BRITISH STANDARD

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Advanced technical ceramics — Mechanical properties of ceramic composites at room temperature — Determination of fatigue properties at constant amplitude

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ICS 81.060.30

British Standards

National foreword

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Hochleistungskeramik - Mechanische Eigenschaften von keramischen Verbundwerkstoffen bei Raumtemperatur - Bestimmung der Dauerschwingeigenschaften bei Belastung mit konstanter Amplitude

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Foreword

This document (EN 15156:2006) has been prepared by Technical Committee CEN/TC 184 "Advanced technical ceramics", the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by February 2007, and conflicting national standards shall be withdrawn at the latest by February 2007.

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1 Scope

This European Standard specifies the conditions for the determination of constant-amplitude of load or strain in uniaxial tension/tension or in uniaxial tension/compression cyclic fatigue properties of ceramic matrix composite materials (CMCs) with fibre reinforcement at room temperature.

This European Standard applies to all ceramic matrix composites with fibre reinforcement, unidirectional (1D), bi-directional (2D), and tri-directional (xD, where $2< x \leq 3$).

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.

EN 658-1, *Advanced technical ceramics — Mechanical properties of ceramic composites at room temperature — Part 1: Determination of tensile properties*

EN 1892, *Advanced technical ceramics — Mechanical properties of ceramic composites at high temperature under inert atmosphere — Determination of tensile properties*

EN 1893, *Advanced technical ceramics — Mechanical properties of ceramic composites at high temperature in air at atmospheric pressure — Determination of tensile properties*

EN 12291, *Advanced technical ceramics — Mechanical properties of ceramic composites at high temperature in air at atmospheric pressure — Determination of compression properties*

prCEN/TR 13233:2007[1], *Advanced technical ceramics — Notations and symbols*

EN ISO 7500-1, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system (ISO 7500-1:2004)*

EN ISO 9513, *Metallic materials — Calibration of extensometers used in uniaxial testing (ISO 9513:1999)*

ISO 3611, *Micrometer callipers for external measurement*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in prCEN/TR 13233:2007 and the following apply.

3.1
calibrated length, l
part of the test specimen which has uniform and minimum cross-section area

3.2
gauge length, L_0
initial distance between reference points on the test specimen in the calibrated length

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[1] To be published in 2007

3.3
initial cross-section area, S_o
initial cross-section area of the test specimen within the calibrated length, at the test temperature

NOTE Two initial cross-section areas of the test specimen can be defined:

- apparent cross-section area: this is the total area of the cross-section $S_{o\ app}$;
- effective cross-section area: this is the total area corrected by a factor, to account for the presence of a coating, $S_{o\ eff}$.

3.4
longitudinal deformation, A
change in the gauge length between reference points under an uniaxial force

3.5
strain, ε
relative change in the gauge length defined as the ratio A/L_o

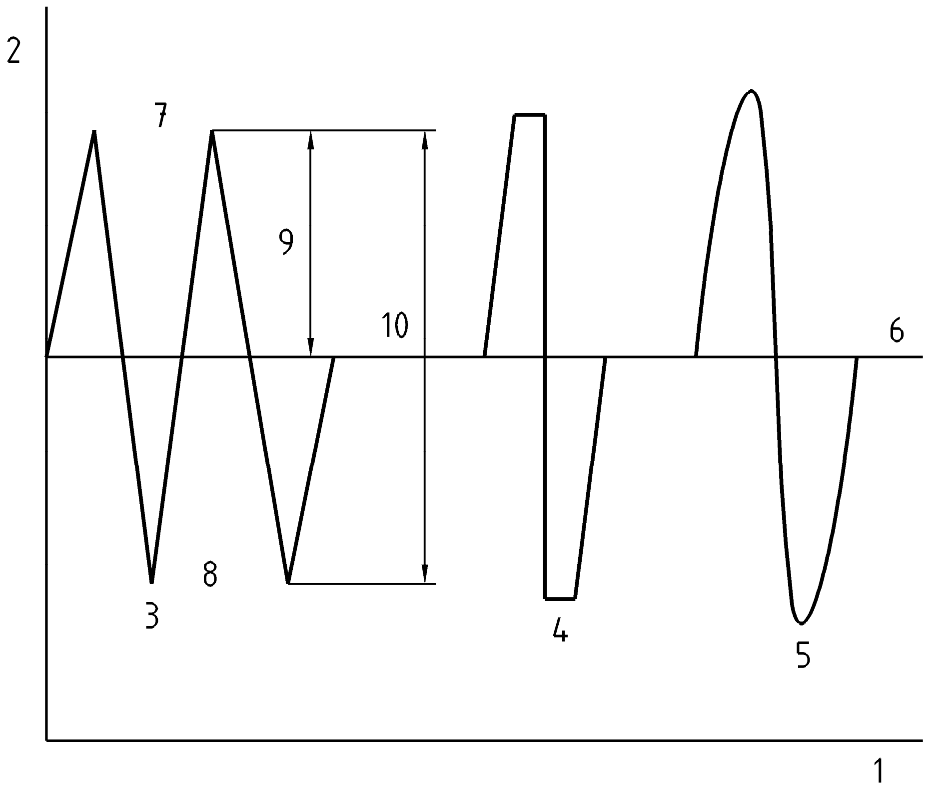
3.6
stress, σ
force supported by the test specimen at any time in the test, divided by the initial cross-section area

