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Metallic materials — Fatigue testing — Statistical planning and analysis of data

Matériaux métalliques — Essais de fatigue — Programmation et analyse statistique de données

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 12107 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 5, *Fatigue testing*.

Introduction

It is known that the results of fatigue tests display significant variations even when the test is controlled very accurately. In part, these variations are attributable to non-uniformity of test specimens. Examples of such non-uniformity include slight differences in chemical composition, heat treatment, surface finish, etc. The remaining part is related to the stochastic process of fatigue failure itself that is intrinsic to metallic engineering materials.

Adequate quantification of this inherent variation is necessary to evaluate the fatigue property of a material for the design of machines and structures. It is also necessary for test laboratories to compare materials in fatigue behaviour, including its variation. Statistical methods are necessary to perform these tasks. They include both the experimental planning and procedure to develop fatigue data and the analysis of the results.

Metallic materials — Fatigue testing — Statistical planning and analysis of data

1 Scope

1.1 Objectives

This International Standard presents methods for the experimental planning of fatigue testing and the statistical analysis of the resulting data. The purpose is to determine the fatigue properties of metallic materials with both a high degree of confidence and a practical number of specimens.

1.2 Fatigue properties to be analysed

This International Standard provides a method for the analysis of fatigue life properties at a variety of stress levels using a relationship that can linearly approximate the material's response in appropriate coordinates.

Specifically, it addresses:

a) the fatigue life for a given stress, and

b) the fatigue strength for a given fatigue life.

The term “stress” in this International Standard can be replaced by “strain”, as the methods described are also valid for the analysis of life properties as a function of strain. Fatigue strength in the case of strain-controlled tests is considered in terms of strain, as it is ordinarily understood in terms of stress in stress-controlled tests.

1.3 Limit of application

This International Standard is limited to the analysis of fatigue data for materials exhibiting homogeneous behaviour due to a single mechanism of fatigue failure. This refers to the statistical properties of test results that are closely related to material behaviour under the test conditions.

In fact, specimens of a given material tested under different conditions may reveal variations in failure mechanisms. For ordinary cases, the statistical property of resulting data represents one failure mechanism and may permit direct analysis. Conversely, situations are encountered where the statistical behaviour is not homogeneous. It is necessary for all such cases to be modelled by two or more individual distributions.

An example of such behaviour is often observed when failure can initiate from either a surface or internal site at the same level of stress. Under these conditions, the data will have mixed statistical characteristics corresponding to the different mechanisms of failure. These types of results are not considered in this International Standard because a much higher complexity of analysis is required.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3534 (all parts), *Statistics — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3534 and the following apply.

3.1 Terms related to statistics

3.1.1
confidence level
value $1 - \alpha$ of the probability associated with an interval of statistical tolerance

3.1.2
degree of freedom
number calculated by subtracting from total number of items of test data the number of parameters estimated from the data

3.1.3
distribution function
function giving, for every value x, the probability that the random variable X is less than or equal to x

3.1.4
estimation
operation made for the purpose of assigning, from the values observed in a sample, numerical values to the parameters of a distribution from which this sample has been taken

3.1.5
population
totality of individual materials or items under consideration

3.1.6
random variable
variable that may take any value of a specified set of values

3.1.7
sample
one or more items taken from a population and intended to provide information on the population

3.1.8
size
n
number of items in a population, lot, sample, etc.

3.1.9
standard deviation
σ
positive square root of the mean squared deviation from the arithmetic mean

3.2 Terms related to fatigue

3.2.1
fatigue life
N
number of stress cycles applied to a specimen, at an indicated stress level, before it attains a failure criterion defined for the test

3.2.2
fatigue limit
fatigue strength at infinite life

3.2.3
fatigue strength
value of stress level S, expressed in megapascals, at which a specimen would fail at a given fatigue life

3.2.4
specimen
portion or piece of material to be used for a single test determination and normally prepared in a predetermined shape and in predetermined dimensions

3.2.5
stress level
S
intensity of the stress under the conditions of control in the test

EXAMPLES Amplitude, maximum, range.

