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Fine ceramics (advanced ceramics, advanced technical ceramics) — Mechanical properties of ceramic composites at ambient temperature in air atmospheric pressure — Determination of tensile properties of tubes

Céramiques techniques — Propriétés mécaniques des composites céramiques à température ambiante et à pression atmosphérique — Détermination des propriétés en traction de tubes

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Foreword

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

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Mechanical properties of ceramic composites at ambient temperature in air atmospheric pressure — Determination of tensile properties of tubes

1 Scope

This document specifies the conditions for the determination of tensile properties of ceramic matrix composite tubes with continuous fibre-reinforcement at ambient temperature in air atmospheric pressure. This document is specific to the tubular geometries since fibre architecture and specimen geometry factors are distinctly different in composite tubes than in flat specimens.

This document provides information on the uniaxial tensile properties and tensile stress-strain response such as tensile strength and strain, tensile elastic modulus and Poisson's ratio. The information may be used for material development, control of manufacturing (quality insurance), material comparison, characterization, reliability and design data generation for tubular components.

This document addresses, but is not restricted to, various suggested test piece fabrication methods. It applies primarily to ceramic and/or glass matrix composite tubes with a continuous fibrous-reinforcement: unidirectional (1D filament winding and tape lay-up), bi-directional (2D braid and weave) and tri-directional (xD, with $2 < x < 3$), loaded along the tube axis.

Values expressed in this document are in accordance with the International System of Units (SI).

NOTE In most cases, ceramic matrix composites to be used at high temperature in air are coated with an antioxidation coating.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 20507, *Fine ceramics (advanced ceramics, advanced technical ceramics) — Vocabulary*

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

ISO 17161, *Fine ceramics (advanced ceramics, advanced technical ceramics) — Ceramic composites — Determination of the degree of misalignment in uniaxial mechanical tests*

ISO 9513, *Metallic materials — Calibration of extensometer systems used in uniaxial testing*

ISO 3611, *Geometrical product specifications (GPS) — Dimensional measuring equipment: Micrometers for external measurements — Design and metrological characteristics*

ASTM E2208-02, *Standard Guide for Evaluating Non-Contacting Optical Strain Measurement Systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 20507 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
calibrated length
l
part of the test specimen that has uniform and minimum external diameter

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

3.3
initial cross-section area
S_0
area of the test specimen within the calibrated length

3.4
effective cross-section area
$S_{0,\text{eff}}$
total area corrected by a factor, to account for the presence of an anti-oxidative protection

3.5
external diameter
d_0
outer distance through the centre of a tube from one side to the other

3.6
internal diameter
d_i
inner distance through the centre of a tube from one side to the other

3.7
longitudinal deformation
A
increase in the gauge length between reference points under a tensile force

3.8
longitudinal deformation under maximum tensile force
A_m
increase in the gauge length between reference points under maximum tensile force

3.9
tensile strain
ε_{zz}
relative change in the gauge length defined as the ratio A/L_0

3.10
tensile strain under maximum force
$\varepsilon_{zz,m}$
relative change in the gauge length defined as the ratio A_m/L_0

3.11
circumferential strain
$\varepsilon_{\theta\theta}$
relative change in circumferential direction in the gauge length

3.12
tensile stress
σ
tensile force supported by the test specimen at any time in the test divided by the initial cross-section area (S_0)

3.13
effective tensile stress
σ_{eff}
tensile force supported by the test specimen at any time in the test divided by the effective cross-section area ($S_{0,eff}$)

3.14
maximum tensile force
F_m
highest recorded tensile force in a tensile test on the test specimen when tested to failure

3.15
tensile strength
σ_m
ratio of the maximum tensile force to the initial cross-section area (S_0)

3.16
effective tensile strength
$\sigma_{m,eff}$
ratio of the maximum tensile force to the effective cross-section area ($S_{0,eff}$)

3.17
proportionality ratio
pseudo-elastic modulus
E_P
slope of the initial linear section of the stress-strain curve

Note 1 to entry: Examination of the stress-strain curves for ceramic matrix composites allows definition of the following cases:

a) Material with an initial linear domain in the stress-strain curve.

The proportionality ratio or pseudo-elastic modulus is termed the elastic modulus, E, in the single case where the linearity starts near the origin.

b) Material with no-linear section in the stress-strain curve.

In this case only stress-strain couples can be fixed.

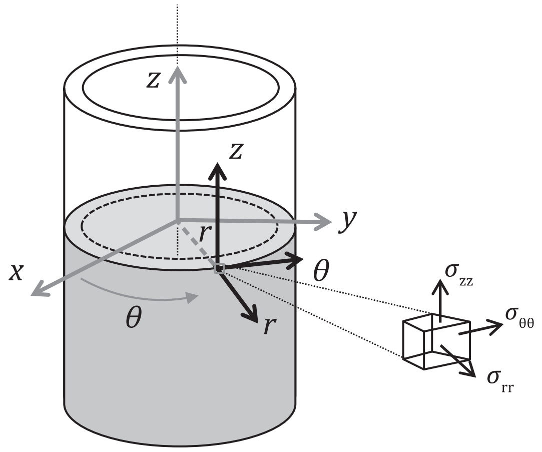
3.18
effective proportionality ratio
effective pseudo-elastic modulus
$E_{P,eff}$
slope of the linear section of the stress-strain curve, if any, when the effective tensile stress is used

3.19
Poisson's ratio
$\nu_{\theta z}$
negative ratio of circumferential to axial strain

3.20
coordinate system
system used to determine location in space

Note 1 to entry: Cylindrical coordinates are adopted in the present document.

