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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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Contents

Page

Foreword v

Introduction vi

1 Scope 1
1.1 Objectives 1
1.2 Fatigue properties to be analysed 1
1.3 Limit of application 1

2 Normative references 2

3 Terms and definitions 2
3.1 Terms related to statistics 2
3.2 Terms related to fatigue 3

4 Statistical distributions in fatigue properties 4
4.1 Concept of distributions in fatigue 4
4.2 Distribution of fatigue life 4
4.3 Distribution of fatigue strength 5

5 Statistical planning of fatigue tests 6
5.1 Sampling 6
5.2 Allocation of specimens for testing 7

6 Statistical estimation of fatigue life at a given stress 7
6.1 Testing to obtain fatigue life data 7
6.2 Plotting data on normal probability paper 7
6.3 Estimating distribution parameters 7
6.4 Quantitative evaluation of the assumption of normality 8
6.5 Estimating the lower limit of the fatigue life 8

7 Statistical estimation of fatigue strength at a given fatigue life 9
7.1 Testing to obtain fatigue strength data 9
7.2 Statistical analysis of test data 9
7.3 Estimating the lower limit of the fatigue strength 10
7.4 Modified method when standard deviation is known 10

8 Statistical estimation of the *S*-*N* curve 11
8.1 Introduction 11
8.2 Estimation of regression parameters 15
8.2.1 Estimation of the parameters for the linear model 15
8.2.2 Estimation of the regression parameters for the quadratic model 16
8.3 Analysis approach 17
8.3.1 Plot the curve on the *S*-*N* diagram 17
8.3.2 Residuals plots 17
8.3.3 Normal probability plot 19
8.3.4 Quantitative measures of normality for the residuals 21
8.3.5 Remedial measures 22
8.3.6 Determination of the need for a quadratic model 22
8.4 Calculation of the lower tolerance limit 23
8.5 Experimental plan for the development of *S*-*N* curves 24

9 Test report 24
9.1 Presentation of test results 24
9.2 Fatigue strength at a given life 24

9.3 *S-N* curve ... 25
Annex A (informative) Examples of applications ... 26
A.1 Example of statistical estimation of fatigue life ... 26
A.2 Examples of statistical estimation of fatigue strength ... 28
A.2.1 Staircase method ... 28
A.2.2 Modified staircase method ... 29
A.3 Examples of statistical estimation of *S-N* curve ... 30
A.3.1 Example of force-contolled fatigue life data ... 30
A.3.2 Example of strain–controlled fatigue life data ... 32
A.4 Example of an experimental plan to develop *S-N* fatigue data ... 37
Annex B (informative) Statistical tables ... 38
Bibliography ... 40

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is 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.

It shall be noted that his ISO standard does not address safety or health concerns, should such issues exist, that may be associated with its use or application. The user of this standard has the sole responsibility to establish any appropriate safety and health concerns as well as to determine the applicability of any national or local regulatory limitations regarding the use of this standard.

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.

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

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 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
v
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
μ
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
σ
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.

3.1.13
estimated stress or strain
$\hat{S}$
at a given N

3.1.14
one-sided tolerance limit for a normal distribution
k
number dependent on the failure probability, the confidence level and the degrees of freedom.

3.2 Terms related to fatigue

3.2.1
fatigue life
N
number of cycles observed in the test to achieve the intended failure criterion.

Note The dependent variable in a fatigue test conducted under force or strain control.

3.2.2
fatigue strength
value of stress level S at which a specimen would fail at a given fatigue life

Note 1 to entry: This is expressed in megapascals.

