the steps are arranged within the block.</td>
</tr>
<tr>
<td>Size of Block</td>
<td>Total number of cycles or value of $\Sigma N$ or the estimated number of blocks to failure.</td>
</tr>
<tr>
<td>Period</td>
<td>Fixed number of stress cycles of magnitude varying continuously according to a given pattern.</td>
</tr>
<tr>
<td>Preload Test</td>
<td>A fatigue test which is preceded by a number of high loads.</td>
</tr>
<tr>
<td>Prestress</td>
<td>A step preceding the last stress level which is continued until failure occurs.</td>
</tr>
<tr>
<td>Programme Test</td>
<td>Load is composed of a limited number of steps, usually grouped into blocks which are repeated until failure occurs.</td>
</tr>
<tr>
<td>Randomized Programme Test</td>
<td>The sequence of the steps is random.</td>
</tr>
<tr>
<td>Spectrum Test</td>
<td>Consecutive stress cycles are of different magnitude.</td>
</tr>
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CHAPTER II

FATIGUE TESTING METHODS

SECTION 20. GENERAL

The objective of a fatigue test is, generally speaking, to determine the fatigue life and/or the danger point, i.e. the location of failure, of a test piece subjected to a prescribed sequence of stress amplitudes. In some specific cases this may be the sole purpose of the test; e.g. if the test piece is a complicated machine part or an assembly of components and the applied load is a sequence of varying stress amplitudes intended to simulate the stress history encountered in actual service.

In most cases, however, it is required that the test be designed in such a way that it does not only answer the specific question which has been put, but will also allow a generalization of the result obtained and contribute to the discovery of laws or rules relating fatigue life with various influential factors. For this purpose it is indispensable that the test conditions be simplified, be it with regard to the sequence of stress amplitudes or to the test piece or to both of these factors. By simplifying and idealizing the test conditions it will be possible to vary one or a few of the factors which influence the fatigue life and to state their effects.

Even if these conditions are fulfilled, there will always remain a number of unknown and uncontrollable factors which produce a large scatter in fatigue life even of test pieces which are considered to be identical. In the past, this scatter in fatigue life was not regarded as a problem and only a few specimens were used to determine the fatigue limit or the relation between load and life. It is now generally accepted that the scatter is an inherent part of the fatigue properties, and that a large number of specimens is required even if average values only are concerned. This requirement has some influence on the choice of the testing procedure.

The two above-mentioned factors: (i) the sequence of stress amplitudes and (ii) the test piece, will now be used as a basis for a classification of the different methods of fatigue testing.

The simplest sequence of amplitudes is obtained by applying reversals of stress of a constant amplitude to the test piece until failure occurs. Different specimens of the test series may be subjected to different stress amplitudes, but for each individual item the amplitude will never be varied. This type of fatigue testing is called a constant-amplitude test.

Depending upon the choice of stress levels, constant-amplitude tests may be classified into three categories:
(i) the routine test, where applied stresses are chosen in such a way that all specimens are expected to fail after a moderate number of cycles, say $10^4$ to $10^7$. A few run-outs, although not intended, may be allowed;
Fatigue Testing and Analysis of Results

(ii) the short-life test, where stress levels are situated above the yield stress and some of the specimens are expected to fail statically at the application of the load; and

(iii) the long-life test, where stress levels are situated below or just above the fatigue limit and a fraction of the specimens does not fail after a preassigned number of cycles (usually between $10^4$ and $10^7$).

Obviously, there is no abrupt transition from one type to another. Suppose for example that five samples of equal size are drawn at random from a real or hypothetical population and tested at five different stress levels as indicated in Fig. 20.1; then it may be postulated that all specimens having the same order number, from least to greatest fatigue life, will have approximately identical static and fatigue properties—the larger the sample, the smaller the individual deviations from average—which are represented by a family of $S-N$ curves, of which three, the median and the two extreme curves, are indicated in the Fig. The estimated range of the tensile strength $S_N$ for the given sample size is marked by a–b, and that of the fatigue strength $S_N (N = 10^6, \text{say})$ is marked by c–d. If now the stress level $S = S_N$, fifty per cent of the specimens tested are expected to fail within the first cycle ($N = 0$) whereas the remaining half are expected to have a fatigue life $N \geq 1$. In the same way, if $S = S_N$, fifty per cent of the specimens tested are expected to endure more than $10^6$ stress reversals.

A short-life test thus includes stress levels above the lower bound of the tensile strength (point b) and a long-life test includes stress levels below the upper bound of the fatigue strength (point c).

In some cases it will be required to substitute more complicated sequences of stress amplitudes than constant ones. The sequence obtained by subjecting each test piece to reversals of monotonic increasing amplitude is called the increasing-amplitude test. It is a typical long-life test, exclusively used for the same purpose as the response test (see Section 23, paragraph 1), and it is, therefore, in spite of not being a constant-amplitude test, presented in the same section as the response test. The increase in amplitude may be either by steps or continuous as demonstrated in Section 23, paragraph 2.