3.2.6
stress step
d
difference between neighbouring stress levels, expressed in megapascals, when conducting the test by the staircase method

4 Statistical distributions in fatigue properties

4.1 Concept of distributions in fatigue

The fatigue properties of metallic engineering materials are determined by testing a set of specimens at various stress levels to generate a fatigue life relationship as a function of stress. The results are usually expressed as an S-N curve that fits the experimental data plotted in appropriate coordinates. These are generally either log-log or semi-log plots, with the life values always plotted on the abscissa on a logarithmic scale.

Fatigue test results usually display significant scatter even when the tests are carefully conducted to minimize experimental error. A component of this variation is due to inequalities, related to chemical composition or heat treatment, among the specimens, but another component is related to the fatigue process, an example being the initiation and growth of small cracks under test environments.

The variation in fatigue data is expressed in two ways: the distribution of fatigue life at a given stress and the distribution of strength at a given fatigue life (see [1] to [5]).

4.2 Distribution of fatigue life

Fatigue life, N, at a given test stress, S, is considered as a random variable. It is expressed as the normal distribution of the logarithm of the fatigue life. This relationship is:

$$P(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\infty}^{x} \exp\left[-\frac{1}{2}\left(\frac{x-\mu_x}{\sigma_x}\right)^2\right] \mathrm{d}x \qquad (1)$$

where $x = \log N$ and μ_x and σ_x are, respectively, the mean and the standard deviation of x.

Equation (1) gives the cumulative probability of failure for x. This is the proportion of the population failing at lives less than or equal to x.

Equation (1) does not relate to the probability of failure for specimens at or near the fatigue limit. In this region, some specimens may fail, while others may not. The shape of the distribution is often skewed, displaying even greater scatter on the longer-life side. It also may be truncated to represent the longest failure life observed in the data set.

This International Standard does not address situations in which a certain number of specimens may fail, but the remaining ones do not.

Other statistical distributions can also be used to express variations in fatigue life. The Weibull [4] distribution is one of the statistical models often used to represent skewed distributions.

Figure 1 shows an example of data from a fatigue test conducted with a statistically based experimental plan using a large number of specimens (see [5]). The shape of the fatigue life distributions is demonstrated for explanatory purposes.

4.3 Distribution of fatigue strength

Fatigue strength at a given fatigue life, N, is considered as a random variable. It is expressed as the normal distribution:

$$P(y) = \frac{1}{\sigma_y \sqrt{2\pi}} \int_{-\infty}^{y} \exp\left[-\frac{1}{2} \left(\frac{y - \mu_y}{\sigma_y} \right)^2 \right] \mathrm{d}y \qquad (2)$$

where $y = S$ (the fatigue strength at N), and μ_y and σ_y are, respectively, the mean and the standard deviation of y.

Equation (2) gives the cumulative probability of failure for y. It defines the proportion of the population presenting fatigue strengths less than or equal to y.

Other statistical distributions can also be used to express variations in fatigue strength. When a linear relationship is assumed between stress and fatigue life using log-log coordinates, the distribution of $y = \log S$ is assumed to be normal as long as $x = \log N$ is normal.

Figure 2 is based on the same experimental data as Figure 1. The variation in the fatigue property is expressed here in terms of strength at typical fatigue lives (see [5]).

