BS EN 61788-6:2011

BSI Standards Publication

Superconductivity

Part 6: Mechanical properties measurement — Room temperature tensile test of Cu/Nb-Ti composite superconductors

National foreword

This British Standard is the UK implementation of EN 61788-6:2011. It is identical to IEC 61788-6:2011. It supersedes BS EN 61788-6:2008, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee L/-/90 Super Conductivity.

A list of organizations represented on this committee can be obtained on request to its secretary.

ISBN 978 0 580 65698 9

ICS 29.050; 77.040.10

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2011.

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 61788-6

August 2011

ICS 29.050; 77.040.10

Supersedes EN 61788-6:2008

English version

Superconductivity - Part 6: Mechanical properties measurement - Room temperature tensile test of Cu/Nb-Ti composite superconductors
(IEC 61788-6:2011)

Supraconductivité -
Partie 6: Mesure des propriétés mécaniques -
Essai de traction à température ambiante des supraconducteurs composites de Cu/Nb-Ti
(CEI 61788-6:2011)

Supraleitfähigkeit -
Teil 6: Messung der mechanischen Eigenschaften -
Messung der Zugfestigkeit von Cu/Nb-Ti-Verbundsupraleitern bei Raumtemperatur
(IEC 61788-6:2011)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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Foreword

The text of document 90/267/FDIS, future edition 3 of IEC 61788-6, prepared by IEC TC 90, Superconductivity was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61788-6:2011.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2012-05-15
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2014-08-15

This document supersedes EN 61788-6:2008.

EN 61788-6:2011 includes the following significant technical changes with respect to EN 61788-6:2008:

– specific example of uncertainty estimation related to mechanical tests was supplemented as Annex C.

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

Endorsement notice

The text of the International Standard IEC 61788-6:2011 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 61788-5	NOTE Harmonized as EN 61788-5.
ISO 3611:2010	NOTE Harmonized as EN ISO 3611:2010 (not modified).

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-815	-	International Electrotechnical Vocabulary - Part 815: Superconductivity	-	-
ISO 376	-	Metallic materials - Calibration of force-proving instruments used for the verification of uniaxial testing machines	EN ISO 376	-
ISO 6892-1	-	Metallic materials - Tensile testing - Part 1: Method of test at room temperature	EN ISO 6892-1	-
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	EN ISO 7500-1	-
ISO 9513	-	Metallic materials - Calibration of extensometers used in uniaxial testing	EN ISO 9513	-

CONTENTS

INTRODUCTION

The Cu/Nb-Ti superconductive composite wires currently in use are multifilamentary composite material with a matrix that functions as a stabilizer and supporter, in which ultrafine superconductor filaments are embedded. A Nb-40~55 mass % Ti alloy is used as the superconductive material, while oxygen-free copper and aluminium of high purity are employed as the matrix material. Commercial composite superconductors have a high current density and a small cross-sectional area. The major application of the composite superconductors is to build superconducting magnets. While the magnet is being manufactured, complicated stresses are applied to its windings and, while it is being energized, a large electromagnetic force is applied to the superconducting wires because of its high current density. It is therefore indispensable to determine the mechanical properties of the superconductive wires, of which the windings are made.

SUPERCONDUCTIVITY –

Part 6: Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors

1 Scope

This part of IEC 61788 covers a test method detailing the tensile test procedures to be carried out on Cu/Nb-Ti superconductive composite wires at room temperature.

This test is used to measure modulus of elasticity, 0,2 % proof strength of the composite due to yielding of the copper component, and tensile strength.

The value for percentage elongation after fracture and the second type of 0,2 % proof strength due to yielding of the Nb-Ti component serves only as a reference (see Clauses A.1 and A.2).

The sample covered by this test procedure has a round or rectangular cross-section with an area of 0,15 mm^2 to 2 mm^2 and a copper to superconductor volume ratio of 1,0 to 8,0 and without the insulating coating.

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.

IEC 60050-815, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

ISO 376, *Metallic materials – Calibration of force-proving instruments used for the verification of uniaxial testing machines*

ISO 6892-1, *Metallic materials – Tensile testing – Part 1: Method of test at room temperature*

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 9513, *Metallic materials – Calibration of extensometers used in uniaxial testing*

3 Terms and definitions

For the purposes of this document, the definitions given in IEC 60050-815 and ISO 6892-1, as well as the following, apply.

3.1
tensile stress
tensile force divided by the original cross-sectional area at any moment during the test

3.2
tensile strength
R_m
tensile stress corresponding to the maximum testing force

NOTE The symbol σ_{UTS} is commonly used instead of R_m.

3.3
extensometer gauge length
length of the parallel portion of the test piece used for the measurement of elongation by means of an extensometer

3.4
distance between grips
L_g
length between grips that hold a test specimen in position before the test is started

3.5
0,2 % proof strength
$R_{p0,2}$ (see Figure 1)
stress value where the copper component yields by 0,2 %

NOTE 1 The designated stress, $R_{p0,2A}$ or $R_{p0,2B}$ corresponds to point A or B in Figure 1, respectively. This strength is regarded as a representative 0,2 % proof strength of the composite. The second type of 0,2 % proof strength is defined as a 0,2 % proof strength of the composite where the Nb-Ti component yields by 0,2 %, the value of which corresponds to the point C in Figure 1 as described complementarily in Annex A (see Clause A.2).

NOTE 2 The symbol $\sigma_{0,2}$ is commonly used instead of $R_{p0,2}$.

3.6
modulus of elasticity
E
gradient of the straight portion of the stress-strain curve in the elastic deformation region

4 Principle

The test consists of straining a test piece by tensile force, generally to fracture, for the purpose of determining the mechanical properties defined in Clause 3.

5 Apparatus

5.1 Conformity

The test machine and the extensometer shall conform to ISO 7500-1 and ISO 9513, respectively. The calibration shall obey ISO 376. The special requirements of this standard are presented here.

5.2 Testing machine

A tensile machine control system that provides a constant cross-head speed shall be used. Grips shall have a structure and strength appropriate for the test specimen and shall be constructed to provide an effective connection with the tensile machine. The faces of the grips shall be filed or knurled, or otherwise roughened, so that the test specimen will not slip on them during testing. Gripping may be a screw type, or pneumatically or hydraulically actuated.

5.3 Extensometer

The weight of the extensometer shall be 30 g or less, so as not to affect the mechanical properties of the superconductive wire. Care shall also be taken to prevent bending moments from being applied to the test specimen (see Clause A.3).

6 Specimen preparation

6.1 Straightening the specimen

When a test specimen sampled from a bobbin needs to be straightened, a method shall be used that affects the material as little as possible.

6.2 Length of specimen

The total length of the test specimen shall be the inward distance between grips plus both grip lengths. The inward distance between the grips shall be 60 mm or more, as requested for the installation of the extensometer.

6.3 Removing insulation

If the test specimen surface is coated with an insulating material, that coating shall be removed. Either a chemical or mechanical method shall be used, with care taken not to damage the specimen surface (see Clause A.4).

6.4 Determination of cross-sectional area (S_o)

A micrometer or other dimension-measuring apparatus shall be used to obtain the cross-sectional area of the specimen after the insulation coating has been removed. The cross-sectional area of a round wire shall be calculated using the arithmetic mean of the two orthogonal diameters. The cross-sectional area of a rectangular wire shall be obtained from the product of its thickness and width. Corrections to be made for the corners of the cross-sectional area shall be determined through consultation among the parties concerned (see Clause A.5).

7 Testing conditions

7.1 Specimen gripping

The test specimen shall be mounted on the grips of the tensile machine. At this time, the test specimen and tensile loading axis must be on a single straight line. Sand paper may be inserted as a cushioning material to prevent the gripped surfaces of the specimen from slipping and fracturing (see Clause A.6).