More complicated sequences of amplitude are required in order to simulate the stresses to which a specimen is subjected in actual service. A realistic simulation is very complicated. In order to discover laws in relation to the accumulation of fatigue damage in a specimen subjected to stress reversals of different amplitudes, the sequence of stress amplitudes, also called the programme or the spectrum of loading, may be simplified. Independent of the pattern used such tests will be designated variable-amplitude tests, the only exception being the monotonic increasing-amplitude test which is regarded as a category by itself. Two alternatives will be considered. If the objective of the test is to investigate cumulative damage theory, in which case the sequence is frequently simplified, composed of perhaps two or three stress levels only, the test will be called the cumulative-damage test, discussed in Section 24, whereas tests using a more elaborate pattern for simulating purposes will be called the service-simulating tests, discussed in Section 25.

Having thus classified the various fatigue tests on the basis of the sequence of stress amplitudes, subclasses may be obtained by considering the different types of test piece available. It will suffice to divide the test pieces into two categories, which will be designated specimens and components.

The term specimen is here used in the sense of a test piece of simple shape, frequently standardized, of small size, and prepared carefully and with good surface finish. The purpose of the simplification is not only to make it less expensive but more to reduce the variability of the product and to keep different influential factors under control. Test pieces of this type were originally intended for testing the material and for stating its fatigue properties. They are now also used extensively for research purposes.

Even if the simplified specimen may simulate many of the properties of actual machine parts, there are two factors pertaining to the component which are not represented in the specimen, i.e. design and fabrication. For this reason it is indispensable to carry out actual tests with components in exactly the same condition as used in actual service.

The term component is here used to signify any machine part, actual structure, machine and assembly, including elements simulating actual components.

The different types of tests mentioned above may be applied either to specimens or to components. Of the different combinations possible, Templin (1949) has paid particular attention to three of these combinations, viz. the routine test applied to specimens and components and the service-simulating test applied to components. They have been designated by him as the material test, the structural test and the actual-service test.

It may be appropriate to mention some of the purposes for which data from such tests are intended.

Tests of the material type are useful for a comparison of the behaviour of different materials subjected to repeated stresses, of the effects of various
manufacturing processes, of the behaviour of materials in various environments, of various simple geometrical factors such as different sizes and shapes of notches, and different surface finishes. They may also be used to establish correlations with other mechanical properties, different types of stressing, chemical compositions and for evaluating the effects of surface treatments such as case-hardening, decarburization, nitriding, shot-peening and plating on the fatigue properties of different materials.

Tests of the structural type may be useful for a comparison of components made from different materials, of different design and of structures fabricated by different procedures. They may also be used for revealing stress concentrations and fabrication faults, for developing better designs or fabrication procedures and for establishing design criteria. In some cases, the location of the failure point is the only information required (De Leieres, 1956).

All fatigue tests are very time-absorbing, particularly when a number of tests sufficiently large to allow statistical treatment is required. This difficulty has been apparent to research workers almost from the beginning of fatigue testing, and several methods have been suggested in an attempt to discover some rapid method which could be substituted for the normal fatigue testing methods. Such abbreviated and accelerated tests are discussed in Section 26.

Fatigue tests completely different in type from the above-mentioned tests are those which have as objective a study of the initiation and propagation of fatigue cracks. In the routine tests the most common practice is to run the test until complete fracture of the specimen occurs. From a theoretical point of view, it would be much better to split up the test into two parts. The pre-crack stage and the post-crack stage, owing to the fact that the fatigue damage is of a quite different character in these two stages. Simple laws are therefore not to be expected without such a separation. This is perhaps particularly true when size effects and similar problems are concerned. Some comments on tests intended for the determination of the crack initiation and for a study of the crack propagation are to be found in Section 27.

The above-mentioned methods must be modified for certain special purposes. Some particular cases are indicated and references are given in Section 28.


SECTION 21. ROUTINE TESTS

The purpose of the routine test is to estimate the relation between load and life; in the past, with the chief aim of determining the fatigue limit by an extrapolation of the curve fitted by eye to the data points.

Later it has become apparent that not too much confidence should be placed on results obtained from an extrapolation of empirical curves carried out without using proper caution, and since more powerful tests for stating long-life fatigue properties have been available, the use of a routine test should be restricted to the range of stress levels actually studied. (The problem of extrapolating curves to ranges outside the observations is discussed in Sections 71 and 91.)

This type of test is usually designed with the intention of having all the specimens fail. There is, however, in some cases and for some purposes reason to discontinue the test when a certain fraction at each stress level has failed, and the routine tests may then be classified into all-failed and fraction-failed tests.

21.1 All-failed Tests

The purpose of the all-failed test is usually to determine the relation between the fatigue life and the amplitude of the applied stress for the test piece used, keeping the mean stress $S_m$ or the stress ratio $R$ constant. The result and its usefulness depend upon the total number of specimens, the choice of stress levels, and the allocation of specimens to the stress levels.

