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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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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

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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*.

This second edition cancels and replaces the first edition (ISO 12107:2003), which has been technically revised.

## 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. This International Standard includes a full methodology for application of the Bastenaire model as well as other more sophisticated relationships. It also addresses the analysis of runout (censored) data.

# 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.

Finally, for the $S$-$N$ case (discussed in Clause 8), this International Standard addresses only complete data. Runouts of censored data are not addressed.

## 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**
**degrees of freedom**
$\nu$
number calculated by subtracting from the total number of observations 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**
**mean**
$\mu$
sum of all the data in a population divided by the number of observations

**3.1.10**
**sample mean**
$\hat{\mu}$
sum of all the data in a sample divided by the number of observations

**3.1.11**
**standard deviation**
$\sigma$
positive square root of the mean squared standard deviation from the mean from a population.

**3.1.12**
**estimated standard deviation**
$\hat{\sigma}$
positive square root of the mean squared standard deviation from the mean of a sample.

## 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 long life

NOTE Historically, this has usually been defined as the stress generating a life at $10^7$ cycles.

**3.2.3**

**fatigue strength**

value of stress level $S$ at which a specimen would fail at a given fatigue life

NOTE This is expressed in megapascals.

**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 when conducting the test by the staircase method

NOTE This is expressed in megapascals.

# 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 are expressed in two ways: the distribution of fatigue life at a given stress and the distribution of strength at a given fatigue life (see References [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 frequently observed the distribution of fatigue life values at any stress is normal in the logarithmic metric. That is, the logarithms of the life values follow a normal distribution (See 6.4). 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 $\mu_x$ and $\sigma_x$ are, respectively, the mean and the standard deviation of $x$.

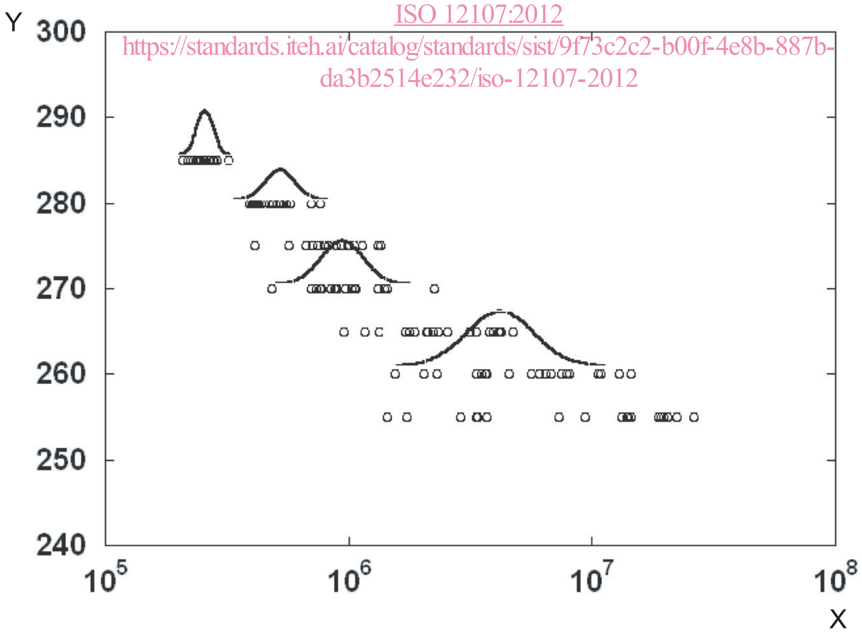
Formula (1) gives the cumulative probability of failure for $x$. This is the proportion of the population failing at lives less than or equal to $x$.

Formula (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. On occasion, this distribution may apply to lives at low stresses, but this special case is not addressed in this International Standard.

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 Reference [5]). The shape of the fatigue life distributions is demonstrated for explanatory purposes.