Note 2 to entry: The notations shown in Figure 1 apply for space representation.



Key

z axial

r radial

θ circumferential

Figure 1 — Cylindrical coordinate system used for the CMC tubes

4 Principle

A prepared tubular test specimen of specified dimensions is loaded in monotonic uniaxial tension up to fracture. The test is performed at constant cross-head displacement, or constant strain (or constant loading rate). Both the applied force and resulting longitudinal strain are measured and recorded simultaneously. The uniaxial tensile strength and strain are determined from the maximum applied force, while the various other tensile properties are determined from the stress-strain response data.

Generally, the test is carried out under conditions of ambient temperature and environment.

NOTE 1 In uniaxial loading, the force is applied parallel to the tube axis. Monotonic refers to a continuous nonstop test rate with no reversals from test initiation to final fracture.

NOTE 2 The use of constant loading rate only gives a valid tensile curve when the behaviour is linear up to failure.

5 Apparatus

5.1 Test machine.

The test machine shall be equipped with a system for measuring the force applied to the tubular test specimen conforming to grade 1 or better in accordance with ISO 7500-1.

5.2 Test specimen gripping.

Various types of gripping device may be used to transmit the measured force applied by the testing machine to the tubular test specimen. It shall prevent the tubular test specimen from slipping.

The brittle nature of the matrices of continuous fibre ceramic composites (CFCCs) requires a uniform and continuous contact between the grip components and the gripped section of the tubular test specimen in order to minimize crack initiation and fracture in this area.

Gripping devices can be generally classified as those employing active grip interfaces and those employing passive grip interfaces that include gripping system with adhesive bonding or through a pin-loaded fixture. Examples, descriptions and designs for both the gripping types are discussed in Annex A.

If an active grip interface system is used, the length of the grip section shall be long enough to develop sufficient friction force to transmit the tensile forces to the tubular test specimen. As a general rule, grip lengths are defined at least 1,5 times higher than the external diameter of the specimen. If the tubular test specimen is pulling out of the grips, thus failing to increase the clamping pressure, longer grip lengths might be needed.

To prevent crushing of the tubular test specimen by the lateral pressure and subsequent collapse of the tube wall, it is advisable to insert an end plug into the interior of the grip section of the tube specimen or to provide a suitable geometry for end collars (see 6.3).

5.3 Load train couplers.

Various types of devices may be used to fix the active or passive grip interface assemblies to the testing machine. The load train couplers in conjunction with the type of gripping device play major roles in the alignment of the load train and extraneous bending imposed in the tubular test specimen; they can be generally classified as fixed and non-fixed and are discussed in Annex A.

If each system type can be used, the load train configuration shall ensure that the load indicated by the load cell and the load experienced by the tubular test specimen are the same. The alignment shall be checked and documented in accordance with, for example, the procedure described in ISO 17161 adapted to the tubular geometry of specimen.

The maximum relative bending shall not exceed 5 % at an average strain of $5{,}10^{-4}$.

5.4 Strain measurement.

5.4.1 General

Strain should be locally measured in order to avoid having to take into account the compliance of the machine. This may be by means of suitable extensometers, bonded resistance strain gauges or digital image correlation (DIC). If Poisson's ratio is to be determined, the tubular test specimen must be instrumented to measure strain in both longitudinal and circumferential directions.

5.4.2 Extensometers

Extensometers used for tensile testing of CFCC tubular test specimens shall be capable of continuously recording the longitudinal strain at test temperature. They shall be of class 1 in accordance with ISO 9513.

Extensometers with the highest gauge length are recommended (minimum of 25 mm required) and shall be centrally located in the mid region of the axial direction of the gauge section of the tubular test specimen.

If mechanical extensometers are used, the selected attachment should cause no damage to the specimen surface. In addition, the weight of the extensometers should be supported, so as not to introduce bending stresses in the tubular test specimen greater than that allowed in 5.3.

Extensometers should preferably be of a type that is capable of measuring elongation on two places of the tubular test specimen for averaging of strain and/or determination of in-situ relative bending. Care should be taken to correct for changes in calibration of the extensometer that may occur as a result of operating under conditions different from calibration.

5.4.3 Strain gauges

5.4.3.1 General

Although extensometers are commonly used to measure strain in tensile test of CFCC tubes, strain can also be determined with bonded resistance strain gauges and suitable strain recording equipment. The strain gauges, the surface preparation and the bonding agents should be chosen to provide adequate performance on the tested materials.

Some guidelines on the use of strain gauges on CFCC tubes are as follows.

5.4.3.2 Strain gauge selection

Unless it can be shown that strain gauge readings are not unduly influenced by localized strain events such as fibre crossovers, strain gauges should be not less than 9 mm to 12 mm in length for the longitudinal direction and not less than 6 mm in length for the circumferential direction.

When testing braided or woven fabric composites, the strain gauges should have an active gauge length that is at least as great as the characteristic unit cell (repeating unit) of the reinforcement; this averages the localized strain effects of the fibre crossovers.

In uniaxial loading, a single-grid gauge pattern would normally be used with the gauge axe aligned to coincide with the longitudinal direction of the tubular test specimen.

NOTE Poisson’s ratio can be determined with biaxial two-element (0–90) strain gauge rosettes which measure the strain in both the longitudinal and circumferential directions.

5.4.3.3 Surface preparation

The relatively rough surface of composites usually requires some preparation prior to strain gauge bonding. The basic steps have to include solvent degreasing, abrading or filling and cleaning.