If the total number of specimens is small, the only information obtainable is an estimate of the average $S-N$ curve corresponding to a probability of failure (or of survival) of about fifty per cent. In the past, before designing for limited life was actually needed, this was all that was required of the test. It was considered neither necessary nor desirable to use many specimens for each test series. The normal procedure was to run a single test at each stress level, reducing the range of stress with each succeeding specimen. The pretensions were very moderate indeed. It was stated that the determination of the limiting stress of a metal could be determined with "a number of specimens which cannot be safely reduced below four, even under the best circumstances".

Findley (1949) suggests that at least ten specimens be tested for an $S-N$ diagram, but that a larger number of specimens would be desirable for establishing the $S-N$ diagram accurately and indicating the variability of the material. He proposes that for this purpose at least 20 (preferably 50) specimens should be prepared and tested.

It has been experimentally verified (Weibull, 1958a) that, even if the number of specimens tested has a self-evident influence on the accuracy of the parameters computed from the observations, other factors may be of equal importance. In some cases, small test series could give just as good or even better accuracy than series three or four times as large. The efficiency of a test series in this respect depends also upon the choice of the stress levels, the inherent scatter of the specimens used and of the testing machine and possibly of some other factors; so, in a way, a small number of specimens can to some extent be compensated by a more efficient design of the test conditions. This problem will, however, be more thoroughly discussed in Section 71.

It is believed that some twenty to thirty specimens will give a fair estimate of the variance of the fatigue strength and that fifty to one-hundred specimens will be required for establishing an acceptable $P-S-N$ diagram, provided efficient statistical methods are used for the evaluation of the observed data.
Fatigue Testing and Analysis of Results

The choice of stress levels depends upon the purpose for which the data are required. If the main interest is in the long-life range of the S-N curve, low stress levels will be chosen. If the complete S-N diagram or the P-S-N diagram is wanted, the stress levels may be more evenly distributed. It is strongly recommended that some static tests should also be included, if possible using specimens identical to those used in the fatigue tests. It is desirable to introduce the experimentally determined value of the static tensile strengths $S_t$ as a unit and to use relative stresses, i.e. to express the stresses as percentage of $S_t$, because parameters referring to relative stresses have a more general validity than if the stresses are given in absolute dimensions.

The influence of the magnitude of the stress levels on the efficiency of the test series with regard to the accuracy of computed parameters may briefly be stated by saying that the greater the difference between the highest and the lowest stress levels, the greater the accuracy. Also from this point of view it is advantageous if the static strength $S_t$ can be used as an integrating part for the evaluation of the test data.

The allocation of tests to the stress levels is not very crucial on condition that a proper transformation of the quantities $(S_t, N)$ has been performed, resulting in a homogeneous variance of the variables, as demonstrated in Section 91. All the observations can then be pooled and used to determine the distribution of the deviations from the average curve. Frequently, the best method appears to be to allocate an equal number of tests to the stress levels; the fitting of P-S-N diagrams can then be performed more easily as demonstrated in Section 94.

Since the numbers of specimens at each stress level have been decided, attention must be paid to an unbiased distribution of the items. The problem of designing the test series properly is discussed more thoroughly in Section 71.


21.2 Fraction-failed Tests

For practical design purposes it is of little interest to know the fatigue life of the better specimens of a fatigue tested group, as the designer has to base his calculations on the worst part of the group. It would be quite sufficient for him to have a safe knowledge of the lower part of the life or strength distribution.

Since the total time required for a test series is largely determined by the long-life items, it is obvious that a considerable saving in time may be obtained by stopping the tests when a certain fraction of the group has failed. For example, a series of 120 specimens allocated to five stress levels (Weibull, 1956c, Table 1) required a total machine time of 144-2 million cycles, the 12 smallest values of each stress level taking 17.3 million or 12 per cent and the 12 largest taking 126.8 million or 88 per cent of the total time. If the latter had been stopped at the median values of life, a saving of 91.8 million cycles would have resulted. The total time of the 50 per cent fraction-failed series is thus 36.3 per cent of that of the all-failed series.

Still more reduction in testing time will result according to a "least-of-four method", proposed by Schüttle (1954). Four specimens are tested simultaneously and the test is discontinued as soon as one of them has failed. By means of these data an S-N curve for approximately 80 per cent survival is obtained.

If the observations are evaluated by efficient statistical methods not very much design information is lost by testing a fraction only. Such methods are discussed in Sections 91–94. A reduction of the time required for the experiment can be important when the results are needed as soon as possible or when the cost associated with a failed item is much larger than the cost of a life-tested item which did not fail.

There is no fundamental difference in testing technique between this type and the all-failed test. If a sufficient number of testing machines is available for simultaneous testing, the test can be stopped at exactly the desired fraction. Otherwise a safe value of the median life for each stress level must be estimated and an approximate fraction of failures will result.

