

INTERNATIONAL STANDARD

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Superconductivity –

Part 19: Mechanical properties measurement – Room temperature tensile test of reacted Nb₃Sn composite superconductors

Supraconductivité –

Partie 19: Mesure des propriétés mécaniques – Essai de traction à température ambiante des supraconducteurs composites de Nb₃Sn mis en réaction



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SUPERCONDUCTIVITY –

**Part 19: Mechanical properties measurement –
Room temperature tensile test of reacted Nb₃Sn
composite superconductors**

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The text of this standard is based on the following documents:

FDIS	Report on voting
90/328/FDIS	90/330/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61788 series, published under the general title *Superconductivity*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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INTRODUCTION

The Cu/Nb₃Sn superconductive composite wires are multifilamentary composite materials. They are manufactured in different ways. The first method is the bronze route, where fine Nb / Nb alloy filaments are embedded in a bronze matrix, a barrier and a copper stabilizer. The second is the internal-tin method, where fine multifilaments are composed with copper matrix including Sn reservoirs, a barrier, and a copper stabilizer. The third is the powder-in-tube method, where Nb / Nb alloy tubes are filled with Sn rich powders and are embedded in a Cu stabilizing matrix.

Common to all types of Nb₃Sn composite wires is that the superconducting A15 phase Nb₃Sn has been formed at final wire dimension by applying one or more heat treatments for several days with a temperature at the last heat treatment step of around 640 °C or above. This superconducting phase is very brittle and failure of filaments occurs – accompanied by the degradation of the superconducting properties.

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. This can be done either by winding the superconductor on a spool and applying the heat treatment together with the spool afterwards (wind and react) or by heat treatment of the conductor before winding the magnet (react and wind). While the magnet is being manufactured, complicated stresses are applied to its windings. Therefore the react and wind method is the minority compared to the wind and react manufacturing process.

In the case that the mechanical properties should be determined in the unreacted, non-superconducting stage of the composite, one should also apply this standard or alternatively IEC 61788-6 (*Superconductivity– Part 6: Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors*).

While the magnet is being energized, a large electromagnetic force is applied to the superconducting wires because of their high current density. In the case of the react and wind manufacturing technique, the winding strain and stress levels are very restricted.

It is therefore a prerequisite to determine the mechanical properties of the superconductive reacted Nb₃Sn composite wires of which the windings are manufactured.

SUPERCONDUCTIVITY –

Part 19: Mechanical properties measurement – Room temperature tensile test of reacted Nb₃Sn composite superconductors

1 Scope

This part of IEC61788 covers a test method detailing the tensile test procedures to be carried out on reacted Cu/Nb₃Sn composite superconducting wires at room temperature.

The object of this test is to measure the modulus of elasticity and to determine the proof strength of the composite due to yielding of the copper and the copper tin components from the stress versus strain curve.

Furthermore, the elastic limit, the tensile strength, and the elongation after fracture can be determined by means of the present method, but they are treated as optional quantities because the measured quantities of the elastic limit and the elongation after fracture have been reported to be subject to significant uncertainties according to the international round robin test.

The sample covered by this test procedure should have a bare round or rectangular cross-section with an area between 0,15 mm² and 2,0 mm² and a copper to non-copper volume ratio of 0,2 to 1,5 and should have no insulation.

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.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at <<http://www.electropedia.org>>)

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 extensometer systems 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

R

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

3.2 strain

A

displacement increment divided by initial gauge length of extensometers at any moment during the test

3.3 modulus of elasticity

E

gradient of the straight portion of the stress-strain curve in the elastic deformation region

3.4 extensometer gauge length

length of the parallel portion of the test piece used for the measurement of displacement by means of an extensometer

3.5 distance between grips

L_g

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

3.6 0,2 % proof strength

$R_{p0,2}$

stress value where the ductile components yield by 0,2 %.

Note 1 to entry: The designated proof strengths, $R_{p0,2-0}$ and $R_{p0,2-U}$ correspond to point A or point C obtained from unloading slope U between 0,3 % and 0,4 % in Figure 1(a), respectively. This strength is regarded as a representative 0,2 % proof strength of the composite.

3.7 tensile strength

R_m

tensile stress corresponding to the maximum testing force

3.8 tensile stress at elastic limit

$R_{elasticmax}$

tensile force divided by the original cross-sectional area at the transition of elastic to plastic deformation

3.9 strain at elastic limit

$A_{elasticmax}$

strain at the transition of elastic to plastic deformation

Note 1 to entry: The stress $R_{elasticmax}$ and the corresponding strain $A_{elasticmax}$ refer to point G in Figure A.6 of Annex A.5 and are regarded as the transition point of elastic to plastic deformation.

4 Principles

The test consists of straining a test piece by tensile force beyond the elastic deformation regime, in principle for the purpose of determining the modulus of elasticity (E) and the proof strengths of $R_{p0.2}$.

5 Apparatus

5.1 General

The test machine and the extensometers 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 stroke speed shall be used. Grips shall have a structure and strength appropriate for the test specimen and shall be constructed to provide a firm 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 screw type, pneumatically, or hydraulically actuated.

5.3 Extensometer

The mass of the extensometer shall be 30 g or depending on wire diameter even less, so as not to affect the mechanical properties of the brittle reacted superconductive wire. The mass of the extensometers had to be balanced symmetrically around the wire to avoid any non-alignment force (see Clause A.2). Care shall also be taken to prevent bending moments from being applied to the test specimen.

Depending on the employed strain measuring method, however, the quantities determined by the present test should be limited. When using the conventional single extensometer system, the determination of E_U and $R_{p0.2-U}$ is recommended. On the other hand, it is possible to determine all quantities described here by using an averaging double extensometer system, because of its capability to compensate the bending effects of the reacted sample and to guarantee a proper determination of the modulus of elasticity E_0 .

NOTE Further information is given in Clauses A.2 and A.3.

6 Specimen preparation

6.1 General

The wire should be straightened before heat treatment and should be inserted into a ceramic or quartz tube with slightly larger inner diameter referring to the wire size.

The constant temperature zone length of the heat treatment furnace shall be longer than the total length mentioned below in 6.2.

Care shall be taken to prevent bending or pre-loading when the reacted specimen is manually handled during removal from the ceramic or quartz tube and mounting.

6.2 Length of specimen

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

6.3 Removing insulation

If the test specimen surface is coated with an insulating material, the coating shall be removed before the heat treatment. Either a chemical or mechanical method shall be used with care taken not to damage the specimen surface (see Clause A.7).