Matrix-rich surfaces can usually be abraded with 320-grit silicon carbide paper (SCP-2) to produce a satisfactory matte finish. However, unless their surfaces have been machined or have received a smoothing treatment, tubular test specimens of poor matrix content composites or those with textured surface require alternative techniques.

NOTE A typical method is to apply a thin epoxy precoat to smooth the surface irregularities and finish by polishing.

Reinforcing fibres should not be exposed or damaged during the surface preparation process. In particular, abrasion should be kept to a minimum to avoid possible damage to fibres in the external surface of the composite.

5.4.4 Digital image correlation

5.4.4.1 General

The DIC method can also be used to determine local strain of CFCC tubular test specimens loaded in tensile from the displacement field measurement. The general procedure to be followed for estimating the strain shall be in accordance with ASTM E2208-02.

Some guidelines on the use of the DIC method on CFCC tubes are as follows.

5.4.4.2 Experimental setup

The experimental setup for DIC measurements requires a digital CCD camera coupled with an optical macro lens to acquire high spatial resolution micrographs (a minimum of 20 µm per pixel is recommended). In the present case, the use of a telecentric lens is required to overcome the curvature effect of the tubular test specimens.

The imaging conditions for DIC measurements have to be selected to ensure that the entire coupon surface is in the best focal plane of the camera and that the highest possible magnification could be attained. Annular illumination with white or monochromantic light is recommended to provide a correct signal-to-noise ratio.

The camera needs to be able to acquire micrographs at a suitable frame rate in order to achieve a sufficient temporal resolution of the test. Depending on the device, special timing and triggering control is required to synchronize the acquisition of the camera with the applied load.

For mechanical tensile test, the maximum frame rate of the camera limits the maximum speed of the displacement that can be imposed on the specimen. In general, the frame rate of the camera should be at least twice the displacement rate.

5.4.4.3 Surface preparation

The requirement for surface preparation depends on both the magnification of the imaging system and the surface characteristics of the composite. In general, the technique requires sharp grayscale information of the order of 1 pixel in size at the CCD recording device.

The most common way to prepare a suitable surface is the use of high-contrast speckle patterns. These can be obtained by applying a matt randomized coating such as speckled black dots on a homogenous white background. The composite materials with a pronounced roughness average are expected to naturally produce highly micro-textured images.

5.4.4.4 Calculation

Correlation may be then carried out using DIC commercial software. The selection of the correlation area in terms of dimensions should be such as calculations led to determine the longitudinal strain.

Reference to the software provider’s instructions must be followed for the execution and interpretation of the measure.

NOTE Poisson’s ratio can be determined by applying a similar calculation to measure the circumferential strain on a close area.

5.5 Data recording system.

A calibrated recorder should be used to record the applied tensile force and the gauge section elongation (or strain) versus time. The use of a digital data recording system is recommended for this purpose.

Recording devices shall be accurate to within ±0,1 % for the entire testing system including readout unit, and shall have a minimum data acquisition rate of 10 Hz with a response of 50 Hz deemed more than sufficient.

Crosshead displacement of the test machine may also be recorded but shall not define displacement or strain in the gauge section, especially when self-aligning couplers are used in the load train.

5.6 Dimensions measurement.

Micrometers used for the measurement of the dimensions of the test specimen shall conform to ISO 3611. The internal and external diameters of the tubular test specimen should be measured with an accuracy of 0,02 mm or 1 % of the measured dimension, whichever is higher. Flat anvil type micrometer or calipers of similar resolution may be used for measuring the overall test specimen length and the defined gauge length.

Ball-tipped or sharp anvil micrometers are not recommended for tubular CFCCs because the resulting measurements may be affected by the peaks and troughs of the weave.

In some cases it is desirable, but not required, to determine dimensions of the tubular test specimen subtracted from surface roughness (internal and external diameters). Methods such as contacting/optical profilometry or image analysis on a polished transverse cross section may be used for this purpose.

6 Tubular test specimens

6.1 Specimen specifications

6.1.1 General

CFCC tubes are fabricated in a wide range of sizes and geometries and across a wide spectrum of different reinforcement fibres, distinctive ceramic matrix materials and markedly different fabrication methods. The fibre architecture for CFCC tubes also has a broad range of configurations with different fibre loadings and directional variations. Therefore, it is currently not practical to define a single test specimen geometry that is applicable to all CFCC tubes.

The selection and definition of a tubular test specimen geometry depends on the purpose of the tensile test. In addition, grip devices and load train couplers (as discussed in 5.2 and Annex A) may influence the design of the test specimen geometry.

6.1.2 Dimension

The test method described applies to CFCC tubes with external diameters greater than 7 mm and a minimum of 0,5 mm in wall thickness, roughly corresponding to minimum one single layer. The ratio of external diameter to wall thickness ($\varnothing/h$) is commonly extended in the range of 5 to 30.

The total length of specimen depends on the selected experimental configuration for testing, but the volume in the gauge length shall be representative of the composite material. As a general rule, the calibrated length (l) should be commonly selected to keep the ratio ($l/\varnothing$) between 2 and 3 with a minimum value of 30 mm recommended.

Deviations outside the recommended ranges may be necessary depending upon the particular CFCC being evaluated.

6.1.3 Geometry

A straight-sided tube geometry that often does not require machining to obtain proper dimensions is recommended to carry out the test. It can be used with active and passive grips. For this geometry, both the internal and external surfaces of the specimens may be rough and irregular.