This type of test may be regarded as a modification of the all-failed test and it is run for the same purpose, i.e. to establish the S-N diagram or part of the P-S-N diagram. The alternative fraction-failure test, the response test, where the tests are stopped at a preassigned cycle life, equal for all stress levels, is different in character and has another objective. It will therefore be discussed in a separate Section.


SECTION 22. SHORT-LIFE TESTS

By far the greater part of conventional fatigue testing has been concerned with establishing fatigue lives at stresses well below the yield stress of the material. In some cases, however, optimum design requires knowledge of the behaviour of the material under stresses leading to fatigue failure after a small number of stress—or strain—reversals.

One of the difficulties associated with testing at stresses producing large plastic deformations is the accurate control of applied loads, in particular of the mean stress. For this reason, it appears easier to base the testing equipment on the strain amplitude, rather than on the stress amplitude. It must be emphasized, however, that there is a basic difference between curves relating stress and fatigue life and curves relating strain and fatigue life, and at present it is impossible to transform one to the other.

It is obvious that these two modes of stressing are equivalent as long as the test piece is acting as a perfect elastic body, i.e. as long as there is a unique relation between displacement and applied load. This condition may, at low stresses, be fulfilled during the first stage of the fatigue life, but it will be invalidated as soon as cracks appear. At high stresses, it may be invalidated even during the first stress reversals. As an example reference is made to a paper by Liu et al. (1948). Unnotched specimens of aluminium alloy 24S–T were subjected to completely reversed axial strains of such a
magnitude that failure occurred in some seven cycles. The maximum true stress in each succeeding cycle increased until it had reached a value of 12 per cent higher than the initial value.

Another example is reported by Low (1956). A preset angular movement was applied to the ends of a flat rectangular test piece. The curvature at the test section, and therefore the maximum fibre strain, amounting to a value of up to 5 per cent, was determined by a spherometer. Preliminary tests showed that the spherometer readings remained the same throughout the greater part of a test, but once localized yielding or cracking of the test piece occurred, the angular movement, required to give the same reading, altered considerably. It is obvious that the fatigue life observed will depend considerably on whether the preset angular movement of the testing machine is changed or not. A proper interpretation of the result of a short-life test thus requires a more detailed description of the test conditions.

Usually different testing machines have to be used to cover the complete range of the S—N curves. Tests in which failure occurs in less than 10 kc are impracticable to perform with most of the conventional testing machines. Tests in which failure is expected to occur in 0-5 to 10 kc are frequently carried out with hydraulically operated testing machines, whereas failures expected to appear in less than 500 cycles are usually performed by the use of manually operated machines. For this purpose, conventional static testing machines may be used. The speed is, of course, very low. A few cycles per minute may be obtained in this way. A reduction of the speed is required not only because of the machine but in order to keep the heating of the test piece due to large plastic deformations, within reasonable limits.

For all specimens tested at stress levels higher than the yield stress of the material, it is advisable to apply the first reversal of load manually in order to produce the plastic deformation. This procedure simplifies the maintenance of the desired mean load.

From the preceding, it is apparent that short-life tests have to be divided into constant-stress amplitude and constant-strain amplitude tests.

Methods of analysing data from fatigue tests including static fractures are discussed in Section 91.

22.1 Constant-stress Amplitude Tests

Available data on fatigue testing of steel specimens at stresses producing failure in less than 30 kc are summarized by Weisman and Kaplan (1950). Only a few of the data are for tests resulting in failure in less than 1 kc. They were performed on unnotched specimens subjected to bending and to axial load at a stress ratio \( R = 0 \).

Tests with notched specimens of steel and of 61S—T6, 24S—T3 and 75S—T6 aluminium alloys have been conducted by Hardrath and Illg (1954). A most remarkable result was that the minimum life to failure at stresses near the ultimate strength was drastically reduced with increasing stress-concentration factor. Failure was found to occur in approximately 10 kc for unnotched specimens, 1 kc for specimens with \( K_t = 2 \), and in 0-1 kc for specimens with \( K_t = 4 \). Further, in tests with \( R = -1 \) and \( K_t = 4 \), the

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\( S \) against \( \log N \) curves were found to be concave upwards for almost the complete range, a reversal in curvature occurring at about 10 cycles of reversals.

**References:** Hardrath, Landers and Utley (1953), Hardrath and Illg (1954), Weisman and Kaplan (1950).

22.2 Constant-strain Amplitude Tests

Tests of this type were already in use by Kommers (1912) who applied maximum fibre strains in the range of 2-5 to 0-7 per cent to specimens of steel. A bending fatigue test including five widely differing materials, steels and aluminium alloys, is reported by Low (1956). The fatigue life in reversed bending was found to depend solely on the degree of strain, and is independent of the material for maximum fibre strains between \( \pm 5 \) and \( \pm 4 \) per cent. In tests using lower strains, the fatigue depended also on the material. Curves of deflexion against cycle life were found to be smooth over the whole range, from which it follows that the curves of stress against cycle life all show an abrupt change of slope at the yield stress of the material. It is a remarkable result that all the curves plotted on log-log scales are, within a reasonable, non-systematic scatter, identical. The slope \( d \log N/d \log S = -2-4 \) (\( S \) denoting the strain). This result agrees very closely with that obtained by Kommers (1912).