NOTE Two stresses can be distinguished:

- apparent stress, σ_{app}, when the apparent cross-section area (or total cross-section area) is used;
- effective stress, σ_{eff}, when the effective cross-section area is used.

Stress can be either in tension or in compression.

3.7
constant amplitude loading
in cyclic fatigue loading, constant wave form loading in which the peak loads and the valley loads are kept constant during the test (see Figure 1 for nomenclature relevant to cyclic fatigue testing)



Key

1	time	6	mean
2	control parameter (test mode)	7	peak (maximum)
3	triangular form	8	valley (minimum)
4	trapezoidal form	9	amplitude
5	sinusoidal form	10	range

Figure 1 — Cyclic fatigue nomenclature and wave forms

3.8 Cyclic fatigue phenomena

3.8.1
load ratio, R
in cyclic fatigue loading, the algebraic ratio of the two loading parameters of a cycle

NOTE the most widely used ratios are:

R = (minimum load/maximum load) or

R = (valley load/peak load).

3.8.2 Stress cyclic fatigue

3.8.2.1
maximum stress, σ_{max}
maximum applied stress during cyclic fatigue

3.8.2.2
minimum stress, σ_{min}
minimum applied stress during cyclic fatigue

3.8.2.3
mean stress, σ_m
average applied stress during cyclic fatigue such that:

$$\sigma_m = (\sigma_{max} + \sigma_{min})/2$$

3.8.2.4
stress amplitude, σ_a
difference between the maximum stress and the minimum stress, such that:

$$\sigma_a = (\sigma_{max} - \sigma_{min})/2 = \sigma_{max} - \sigma_m = \sigma_m - \sigma_{min}$$

3.8.3 Strain cyclic fatigue

3.8.3.1
maximum strain, ε_{max}
maximum applied strain during cyclic fatigue

3.8.3.2
minimum strain, ε_{min}
minimum applied strain during cyclic fatigue

3.8.3.3
mean strain, ε_m
average applied strain during cyclic fatigue such that:

$$\varepsilon_m = (\varepsilon_{max} + \varepsilon_{min})/2$$

3.8.3.4
strain amplitude, ε_a
difference between the maximum stress and the minimum stress, such that:

$$\varepsilon_a = (\varepsilon_{max} - \varepsilon_{min})/2 = \varepsilon_{max} - \varepsilon_m = \varepsilon_m - \varepsilon_{min}$$

3.8.4 Fatigue parameters

3.8.4.1
number of cycles, N
total number of loading cycles which is applied to the test specimen during the test

3.8.4.2
cyclic fatigue life, N_f
total number of loading cycles which is applied to the test specimen up to failure

3.8.4.3
time to failure, t_f
time duration required to obtain the number of cycles N_f

3.8.5 Stress-strain curve parameters

Stress-strain curve parameters are defined as given in Figure 2.

4 Principle

A test specimen of specified dimensions is heated to the testing temperature and tested in cyclic fatigue as follows:

— method A: the test specimen is cycled between two constant stress levels at a specified frequency;

— method B: the test specimen is cycled between two constant strain levels at a specified frequency.

The total number of cycles is recorded. If strain is not determined, only the life-time duration or the residual mechanical properties can be determined. If strain is determined, a number of stress-strain cycles are recorded at specified intervals to determine damage parameters, in addition to the life-time duration and residual mechanical properties.