6.4 Determination of cross-sectional area (S_0)

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.8).

7 Testing conditions

7.1 Specimen gripping

When the test specimen is mounted on the grips of the tensile machine, the test specimen and tensile loading axis shall be on a single straight line with a minimum of machine/specimen mismatch. Gripping techniques of specimen are described in Clause A.9.

7.2 Setting of extensometer

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.

During mounting care should be taken not to pre-load the specimen. After installation, loading shall be physically zeroed.

Double extensometer shall be mounted symmetrically around the cross-section to allow averaging of the strain to compensate the bending effects.

To guarantee best performance of the stress-strain curve of rectangular wires the extensometer should be mounted in such a way that strain is measured symmetrically on the small sides of the wire.

7.3 Testing speed

The tensile tests shall be performed with displacement control. The machine crosshead speed is recommended to be set between 0,1 mm/min and 0,5 mm/min.

7.4 Test

Following this procedure the tensile machine shall be started after the crosshead speed has been set to a specific level. The signals from the extensometers and the load cell shall be recorded, saved, and plotted on the abscissa and ordinate of the diagram as shown in Figures 1 (a) and 1 (b). When the total strain has reached a value between 0,3 % and 0,4 % the tensile force shall be reduced by 30 % to 40 % without changing the crosshead speed. Following this procedure the wire shall be reloaded again until final fracture.

Prior to the start of any material test program it is advisable to check the complete test equipment using similar size wires of known elastic properties (See Clause A.14).

8 Calculation of results

8.1 Modulus of elasticity (E)

Modulus of elasticity shall be calculated in general using the following formula and the straight portion of the unloading curve and of the initial loading one. Appropriate software for data evaluation should be used for post analyses of the plotted data with the possibility of enlargement of the stress versus strain graph, especially around the region where the deviation from linearity is expected.

$$E = \Delta F / (S_0 \Delta A) \quad (1)$$

where

E is the modulus of elasticity;

ΔF is the increment of the corresponding force;

ΔA is the increment of strain corresponding to ΔF ;

S_0 is the original cross-sectional area of the test specimen. Since unloading process is carried out at the strain indicated by the point A_U in Figure 1(a), the same Formula (1) is used for both the unloading modulus of elasticity (E_U) and the initial loading one (E_0). It is recommended to measure the unloading curve at the starting point A_U , where A_U is recommended to be between 0,3 % and 0,4 %.

The modulus of elasticity determined from the unloading curve is expressed as E_U which is given by the slope of the line (U between 0,3 % and 0,4 % strain) in Figure 1(a) and that from the initial loading curve is expressed as E_0 by the zero offset line.

It should be, however, noted that the straight portion of the initial stress – strain curve is very narrow as indicated in Figure A.6 of Clause A.5. To measure this quantity with a low relative standard uncertainty the only currently possible technique is the use of an averaging double extensometer system. In this sense, the quantity of E_U should be a representative data for the present text, while E_0 should be reported only when the measure is performed by means of double extensometer system.

After the test, the results shall be examined using the ratio E_0/E_U . The ratio shall satisfy the condition as given in Equation 2 in which $\Delta = 0,3$ (see Clause A.12).

$$1-\Delta < E_0/E_U < 1+\Delta \quad (2)$$

When it does not satisfy the condition, the test is judged not to be valid. Then the test shall be repeated after the experimental procedure is reexamined according to the present test method.

It is guided to achieve the unloading-reloading procedure as follows: when the loading curve arrives at the strain A_U (between 0,3 % and 0,4 %), the stress is reduced to r_{umin} of the maximum stress (stress position where the unloading started r_{umax}) and then the wire is reloaded. The slope of the unloading curves shall be obtained in the linear portion between the stress r_{umax} and r_{umin} .

NOTE 3 Typical range of r_{umax} is 99 % of the maximum stress (stress where the unloading starts). The range of r_{umin} is at 90 % referring to the onset of the unloading stress (see Figure 1 (b)).

8.2 0,2 % proof strength ($R_{p0,2-0}$ and $R_{p0,2-U}$)

The 0,2 % proof strength of the composite is determined in two ways from the unloading/reloading and initial loading part of the stress-strain curve as shown in Figures 1(a) and 1(b).

The 0,2 % proof strength of the composite under unloading $R_{p0,2-U}$ shall be determined as follows: the linear portion of the unloading slope is moved parallel to the origin of the fitted curve, which may include a negative strain value. Thereafter, a parallel line shall be shifted to 0,2 % on the abscissa from this strain point. The intersection of this line U with the stress-strain curve determines the point C that shall be defined as the 0,2 % proof strength. Depending of the unloading line (e. g. $U_{0,35}$ in Fig 1(a)), 0,2 % proof strength ($R_{p0,2-U}$) is determined.

The 0,2 % proof strength under loading $R_{p0,2-0}$ shall be determined as follows: the initial linear portion at zero offset position of the loading line of the stress-strain curve is moved 0,2 % along the strain axis 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.

Each of 0,2 % proof strength value shall be calculated using the formula (3) given below:

$$R_{p0,2-i} = F_i / S_0 \quad (3)$$

where

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

F_i is the force (N) at each point;

as $i = 0$ or U .

9 Uncertainty of measurand

Unless otherwise specified, measurements shall be carried out in a temperature that can range from 283 K to 308 K. A force measuring cell with the relative standard uncertainty less than 0,1 %, valid between zero and the maximum force capacity of load cell shall be used. The extensometers should have the relative standard uncertainty of strain less than 0,05 %. The displacement measuring transducer (e.g. LVDT [linear variable differential transformer]) used for the calibration should have the relative standard uncertainty less than 0,01 %.

The relative standard uncertainty values of measured moduli of elasticity E_0 and E_U and the proof strengths $R_{p0,2-0}$ and $R_{p0,2-U}$ currently achieved with respect to the international round robin test of eleven representative research groups are given in Table A.1 (see Clause A.12).

According to the international round robin test (see (9) of Clause A.15), the relative standard uncertainty was reported to be 1,4 % for E_0 for the test data of $N = 17$ in average after the qualification check. Similarly, 1,3 % for E_U ($N = 15$), 1,5 % for $R_{p0,2-0}$ ($N = 17$) and 2,5 % for $R_{p0,2-U}$ ($N = 13$) were reported.