Figure 2 represents a tubular test specimen with straight-sided geometry. Dimensional requirements for acceptable specimen are contained in Table 1.

In some cases, another geometry of CFCC tube can be accepted. Annex B provides an example of contoured gauge test specimen tube geometry with dimensional requirements.

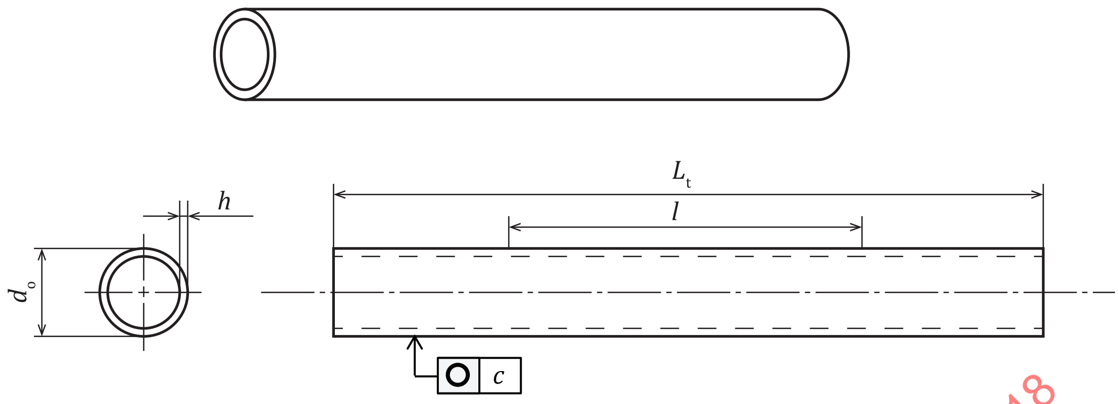


Figure 2 — “Generic” straight-sided tube test specimen

Table 1 — Dimensional requirements for straight-sided tube test specimen type

Dimensions in millimetres

Variable	Symbol	Minimum value	Tolerance
Total length	L_t	≥60	±2
Calibrated length	l	≥30 for a minimal gauge length of 25 mm	±0,2
External diameter	d_o	≥7	±0,2
Wall thickness	h	≥0,5 and corresponding to at least a single layer	±0,2
Roundness	c	—	0,1

6.1.4 Tolerances and variability

Dimensional tolerances are related on the specific selected specimen geometry, the method of manufacturing and the performance requirements of the CFCC application. It is common for CFCC tubes to have a relative diametral variability, particularly for larger diameter tubes.

The gauge section may or may not be machined to a specific tolerance (see Table 1). However, the difference in calibrated diameters taken out of three measurements for all the specimen types (as the centre and at each end of the calibrated length) shall not exceed 2 % of the average of the three measurements.

NOTE Measurements of inner diameters of CMC tubes can be performed by using suitable instruments such as “3 point internal micrometer” or “inside micrometer rod-type”.

6.2 Specimen preparation

6.2.1 General

Any test sample preparation route, including those discussed here, may be used as long as the preparation procedure is reported in sufficient detail to allow replication.

Machining or grinding of the tubular test specimen may be necessary for two purposes: (i) to develop a controlled diameter in the gauge section and/or (ii) to produce a uniform diameter in the grip section for fitting into the grip fixture. Depending upon the intended application of the tensile behaviour data, use one of the following test specimen preparation procedures.

6.2.2 As-fabricated

The tubular tensile test specimen should simulate the surface conditions and processing route where no machining is used. No additional machining specifications are relevant. As-processed test specimens may possess rough surface textures and non-uniform wall thicknesses and therefore may cause excessive misalignment or be prone to non-gauge section fractures or both.

6.2.3 Application-matched machining

The tubular tensile test specimen should have the same surface preparation as that given to the component. Unless the process is proprietary, the report should be specific about the stages of material removal, wheel grits, wheel bonding, amount of material removed per pass and the type of lubricant used.

6.2.4 Customary practices

In instances where a customary machining procedure has been developed and defined that is completely satisfactory for a class of material (i.e. that introduces no unwanted surface and subsurface damage or residual stress), this procedure can be used and should be reported.

6.2.5 Standard procedure

When the procedures mentioned above are not appropriate, the baseline cutting and grinding rules shall apply to prepare the tubular test specimens.

All grinding or cutting shall be done with ample supply of appropriate lubricant to keep the specimen and grinding wheel cool, constantly flooded and particles flushed. Grinding can be done from around the circumference where at least two stages are performed, ranging from coarse to fine rate of material removal. Stock removal rate should be of the order of 0,03 mm maximal per pass using diamond tools. All cutting can be done in one stage appropriate for the depth of cut. The test specimen should be fully dried after wet cutting.

More detailed and stringent procedures may be necessary for specific CFCC systems.

6.3 End collars

End collars (or sleeves) are required to provide a compliant layer for gripping the CFCC tubular test specimen. If using a passive grip interface with an adhesive bond, the end collars may correspond to the grip fixtures.

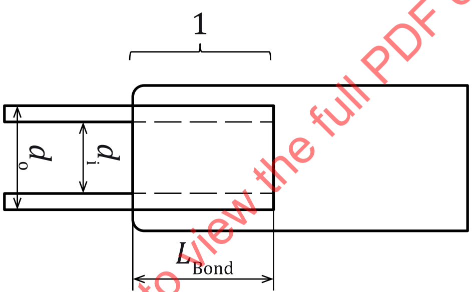
End collars are commonly steel or aluminium. They shall be bonded to the specimen before mounting in the test machine with a high shear strength adhesive (as epoxy). The tubular test specimen shall fit snugly in the bonding cavity with a thin space (0,1 mm to 0,2 mm) for the adhesive, providing uniform bonding contact between the gripped section and the grip cavity.