5 Statistical planning of fatigue tests

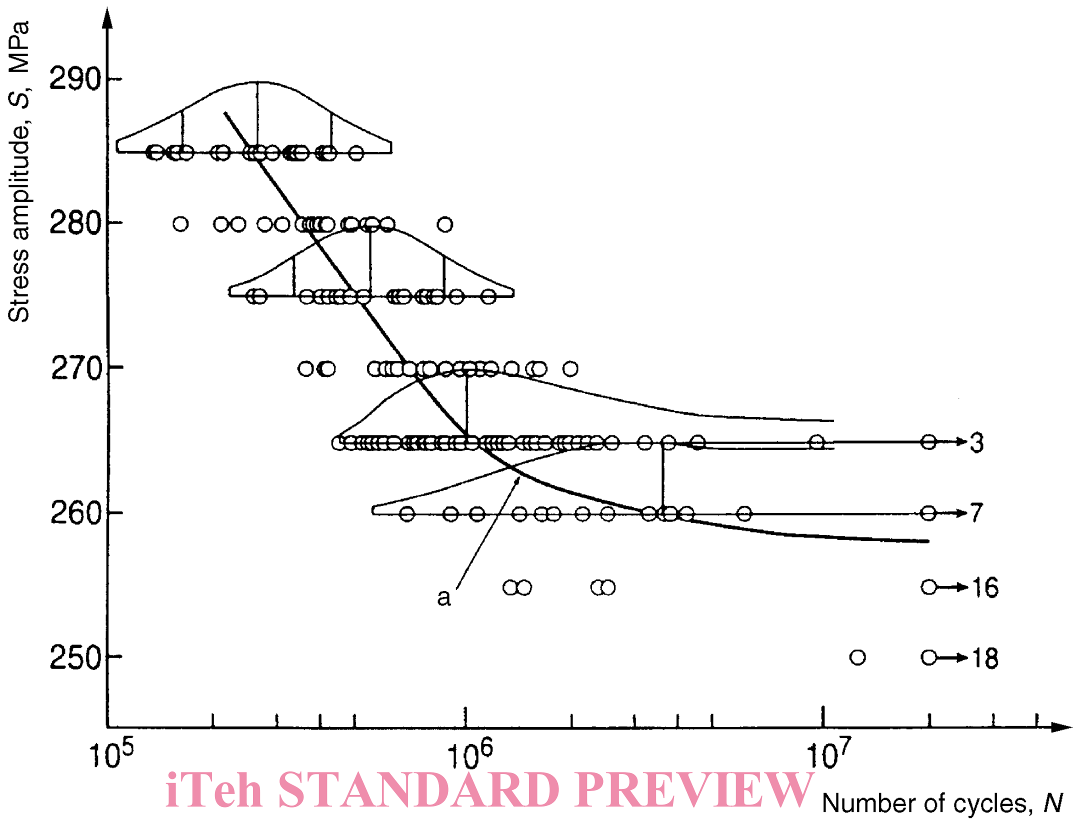
5.1 Sampling

It is necessary to define clearly the population of the material for which the statistical distribution of fatigue properties is to be estimated. Specimen selection from the population shall be performed in a random fashion. It is also important that the specimens be selected so that they accurately represent the population they are intended to describe.

If the population consists of several lots or batches of material, the test specimens shall be selected randomly from each group in a number proportional to the size of each lot or batch. The total number of specimens taken shall be equal to the required sample size, n.

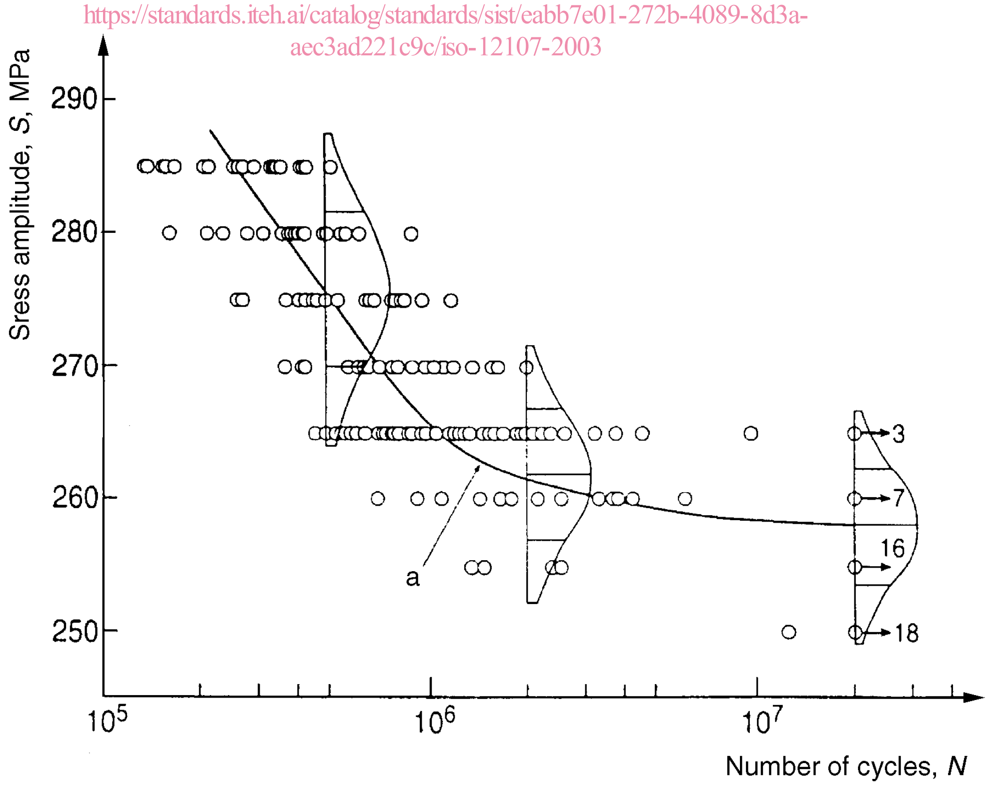
If the population displays any serial nature, e.g. if the properties are related to the date of fabrication, the population shall be divided into groups related to time. Random samples shall be selected from each group in numbers proportional to the group size.