**Key**

X cycles to failure

Y stress amplitude, in MPa

**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**

### 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:

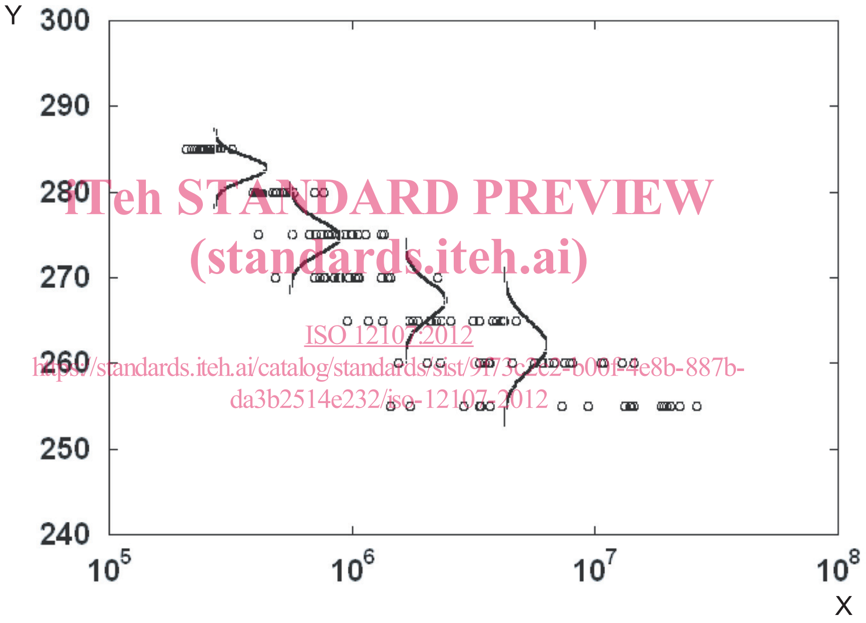
$$P(y) = \frac{1}{\sigma_y\sqrt{2\pi}} \int_{-\infty}^{y} \exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right] \mathrm{d}y \qquad (2)$$

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

Formula (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.

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 Reference [5]).



**Key**

X cycles to failure

Y stress amplitude, in MPa

**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**

## 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. A complete plan would include additional considerations.

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 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.

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 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.

When the test programme includes several independent test series, e.g. tests at different stress levels or on different materials for comparison purposes, each test series shall be carried out at equal or nearly equal rates of progress, so that all testing can be completed at approximately the same time.

## 6 Statistical estimation of fatigue life at a given stress

### 6.1 Testing to obtain fatigue life data

Conduct fatigue tests at a given stress, $S$, on a set of carefully prepared specimens to determine the fatigue life values for each. The number selected will be dependent upon the purpose of the test and the availability of test material. A set of seven specimens is recommended in this International Standard for exploratory tests. For reliability purposes, however, at least 28 specimens are recommended.

### 6.2 Plotting data on normal probability paper

Plot the fatigue lives on log-normal probability coordinates. The results should plot as a straight line. Should one or two data points (really a very low proportion of the data set) deviate from the curve, this is usually the result of invalid data. Examining test records and failed specimens is useful when there is non-conforming behaviour. The purpose is to identify a cause for such deviant behaviour to learn if these results can be discounted. Other statistical distributions e.g. Weibull may be evaluated. However, since the vast majority of unimodal fatigue results have proven to be distributed log-normally, the standard does not consider Weibull statistics. Subclause 8.3.3 gives some examples of normal probability plots constructed from data used to generate an $S$-$N$ curve. Refer to these plots to understand how they will appear when the data conform well to the assumption and in other cases when there might be some issues. Please note that for the present case, the y-axis will just be the property in question as opposed to the standardized residuals given the y-axis on the presented plots in 8.3.3.

One other issue is that if the data appear to support two distinct failure distributions, the data should be segregated by the root cause. For example, results for both surface and internal initiation sites should be separated into two groups and evaluated uniquely.

## 6.3 Estimating distribution parameters

Calculation of the sample mean is performed as follows:

$$\hat{\mu} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{3}$$

where

$\hat{\mu}$ is the sample mean;

$x_i$ is the $i$th observed value;

$n$ is the number of data points.

Note that the symbol “^” means an estimation based upon a sample.

The sample standard deviation is calculated using the following relationship:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \hat{\mu}\right)^2}{n-1}} \tag{4}$$

## 6.4 Quantitative evaluation of the assumption of normality

A number of statistical tests have been developed attempting to quantitatively consider the assumption of normality. These tests can sometimes generate conflicting results. However, one that seems quite useful is the Anderson-Darling Test. The details for performing this evaluation as well as others can be found in Reference [9]. Also, there are commercially available statistical software packages that perform quantitative evaluations of normality.

## 6.5 Estimating the lower limit of the fatigue life

Estimate the lower limit of the fatigue life at a given probability of failure, assuming a normal distribution, at the confidence level $1 - \alpha$ from the equation:

$$\hat{x}_{(P,1-\alpha)} = \hat{\mu}_x - k_{(P,1-\alpha,\nu)}\hat{\sigma}_x \tag{5}$$

The coefficient $k_{(P,\,1-\alpha,\,\nu)}$ is the one-sided tolerance limit for a normal distribution, as given in Table B.1. $P$ corresponds to the reliability of the prediction (say 99 % probability) and $1 - \alpha$ is the confidence of the reliability statement. These values are generated by integration of the non-central $t$ distribution with non-centrality parameter:

$$\delta = \sqrt{n} \tag{6}$$

The number of degrees of freedom, $\nu$, is the same number used in estimating the standard deviation. For the present case, this is $n - 1$.

A worked example is given in A.1.