The end collars shall cover the total gripping length. Insufficient bonding surface in the grips may produce sliding or bond failure before specimen failure. As a rule of thumb, the bond shear forces which develop from the maximum tensile force shall produce shear stresses <50 % of the nominal shear strength of the adhesive. The bonding surface length (L_{Bond}) for tube can be estimated with Formula (1) (see Figure 3).

$$L_{Bond} = K \times \frac{\sigma_{CFCC}}{\sigma_{Ad}} \times \frac{d_o^2 - d_i^2}{4D_{Bond}} \quad (1)$$

where

K	is the selected safety factor (2 for 50 % reduction);
σ_{CFCC}	is the expected tensile strength of the composite;
σ_{Ad}	is the shear stress strength of the adhesive;
d_o	is the external diameter of the tubular test specimen;
d_i	is the internal diameter of the tubular test specimen;
D_{Bond}	is the effective diameter of the bonding zone [d_o for bonding on the outer circumference; ($d_o + d_i$) for bonding on both the outer and inner circumference].



Key

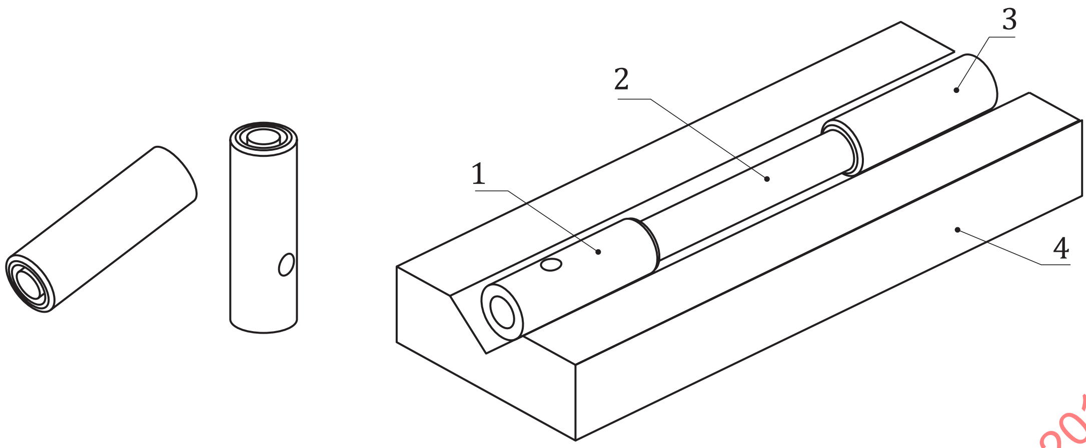
1 bonding zone

Figure 3 — Bonding zone with dimensions for a CFCC tubular test specimen

It is recommended that bonding is made in a tough V-shaped support to ensure concentric alignment between both the two end collars and the CFCC tubular test specimen.

Figure 4 shows an example of a successful end collar design with a V-shaped piece supporting the tubular test specimen for the adhesive stage.

NOTE In most cases, end collars can be recycled by removing the adhesive after testing by either chemical or thermal action, depending on the nature of the adhesive. Sleeves (as those shown in Figure 5) are easy to extract from tubular test specimens for reuse after cleaning.



Key

1 end collar (lower)

2 tubular test specimen

3 end collar (upper)

4 V-shaped piece

Figure 4 — Example of end collars with V-shaped supporting piece for bonding

6.4 Test count and test specimens sampling

A minimum of three valid tubular test specimens, as specified in Clause 7, is required for any condition in order to estimate a mean or average. A greater number of valid test specimens may be necessary, if estimates regarding the form of the strength distribution are required.

Test specimens should be selected and prepared from representative CFCC samples that meet the stated testing objectives and requirements. The method of sampling shall be reported.

7 Test procedure

7.1 General

The recommended test procedure consists of three main steps as follows. Any deviation from this procedure shall be described in detail in the test report.

7.2 Test mode and rates

Test mode may involve force, displacement or strain control. The recommended rate of testing shall be sufficiently fast to obtain the maximum possible tensile strength at fracture of the material. Typically, fracture should occur within 60 seconds of the start of the test.

The test mode and the displacement rate shall be reported.

The test mode can have a strong influence on the fracture behaviour of advanced ceramics. In order to prevent a “runaway” condition (e.g. a rapidly uncontrolled deformation), which can occur with force- or stress-controlled test mode due to the cumulative damage process of the CFCCs, displacement or strain control is preferred.

7.3 Testing technique

7.3.1 Measurement of test specimen dimensions

The cross-section area is determined before testing at the centre of the tubular test specimen and at each end of the gauge length by measuring both the external and internal diameters.

Dimensions shall be preferentially measured with a micrometer, as described in 5.6. The arithmetic means of the measurements shall be used for the stress calculation.

The test specimen free length between the end collars and the gauge length of the gauge section (if it is defined) shall be known with an accuracy of ±1 %.

NOTE Alternatively, in cases where it is not possible to infer or determine gauge section wall thickness with a micrometer, measurements can be performed by optical profilometry or by an image analysis method on a polished transverse cross section provided for this purpose.

7.3.2 Instrumentation of test specimen

Depending on the method selected for the measuring strain, the strain gauges installation is done on the specimen, ensuring that they are properly oriented and securely bonded in accordance with the manufacturer's instructions (see recommendations in 5.4.3).