Tests of this type are described also by Liu et al. (1948) as mentioned above and by Pardue et al. (1950). The latter investigation examines specimens of seven different materials subjected to strain reversals resulting in failure in less than 10 kc.

**References:** Kommers (1912), Liu, Lynch, Ripling and Sachs (1940), Low (1956), Pardue, Melchior and Good (1950).

**Section 23. Long-life Tests**

The object of the long-life test is to determine a number of percentage points of the distribution of the fatigue strength at a preassigned cycle life. It differs from the routine test in that the observed values of fatigue life are not used directly, only the fraction that failed at different stress levels being used. This procedure obviously means a loss of some of the information which is provided by the test. It is therefore recommended that the observed cycle-to-failure should be regarded as part of a routine test, and used accordingly.

The long-life tests may be classified into a constant-amplitude test, which is called the response test, and the increasing-amplitude test.

23.1 Response Tests

The response test is conducted according to two different methods. The first, using the probit method, is designed with predetermined stress levels and numbers of specimens at each stress level; the second, using the stair-case method, is a sequential test, the choice of stress level is determined by the preceding result.

23.11 The probit method.—The object of the probit method is to determine the complete distribution function of the fatigue strength or part
of it. The examination may be concentrated to different parts of the distribution, but the number of tests required for a safe estimate of extreme percentage points would be prohibitive.

The common procedure is to divide the specimens available into several groups and to test one group at a chosen stress level, the next group at a second level, and so on. The data which are used for the evaluation consist of the numbers of failures and non-failures at each stress level.

The stress levels are chosen in such a way that one of them will give a fraction of failures prior to the preassigned fatigue life estimated to be equal to the percentage of main interest, be it 50 per cent or some other value. It is recommended that there should be two stress levels above and two below the mean level. If the region of the median is of main interest the stress levels could be located close together, and sometimes three levels would be sufficient. If more general information is desired, the levels ought to be more widely spread.

The analysis of the data may be made graphically or analytically. In any case, if equal groups have been used a weighting procedure is required. This complication can be eliminated by allocating more tests to percentage points corresponding to large variance of the observations. If the distribution is assumed to be normal, the following table indicates appropriate sizes of the groups. This table may also apply to distributions other than normal.

An acceptable accuracy of the response curve, including confidence limits, will require a total number of some fifty specimens.

Methods for analyzing the data are discussed in Section 95, paragraph 1.

<table>
<thead>
<tr>
<th>Expected Percentage Survival</th>
<th>Relative Group Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 to 75</td>
<td>1</td>
</tr>
<tr>
<td>15 to 20</td>
<td>1·5</td>
</tr>
<tr>
<td>80 to 85</td>
<td>1·5</td>
</tr>
<tr>
<td>10 to 90</td>
<td>2</td>
</tr>
<tr>
<td>5 to 95</td>
<td>3</td>
</tr>
<tr>
<td>2 to 98</td>
<td>5</td>
</tr>
</tbody>
</table>

(From the ASTM STP 91-A)

References: Bliss (1935a, b, 1937), Finney (1952), Fisher and Yates (1943), Golub and Grubb (1956), Moore and Wishart (1933).

23.12 The staircase method.—If the main interest is limited to the median value of the fatigue strength the stair-case method will reduce the number of specimens required. On the other hand, it is not a good method for estimating small or large percentage points unless the distribution is assuredly normal.

The procedure of the staircase method is as follows. The first test is started at a stress level which is equal to an estimated mean value of the fatigue strength. If a failure occurs prior to the preassigned cycle life, the next specimen is tested at a lower level; if the specimen does not fail within the preassigned number of cycles, the next test is run at a higher level. The intervals between the stress levels should be approximately equal to the standard deviation, but this is not a strict condition. The interval should not, however, be larger than twice the standard deviation.

The test continues in this way, the stress level of each succeeding test being raised or lowered depending on the preceding result.

This procedure results in the testing being concentrated mainly on three stress levels, centred on the mean level. For this reason, this method is more efficient than the probit method with regard to the determination of the mean value, resulting in a reduction in number of specimens of about forty per cent.

A disadvantage of this—as of all—sequential methods is that only one specimen can be tested at a time. If more than 30 specimens are required, the time required for the test will be rather long. A modification may then be introduced, whereby the total number of specimens is split into subgroups of equal size. Each group may then be tested simultaneously and independently of each other. This method is called the modified stair-case test.

Methods for analysing the data are discussed in Section 95, paragraph 2.