NOTE Residual properties can be determined on the test specimens which have not failed during the test, using the methods described in the appropriate European Standards.

5 Significance and use

This test method enables characterization of the cyclic fatigue behaviour at constant amplitude of CMCs subjected to long duration loading. The simplest way to determine the fatigue properties of a material is to establish life-time diagrams. In these diagrams, the time to failure (or the cyclic fatigue life) is plotted versus stress (or strain) amplitude.

The complete life-time diagram requires the use of a great number of test specimens, which is expensive and time consuming. Hence, it is sufficient to know the cyclic-fatigue under specified stress (or strain) conditions, or to measure the fatigue limit. In any case, the typical fatigue test is defined by cyclic loading, constant amplitude, environment, temperature and frequency.

To better characterize the mechanical behaviour during a fatigue test, it is possible to determine several mechanical parameters from stress-strain curves. These parameters can then be plotted versus time or versus number of cycles. This displays the damage evolution during the cyclic loading. The following parameters can be considered (see Figure 2):

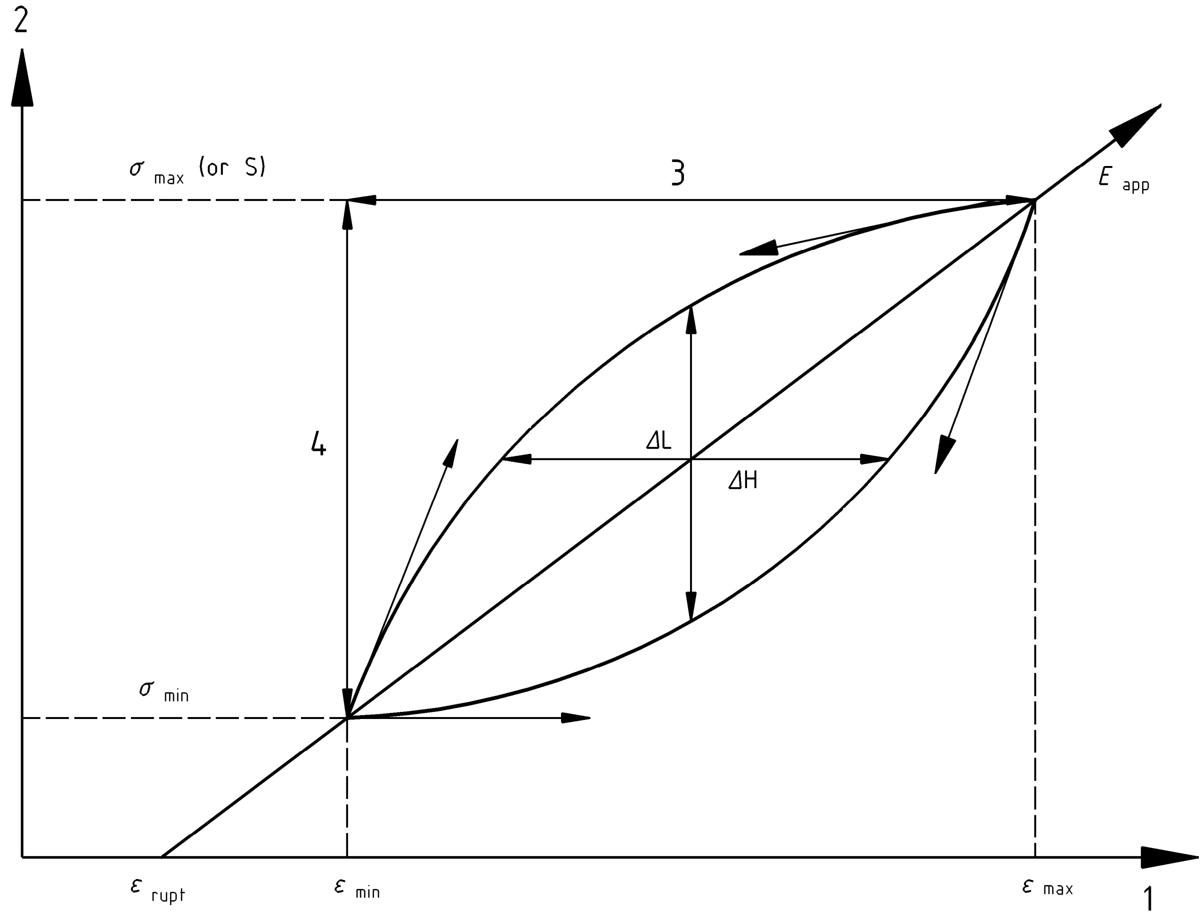
— the residual strain at zero load;

— the secant elastic modulus, or the relative damage parameters;

— the area of the stress-strain hysteresis loop, or the internal friction;

— the maximum strain, the minimum strain, or the difference between them for a selected cycle;

— some specific tangent elastic moduli, for example at the top or at the bottom of the stress-strain loop.