A high-contrast speckle pattern can be performed on the tubular test specimen surface if the DIC method is also employed to measure strain (see recommendations in 5.4.4).

7.3.3 Test specimen mounting

The tubular test specimen is mounted into the gripping system, ensuring that its longitudinal axis coincides with that of the test machine. The grips should be tightened evenly and firmly in order to prevent slippage of the tube sample during the test while avoiding crushing of the specimen.

If special fixture components are required, these should be identified and noted for each test in the test report.

Care shall be taken not to induce flexural or torsional loads.

When load train alignment is done with the actual tubular test specimen, the adjustment shall be conducted for each test.

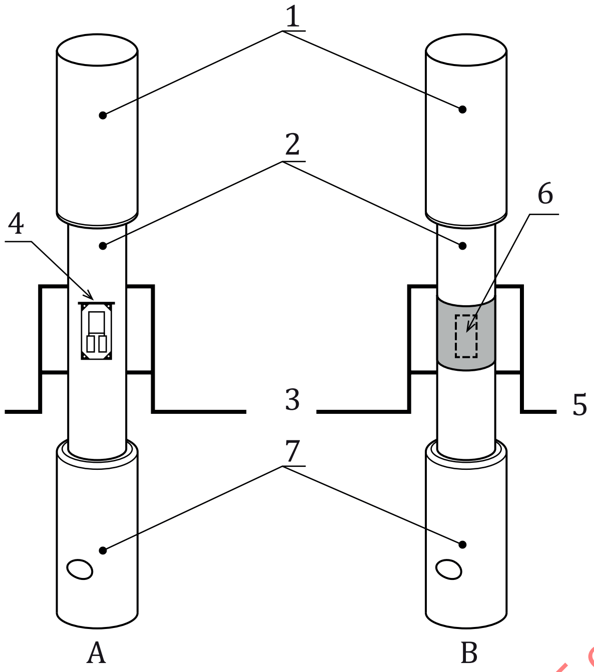
If strain gauges are used to monitor bending, the strain gauges should be zeroed with the tubular test specimen attached at only one end, so that it is hanging free. This will ensure that bending due to the grip closure is factored into the measured bending.

The recommended maximum allowable percentage bending at the onset of the cumulative fracture process for CFCC tubular test specimens is 5 %.

7.3.4 Setting-up of strain measurement means

All the selected strain measurement means are installed and/or calibrated while no force is applied to the tubular test specimen.

The extensometer(s) should be mounted longitudinally, centred with the axis of the tubular test specimen in the gauge section.



Key

1	end collar (upper)	6	observation area (speckle pattern, 1 024 mm × 1 024 mm)
2	tubular test specimen	7	end collar (lower)
3	extensometer 1 (gauge length min. 25 mm)	A	front view
4	longitudinal strain gauge	B	rear view
5	extensometer 2		

Figure 5 — Example of successful configuration for tensile testing of tubular test specimen

If strain gauges are used, all the lead wires should be connected to the conditioning equipment and the strain gauges should be allowed to equilibrate under power for at least 30 min prior to conducting the test.

If the DIC method is being used, the optical lens should be focused to view the area of interest on the gauge section surface. Illumination should be adjusted to achieve the brightest possible image while avoiding any reflections and the recording mode should be selected to acquire the displacement during the loading in an appropriate rate.

An example of successful configuration for tensile testing on a tubular test specimen is shown in Figure 5.

7.3.5 Measurements

The tensile test shall be conducted in the following sequence:

— Activate and adjust the testing machine for initial cross-head position, zero load and desired test rate.

— Assemble and activate the data recording instrumentation for force and strain measurements. Set the range of sensitivity and data collection rate.

— Initiate the data acquisition. Preload the tubular test specimen to the designated force level, if necessary.

— Initiate the displacement mode and record force versus strain (or images) continuously.

— Load the tubular test specimen to final fracture.

After specimen fracture, disable the action of the test machine and the data acquisition systems. Carefully remove the tubular test specimen halves from the grip interfaces. Take care not to damage the fracture surfaces by preventing contact with other fracture surfaces or with other objects. Place the test specimen halves along with other fragments from the gauge section into a suitable and protective package for later analysis.

NOTE Fracture is marked by specimen breakage and separation or where the applied force drops off significantly. Typically, a 10 % force drop-off is considered significant.

7.3.6 Post-test analyses

Fracture location shall be measured and reported relative to the midpoint of the gauge section. The convention used should be that the midpoint of the gauge section is 0 mm with positive (+) measurements toward the top of the tubular test specimen as tested and negative (−) measurements toward the bottom of the test specimen as tested.

For fracture surfaces which are not perpendicular to the longitudinal axis, the orientation of the fracture location should be reported. For fracture into several fragments, the location and number of fragments should be reported.

Visual examination and optical microscopy of the fracture surfaces should be conducted to determine the type of fracture as a function of CFCC composition and architecture, material variability, damage accumulation and failure zones. The results of the fractographic analysis should be reported.

NOTE In addition, subjective observations can be made of the length of fibre pullout, fracture plane orientation, degree of interlaminar fracture and other pertinent details of the fracture surface.

7.4 Test validity

Individual tests are considered as being valid when all the testing requirements of this document are met and when final fracture occurs in the uniformly stressed gauge section.

The following circumstances invalidate a test:

— failure to specify and record test conditions;

— fracture occurring in the grip section or outside the designated gauge section;

— specimen slippage.