23.2 Increasing-amplitude Tests

It appears very tempting for the purpose of saving time and specimens to use for further tests a specimen which has survived a preassigned number of cycles. In view of the fact that the fatigue properties of the specimen, in particular its fatigue limit, may have changed considerably as a result of the prestressing, caution is strongly recommended before this type of test be used. The effect of prestressing depends upon the material and stress concentrations within the specimen.

If this effect has not been proven to be negligible, the results of increasing-amplitude tests may be quite misleading, but for some materials this type of test appears to be quite satisfactory.

A convincing example where excellent agreement of the distribution of the fatigue limit obtained by a probit method and by a step test (see below) is presented by Stulen (1951). The material was SAE 4330 heat treated to a Rockwell C hardness of 30.

This type of test can be conducted in two different ways. In the first alternative, the stress level is raised by steps; this method is called the step method. In the second alternative, the stress level is raised continuously; this method is called, after its inventor, the Probit method.

The object of both of them is to determine the fatigue limit.

23.21 Step tests.—The step test should be started at a stress level which is estimated to correspond to a fraction failed of approximately 30 per cent after a preassigned number of cycles, being usually 107. If the specimen survives, the stress level is raised to a value estimated to give 5 per cent more failures. This procedure is repeated with the same specimen until failure
occurs. The fatigue limit is supposed to be the mean between the last and the next to last stress level. This method requires at least 10, and preferably 20, specimens for a determination of the fatigue limit.

Methods of analysing the data are discussed in Section 96, paragraph 1.

References: Hempel (1952), Körber (1939a,b), Körber and Hempel (1940), Moore and Jasper (1924), Sinclair (1952), Stulen (1951), Komers (1934), Jenkins (1923).

23.22 The Prot tests.—If the fatigue limit be determined by increasing the amplitude until failure occurs, it appears to be more rational to raise the stress level continuously. This method has been proposed by Prot (1945), who used a rotating bending machine. This type of fatigue testing machine is very easily adapted for this purpose.

The test is started at a stress level estimated to be 60 to 70 per cent of the fatigue limit of the specimen, and the stress level is raised at a constant rate. This procedure is repeated with a group of specimens. Two other groups are tested in the same manner but with different rates. The lowest rate should be as small as possible, the highest rate should not exceed the rate causing yielding of the specimen.

This type of test requires 10, and preferably 20, tests for each rate, i.e., about three times as many tests as the step test.

Methods of analysing the data are discussed in Section 96, paragraph 2.


SECTION 24. CUMULATIVE-DAMAGE TESTS

The cumulative-damage test differs from the preceding types (except the increasing-amplitude test) in that each individual specimen is subjected to more than one stress level. The purpose of the test is to discover laws or rules relating the fatigue life of the specimen or of the component to different patterns of applied sequences of stress levels in order to make it possible to predict a safe life of a machine part or an assembly from the stress history encountered in actual service.

The normal procedure for a cumulative-damage test is to subject the specimen to a well-defined fatigue treatment, preferably of a simple pattern, composed of single loads or a fixed number of stress cycles of two or more amplitudes, after which the fatigue damage suffered by the test piece is measured.

Various methods have been proposed for measuring this damage. One of them, frequently used, consists of subjecting the damaged test piece to a fixed stress level, called the test stress, until failure occurs. The remaining life is taken as a measure of the damage. It has been found that this measure depends entirely upon the magnitude of the test stress chosen, and one and the same fatigue treatment may produce a reduced life at one stress level and an increased life at another.

The only rational and safe method of designing a damage test therefore appears to be to establish the complete S-N curve, or still better the P-S-N diagram, of the damaged test piece. For this purpose, a large group of identical test pieces is subjected to a specified fatigue treatment. Afterwards they may be regarded as new test pieces with different fatigue properties which have to be compared with those of the virgin test pieces. For special purposes, this rather elaborate procedure may be replaced by a simple determination of the fatigue limit, the ultimate tensile strength, or some other statistic of immediate interest. In any case, the failure of the test piece will always occur at a predetermined stress level, this being the definition of the damage test in contrast to the service-simulating test discussed below.

The fatigue-damage tests may be divided into two classes with regard to the nature of the fatigue treatment. The first, the preloading test is defined by a pretreatment consisting of a single or a few preloads; the second is the prestressing test, where the pretreatment consists of one or more steps, each step being a fixed number of stress cycles of constant stress amplitude and mean stress.

24.1 Preloading Tests

The test piece is subjected to one or more prior loads, tension or compression, by which the fatigue properties will be affected.

This type of test is of particular interest in connexion with notched specimens or components such as riveted or bolted joints, where the preload may frequently have a beneficial effect resulting from the smoothing out of initial stress concentrations. The preload may be repeated a fixed number of times after the application of the test stress level.


24.2 Prestressing Tests

In this type of test, the test piece is subjected to one or more steps of a programme or to some pattern of continuously varied stress amplitude.