7.2 Pre-loading and setting of extensometer

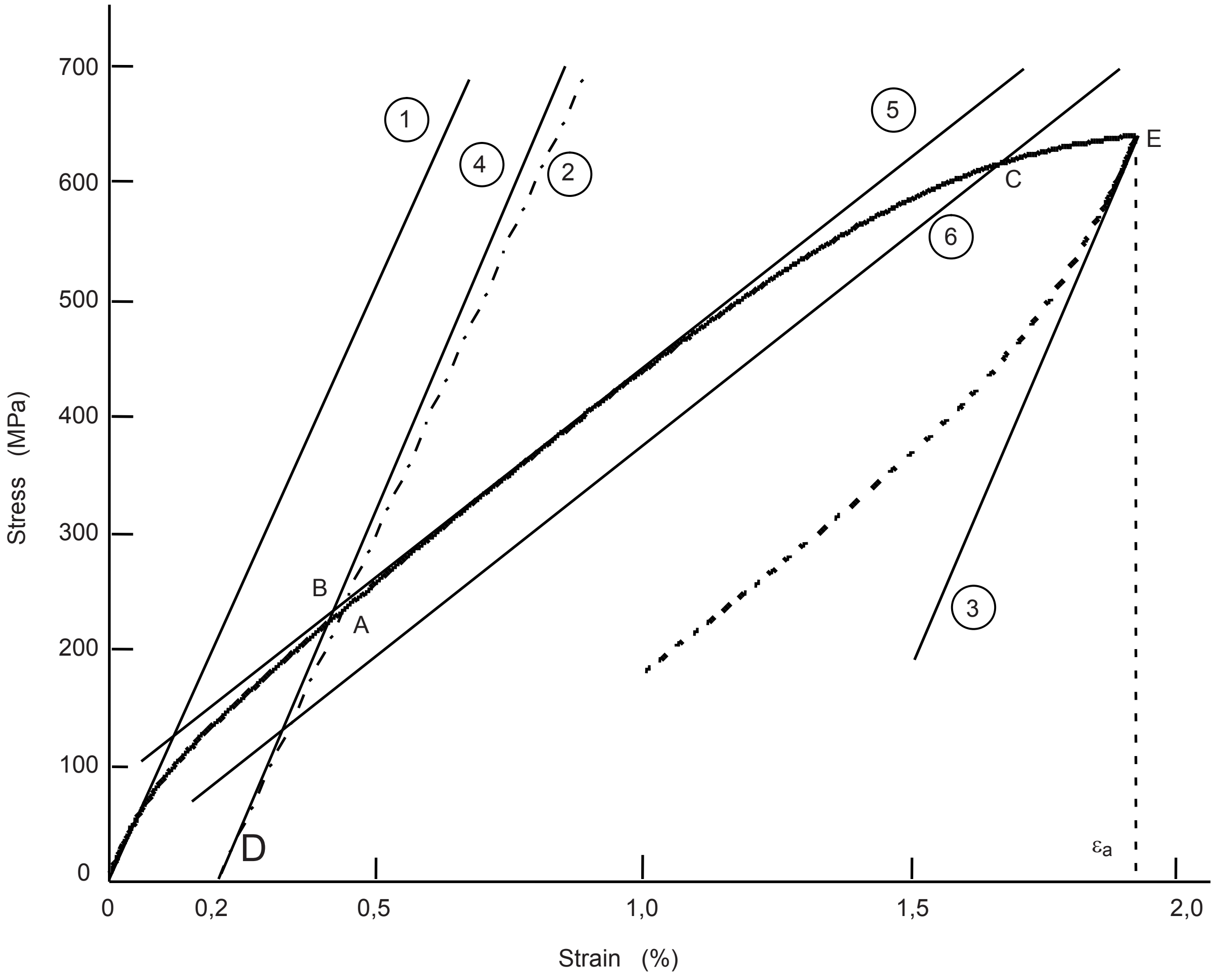
If there is any slack in the specimen when it is mounted, a force not greater than one-tenth of the 0,2 % proof strength of the composite shall be applied to take up the slack before the extensometer is mounted. When mounting the extensometer, care shall be taken to prevent the test specimen from being deformed. The extensometer shall be mounted at the centre between the grips, aligning the measurement direction with the specimen axis direction. After installation, loading shall be zeroed.

7.3 Testing speed

The strain rate shall be 10^{-4}/s to 10^{-3}/s during the test using the extensometer. After removing the extensometer, the strain rate may be increased to a maximum of 10^{-3}/s.

7.4 Test

The tensile machine shall be started after the cross-head speed has been set to the specified level. The signals from the extensometer and load cell shall be plotted on the abscissa and ordinate, respectively, as shown in Figure 1. When the total strain has reached approximately 2 %, reduce the force by approximately 10 % and then remove the extensometer. The step of removing the extensometer can be omitted in the case where the extensometer is robust enough not to be damaged by the total strain and the fracture shock of this test. At this time, care shall be taken to prevent unnecessary force from being applied to the test specimen. Then, increase loading again to the previous level and continue testing until the test specimen fractures. Measurement shall be made again if a slip or fracture occurs on the gripped surfaces of the test specimen.



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Key

① Initial loading line

② Line shifted by an offset of 0,2% parallel to the initial loading line

③ Unloading line

④ Line shifted by an offset of 0,2% parallel to the unloading line

⑤ Second linear part of loading line

⑥ Line shifted by an offset of 0,2% parallel to the second linear loading line

NOTE 1 When the total strain has reached ~2 % (point E), the load is reduced by 10 % and the extensometer is removed, if necessary. Then, the load is increased again.

NOTE 2 The slope of the initial loading line is usually smaller than that of the unloading line. Then, two lines can be drawn from the 0,2 % offset point on the abscissa to obtain 0,2 % proof strength of the composite due to yielding of the copper component. Point A is obtained from the initial loading line, and Point B is obtained from the unloading line. Point C is the second type of 0,2 % proof strength of the composite where the Nb-Ti component yields.

Figure 1 – Stress-strain curve and definition of modulus of elasticity and 0,2 % proof strengths

8 Calculation of results

8.1 Tensile strength (R_m)

Tensile strength R_m shall be the maximum force divided by the original cross-sectional area of the wire before loading.

8.2 0,2 % proof strength ($R_{p0,2A}$ and $R_{p0,2B}$)

The 0,2 % proof strength of the composite due to yielding of the copper component is determined in two ways from the loading and unloading stress-strain curves as shown in Figure 1. The 0,2 % proof strength under loading $R_{p0,2A}$ shall be determined as follows: the initial linear portion under loading of the stress-strain curve is moved 0,2 % in the strain axis (0,2 % offset line under loading) and the point A at which this linear line intersects the stress-strain curve shall be defined as the 0,2 % proof strength under loading. The 0,2 % proof strength of the composite under unloading $R_{p0,2B}$ shall be determined as follows: the linear portion under unloading is to be moved parallel to the 0,2 % offset strain point. The intersection of this line with the stress-strain curve determines the point B that shall be defined as the 0,2 % proof strength. This measurement shall be discarded if the 0,2 % proof strength of the composite is less than three times the pre-load specified in 7.2.

Each 0,2 % proof strength shall be calculated using formula (1) given below:

$$R_{p0,2i} = F_i / S_o \qquad (1)$$

where

$R_{p0,2i}$ is the 0,2 % proof strength (MPa) at each point;

F_i is the force (N) at each point;

S_o is the original cross-sectional area (in square millimetres) of the test specimen;

Further, i = A and B.

8.3 Modulus of elasticity (E_o and E_a)

Modulus of elasticity shall be calculated using the following formula and the straight portion, either of the initial loading curve or of the unloading one.

$$E = \Delta F\ (1 + \varepsilon_a)/(S_o\ \Delta\varepsilon) \qquad (2)$$

where

E is the modulus of elasticity (MPa);

ΔF is the increments (N) of the corresponding force;

$\Delta\varepsilon$ is the increment of strain corresponding to ΔF;

ε_a is the strain just after unloading as shown in Figure 1.

E is designated as E_o when using the initial loading curve ($\varepsilon_a = 0$), and as E_a when using the unloading curve ($\varepsilon_a \neq 0$).

9 Uncertainty

Unless otherwise specified, measurements shall be carried in a temperature range between 280 K and 310 K. A force measuring cell with a combined standard uncertainty not greater than 0,5 % shall be used. An extensometer with a combined standard uncertainty not greater than 0,5 % shall be used. The dimension-measuring apparatus shall have a combined standard uncertainty not greater than 0,1 %. The target combined standard uncertainties are defined by root square sum (RSS) procedure, which is given in Annex B.