The main factors of concern that can produce invalid tests include the alignment of the test specimen in the fixtures, the alignment of the fixtures in the grips and the adhesive used to bond the test specimen to the fixtures or to the collars.

Results from tubular test specimens fracturing outside the uniformly stressed gauge section (or outside the extensometer gauge length of straight-side test specimen) are considered anomalous and invalid. Under no circumstances should the calculation of an average tensile strength of fracture strength be used for the entire test set.

8 Calculation of results

8.1 Test specimen origin

A diagram illustrating the reinforcement directions of the material with respect to the longitudinal axis of the tubular specimen shall accompany the test results.

If known, the average angle ($\pm\theta$) between the reinforcement directions and the tube axis shall be specified.

8.2 Engineering stress and strain

The engineering stress is calculated as in Formula (2).

$$\sigma = \frac{F}{S_0} \tag{2}$$

where

σ is the engineering stress in megapascals (MPa);

F is the applied uniaxial tensile force at any time in newtons (N);

S_0 is the initial cross-sectional area of the tubular test specimen in square millimetres (mm^2).

The cross-sectional area (S_0) of the tubular test specimen is calculated as in Formula (3).

$$S_0 = \frac{\pi\left(d_o^2 - d_i^2\right)}{4} \tag{3}$$

where

d_o is the average external diameter of the gauge section in millimetres (mm);

d_i is the average internal diameter of the gauge section in millimetres (mm).

Indications for the measurement of d_o and d_i are detailed in 5.6 and 7.3.1.

For strain measurement by extensometer, the engineering axial strain is calculated as in Formula (4).

$$\varepsilon_{zz} = \frac{L - L_0}{L_0} \tag{4}$$

where

ε_{zz} is the engineering strain in the axial direction (no dimensions);

L is the gauge length (extensometer gauge length) at any time in millimetres (mm);

L_0 is the initial gauge length in millimetres (mm).

If strain gauges or the DIC method are used, the engineering axial (ε_{zz}) and/or circumferential ($\varepsilon_{\theta\theta}$) strain based on the orientation of the measure are determined directly.

NOTE In cases of strain measurement with two extensometers, the engineering axial strain to be considered is the mean value.

8.3 Tensile strength

The tensile strength is calculated as in Formulae (5) and (6).

$$\sigma_m = \frac{F_m}{S_0} \tag{5}$$

$$\sigma_{m,eff} = \frac{F_m}{S_{0,eff}} \tag{6}$$

where

σ_m is the tensile strength in megapascals (MPa);

$\sigma_{m,eff}$ is the effective tensile strength using the effective cross-sectional area in megapascals (MPa);

F_m is the maximum uniaxial tensile force applied in newtons (N);

S_0 is the initial cross-sectional area of the tubular test specimen as defined in 8.2, in square millimetres (mm^2);

$S_{0,eff}$ is the effective cross-sectional area of the tubular test specimen, corrected to take into account an oxidative protection or a surface smoothing processing in square millimetres (mm^2).

When using the effective cross-section area, the applied correction factor shall be given and justified in the test report.

8.4 Strain at maximum tensile force

The axial strain at maximum tensile force $\varepsilon_{zz,m}$ (no dimension) corresponding to the tensile strength measured during the test is calculated as in Formula (7).

$$\varepsilon_{zz,m} = \frac{A_m}{L_0} \tag{7}$$

where

A_m is the longitudinal deformation under maximum tensile force, in millimetres (mm);

L_0 is the initial gauge length, in millimetres (mm).

8.5 Proportionality ratio or pseudo-elastic modulus, elastic modulus

8.5.1 Stress-strain curves with a linear region

Calculate the proportionality ratio or pseudo-elastic modulus, EP, defined between two points (A_1, F_1) and (A_2, F_2) measured near the lower and upper limits of the linear part of the force-deformation recorded curve, according to Formulae (8) and (9).

$$E_P(\sigma_1,\sigma_2)=\frac{L_0}{S_0}\left(\frac{F_2-F_1}{A_2-A_1}\right)\times 10^{-3} \tag{8}$$

$$E_{P,eff}(\sigma_1,\sigma_2)=\frac{L_0}{S_{0,eff}}\left(\frac{F_2-F_1}{A_2-A_1}\right)\times 10^{-3} \tag{9}$$

where

E_P is the pseudo-elastic modulus, in gigapascals (GPa);

$E_{P,eff}$ is the effective pseudo-elastic modulus, in gigapascals (GPa);

F is the applied uniaxial tensile force, in newtons (N);

S_0 is the initial cross-sectional area of the tubular test specimen as defined in 8.2, in square millimetres (mm^2);

$S_{0,eff}$ is the effective cross-sectional area of the tubular test specimen, corrected to take account of an oxidative protection or a surface smoothing processing, in square millimetres (mm^2);

L_0 is the initial gauge length, in millimetres (mm);

A is the longitudinal deformation measured on the curve corresponding to F, in millimetres (mm).

When the material has a linear behaviour at the origin, the proportionality ratio or pseudo-elastic modulus is termed the tensile elastic modulus and may be calculated according to Formulae (10) and (11).

$$E=\frac{FL_0}{S_0 A}\times 10^{-3} \tag{10}$$

$$E_{eff}=\frac{FL_0}{S_{0,eff} A}\times 10^{-3} \tag{11}$$

where

E is the tensile elastic modulus, in gigapascals (GPa);

E_{eff} is the effective tensile elastic modulus, in gigapascals (GPa).

Any point (A, F) on the linear section of the force-deformation recorded curve may be used for its determination. A schematic diagram of methods for determining proportional limit stress on characteristic stress-strain curve with linear region is shown in Figure 6.