10 Test report

10.1 Specimen

The following information shall be reported:

- a) Name of the manufacturer of the specimen
- b) Classification and/or symbol

- c) Lot number

The following information shall be reported if possible:

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

10.2 Results

Results of the following mechanical properties shall be reported.

- a) Modulus of elasticity (E_0 and E_U)
- b) 0,2 % proof strengths ($R_{p0,2-0}$ and $R_{p0,2-U}$)

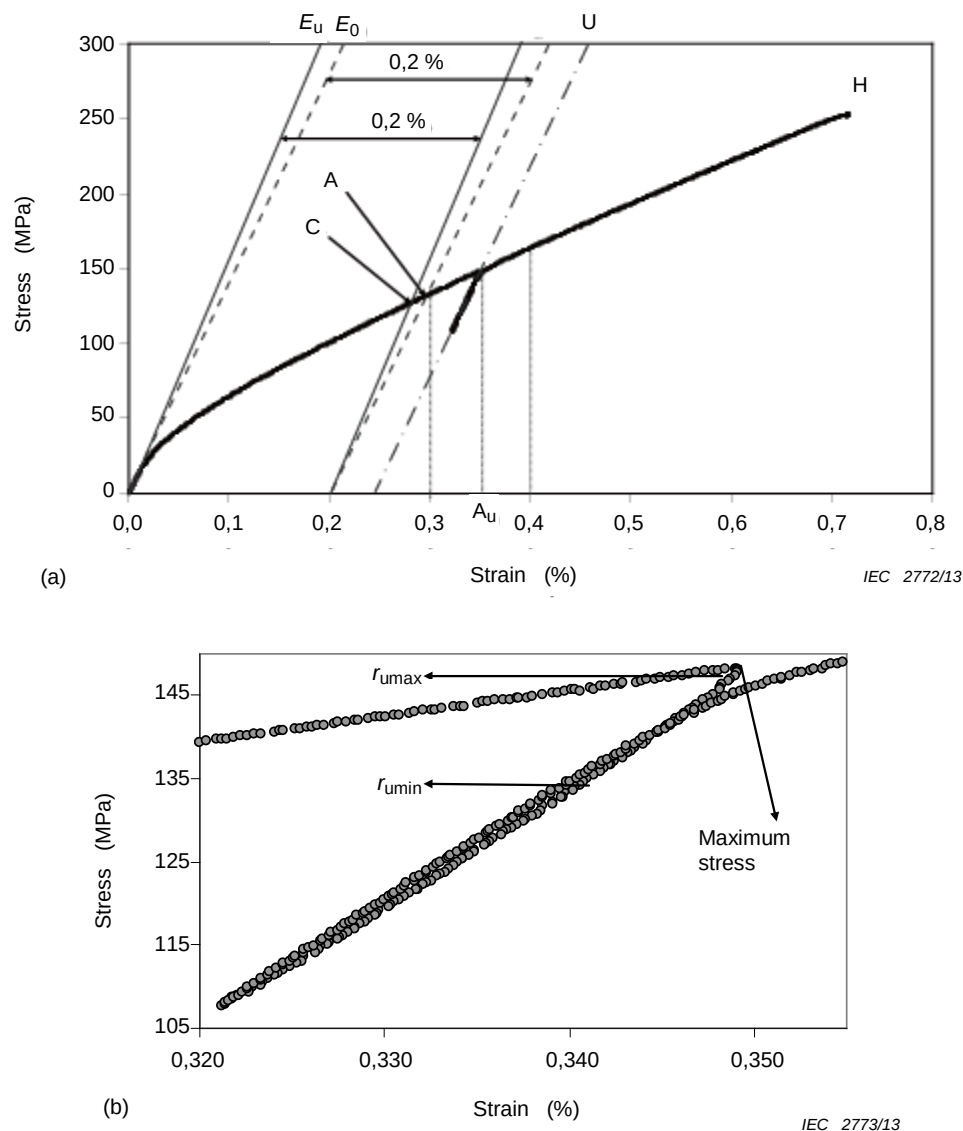
The following information shall be reported if required:

- c) Tensile stress $R_{\text{elasticmax}}$
- d) Strain $A_{\text{elasticmax}}$
- e) Tensile strength (R_m)
- f) Percentage elongation after fracture (A)
- g) 0,2 % proof strength determined by means of function fitting method ($R_{p0,2-F}$)

10.3 Test conditions

The following information shall be reported:

- a) Crosshead speed
- b) Distance between grips
- c) Temperature
- d) Manufacturer and model of testing machine
- e) Manufacturer and model of extensometers
- f) Gripping method



The Figure 1(a) shows the over-all relation between stress and strain; (b) is the enlarged view indicating the unload and reload procedure.

Key

- U: Computed unloading line of U between 0,3 % and 0,4 % strain using 1st order regression line in Figure 1(a)
- Point A: 0,2 % strain shift from initial origin of the loading line (zero offset line). $R_{p0,2-0}$ obtained experimentally.
- Point C: 0,2 % strain shift from origin of fit curve with the determined slope of unloading line U (e.g. $U_{0,35}$). $R_{p0,2-U}$ is obtained by computation.
- Point H: Final fracture point of the wire.

The slope of the initial loading line is usually smaller than that of the unloading lines. In such cases the line has to be drawn from 0,2 % offset point on the abscissa to obtain 0,2 % proof strength ($R_{p0,2-0}$) of the composite due to yielding of the ductile components such as copper and bronze (point A). Point A is obtained from the initial loading line.

Point C is obtained using the unloading line. The slope of the unloading line between 0,3 % and 0,4 % should be shifted to the origin of the fit curve, which may include a negative strain shift (see Clause A.6). The parallel 0,2 % strain shift of this slope as a line on the abscissa intersects the fitted curve at point C, which is defined as the 0,2 % proof strength of the composite ($R_{p0,2-U}$).

The graph in Figure 1(b) shows the raw data of the unloading region. The slope should be determined between 99 % of maximum stress at the onset of unloading and 90 % stress of the maximum stress as indicated (see 8.1).