There are no reliable experimental data with respect to uncertainties on moduli of elasticity and 0,2 % proof strengths as mentioned in Clause A.7. As described in Annex C, on the other hand, their uncertainties could be evaluated from the experimental conditions, of which parts are indicated above like uncertainty of force measuring cell. Consequently the relative expanded uncertainties (k=2) for the modulus of elasticity, E_o , and the 0,2 % proof strength, $R_{p0,2A}$, are expected to be 2, 0 % (N=1) and 0,78 % (N=1), respectively, where N indicates the time of repeated tests.

NOTE Uncertainties reported in the present text, if used for the purpose of practical assessment, have to be taken under the specific considerations with detailed caution as indicated in Annex B.

10 Test report

10.1 Specimen

a) Name of the manufacturer of the specimen
b) Classification and/or symbol
c) Lot number

The following information shall be reported as necessary.

d) Raw materials and their chemical composition
e) Cross-sectional shape and dimension of the wire
f) Filament diameter
g) Number of filaments
h) Twist pitch of filaments
i) Copper to superconductor ratio

10.2 Results

a) Tensile strength (R_m)
b) 0,2 % proof strengths ($R_{p0,2A}$ and $R_{p0,2B}$)
c) Modulus of elasticity (E_o and E_a with ε_a)

The following information shall be reported as necessary.

d) Second type of 0,2 % proof strength ($R_{p0,2C}$)
e) Percentage elongation after fracture (A)

10.3 Test conditions

a) Cross-head speed
b) Distance between grips
c) Temperature

The following information shall be reported as necessary.

d) Manufacturer and model of testing machine
e) Manufacturer and model of extensometer
f) Gripping method

Annex A
(informative)

Additional information relating to Clauses 1 to 10

A.1 General

This annex gives reference information on the variable factors that can seriously affect the tensile test methods, together with some precautions to be observed when using the standard.

A.2 Percentage elongation after fracture (A)

In Cu/NbTi superconductive wires there is a difference in strength between the copper and NbTi, and the wire is often deformed in waves by the shock of fracture. In such a case, it is difficult to find the elongation accurately after fracture using the butt method. Hence, the measurement of elongation after fracture should serve only as a reference. The movement of the cross-head may be used to find the approximate value for elongation after fracture, instead of using the butt method, as shown below. To use this method, the cross-head position at fracture must be recorded. Use the following formula to obtain the elongation after fracture, given in percentage.

$$A = 100\ (L_u - L_c)\ /\ L_c \tag{A.1}$$

where

A is the percentage elongation after fracture;

L_c is the initial distance between cross-heads;

L_u is the distance between cross-heads after fracture.

A.3 Second type of 0,2 % proof strength ($R_{p0,2C}$)

The second type of 0,2 % proof strength, at which the Nb-Ti component yields, is defined reasonably on the basis of the rule-of-mixture for the bimetallic composite including continuous filaments. As indicated in Figure 1, it should be the stress $R_{p0,2C}$ corresponding to point C, at which the straight portion of the loading curve after the point A is moved by 0,2 % along the strain axis intersects the stress-strain curve. The relevant straight portion is usually observed for the commercial Cu/Nb-Ti superconductive wires, because the copper component deforms plastically in a linear behaviour. Often the stress-strain curve does not show any straight line, but is rounded off for some wires, when they have high copper/non-copper ratio and are highly cold worked. It has been empirically made clear that the rounded-off appearance is observed when the following k-factor is less than 0,4:

$$k = (R_m - R_{p0,2A})\ /R_{p0,2A} \tag{A.2}$$

The $R_{p0,2C}$ is one of the important parameters describing the mechanical property of the composite material in the scientific viewpoint, but its use is not always demanded in the engineering sense.

A.4 Extensometer

When using a special type of extensometer, which is attached with an unremovable spacer for determining the gauge length, it may introduce a problem during the unloading of the wire to zero force. To avoid a compressive force on the spacer, the actual gauge length must be adjusted during installation with sufficient clearance. If the clearance after unloading is not negligible, it must be included in calculating the strain values.

If the test specimen is thin and the extensometer is relatively heavy, any bending moment caused by the weight of the extensometer can stress the specimen, eventually resulting in the specimen yielding. To avoid this, a light extensometer with a balance weight is to be carefully attached. Alternatively, a sufficiently light extensometer without a balance weight is also acceptable to use. Figure A.1 shows an extensometer made with a Ti alloy, with a total mass of about 3 g. It is so light that even a single use without a balance weight could provide enough uncertainty according to the procedure of the present standard. Figure A.2 shows one of the lightest extensometers commercially available, with a total mass of 31 g together with a balance weight. Using it, a round robin test (RRT) was conducted in Japan and good results were obtained. The results were used to establish the present international standard.

Dimensions in millimetres

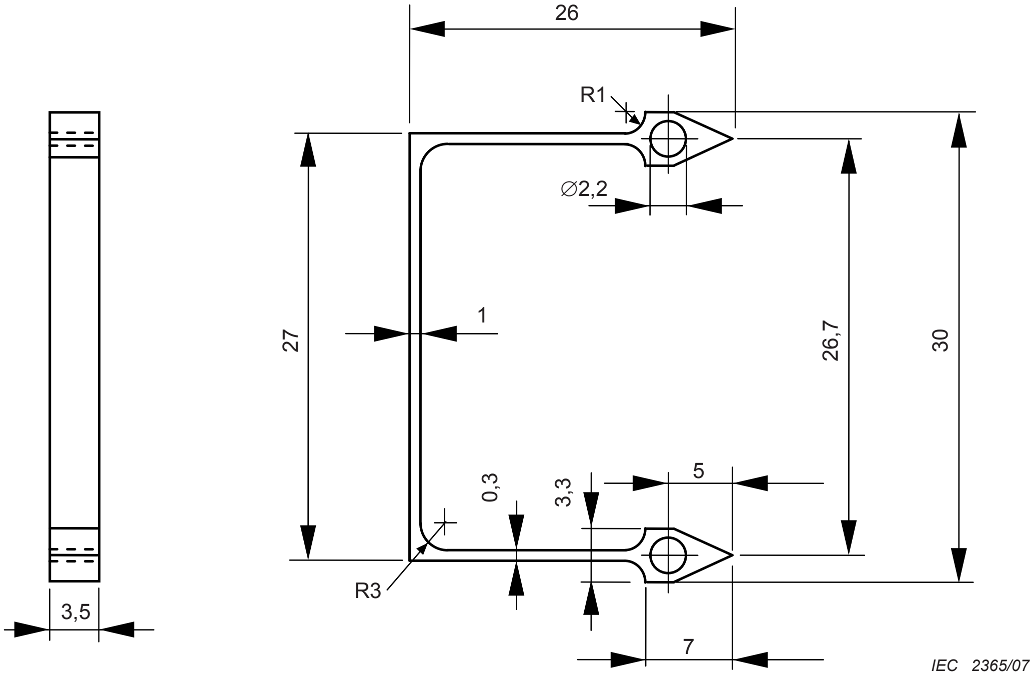
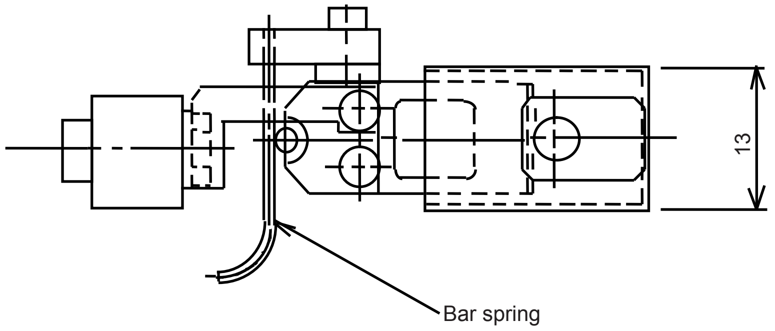