The specimens taken from a particular batch of material will reveal a variability specific to the batch. This within-batch variation can sometimes be of the same order of importance as the between-batch variation. When the relative importance of different kinds of variation is known from experience, sampling shall be performed taking this into consideration.



a median curve

Figure 1 — Concept of variation in a fatigue property — Distribution of fatigue life at given stresses for a 0,25 % C carbon steel tested in the rotating-bending mode



a median curve

Figure 2 — Concept of variation in a fatigue property — Distribution of fatigue strength at typical fatigue lives for a 0,25 % C carbon steel tested in the rotating-bending mode

Hardness measurement is recommended for some materials, when possible, to divide the population of the material into distinct groups for sampling. The groups should be of as equal size as possible. Specimens may be extracted randomly in equal numbers from each group to compose a test sample of size n. This procedure will generate samples uniformly representing the population, based upon hardness.

5.2 Number of specimens to be tested

The reliability of test results is primarily dependent on the number of specimens tested. It increases with the number of tests, n.

For a random variable, x, taking values always less than or equal to $x_{(P)}$ at a probability, P, in a population, define x_1 as a minimum observed value in a set of n specimens extracted from the population. The probability that $x_1 \geqslant x_{(P)}$ is less than or equal to α, i.e. $(1 - P)^n$. Therefore, it can be expected that $x_{(P)}$ is greater than x_1 with a probability of at least $1 - \alpha$, i.e. at least $1 - (1 - P)^n$. This gives:

$$n = \frac{\ln \alpha}{\ln(1 - P)} \tag{3}$$

In the case of fatigue life tests, Equation (3) indicates at a confidence level of $1 - \alpha$ that the true fatigue life at probability of failure P of the population can be expected to be greater than the minimum life observed from n specimens.

The same concept can be applied to the case of S-N data items, because the deviations in individual log-life data from the mean S-N curve are considered to be randomly distributed. Further, the variance is assumed to be constant for different stresses, as a model S-N curve is fitted by an ordinary least-squares method in many cases.

Table 1 gives some typical figures for the number of specimens. The numbers in the column corresponding to a confidence level of 95 % are used for reliability design purposes, those at the 50 % confidence level for exploratory tests and the others for general engineering applications.

Table 1 — Number of specimens required so that the minimum value of test data can be expected to fall below the true value for the population at a given level of probability of failure at various confidence levels

Probability of failure P (%)	Confidence level, $1 - \alpha$ (%)		
	50	90	95
	Number of specimens, n [a]		
50	1	3	4
10	7	22	28
5	13	45	58
1	69	229	298

[a] The values of n are rounded to the nearest whole number.

5.3 Allocation of specimens for testing

Specimens taken from the test materials shall be allocated to individual fatigue tests in principle in a random way, in order to minimize unexpected statistical bias. The order of testing of the specimens shall also be randomized in a series of fatigue tests.

When several test machines are used in parallel, specimens shall be tested on each machine in equal or nearly equal numbers and in a random order. The equivalence of the machines in terms of their performance shall be verified prior to testing.