Figure 1 – Stress-strain curve and definition of modulus of elasticity and 0,2 % proof strengths for Cu/Nb₃Sn wire

Annex A (informative)

Additional information relating to Clauses 1 to 10

A.1 Scope

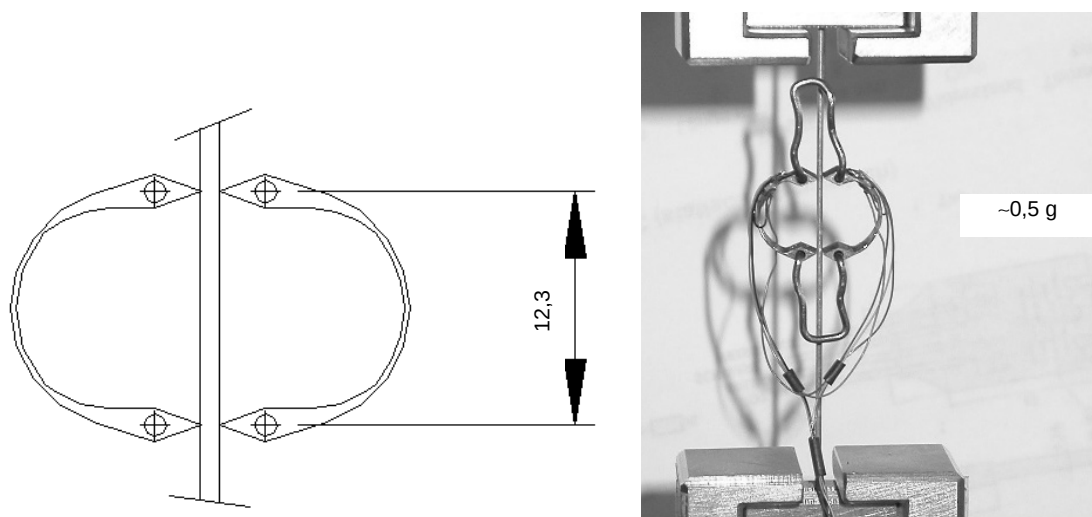
This annex gives reference information on the variable factors that may affect the tensile test methods. All items described in this annex are informative.

A.2 Extensometer

A.2.1 Double extensometer

Any type of extensometer can be used if it consists of two single extensometers capable of recording two signals to be averaged by software or one signal already averaged by the extensometer system itself.

In Figures A.1 and A.2 typical advanced light weight extensometers are shown.

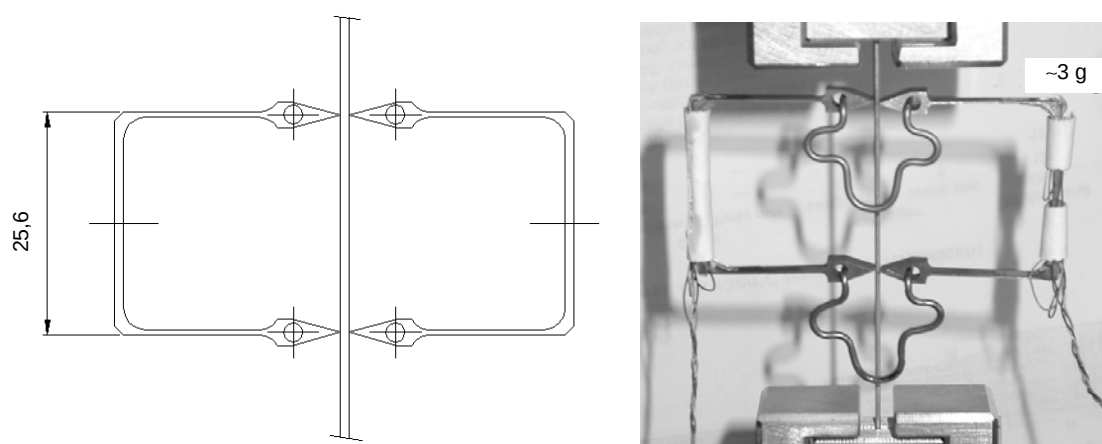


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Dimensions in millimetres

The extensometer has a gauge length of ~ 12 mm (total mass ~ 0,5 g). The two extensometers are wired together into a single type extensometer, thus averaging the two displacement records electrically.

Figure A.1 – Light weight ultra small twin type extensometer



IEC 2167/13

Dimensions in millimetres

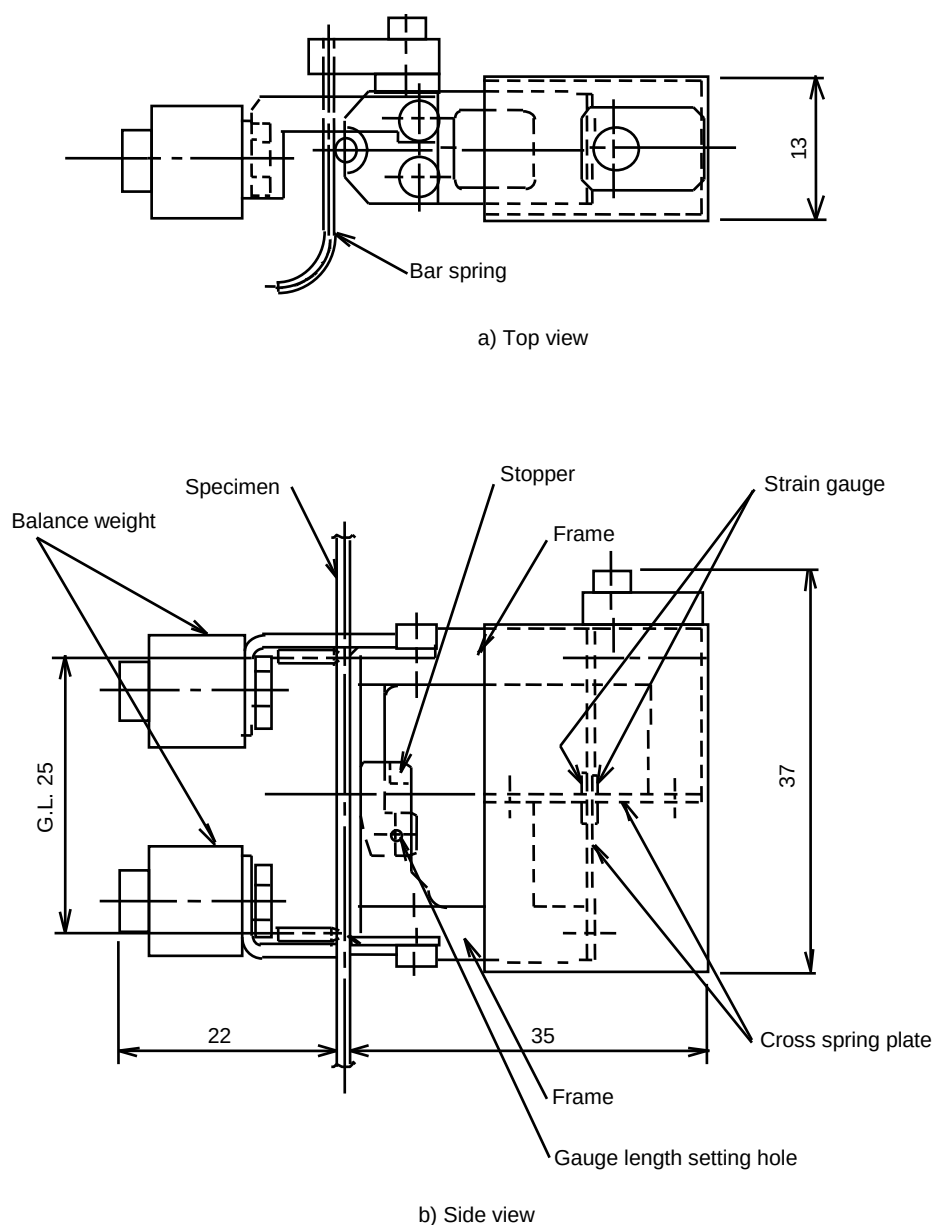
The extensometer has a gauge length of ~ 26 mm (total mass ~ 3 g). Each of the two extensometers is a single type extensometer, the averaging should be carried out by software.