These tests are extensively used to examine the damaging effect of simplified combinations of steps or spectra with regard to the number of prestress cycles, differences between ascending and descending sequences of stress levels, etc.

SECTION 25. SERVICE-SIMULATING TESTS

A component in actual service is subjected to an extremely complicated pattern of stress cycles of varying amplitude and mean stress. These appear in a random order, and must therefore be described in statistical terms. When these stresses are simulated in a fatigue testing machine, the only workable method is to introduce considerable simplifications. Two ways of doing this may be distinguished. The first alternative is called programme testing, where a block—i.e. an aggregate of steps, each step consisting of a fixed number of stress cycles of constant amplitude—is applied to the test piece and repeated until failure occurs. This may happen within any of the steps, and consequently the stress level at which failure occurs cannot be anticipated. The second alternative is called spectrum testing and is defined by the condition that consecutive stress cycles be of different magnitude, arranged according to some pattern.

25.1 Programme Tests

The relative frequency of a stress cycle of a certain amplitude has been determined by a counting instrument. A limited number of amplitudes is selected and to each of them is assigned a fixed number which constitutes a step.

The fewer the cycles within each step, naturally the more realistic will be the simulation. A limit is imposed, however, by the condition that the largest amplitude must have at least one or preferably a few cycles in the step. In addition, conventional testing machines make it preferable to have a randomized programme test. Reference may be made to HYLER et al., where the correlation between composite structures (aluminium-alloy box beams and I-beams) and simple simulation elements has been stated on the condition that the failure mode and the secondary stresses are duplicated.


25.2 Spectrum Tests

The spectrum test represents a more realistic simulation, but it requires new designs of testing machines or at least a modification of the conventional ones. The easiest way of realizing this condition is accomplished by an amplitude modulation of rotating bending machines, or by the superposition of two vibrations of different frequencies, but the requirement of simulating the relative frequencies of each stress amplitude is not as easily satisfied as by means of programme testing.

The completely randomized spectrum load is obtained by randomizing the individual stress cycles. This has been performed by monitoring electro-mechanical testing machines according to experimentally recorded stress histories. This device is particularly useful for a study of the effects on the fatigue life of jet noise, wing flutter, and vibrations of a similar nature.

In general, actual components are used in the service-simulating tests, but it may in some cases be convenient and also acceptable to simulate, not only the stress history, but also the test piece. Reference may be made to an investigation (Hyler et al., 1958) where the correlation between composite structures (aluminium-alloy box beams and I-beams) and simple simulation elements has been stated on the condition that the failure mode and the secondary stresses are duplicated.


SECTION 26. ABBREVIATED AND ACCELERATED TESTS

The possibility of substituting some short-cut method for the time-absorbing fatigue test is an old dream. Since it has become apparent that the large scatter in fatigue life requires the testing of a considerable number of test pieces, and that no reliable results can be expected from an extrapolation outside the range covered by observations, a solution of this problem has become even more urgent.

It seems safe to say that almost any physical property of the material which can reasonably be expected to be correlated to its fatigue behaviour has been investigated for this purpose. Among such properties can be mentioned: static proportional limit and yield limit, apparent and true tensile strength, dynamic proportional limit, damping, modulus of elasticity, magnetic properties, electrical resistance, surface activity of stressed material, coefficient of thermal expansion. Methods have been based on progressive loads, effect of prior fatigue stress on the static tensile strength, and the application of X-ray diffraction.

An extensive inventory of the possibilities of predicting fatigue properties by means of the properties listed above has been presented in a WADC Report by Vitovec and Lazen (1953), but no method, even if useful for comparative purposes, has been found capable of substituting the regular long-time fatigue test.
FATIGUE TESTING AND ANALYSIS OF RESULTS

Instead of describing the efforts bestowed on this problem without definite success, it seems better to quote part of the summary of the above-mentioned report which still gives a good picture of the actual status:

Since fatigue cracks are, in general, brittle tensile cracks, proportionality between fatigue strength and tensile strength was assumed in early work. However, no general relationship of this type could be found for all types of materials and all conditions. The relationship between fatigue and other static properties such as proportional limit, yield strength, and true tensile strength have been considered again without success. This approach has been elaborated upon by developing formulas, particularly for steel, which give the fatigue limit as a function of several static properties such as yield strength, apparent tensile strength, elongation, and reduction of area, etc. These formulas seem applicable only under special and highly limited conditions.

Based on the fact that fatigue is caused by reversed slipping, the fatigue limit was proposed to be identical to that stress at which slip lines begin to form or at which slip lines do not appear again after prestressing. No proportionality between this so determined stress and the fatigue strength could be observed since other secondary effects such as strain hardening, aging, etc., influence the fatigue properties.

Attempts have also been made to associate fatigue properties with the stress-strain characteristics under reversed stress. A large number of fatigue tests showed that the dynamic proportional limit gives a good indication of the fatigue strength for many metals and alloys and appears to have fewer exceptions (for example, Duralumin) than do other methods.