Key

1 strain (ε)

2 stress (σ)

3 width (L)

4 height (H)

Figure 2 — Parameters that can be considered to assess the cyclic fatigue behaviour

6 Apparatus

6.1 Fatigue test machine

The fatigue test machine shall be of a hydraulic type and shall be load control operated or strain control operated.

The system for measuring the force applied to the test specimen shall be specially designed for fatigue tests and shall conform to grade 1 or better in accordance with EN ISO 7500-1. This shall apply during actual test conditions. The machine shall be equipped with a cycle counter for the chosen test frequency.

6.2 Load train

The load train configuration shall ensure that the load indicated by the load cell and the load experienced by the test specimen are the same.

The attachment fixtures shall align the test specimen axis with that of the applied force.

The grip design shall prevent the test specimen from slipping.

The use of hydraulic grips is recommended.

6.3 Extensometer

If applicable, extensometry shall be capable of continuously recording the longitudinal deformation and compatible with the chosen test frequency. The extensometer shall conform to class 1 or better in accordance with EN ISO 9513.

The commonly used type of extensometer is the mechanical type.

In this case, the gauge length is the longitudinal distance between the two locations where the extensometer rods contact the test specimen.

NOTE Care should be taken to correct for changes in calibration of the extensometer which may occur as a result of operating under conditions different from those for calibration.

The extensometer performance shall not change because of the test duration.

Rod pressure on the test specimen shall be the minimum necessary to prevent slippage of the extensometer rods as well as failure initiation under the contact points.

6.4 Data recording system

A calibrated recorder may be used to record a force-deformation curve. The use of a digital data recording system combined with an analogue recorder is recommended.

6.5 Micrometers

Micrometers used for the measurement of the dimensions of the test specimen shall conform to ISO 3611.

7 Test specimens

The lifetime of CMCs depends, among other factors, on stress or strain. Therefore the configuration of the test specimen shall be designed to obtain a rupture in the gauge length. For this purpose, a dog-bone test specimen shall be used as specified in Figure 3 and Table 1.

In addition, the choice of the test specimen geometry depends on the nature of the material and of the reinforcement structure.

The volume in the gauge length shall be representative of the material. The total length l_t depends on the gripping system.

NOTE Generally, the total length is greater than 150 mm.

In the case of tensile-compressive fatigue tests, the test specimen configuration shall be chosen such as to avoid buckling failure, as defined in EN 12291.

Within the gauge length, any temperature variation shall remain within 30 °C of the test temperature.