Figure A.2 – Low mass averaging double extensometer

A.2.2 Single extensometer

Figure A.3 shows a single extensometer with a total weight of 31 g together with a balance weight. It was used during a RRT for Cu/Nb-Ti wires conducted in Japan and sound results were obtained. The results were used to establish the international standard (IEC 61788-6) [3, 4]¹.

¹ Figures in square brackets in this annex refer to the Reference documents listed in Clause A.15



IEC 2168/13

Dimensions in millimetres

Figure A.3 – An example of the extensometer provided with balance weight and vertical specimen axis

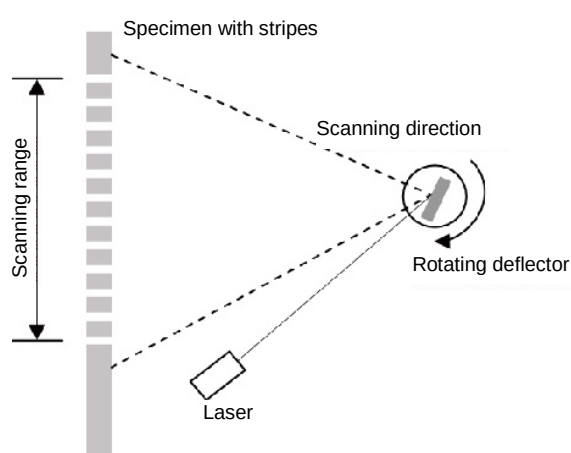
A.3 Optical extensometers

Any type of optical extensometer can be used if it is based on two single optical beams, where the signal can be recorded and averaged.

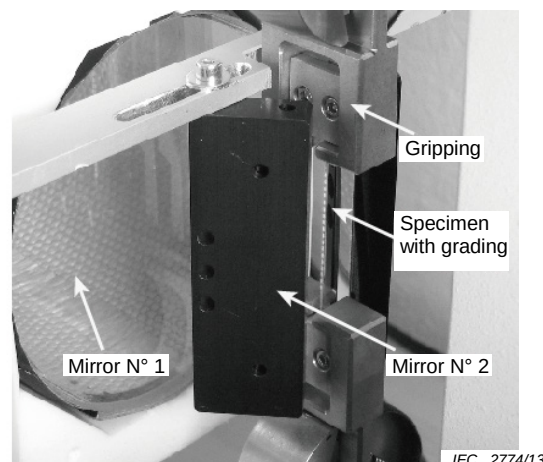
Alternatively, systems without mechanical contact to the specimen can also be used in a way similar to an averaging double extensometer system based either on two laser beams or on two other optical systems.

Figure A.4(a) shows schematically the scan of the stripes with 50 Hz of the rotating deflector. The small displacement changes during the loading of the specimen are analyzed by the

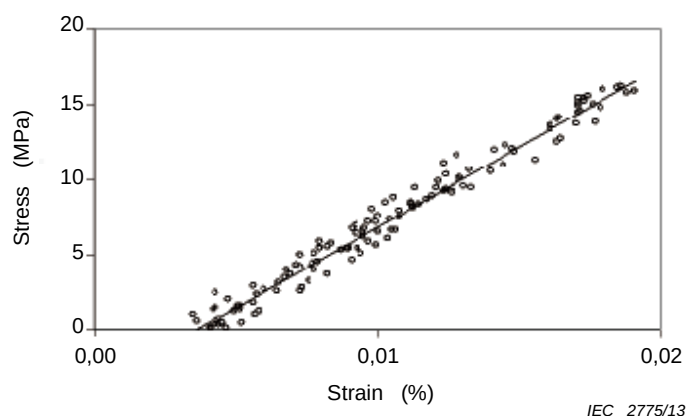
software. Figure A.5(b) shows the picture of the double mirror arrangement of a typical advanced double laser beam system.



(a) Schematic illustration



(b) Overview of the present extensometer



(c) The results of a reacted Nb_3Sn wire with 0,81 mm $\varnothing$ measured with a double beam laser extensometer.

Figure A.4 – Double beam laser extensometer

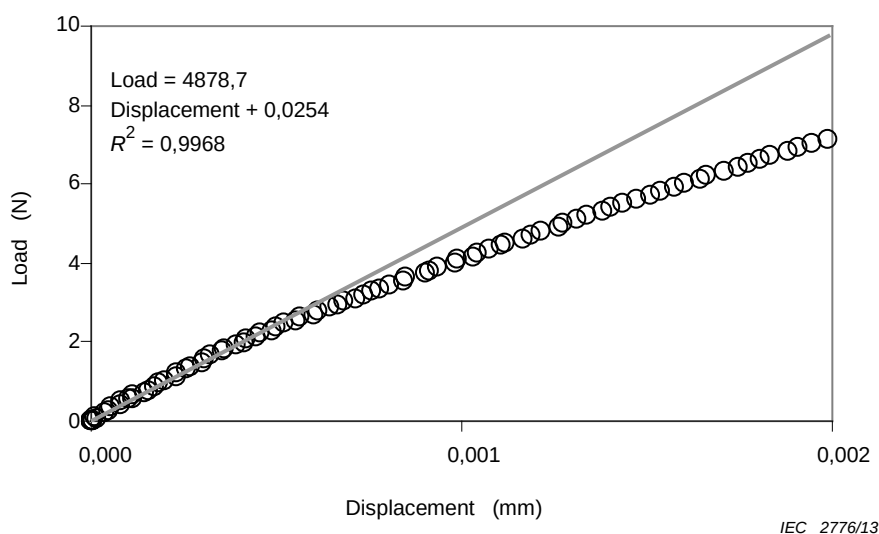
A.4 Requirements of high resolution extensometers