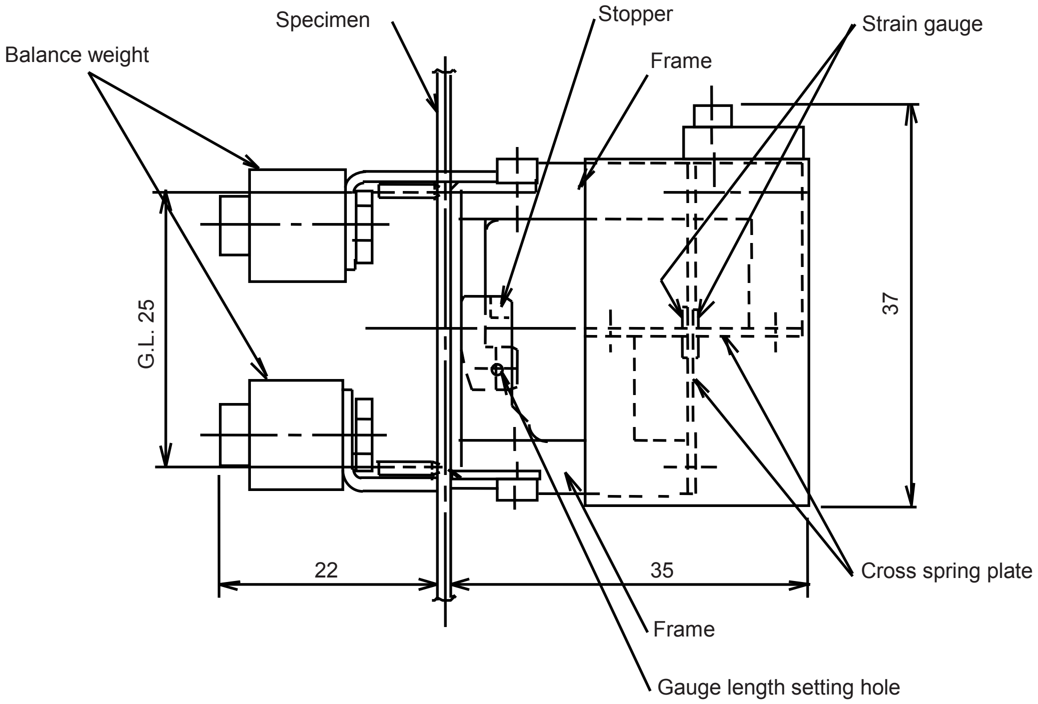
Figure A.1 – An example of the light extensometer, where R1 and R3 indicate the corner radius

Dimensions in millimetres

a) Top view



b) Side view



IEC 1598/11

Figure A.2 – An example of the extensometer provided with balance weight and vertical specimen axis

NOTE Further information about extensometers is obtainable from the Japanese National Committee of IEC/TC90, ISTEC, 10-13, Shinonome 1-chome Koto-ku, Tokyo 135-0062, Japan, Tel 81-3-3536-7214, Fax 81-3-3536-7318, e-mail Koki TSUNODA <tc90tsunoda@istec.or.jp>

Since the superconductive composite wire is covered with a soft copper, a scratch in the surface of the specimen made as it is mounted can be a starting point of fracture. Care should therefore be taken when handling the specimen.

A.5 Insulating coating

The coating on the surface of the test specimen should be removed using an appropriate organic solvent that would not damage the specimen. If the coating material is not dissolved by the organic solvent, a mechanical method should be used with care to prevent the copper from being damaged. If the coating is not removed, it affects the strength to only a small extent. For example, tensile strength decreases by less than 3 % for a low-strength wire which has a high copper ratio of 7. The coating is not designed as a structural component. An analysis of measurement as a three-component composite, i.e. copper, Nb-Ti and insulating coating, is too complicated to conduct. Therefore this test method covers a bare wire in order to maintain the level of uncertainty.

A.6 Cross-sectional area

Where even lower uncertainty is required, the cross-sectional area may be obtained by correcting the radius of the corner of the rectangular wire finished by dies, using the value given on the manufacturing specifications. For rolling or Turk's-head finish, the radius of the corner is not controlled and a correction is made using a microphotograph of the cross-section.

A.7 Gripping force

A weak gripping force results in slippage and a strong gripping force can break the gripped surface. Care should therefore be used when adjusting the gripping force.

A.8 Uncertainty

The Japanese National Committee of IEC TC90 fulfilled the domestic RRT in 1996 by contributions of eight research groups [1] in order to evaluate only the coefficient of variation of experimental data on moduli of elasticity and 0,2 % proof strengths [2], but not their uncertainties. It is, however, not possible to deduce their uncertainties at the present time, because their original data have been insufficient to evaluate uncertainties. Only the way to know the uncertainty is to evaluate it by using the numerical computation based on type B statistics as the procedure is given in Annex C and its results are described in Clause 9 of the main text.

Empirical facts with respect to the scattering source of measured values are described in the following. The modulus of elasticity E_o determined under the loading curve was found to be always smaller than the modulus E_a under unloading. The reason is attributed to the following handling issues: the bending of the wire specimen, the misalignment of sample gripping with respect to the load axis and a weak grip, and so on. Also, it is pointed out that the copper component is in a plastic state at room temperature before the test, depending on a degree of thermal contraction during cooling from the heat treating temperature. As a whole, the initial loading curve with non-linearity causes the result of $E_\mathrm{o} < E_\mathrm{a}$.

The German National Committee of IEC TC90 reported that the modulus of elasticity can be determined with small uncertainty when adopting an initial linear loading at zero-offset. This low uncertainty was achieved by using two light extensometers (Figure A.1) which enabled the cancelling of the possible initial bending effects and ensured a high degree of linearity for the zero-offset loading line.

Care must be taken while handling specimens in order not to induce strain to the copper component. Otherwise, the 0,2 % proof strength of the composite due to yielding of the copper component would increase due to work hardening. Allowable pre-loading limit should be taken into consideration in this fact.

The second type of 0,2 % proof strength $R_\mathrm{p0,2C}$ is the quantity determined with the lowest uncertainty, that should serve only as reference. Care must, however, be taken to ensure an existence of a straight portion in the stress-strain curve after the point A in Figure 1

A.9 Reference documents of Annex A

[1] SHIMADA, M., HOJO, M., MORIAI, H. and OSAMURA. K. *Jpn. Cryogenic Eng*, 1998, 33, p. 665.

[2] OSAMURA, K., NYILAS, A., SHIMADA, M., MORIAI, H., HOJO, M., FUSE T. and SUGANO, M. *Adv. Superconductivity*, 1999, XI, p.1515.

Annex B
(informative)

Uncertainty considerations

B.1 Overview

In 1995, a number of international standards organizations, including IEC, decided to unify the use of statistical terms in their standards. It was decided to use the word “uncertainty” for all quantitative (associated with a number) statistical expressions and eliminate the quantitative use of “precision” and “accuracy.” The words “accuracy” and “precision” could still be used qualitatively. The terminology and methods of uncertainty evaluation are standardized in the Guide to the Expression of Uncertainty in Measurement (GUM) [1] [1].

It was left to each TC to decide if they were going to change existing and future standards to be consistent with the new unified approach. Such change is not easy and creates additional confusion, especially for those who are not familiar with statistics and the term uncertainty. At the June 2006 TC 90 meeting in Kyoto, it was decided to implement these changes in future standards.

Converting “accuracy” and “precision” numbers to the equivalent “uncertainty” numbers requires knowledge about the origins of the numbers. The coverage factor of the original number may have been 1, 2, 3, or some other number. A manufacturer’s specification that can sometimes be described by a rectangular distribution will lead to a conversion number of $1/\sqrt{3}$. The appropriate coverage factor was used when converting the original number to the equivalent standard uncertainty. The conversion process is not something that the user of the standard needs to address for compliance to TC 90 standards, it is only explained here to inform the user about how the numbers were changed in this process. The process of converting to uncertainty terminology does not alter the user’s need to evaluate their measurement uncertainty to determine if the criteria of the standard are met.