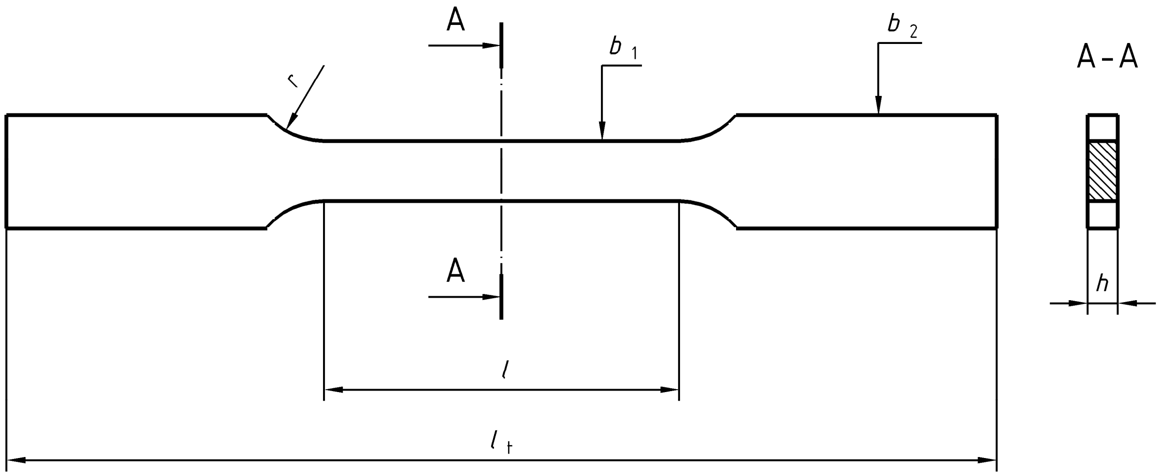


Figure 3 — Test specimen geometry

Table 1 — Recommended test specimen dimensions

Dimensions in millimetres

	1D, 2D and xD	Tolerance
l_t, total length	> 150	± 0,5
l, calibrated length	30 to 80	± 0,5
h, thickness	≥ 2	± 0,2
b_1, width in the calibrated length	8 to 20	± 0,2
b_2, width	$B_2 = \alpha\, b_1$ with α = 1,2 to 2	± 0,2
r, radius	> 30	± 2
Parallelism of machined parts	0,05	-

8 Test specimen preparation

8.1 Machining and preparation

During cutting out, care shall be taken to align the test specimen axis with the desired fibre related loading axis.

Machining parameters which avoid damage to the material shall be established and documented. These parameters shall be adhered to during test specimen preparation.

8.2 Number of test specimens

At least three valid test results, as specified in 9.3 are required for any condition.

9 Test procedure

9.1 Measurement of test specimen dimensions

The cross-section area shall be determined at the centre of the specimen and at each end of the gauge length.

The cross-section area varies with temperature and the variation is very difficult to measure. For this reason, the cross-section area shall be measured at room temperature.

Dimensions shall be measured to an accuracy of ± 0,01 mm. The arithmetic means of the measurements shall be used for calculations.

9.2 Testing technique

9.2.1 Specimen mounting

Install the test specimen in the gripping system with its longitudinal axis coincident with that of the test machine.

Care shall be taken not to induce flexural or torsional loads in the test specimen.

9.2.2 Setting the extensometer

If used, install the extensometer centrally within the calibrated length.

9.2.3 Measurements

- zero the load cell;
- zero the extensometer, if applicable;
- set the maximum number of cycles, N;
- for method A, set the maximum and minimum stress values;
- for method B, set the maximum and minimum strain values;
- set the frequency and the wave shape;

— start the fatigue test:

  — for method A, in load control mode;

  — for method B, in strain control mode;

— record the number of cycles N or N_f,

— if an extensometer is used, record the stress-strain loops up to the total number of cycles.

NOTE A specific computer program is recommended to control the test. Depending on the computerized facilities used, all the loops can be recorded. If this is not possible, the following sequence can be used to record stress versus strain:

  — every cycle for the first 10 cycles,

  — one cycle every 10 cycles between 10 and 100 cycles,

  — one cycle every 100 cycles between 100 and 1 000 cycles,

  — one cycle every 1 000 cycles between 1 000 and 10 000 cycles,

  — etc.

9.3 Test validity

The following circumstances shall invalidate a test for the determination of the lifetime duration:

— failure to specify and record test conditions;

— specimen slippage in the grips.

In addition, the following circumstances shall invalidate a test for the determination of the damage parameter:

— extensometer slippage;

— extensometer drift.

10 Calculation of results

10.1 Time to failure, t_f

Calculate the time to failure in accordance with the following equation:

$$t_f \text{ (hours)} = N_f / (f \times 3\,600)$$

where

N_f is the number of cycles required to obtain failure of the test specimen;

f is the frequency, in hertz (Hz).

10.2 Damage parameters

Calculate the damage parameter D_n for each recorded cycle, n, in accordance with the following equation:

$$D_n = 1 - \frac{E_{n,app}}{E_{1,app}}$$

where

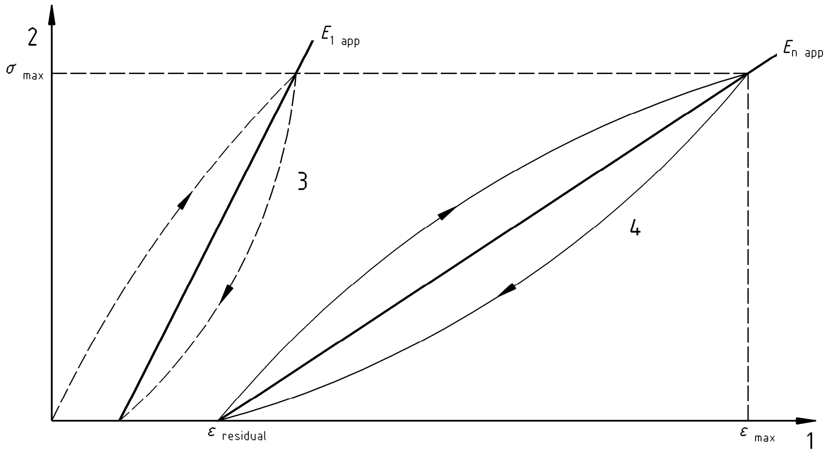
D_n	is the damage parameter at the nth fatigue cycle;
$E_{n,app}$	is the secant modulus of the nth fatigue loop (see Figure 4);
$E_{1,app}$	is the secant modulus of the first fatigue loop (see Figure 4);
$E_{n app}$	is equal to: $(\sigma_{max}) / (\varepsilon_{max} - \varepsilon_{nresidual})$ (see Figure 4).
$\varepsilon_{nresidual}$	is equal to: $(\varepsilon_{unl}+\varepsilon_{l})/2$ (see Figure 4 b)).

The damage parameters, D_n, ε_{max}, ε_{resid} can be plotted versus the number of cycles, N. For N, a log scale is almost always used, although a linear scale may also be used. Figures 4 a) to 4 c) represent three cases of cyclic fatigue of CMCs.

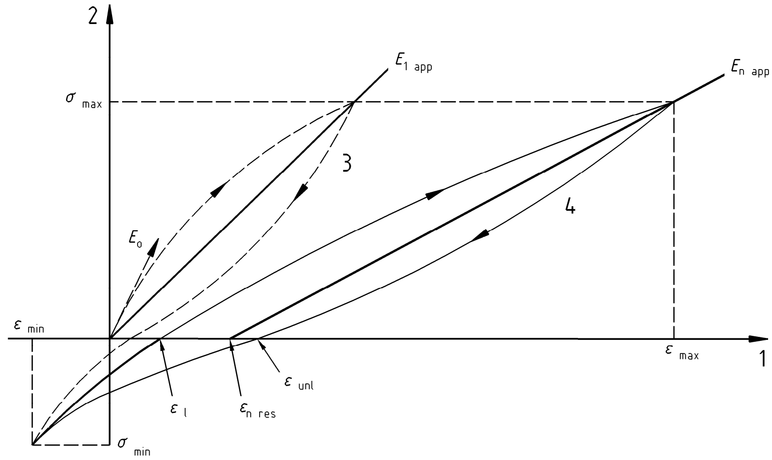
NOTE Annex A shows the schematic evolution of E under different circumstances of damage and creep.

10.3 Residual properties

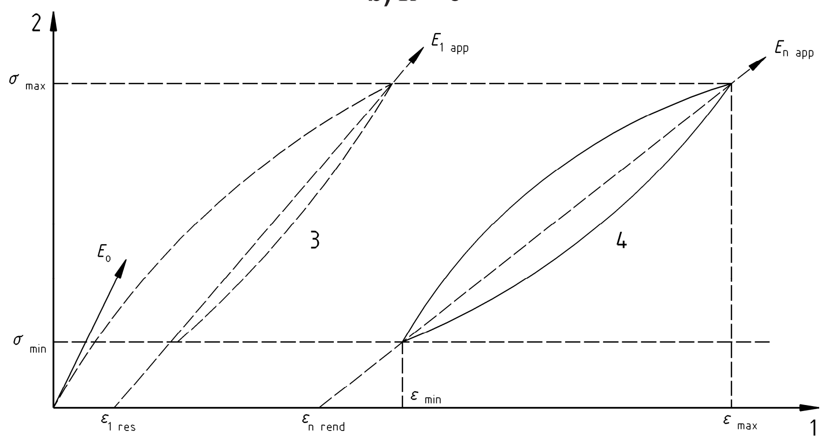
When rupture does not occur before the end of the test, the test specimen shall be tested to rupture in accordance with EN 1892, EN 1893 or EN 658-1.



a) R = 0



b) R < 0



c) R > 0

Key

1 strain (ε)

2 stress (σ)