The requirements for such extensometers can well be derived from Figure A.5. Considering the target that the recorded values plotted from the raw data should have a low relative standard uncertainty, in particular between zero % strain and 0,01 % strain, the total displacement in this range will be 2,5 μm for the case of 25 mm gauge length or 1,2 μm for 12 mm gauge length. In fact, the signals should be acquired with a low noise around 100 times better to ensure stable records within the required strain range. The calibration factor of the used 12 mm gauge length extensometer is 10 V per 1 mm displacement. The V_{pp} of the signal should be less than 1 mV to ensure this low relative standard uncertainty. Using state-of-the-art signal conditioners, shielded and twisted cables and high resolution data acquisition systems of > 16 bit resolution, it is thus possible to ensure this demand. Figure A.5 shows the original raw data of the reacted Nb_3Sn measurement in form of load versus

displacement graph. To achieve the low scatter of the data shown it is necessary to have a high signal to noise ratio enabling to resolve the curve well below the 1 µm range [5,6,8,9]².

To obtain a zero offset gradient with a sufficient low relative standard uncertainty, which allows an assessment for the modulus of elasticity, it is prerequisite to use high resolution extensometers with extreme low noise to signal ratio.

The double extensometer system based either on two mechanical extensometers, on two laser beams, or on two other optical systems arranged symmetrically in a 180° sector to each beam may guarantee a compensation of the bending.



This figure shows the necessary low relative standard uncertainty with respect to the displacement resolution. The data are taken from the measurement of the sample as shown in Figure A.1.

Figure A.5 – Load versus displacement record of a reacted Nb₃Sn wire

A.5 Tensile stress $R_{\text{elasticmax}}$ and strain $A_{\text{elasticmax}}$

The tensile stress at which the transition of elastic to plastic deformation occurs is calculated in general using the following formula (Figure A.6).

$$R_{\text{elasticmax}} = F_{\text{elasticmax}} / S_0 \quad (\text{A.1})$$

where

$R_{\text{elasticmax}}$ is the tensile stress (MPa) at the transition of elastic to plastic deformation;

$F_{\text{elasticmax}}$ is the force (N) at the transition of elastic to plastic deformation.

The strain at which the transition of elastic to plastic deformation occurs (Figure A.6) referred to the stress $R_{\text{elasticmax}}$ is defined as follows:

$$\Delta A_{\text{total}} = A_{\text{max}} - A_0 \quad (\text{A.2})$$

² Figures in square brackets in this annex refer to the Reference documents listed in Clause A.15

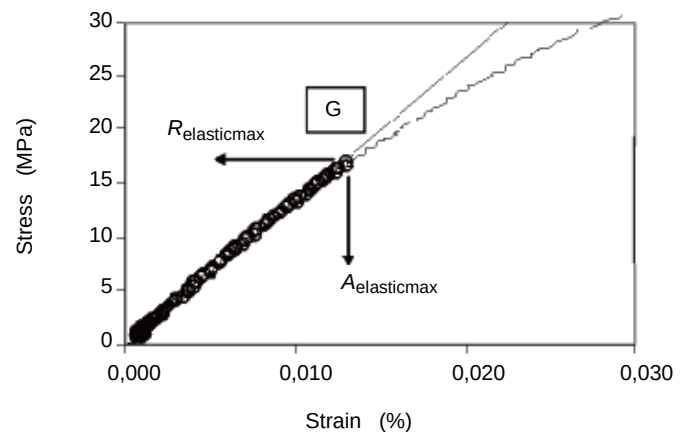
where

ΔA_{total} is the total strain increment referring to zero offset strain and to strain where the transition of elastic to plastic deformation occurs;

A_{max} is the observed value of strain referred to the stress $R_{\text{elasticmax}}$;

A_0 is the zero offset strain.

The values $R_{\text{elasticmax}}$ and $A_{\text{elasticmax}}$ are treated as being of informative character.



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This is the enlarged figure up to the transition region of the elastic plastic deformation (point G). The plots (large circles) show the region of the initial straight portion of the record. The linear 1st order regression analysis gives the modulus of elasticity E ($E_0 = 134,7$ GPa) and the measure of linearity as square of regression coefficient. The value of computed 0,188 MPa is the result of the regression line analysis, where the origin has been determined to have an offset in the ordinate owing to the plot scatter. In addition, the square of regression coefficient should be greater than 0,99 to ensure the linearity. The stress $R_{\text{elasticmax}}$ and the corresponding strain $A_{\text{elasticmax}}$ correspond to the transition region of elastic plastic deformation. In particular, the value of $R_{\text{elasticmax}}$ is an important quantity for the judgment of the determined E_0 . A low value of $R_{\text{elasticmax}}$ (e.g. < 5 MPa) may indicate a higher uncertainty for the E_0 owing to the small portion of the linear region. The smaller linear range has an impact for the measurand E_0 towards high uncertainty due to the data scatter. The uncertainty may raise the question of repeating the measurement.

Figure A.6 – Stress-strain curve of a reacted Nb₃Sn wire

A.6 Functional fitting of stress-strain curve obtained by single extensometer and 0,2 % proof strength ($R_{p0,2-F}$)

The functional fitting method is applicable to determine the 0,2 % proof strength in the case of single extensometer. Usually, constitute materials of copper and bronze in the Cu/Nb₃Sn wire have been yielded during cooling from heat-treatment temperature to room temperature. The stress-strain curve, therefore, is curved from the beginning in the strict sense and the evaluation of initial modulus of elasticity becomes difficult. Furthermore, due to the non-straight form of the specimen as heat-treated condition and pre-straining on handling during setting to the tensile testing machine, the stress-strain curve is bent concave or convex, hence it is difficult to estimate the intrinsic zero strain point. The functional fitting method is effective to exclude such strain included in the experimental data. The stress-strain curves can be approximated by the following exponential function:

$$F / S_0 = a(A - b)^n \quad (\text{A.3})$$

where F , S_0 and A are load, cross section and strain obtained by the test, a , b and n are parameters determined by non-linear least-mean-square-fitting. In order to avoid losing digits

during calculation, A is expressed in %. The upper bound of fitting is 0,5 % and the lower bound of fitting is increased until the three parameters converge.