The procedures outlined in TC 90 measurement standards were designed to limit the uncertainty of any quantity that could influence the measurement, based on the Convener’s engineering judgment and propagation of error analysis. Where possible, the standards have simple limits for the influence of some quantities so that the user is not required to evaluate the uncertainty of such quantities. The overall uncertainty of a standard was then confirmed by an interlaboratory comparison.

B.2 Definitions

Statistical definitions can be found in three sources: the GUM, the International Vocabulary of Basic and General Terms in Metrology (VIM)[2], and the NIST Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (NIST)[3]. Not all statistical terms used in this standard are explicitly defined in the GUM. For example, the terms “relative standard uncertainty” and “relative combined standard uncertainty” are used in the GUM (5.1.6, Annex J), but they are not formally defined in the GUM (see [3]).

B.3 Consideration of the uncertainty concept

Statistical evaluations in the past frequently used the coefficient of variation (COV) which is the ratio of the standard deviation and the mean (N.B. the COV is often called the relative standard deviation). Such evaluations have been used to assess the precision of the

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[1] Figures in square brackets refer to the reference documents in Clause B.5 of this Annex.

measurements and give the closeness of repeated tests. The standard uncertainty (SU) depends more on the number of repeated tests and less on the mean than the COV and therefore in some cases gives a more realistic picture of the data scatter and test judgment. The example below (see Tables B.1 to B.6) shows a set of electronic drift and creep voltage measurements from two nominally identical extensometers using same signal conditioner and data acquisition system. The n = 10 data pairs are taken randomly from the spreadsheet of 32 000 cells. Here, extensometer number one (E_1) is at zero offset position whilst extensometer number two (E_2) is deflected to 1 mm. The output signals are in volts.

Table B.1 – Output signals from two nominally identical extensometers

Output signal [V]	
E_1	E_2
0,001 220 70	2,334 594 73
0,000 610 35	2,334 289 55
0,001 525 88	2,334 289 55
0,001 220 70	2,334 594 73
0,001 525 88	2,334 594 73
0,001 220 70	2,333 984 38
0,001 525 88	2,334 289 55
0,000 915 53	2,334 289 55
0,000 915 53	2,334 594 73
0,001 220 70	2,334 594 73

Table B.2 – Mean values of two output signals

Mean ($\overline{X}$) [V]	
E_1	E_2
0,001 190 19	2,334 411 62

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad [\mathrm{V}] \tag{B.1}$$

Table B.3 – Experimental standard deviations of two output signals

Experimental standard deviation (s) [V]	
E_1	E_2
0,000 303 48	0,000 213 381

$$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2} \qquad [\mathrm{V}] \tag{B.2}$$

Table B.4 – Standard uncertainties of two output signals

Standard uncertainty (*u*) [V]	
E_1	E_2
0,000 095 97	0,000 067 48

$$u = \frac{s}{\sqrt{n}} \quad [\mathrm{V}] \tag{B.3}$$

Table B.5 – Coefficient of Variations of two output signals

Coefficient of variation (*COV*) [%]	
E_1	E_2
25,498 2	0,009 1

$$COV = \frac{s}{\overline{X}} \tag{B.4}$$

The standard uncertainty is very similar for the two extensometer deflections. In contrast the coefficient of variation *COV* is nearly a factor of 2 800 different between the two data sets. This shows the advantage of using the standard uncertainty which is independent of the mean value.

B.4 Uncertainty evaluation example for TC 90 standards

The observed value of a measurement does not usually coincide with the true value of the measurand. The observed value may be considered as an estimate of the true value. The uncertainty is part of the "measurement error" which is an intrinsic part of any measurement. The magnitude of the uncertainty is both a measure of the metrological quality of the measurements and improves the knowledge about the measurement procedure. The result of any physical measurement consists of two parts: an estimate of the true value of the measurand and the uncertainty of this “best” estimate. The GUM, within this context, is a guide for a transparent, standardized documentation of the measurement procedure. One can attempt to measure the true value by measuring “the best estimate” and using uncertainty evaluations which can be considered as two types: Type A uncertainties (repeated measurements in the laboratory in general expressed in the form of Gaussian distributions) and Type B uncertainties (previous experiments, literature data, manufacturer’s information, etc. often provided in the form of rectangular distributions).

The calculation of uncertainty using the GUM procedure is illustrated in the following example:

a) The user must derive in a first step a mathematical measurement model in form of identified measurand as a function of all input quantities. A simple example of such a model is given for the uncertainty of a force measurement using a load cell:

   Force as measurand = W (weight of standard as expected) + d_W (manufacturer’s data) + d_R (repeated checks of standard weight/day) + d_Re (reproducibility of checks at different days).

   Here the input quantities are: the measured weight of standard weights using different balances (Type A), manufacturer’s data (Type B), repeated test results using the digital electronic system (Type B), and reproducibility of the final values measured on different days (Type B).

b) The user should identify the type of distribution for each input quantity (e.g. Gaussian distributions for Type A measurements and rectangular distributions for Type B measurements).

c) Evaluate the standard uncertainty of the Type A measurements,

$u_A = \frac{s}{\sqrt{n}}$ where, s is the experimental standard deviation and n is the total number of measured data points.

d) Evaluate the standard uncertainties of the Type B measurements:

$u_B = \sqrt{\frac{1}{3} \cdot {d_W}^2 + ...}$ where, d_W is the range of rectangular distributed values

e) Calculate the combined standard uncertainty for the measurand by combining all the standard uncertainties using the expression:

$$u_c = \sqrt{u_A^2 + u_B^2}$$

In this case, it has been assumed that there is no correlation between input quantities. If the model equation has terms with products or quotients, the combined standard uncertainty is evaluated using partial derivatives and the relationship becomes more complex due to the sensitivity coefficients [4, 5].

f) Optional – the combined standard uncertainty of the estimate of the referred measurand can be multiplied by a coverage factor (e. g. 1 for 68 % or 2 for 95 % or 3 for 99 %) to increase the probability that the measurand can be expected to lie within the interval.

g) Report the result as the estimate of the measurand ± the expanded uncertainty, together with the unit of measurement, and, at a minimum, state the coverage factor used to compute the expanded uncertainty and the estimated coverage probability.

To facilitate the computation and standardize the procedure, use of appropriate certified commercial software is a straightforward method that reduces the amount of routine work [6, 7]. In particular, the indicated partial derivatives can be easily obtained when such a software tool is used. Further references for the guidelines of measurement uncertainties are given in [3, 8, and 9].

B.5 Reference documents of Annex B

[1] ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM 1995)

[2] ISO/IEC Guide 99:2007, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

[3] TAYLOR, B.N. and KUYATT, C.E. *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.* NIST Technical Note 1297, 1994

[4] KRAGTEN, J. Calculating standard deviations and confidence intervals with a universally applicable spreadsheet technique. *Analyst*, 1994, 119, 2161-2166

[5] EURACHEM / CITAC Guide CG 4 Second edition:2000, *Quantifying Uncertainty in Analytical Measurement*

[6] Available at http://www.gum.dk/e-wb-home/gw_home.html (cited 2011-04-04)

[7] Available at <http://www.isgmax.com/> (cited 2011.04-04)

[8] CHURCHILL, E., HARRY, H.K., and COLLE,R. *Expression of the Uncertainties of Final Measurement Results*. NBS Special Publication 644 (1983)

[9] JAB NOTE Edition 1:2003, *Estimation of Measurement Uncertainty (Electrical Testing / High Power Testing).*

Annex C

(informative)