3 cycle 1

4 Cycle n

ε_l loading

ε_{unl} unloading

Figure 4 — Fatigue stress-strain curves with a) R = 0, b) R < 0 and c) R > 0

11 Test report

The test report shall contain the following information:

a) name and address of the testing establishment;

b) date of the test, unique identification of report and of each page, customer's name, address and signature;

c) a reference to this European Standard, i.e. EN 15156;

d) test specimen drawing or reference;

e) description of the test material (material type, manufacturing code, batch number);

f) description of the test set up: extensometer, gripping system, load cell;

g) frequency in hertz;

h) wave form;

i) maximum and minimum stress (method A);

j) maximum and minimum strain (method B);

k) number of cycles to failure; if test is stopped at a specified number of cycles without failure occurring it shall be so registered;

l) residual properties (if applicable);

m) number of tests carried out and number of valid results obtained;

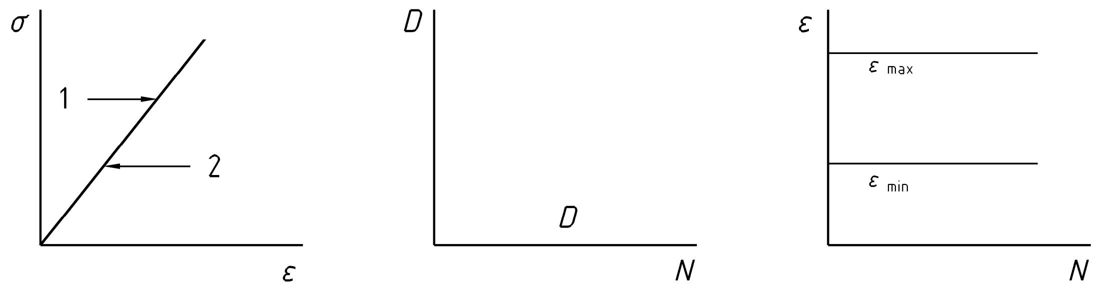
n) damage parameter, if applicable;

o) failure location of all the specimens used for obtaining the above results, if applicable.

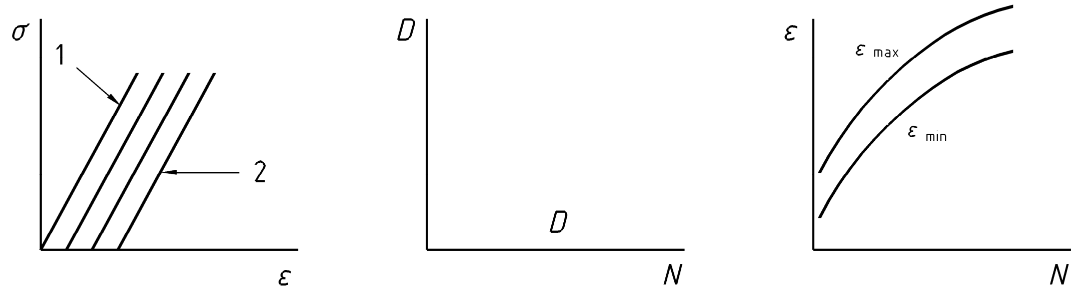
Annex A
(informative)

Schematic evolution of *E*

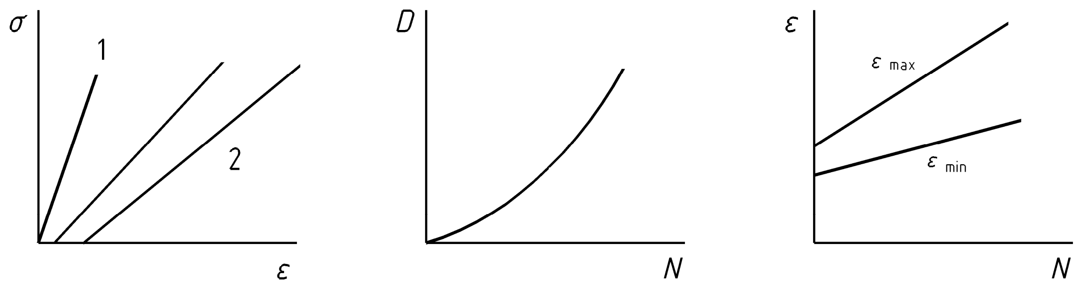
Figure A.1 shows a schematic evolution of *E* where there is a) no damage, b) creep but no fatigue damage and c) fatigue damage and eventual creep.



a) No damage



b) No fatigue damage – only creep



c) Fatigue damage plus eventual creep

Key

1 first cycle

2 last cycle

Figure A.1 — Schematic evolution of *E* with a) no damage, b) creep but no fatigue damage and c) fatigue damage and eventual creep

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