The 0,2 % proof strength $R_{p0,2-F}$ of the composite due to yielding of the copper and bronze components by function fitting method is determined as follows; the linear portion under unloading is to be moved parallel to the 0,2 % offset point with regard to the zero strain point defined by the parameter b . The intersection of this line with the fitted stress – strain curve determines the point C that is defined as the 0,2 % proof strength (Figure 1(a)). Fitting by simplified equation of (A.3) by excluding the parameter b , means neglect of pre-strain and gives larger proof stress value close to the $R_{p0,2-F}$. It is reported that commercially available non-linear least-square-fitting software can produce results almost identical to the experimental data for the same parameters, if the allowable error is selected to less than 0,1 [1,2]³. However, the confirmation of coincidence between data points and the fitting curve is made.

A.7 Removing insulation

The coating on the surface of the test specimen should be removed using an appropriate method. Normally the Nb₃Sn conductors are braided with glass or ceramic fibers which can be easily removed by stripping or peeling. In case of other type of insulation one should use either an organic solvent or a mechanical method. In both case one may do this before the heat treatment reaction and may avoid any damage of the specimen surface.

The coating is not designed as a structural component. An analysis of measurement as a multi component composite including insulation is too complicated to perform. Therefore, this test method covers only the bare reacted wire in order to maintain the mechanical behavior of the wire.

A.8 Cross-sectional area determination

In case a smaller relative standard 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 macro photograph of the cross-section.

A.9 Fixing of the reacted Nb₃Sn wire to the machine by two gripping techniques

For gripping, the specimen may be soft soldered to a metallic sleeve in the region of the grips. These sleeves should provide a firm gripping to the machine's pull rods. Alternatively a gripping can be envisaged by chucking the wire itself. In this case it should be ensured that the wire inside the chucks is not damaged mechanically. The test specimen is mounted using the grips of the tensile machine. In any case, the test specimen and tensile loading axis are aligned to disclose a mismatching. During mounting of the sample, it is necessary to prevent bending or deformation.

According to the international round robin test results, several kinds of gripping techniques were allowable to get proper test results. Therefore it is recommended that the gripping technique proposed in the present standard be treated as one of various possible techniques.

³ Figures in square brackets in this annex refer to the Reference documents listed in Clause A.15

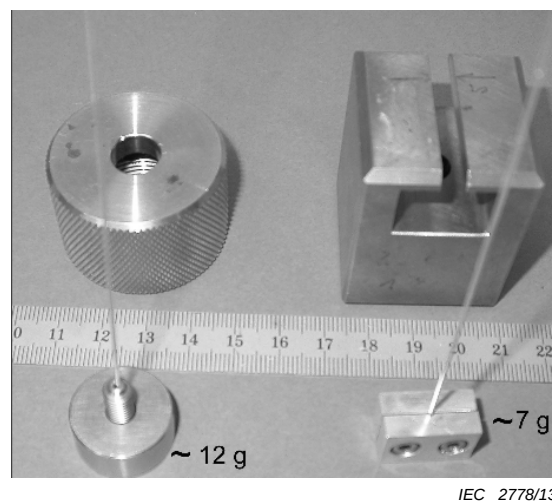
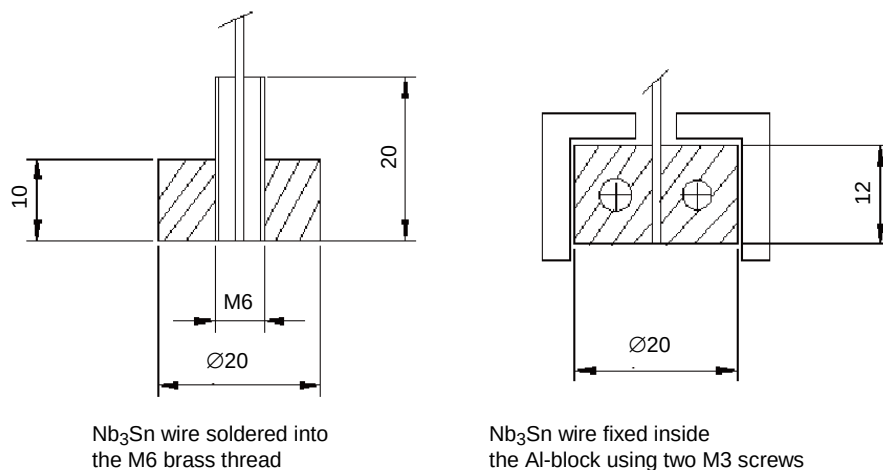


Figure A.7 – Two alternatives for the gripping technique.

The left image shows gripping of the soldered Nb₃Sn wire into a M6 brass thread, which is fixed with an aluminum sleeve serving the pulling action. The total mass of the sleeve together with the M6 thread is around 12 g.

The right portion of the image shows the clamping of the bare Nb₃Sn wire inside a V-groove of an aluminum block. The total mass of the block is around 7 g. This block inserted into a small frame acts as a defined fixture for the pulling action.



Nb₃Sn wire soldered into the M6 brass thread

Nb₃Sn wire fixed inside the Al-block using two M3 screws

IEC 2779/13

Dimensions in millimetres

The drawings show details of the two alternative possibilities of the wire fixing to the machine, by soldering and by clamping. In any case prior to the measurement start it is not allowed to load the wire with a pre-load. The bottom end of the wire with the fixing block should be free of any contact to the machine to avoid any pre-loading.

Figure A.8 – Details of the two alternatives of the wire fixing to the machine

A.10 Tensile strength (R_m)

The tensile strength at which the fracture occurs is calculated using the following formula.

$$R_m = F_{\max} / S_0 \quad (\text{A.4})$$

where

R_m is the tensile stress (MPa) at the fracture;

$F_{\max}$ is the maximum force (N) at the fracture.