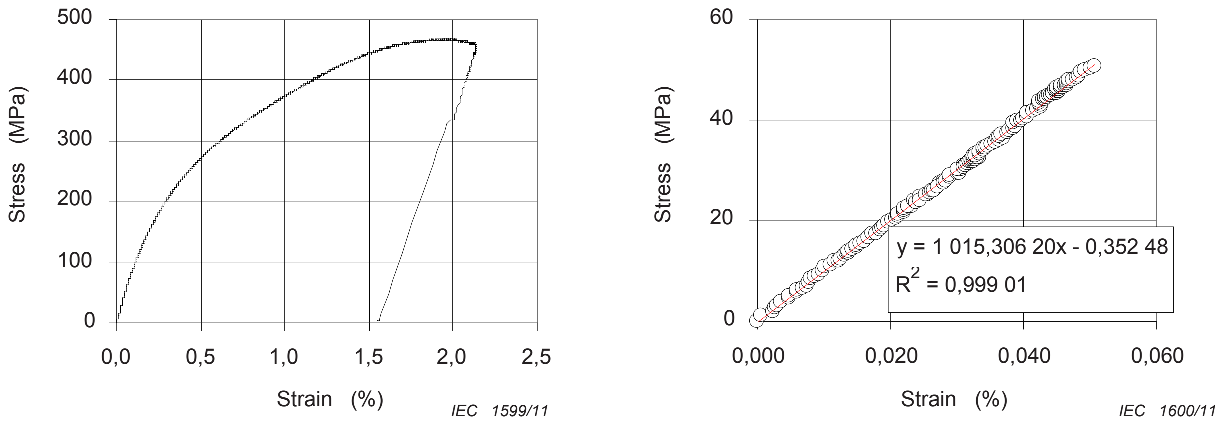
Specific examples related to mechanical tests

These are specific examples to illustrate techniques of uncertainty estimation. The inclusion of these examples does not imply that users must complete a similar analysis to comply with the standard. However, the portions that estimate the uncertainty of each individual influence quantity (load, displacement, wire diameter and gauge length) need to be evaluated by the user to determine if they meet the specified uncertainty limits in the standard.

These two examples are not meant to be exhaustive. They do not include all possible sources of error, such as friction, bent/straightened wire, and removal of insulation, misaligned grips, and strain rate. These additional sources may or may not be negligible.

C.1 Uncertainty of the modulus of elasticity

In Figure C1, the original stress versus strain raw data of a NbTi rectangular wire (1,45 mm × 0,97 mm) is given. These measurements were carried out during the course of an international round robin test in 1999. Figure C.1 (a) shows the loading of the wire up to unloading at around 2 % strain, while Figure C.1 (b) displays points taken during the initial loading up to 50 MPa and the line fit to these data. The computed slope of the trend line is 101 531 MPa (the slope is expand with a factor of 100 due to unit percentage of abscissa) as given in Figure C.1 (b) with a squared correlation coefficient of 0,99901.



a) b)

Figure C.1 a) shows the measured stress versus strain curve of the rectangular cross section NbTi superconducting wire. Figure C.1 b) shows the initial part of the curve and the regression analysis to determine modulus of elasticity. The slope of the line should be multiplied by 100 to convert the percentage strain to strain, so that the units of modulus of elasticity will be MPa.

Figure C.1 – Measured stress versus strain curve of the rectangular cross section NbTi wire and the initial part of the curve

The standard uncertainty estimation of modulus of elasticity for this wire can be processed in following way. The determined modulus of elasticity during mechanical loading is a function of six variables

$$E = f(P, \Delta L, W, T, L_G, b)\,, \tag{C.1}$$

each having its own specific uncertainty contribution. The model equation is

$$E = \frac{P \cdot L_G}{W \cdot T \cdot \Delta L} + b \tag{C.2}$$

where

- E = modulus of elasticity, MPa;
- P = load, N;
- ΔL = deflected extensometer length in zero offset region for the selected load portion, mm
- W = width of superconducting wire, mm;
- T = thickness of superconducting wire, mm;
- L_G = length of extensometer at start of the loading, mm;
- b = estimated deviation from the experimentally obtained modulus of elasticity, MPa.

The actual experimental values are necessary for the standard uncertainty calculation. Using the data of Figure C.1 b) the value of deflected extensometer length can be estimated. Here, a stress of 50 MPa is selected and by using the calculated modulus of elasticity given in Figure C.1 b) the value of ΔL can be established using the equations,

$$\varepsilon = \frac{\sigma}{E} \quad \text{and} \quad \Delta L = \varepsilon \cdot L_G, \tag{C.3}$$

where

- ε = 4,924 6 × 10^{-4};
- ΔL = 7,389 16 × 10^{-3} mm;
- σ = 50 MPa;
- L_G = 15 mm;
- W = 1,45 mm;
- T = 0,97 mm.

In Equation (C.3) ε is the strain and σ is the stress.

Furthermore, with

$$P = \sigma \cdot W \cdot T \tag{C.4}$$

the force P can be calculated as P = 70,325 N

In the case of a round wire, wire diameter D is used instead of W and T. Thus, W•T should be replaced by $\pi D^2/4$ in Equation(C.2) and Equation (C.4).

C.2 Evaluation of Sensitivity Coefficients

The combined standard uncertainty associated with model Equation (C.2) is:

$$u_c = \sqrt{\left(\frac{\partial E}{\partial P}\right)^2 u_1^2 + \left(\frac{\partial E}{\partial \Delta L}\right)^2 u_2^2 + \left(\frac{\partial E}{\partial W}\right)^2 u_3^2 + \left(\frac{\partial E}{\partial T}\right)^2 u_4^2 + \left(\frac{\partial E}{\partial L_G}\right)^2 u_5^2 + \left(\frac{\partial E}{\partial b}\right)^2 u_6^2} \tag{C.5}$$

where u_i (i=1, 2, …6) are described later in C. 3. The partial differential terms are the so-called sensitivity coefficients. By substituting the experimental values in each derivative, the sensitivity coefficients c_i can be calculated as follows:

For c_1:

$$c_1 = \frac{\partial}{\partial P}\left(\frac{L_G \cdot P}{W \cdot T \cdot \Delta L}\right) = \frac{L_G}{W \cdot T \cdot \Delta L} = 1{,}444 \times 10^3 \quad mm^{-2} \tag{C.6}$$

For c_2:

$$c_2 = \frac{\partial}{\partial \Delta L}\left(\frac{L_G \cdot P}{W \cdot T \cdot \Delta L}\right) = -\frac{L_G \cdot P}{W \cdot T \cdot \Delta L^2} = -1{,}374 \times 10^7 \quad N \cdot mm^{-3} \tag{C.7}$$

For c_3:

$$c_3 = \frac{\partial}{\partial W}\left(\frac{L_G \cdot P}{W \cdot T \cdot \Delta L}\right) = -\frac{L_G \cdot P}{W^2 \cdot T \cdot \Delta L} = -7{,}002 \times 10^4 \quad N \cdot mm^{-3} \tag{C.8}$$

For c_4:

$$c_4 = \frac{\partial}{\partial T}\left(\frac{L_G \cdot P}{W \cdot T \cdot \Delta L}\right) = -\frac{L_G \cdot P}{W \cdot T^2 \cdot \Delta L} = -1{,}047 \times 10^5 \quad N \cdot mm^{-3} \tag{C.9}$$

For c_5:

$$c_5 = \frac{\partial}{\partial L_G}\left(\frac{L_G \cdot P}{W \cdot T \cdot \Delta L}\right) = \frac{P}{W \cdot T \cdot \Delta L} = 6{,}769 \times 10^3 \quad N \cdot mm^{-3} \tag{C.10}$$

Sensitivity coefficient c_6 is unity (1) owing to the differentiation of Equation C.2 with respect to quantity *b*.

Using the above sensitivity coefficients, the combined standard uncertainty u_c is finally given by:

$$u_c = \sqrt{(c_1)^2 \cdot (u_1)^2 + (c_2)^2 \cdot (u_2)^2 + (c_3)^2 \cdot (u_3)^2 + (c_4)^2 \cdot (u_4)^2 + (c_5)^2 \cdot (u_5)^2 + (c_6)^2 \cdot (u_6)^2} \tag{C.11}$$

where the square of each sensitivity coefficient is multiplied by the square of the standard uncertainty of individual variables as given in the model Equation (C.2).

C.3 Combined standard uncertainties of each variable

The standard uncertainties u_i in Equation (C.11) are the combined standard uncertainties of force (*P*), deflected length (*ΔL*), width of wire (*W*), thickness of wire (*T*), and gauge length (L_G). In this clause, each combined standard uncertainty will be estimated according to the available data.