In several other methods the change of other physical properties caused by alternating stress have been investigated for possible association with fatigue properties. Properties studied in this way include damping, magnetic properties, electrical resistance, coefficient of thermal expansion, mosaic size detected by X-rays, surface stresses detected by X-rays, surface activity, and ultimate tensile strength. In general, the change of the property as a function of reversed stress only has been investigated, and only recently have stress-history effects been studied. All of these physical properties have been found to be affected by fatigue stress, but in most cases the magnitude of change is relatively small and therefore difficult to determine accurately. To date, insufficient basic work has been completed to clarify the significance of such associations.

In other groups of short-time tests fatigue rupture properties are determined under conditions of uniformly increasing stress or other types of constant load condition. Special attention may be directed to Pflüger's method in which the stress is uniformly increased until failure. For reasons discussed previously the progressive load increase method does not appear to be applicable for all materials.

Reference: Vitovec and Lazan (1953).

SECTION 27. METHODS FOR DETERMINING CRACK INITIATION AND CRACK PROPAGATION

The initiation of a fatigue crack is influenced only by conditions in a small volume near the point of origin, while the propagation is affected by conditions throughout the cross-section of the test piece. It is therefore apparent that general information on the effect of a given variable on the fatigue strength of a metal will be obtained only by studying the crack initiation separately from the crack propagation. "Failure to distinguish between these two stages of the fatigue process lead to erroneous and sometimes dangerous results" as emphasized by Bennett (1956).

Two stages may be distinguished in the process. In the first stage the material undergoes bulk deformation and work hardening. Slip lines which gradually thicken are then formed. When this process has proceeded for a while, final rupture of the lattice occurs and submicroscopic cracks appear. During the second stage these cracks coalesce to form visible cracks resulting in the complete fracture of the test piece. It will be apparent even from this brief description that the separation point between the two stages is to some extent a matter of definition.

Various methods have been employed to detect early cracking, and a comprehensive and thorough examination of these methods has been carried out by Desmer (1953). He also gives a systematic list of factors involved in the selection of crack detection methods which is presented below. The factors are:

(a) Desired sensitivity. As a crack can vary from a discontinuity barely visible under the resolving power of an electronic microscope to one of a macroscopic length, the choice of method depends on the sensitivity required for the purpose of the test.

(b) Type of fatigue testing machine.

(c) Type of fatigue specimen employed.

(d) Nature of applied stress.

(e) Mode of fatigue stress imposed.

(f) Type of material.

(g) Nature of detection method.

(h) Time available for crack examination.

(i) Equipment available for detection purposes.

The detection methods may be classified into two main groups, non-destructive and destructive methods. The former have the advantage of reducing both the number of specimens and the time required for a given investigation. In addition, the progress of failure may be followed on a single specimen, which contributes to the reduction of the scatter. In fact, Weibull (1956a, 1956b) has demonstrated that the scatter in the time of propagation, measured on a single specimen, is considerably less than that of the total fatigue life, which implies that the main reason of scatter in fatigue life is the initiation and not the propagation stage.

The various methods for detection of fatigue cracks in laboratory fatigue test specimen have been classified (loc. cit) as follows, some of them also being applicable for the detection of cracks in actual components.

Non-destructive Tests

(a) Microscopic tests. Optical microscope methods or electron microscope methods.

(b) Magnetic particle testing.

(c) Penetrant tests. Oil-whiting, fluorescent penetrant, dye penetrant or bubble methods.

(d) Surface activity and ultimate tensile strength. In general the change of the property as a function of reversed stress have been investigated for possible association with fatigue properties. Properties such as yield strength, apparent tensile strength, elongation, and reduction of area, etc. These formulas seem applicable only under special and highly limited conditions.

(e) Modal fatigue stress imposed. Alternating tension-compression, reversed flexure, rotating bending, reversed torsion, combinations of above.

(f) Type of material. Magnetic or non-magnetic.

(g) Nature of detection method. Non-destructive or destructive.

(h) Time available for crack examination.

(i) Equipment available for detection purposes.

The detection methods may be classified into two main groups, non-destructive and destructive methods. The former have the advantage of reducing both the number of specimens and the time required for a given investigation. In addition, the progress of failure may be followed on a single specimen, which contributes to the reduction of the scatter. In fact, Weibull (1956a, 1956b) has demonstrated that the scatter in the time of propagation, measured on a single specimen, is considerably less than that of the total fatigue life, which implies that the main reason of scatter in fatigue life is the initiation and not the propagation stage.

The various methods for detection of fatigue cracks in laboratory fatigue test specimen have been classified (loc. cit) as follows, some of them also being applicable for the detection of cracks in actual components.

Non-destructive Tests

(a) Microscopic tests. Optical microscope methods or electron microscope methods.

(b) Magnetic particle testing.

(c) Penetrant tests. Oil-whiting, fluorescent penetrant, dye penetrant or bubble methods.