3.2.3
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

3.2.4
stress or strain level
S
Intensity of the applied test stimulus

Note 1 to entry: The independent variable in a fatigue test conducted under stress or strain control. The stress or strain level can be expressed as amplitude, maximum or range

3.2.5
stress step
d
difference between neighbouring stress levels when conducting the test by the staircase method

Note 1 to entry: 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:

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

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

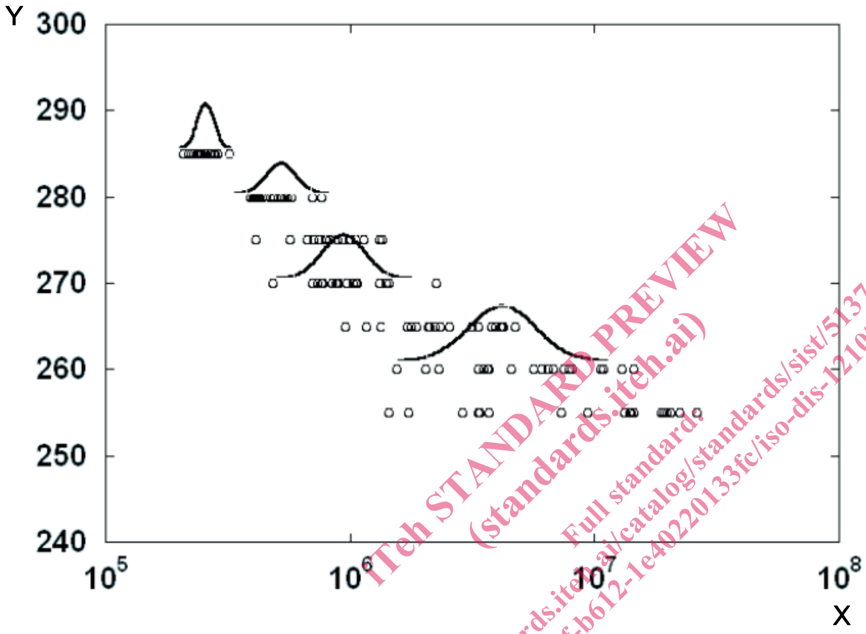
Equation (1) gives the cumulative probability of failure for *x*. This is the proportion of the population failing at lives less than or equal to *x*.

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. 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:

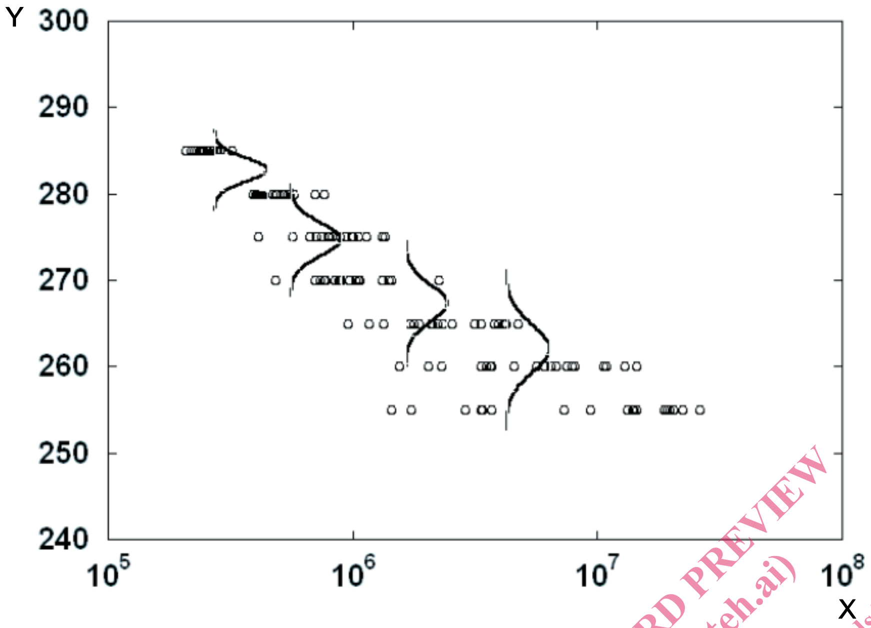
$$P(y) = \frac{1}{\sigma_y \sqrt{2\pi}} \int_{-\infty}^{y} \exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right] \mathrm{d}y \qquad (2)$$

where $y = S$ (at a given 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.

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 randomized. 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.