The combined standard uncertainty u_1 for force *P* is composed of statistical distributions of Type A and Type B. In general, the force is measured with commercially available load cells. The bulk of load cell manufacturers, however, do not give information about uncertainties in their specifications. The given accuracies, along with other information obtained from the data sheets, must be first converted into standard uncertainties prior to the determination of combined standard uncertainty u_1. Typically these manufacturer's specifications are viewed as limits to a rectangular distribution of errors. The standard uncertainty associated with the rectangular distribution is the limit divided by $\sqrt{3}$.

For the measurements given in Figure C.1, the following information for the load cell was available.

Table C.1 – Load cell specifications according to manufacturer's data sheet

Load cell capacity, *N*	**Accuracy class tension / compression** %	**Temperature coefficient of zero** S %/*K*	**Temperature coefficient of sensitivity** S %/*K*	**Creep for 30 min** S%
5 000	0,25	0,25	0,07	0,07

According to this specification, the data should be converted to standard uncertainty values before combining them. These data are treated as Type B uncertainties. The temperature range between 30 °C and 10 °C (ΔT = 20 °C) has been selected to reflect allowable laboratory conditions.

The variables are as follows:

• Accuracy class:	T_{class} = 0,25 %
• Temperature coefficient of zero balance:	$T_{CoefZero}$ = (0,25 × 20) %
• Temperature coefficient of sensitivity:	$T_{CoefSens}$ = (0,07 × 20) %
• Creep for 30 min:	T_{creep} = 0,07 %

The following equation describes the measurement of load and includes the four sources of error from Figure C.1:

$$P=u_P+T_{class}+T_{coefzero}+T_{coefsens}+T_{creep} \qquad (C.12)$$

where u_P is the true value of load.

The percentage specifications are converted to load units based on the measured value of P = 70,325 N obtained from the stress versus strain curve. The resulting values are converted to standard uncertainties assuming a rectangular distribution so that the combined standard uncertainty for the load cell is:

$$u_1=\sqrt{\left(\frac{T_{class}\cdot 70{,}325}{100\cdot\sqrt{3}}\right)^2+\left(\frac{T_{CoeffZero}\cdot 70{,}325}{100\cdot\sqrt{3}}\right)^2+\left(\frac{T_{CoeffSens}\cdot 70{,}325}{100\cdot\sqrt{3}}\right)^2+\left(\frac{T_{creep}\cdot 70{,}325}{100\cdot\sqrt{3}}\right)^2} \qquad (C.13)$$

$$u_1=2{,}11\ \text{N} \qquad (C.14)$$

Tables C.2 to C.5 summarize uncertainty calculations of displacement, wire width, wire thickness, and gauge length. These calculations are similar to those previously demonstrated for force.

Table C.2 – Uncertainties of displacement measurement

Displacement, mm	Type A Gaussian distribution. Creep and noise contribution $u_A = s/\sqrt{n}$ according Annex B 3 2 V = 1 mm (0,0003 V/2)/ $\sqrt{10}$ mm	Type A distribution obtained from data scatter of Figure C.1b) $u_A = s/\sqrt{182}$ mm
7,389 16 Ten to the minus 3	0,000 05	0,000 004 82
$u_2=\sqrt{0{,}000\,05^2+0{,}000\,004\,82^2}=0{,}000\,05$ mm		

Table C.3 – Uncertainties of wire width measurement

Wire width, mm	Type A Gaussian distribution. Five repeated measurement with micrometer device $u_A = s/\sqrt{n}$ $(0{,}001\ 3)/\sqrt{5}$ mm	Half width of rectangular distribution according manufacture data sheet accuracy of +/- 4 µm $u_B = d_w/\sqrt{3}$ mm
1,45	0,000 58	0,002 3
$u_3 = \sqrt{0{,}000\ 58^2 + 0{,}002\ 3^2} = 0{,}002\ 3$ mm		

Table C.4 – Uncertainties of wire thickness measurement

Wire thickness, mm	Type A Gaussian distribution. Five repeated measurement with micrometer device $u_A = s/\sqrt{n}$ $(0{,}001\ 1)/\sqrt{5}$ mm	Half width of rectangular distribution according manufacture data sheet accuracy of +/- 4 µm $u_B = d_w/\sqrt{3}$ mm
0,97	0,000 49	0,002 3
$u_4 = \sqrt{0{,}000\ 49^2 + 0{,}002\ 3^2} = 0{,}002\ 3$ mm		

To measure the gauge length of the extensometer, a stereo microscope was used with a resolution of 20 µm.

Table C.5 – Uncertainties of gauge length measurement

Gauge length, mm	Type A Gaussian distribution. Five repeated measurement with micrometer device $u_A = s/\sqrt{n}$ $(0{,}002)/\sqrt{5}$ mm	Half width of rectangular distribution according manufacture data sheet accuracy of +/-20 µm $u_B = d_w/\sqrt{3}$ mm
12	9×10^{-4}	0,011
$u_5 = \sqrt{0{,}000\ 9^2 + 0{,}001\ 1^2} = 0{,}011$ mm		

Finally, the uncertainty in the slope of the fitted stress versus strain curve given in Figure C.1 b) is estimated. The maximum half width difference between the measured stress values and the calculated stress values using the trend line equation from Figure C.1b) results in +/- 0,528 MPa. Using this value with gauge length (L_G=15 mm) and extensometer deflection value (ΔL= 0,007 389 16 mm), a Type B uncertainty for the modulus of elasticity can be estimated. Rearranging Equation (C.3) results in the simple equation:

$$\sigma = E \cdot \varepsilon \quad ; \quad E = \sigma \cdot \frac{L_G}{\Delta L} \tag{C.15}$$

The Type B uncertainty of the measured modulus of elasticity of the Figure C.1 b) is

$$u_b = \frac{0{,}528 \ \ \text{MPa} \cdot 15 \ \ \text{mm}}{0{,}007\,389\,16 \ \ \text{mm} \cdot \sqrt{3}} = 619 \ \ \text{MPa} \tag{C.16}$$

The final combined standard uncertainty, taking into account the result of Equation (C.16) and using the sensitivity coefficients for the five variables in Equation (C.11), results in:

$$u_c = \sqrt{\begin{aligned}&\left(1{,}444 \times 10^3\right)^2 \cdot (2{,}11)^2 + \left(-1{,}374 \times 10^7\right)^2 \cdot (0{,}000\,05)^2 + \left(-7{,}002 \times 10^4\right)^2 \cdot (0{,}002\,3)^2 + \\ &+ \left(-1{,}047 \times 10^5\right)^2 \cdot (0{,}002\,3)^2 + \left(6{,}769 \times 10^3\right)^2 \cdot (0{,}011)^2 + (1)^2 \cdot (619)^2\end{aligned}} \tag{C.17}$$

$$u_c = 972 \text{ MPa} \tag{C.18}$$

or

$$E = 101 \text{ GPa} \ \ +/- \ 1 \text{ GPa} \tag{C.19}$$

C.4 Uncertainty of 0,2 % proof strength $R_{p0,2}$

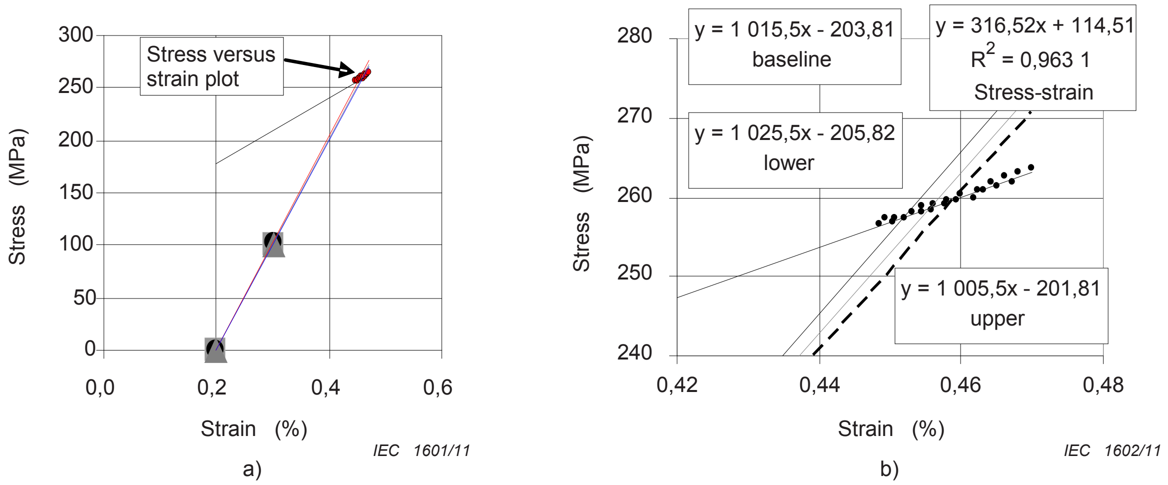
The 0,2 % proof strength $R_{p0,2}$ should be determined by the parallel shifting of the modulus of elasticity zero offset line to the 0,2 % strain position along the abscissa and computing the intersection of this line with the original stress versus strain curve. If the fitted modulus of elasticity line has a different origin than zero, the offset from zero should be also considered. The regression equation in Figure C.1 b has an *x*-axis offset of:

$$Offset \ \ strain \ \ at \ \ zero \ \ stress = \frac{0{,}352\,48}{1\,015{,}306\,2} = 3{,}471 \times 10^{-4} \ \ \% \tag{C.20}$$

Thus, the shifted position of the line along the abscissa is not exactly 0,200 00 % but 0,200 35 %. Table 6 shows the computation of stress using the regression line with and without the uncertainty contribution from Equation (C.18).

Table C.6 – Calculation of stress at 0 % and at 0,1 % strain using the zero offset regression line as determined in Figure C.1b.

Description	Regression line equation with uncertainty contribution at ε % strain	Stress at ε = 0 % strain, MPa	Stress at ε = 0,1 % strain, MPa
Baseline modulus of elasticity	1 015,306·ε - 0,352 5	- 0,353	101,2
Modulus of elasticity with + 0,97 GPa uncertainty contribution (upper line)	1 025,026·ε - 0,352 5	- 0,353	102,2
Modulus of elasticity with – 0,97 GPa uncertainty contribution (lower line)	1 005,586·ε - 0,352 5	- 0,353	100,2



a) b)

Figure C.2 – 0,2 % offset shifted regression line, the raw stress versus strain curve and the original raw data of stress versus strain

Figure C.2a shows the 0,2 % offset shifted regression line and the two lines using plus and minus uncertainty contributions relative to the base line. Four points are necessary to construct the three lines; one common point at zero stress and three calculated stress values at 0,1 % strain as shown in Table C.6, however, the corresponding strain values need to be shifted by 0,2 %. In Figure C.2a the raw stress versus strain curve is also plotted around the region where the three lines intersect the raw data. Figure C.2b shows the original raw data of stress versus strain in an enlarged view and the shifted lines according to the computations of Table C6. The linear regression equation of stress-strain function is also given in this Figure C.2b.

In Table C.6 the selected stresses at 0 % strain and at 0,1 % strain are arbitrarily chosen for the purpose of obtaining two distinct points to determine the shifted lines in Figure C.2. The offset shift value obtained from Equation (C.19) is added to the values of 0 % strain and 0,1 % strain.

Table C.7 lists the linear regression equations after shifting e lines as determined in Figure C.2 b.

Table C.7 – Linear regression equations computed for the three shifted lines and for the stress versus strain curve in the region where the lines intersect

Description of equations	**Linear regression equation**[a]
Linear part of stress versus strain curve (see Figure 2 a)	$y = 316{,}5 \cdot x + 114{,}5$
Shifted modulus of elasticity baseline	$y = 1\,015{,}5 \cdot x - 203{,}8$
Modulus of elasticity with + 0,97 GPa uncertainty contribution (shifted upper line)	$y = 1\,005{,}5 \cdot x - 201{,}8$
Modulus of elasticity with – 0,97 GPa uncertainty contribution (shifted lower line)	$y = 1\,025{,}5 \cdot x - 205{,}8$

[a] x is here the strain in % and y the stress in MPa.

Finally, using the equations of Table C.7, the three intersection points are computed and the stresses at these points are determined. Table C.8 shows the computation and resulting intersection values. The reported value of proof strength is the stress of the intersection of the first line (shifted zero offset) with the stress versus strain curve. The remaining two values of stress at the intersection represent estimated error bounds for the proof strength. The error bounds are based on the uncertainty of the modulus of elasticity slope (Equation (C.18)).

Table C.8 – Calculation of strain and stress at the intersections of the three shifted lines with the stress strain curve

Description	Equation set for strain and stress calculation at intersections	Strain at intersection, %	Stress at intersection, MPa
Shifted baseline (mean)	(-203,8-114,5) / (316,5-1 015,5)	0,455 365	
	316,5·0,455 365 + 114,5		258,6
Shifted upper line	(-201,8-114,5) / (316,5-1 005,5)	0,459 071	
	316,5·0,459 071 + 114,5		259,8
Shifted lower line	(-205,8-114,5) / (316,5-1 025,5)	0,451 763	
	316,5·0,451 763 + 114,5		257,5

The standard uncertainty of the proof strength is a Type B determination, and can be estimated using:

Uncertainty Type B:
$$u_B = \frac{\dfrac{259{,}8 - 257{,}5}{2}}{\sqrt{3}} = 0{,}664 \text{ MPa} \qquad \text{(C.21)}$$

The scatter of the raw data shown in Figure C.2b should also be considered in the final uncertainty estimate. Table C.9 shows the measured stress versus strain data of Figure C.2b. In addition, column 3 of Table C.9 gives the computed stress using the linear fit to the data in the region of interest. Finally, columns 4 shows the differences between measured and computed data.

Table C.9 – Measured stress versus strain data and the computed stress based on a linear fit to the data in the region of interest

Strain %	Stress MPa	Calculated according regression equation, MPa	Difference calculated observed MPa
0,4494	257,25	256,76	0,4896
0,4485	256,52	256,46	0,0603
0,4507	257,47	257,15	0,3203
0,4505	256,80	257,09	–0,289 6
0,4530	258,09	257,90	0,193 3
0,4521	257,38	257,60	–0,222 4
0,4546	258,86	258,40	0,463 2
0,4544	258,08	258,33	–0,250 4
0,4561	259,07	258,87	0,204 7
0,4559	258,27	258,82	–0,551 0
0,4580	259,60	259,48	0,123 8
0,4578	259,04	259,40	–0,357 0
0,4600	260,40	260,11	0,287 6
0,4594	259,52	259,91	–0,393 0
0,4623	260,91	260,84	0,069 6
0,4617	259,85	260,66	–0,806 8
0,4644	261,88	261,49	0,387 6
0,4633	260,87	261,15	–0,283 7
0,4661	262,63	262,03	0,602 7
0,4651	261,36	261,72	–0,360 3
0,4680	263,12	262,63	0,491 3
0,4673	261,90	262,40	–0,504 0
0,4699	263,53	263,23	0,303 1

The extreme differences between the computed and measured stress from the 4th column of Table 9 are:

$$-0{,}806\,8\ \text{MPa and } +0{,}602\,7\ \text{MPa} \qquad \text{(C.22)}$$

The extreme differences represent observed limits to random error which can be converted to a standard uncertainty using:

$$\text{Uncertainty Type B:} \qquad u_B = \frac{\dfrac{0{,}602\,7-(-0{,}806\,8)}{2}}{\sqrt{3}} = 0{,}813\,8\ \text{MPa} \qquad \text{(C.23)}$$

Combined standard uncertainty for 0,2 % proof strength is given:

$$\text{Combined uncertainty:} \qquad u_c = \sqrt{0{,}813\,8^2 + 0{,}664^2} = 1{,}05\ \text{MPa} \qquad \text{(C.24)}$$

Thereafter, the 0,2 % proof strength result is given as:

$$\text{0,2 offset proof strength:}\ R_{p02} = 258{,}6\ \mathit{MPa} \quad +/-\ 1{,}05\ \mathit{MPa} \qquad \text{(C.25)}$$

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