For the wire with small copper to non-copper volume ratio, premature fracture occurs at the grips giving rise to lower tensile strength and smaller percentage elongation after fracture. The tensile strength and percentage elongation after fracture are important not only from the scientific view point describing the mechanical properties of composite material, but also useful for measures of validity of the tests. However, because the variances are large and the strain region of interest for the wire is small, the values are used as references.

A.11 Percentage elongation after fracture (A_f)

The measurement of elongation after fracture may serve only as a reference. The movement of the cross-head may also be used to find the approximate value for elongation after fracture as shown below. To use this method, the cross-head position at fracture must be recorded. The following formula is used to obtain the elongation after fracture, given in percentage.

$$A_f = 100 (L_u - L_g) / L_g \quad (\text{A.5})$$

where

A_f is the percentage elongation after fracture;

L_u is the distance between grips after fracture.

L_g is the initial inward distance between grips.

A.12 Relative standard uncertainty

Owing to the nature of any measurement, the obtained test results have a scatter in all cases. To assess the quality of the measured data the concept of uncertainty serves a sound basis for an independent judgement. In Annex B and C detailed information are supplied with respect to uncertainty of a measurand.

In case of Nb_3Sn wire measurements substantial experiences were gathered during the international round robin tests carried out with 11 research groups [7,9]. In particular, the evaluation of obtained data, supplied valuable information with respect to the modulus of elasticity determined at the zero offset line and from the unloading line between 0,3 % and 0,4 % strain. In general, the obtained moduli of elasticity results from the initial loading line have a larger scatter compared to the determined values from the unloading line. A comprehensive analysis of these data is given in reference [8]⁴ and shows that the ratio of E_0 and E_U varies from unity if all results are collected together. These variation can be described by using the simple relation $1 - \Delta < E_0/E_U < 1 + \Delta$, where Δ defines the quantity of the deviation from unity. To limit the scatter at the initial loading line and to delete disqualified data $\Delta = 0,3$ has been proven to be an adequate value.

In Table A.1 the important quantities such as the modulus of elasticity obtained from initial loading line and also the proof strengths are summarized. The standard uncertainties of these results show that the disqualification of the data beyond $\Delta = 0,3$ reduces the standard uncertainties at least by a factor of 2.

⁴ Figures in square brackets in this annex refer to the Reference documents listed in Clause A.15

The scatter of experimental data obtained from RRT relates to two contributions of the intra- and inter- laboratory. In order to make clear whether the data submitted from their respective laboratories belongs into the same population of all experimental data, the analysis of variance (F-test) was performed under the guidance of the text (GUM H.5.2.1). As a typical example, the experimental data on E_0 were analysed and the results are listed in Table A.1. In order to make exact comparison among laboratories, it is necessary to fix the same number of data from each laboratory, three for example. So three data were chosen randomly from each laboratory when the number of data was equal to or larger than 3, while the data set from laboratory was abandoned in case of a data number less than 3.

According to GUM guidance, the ratio of the inter-laboratory variance (s_a^2) and the intra-laboratory one (s_b^2) was calculated as $F_{\text{exp}} = s_a^2 / s_b^2$ and compared with the theoretical function, $F_{N-J}^{J-1}(\alpha)$. When the hypothesis of $F_{\text{exp}} < F_{N-J}^{J-1}(\alpha)$ holds, the data belong to the same population with the significance level α %. In the case, where all data were employed for F-test, the hypothesis did not hold for some samples, E3, E4, H and M. On the other hand, in another case, where the data qualified by applying Δ of 0,3, were used, the hypothesis held for all the samples, when α was settled on 1 %. Therefore it was concluded that the present F-test guarantees the validity of qualification check with respect to the ratio of moduli of elasticity mentioned in 8.1 of the main text. Further it is possible to judge the qualification condition more rigidly by using the higher significance level.

Table A.1 – Standard uncertainty value results achieved on different Nb₃Sn wires during the international round robin tests

Sample	Property(X)	All Data				Qualified Data			
		N	<X>	SU	RSU	N'	<X'>	SU	RSU
E2	E_0 , [GPa]	35	113,5 [GPa]	2,8[GPa]	2,5[%]	22	114 [GPa]	1,4 [GPa]	0,3[%]
	$R_{p0,2-0}$, [MPa]	35	187,1 [MPa]	3,0[MPa]	1,6[%]	22	181,7 [MPa]	1,3 [MPa]	0,7[%]
E3	E_0 , [GPa]	33	119,2[GPa]	3,2 [GPa]	2,7[%]	21	121[GPa]	1,5[GPa]	1,3[%]
	$R_{p0,2-0}$, [MPa]	34	192,1[MPa]	2,3 [MPa]	1,2[%]	21	191,8 [MPa]	1,6 [MPa]	0,8[%]
E4	E_0 , [GPa]	36	90,3[GPa]	3,9[GPa]	4,3[%]	14	109,2[GPa]	2,0[GPa]	1,9[%]
	$R_{p0,2-0}$, [MPa]	37	113,6[MPa]	2,2 [MPa]	1,9[%]	14	111,9 [MPa]	3,7 [MPa]	3,3[%]
H	E_0 , [GPa]	33	88,5[GPa]	4,2 [GPa]	4,8[%]	9	109,8 [GPa]	2,0 [GPa]	1,8[%]
	$R_{p0,2-0}$, [MPa]	33	118,8[MPa]	2,3[MPa]	1,9[%]	9	110,3[MPa]	2,9[MPa]	2,6[%]
K	E_0 , [GPa]	34	116,2[GPa]	2,8 [GPa]	2,4[%]	25	115,6 [GPa]	1,1 [GPa]	1,0[%]
	$R_{p0,2-0}$, [MPa]	33	182[MPa]	2,6 [MPa]	1,4[%]	25	179,7 [MPa]	2,6 [MPa]	1,4[%]
M	E_0 , [GPa]	29	88,6[GPa]	5,8 [GPa]	6,6[%]	9	120,4[GPa]	3,0[GPa]	2,5[%]
	$R_{p0,2-0}$, [MPa]	28	118 [MPa]	4,0 [MPa]	3,4[%]	9	109,2[MPa]	1,7[MPa]	1,5[%]

N: number of total tested wires,
 N': number of qualified wires,
 X: modulus of elasticity or proof strength,
 <X>: average for total wires,
 <X'>: average for qualified wires,
 SU: standard uncertainty for total data, and
 RSU: relative standard uncertainty.

This table presents results of standard uncertainty values achieved on different Nb₃Sn wires during the international round robin tests carried out by 11 different research laboratories.