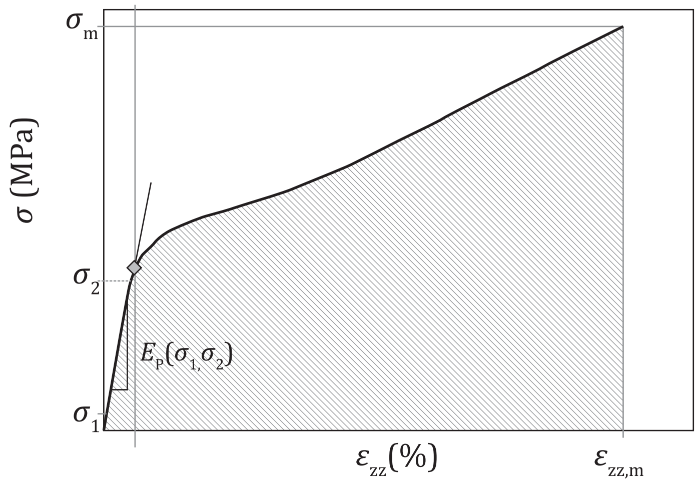


Figure 6 — Methods for determining proportional limit stress

8.5.2 Nonlinear stress-strain curves

The elastic modulus may not be defined for materials that exhibit entirely non-linear stress-strain curves. In this case, it is recommended that the couples of stress-strain value corresponding to stresses of 0,1 σ_m and 0,5 σ_m are used, unless other couples are fixed by agreement between parties.

8.6 Poisson's ratio (optional)

The Poisson's ratio may be determined if circumferential strain is measured from gauges or by the DIC method as shown in Formula (12).

$$\nu_{\theta z} = -\frac{\Delta\varepsilon_{\theta\theta}}{\Delta\varepsilon_{zz}} \tag{12}$$

where

$\nu_{\theta z}$ Poisson's ratio (no dimensions);

$\Delta\varepsilon_{\theta\theta}/\Delta\varepsilon_{zz}$ slope of the linear region of the plot of circumferential strain $\varepsilon_{\theta\theta}$ versus axial strain ε_{zz}.

Poisson's ratio may not be defined for materials which exhibit nonlinear stress-strain curves (although this shall be verified by plotting $\varepsilon_{\theta\theta}$ versus ε_{zz} to determine whether or not a linear region exists).

8.7 Statistics

For each series of tests, calculate the mean, standard deviation and coefficient of variation for each measured value as in Formulae (13) to (15):

— mean

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{13}$$

— standard deviation

$$\mathrm{SD}=\sqrt{\frac{\sum_{i=1}^{n}(X_i-\bar{X})^2}{n-1}} \qquad (14)$$

— coefficient of variation

$$\mathrm{COV}(\%)=\frac{100\times \mathrm{SD}}{\bar{X}} \qquad (15)$$

where

X represents the measured values;

n number of valid tests.

9 Test report

9.1 General

The test report shall contain the following information. Any significant deviations from the procedures and requirements of this document should be noted in the report.

9.2 Testing information

9.2.1 Name and address of the testing establishment.

9.2.2 Date of the test, unique identification of report and of each page, customer name and address, and signatory.

9.2.3 Reference to this document, i.e. "determined in accordance with ISO 20323".

9.3 Test specimen and material

9.3.1 Tubular test specimen drawing or reference.

The tubular test geometry and dimensions, with a description of end collars and/or end plugs if used shall be reported on drawing. The adhesive used shall also be specified.

The method of tubular test specimen preparation including all stages of machining, surface finishing and dimensional measurement shall be reported.

9.3.2 Description of the test material.

All relevant material data shall be reported.

— For commercial materials, at least the material type, the manufacturing code and the batch number are expected.

— For non-commercial materials, the constituents' nature and content, the fibre architecture, the nature of the interface coating and the processing route of the CFCC tubes shall be fully determined and documented.

9.4 Equipment and test parameters

9.4.1 Testing machine type and configuration.

If a commercial test machine was used, the manufacturer and the model number are sufficient.

9.4.2 Force measurement description.

The type, range, resolution and accuracy of the force measurement device shall be reported.

The type and configuration of grip interface, as well as the type and configuration of load train couplers used, shall be reported. If commercial equipment was used, the manufacturer and model number(s) are sufficient.

9.4.3 Test mode and test rate.

9.3.4 Strain measurement description.

The type, the configuration and the resolution of strain measurement equipment used (include drawing or sketch if necessary) shall be reported. If a commercial extensometer or strain gauges were used, the manufacturer and model number are sufficient. If the DIC method was used, a description of the procedure followed shall be reported.

9.5 Test results

9.5.1 Number of tests carried out and number of valid results obtained.

9.5.2 Force – longitudinal deformation records and curves.

9.5.3 Mean, standard deviation and coefficient of variation statistics for valid tests, as follows:

— tensile strength and tensile strain under maximum tensile force;

— proportionality ratio or (pseudo)-elastic modulus;

— Poisson's ratio, if measured.

9.5.4 Value of correction factor applied when effective cross-section area is used and method to obtain it.

9.5.5 Failure location and mode of fracture for all the specimens used in obtaining the above results.

Annex A
(informative)

Gripping devices and load train couplers

A.1 Active grip interfaces

Active grip interfaces require continuous application of a mechanically, hydraulically, or pneumatically derived action to transmit the uniaxial force applied by the testing machine to the tubular test specimen. These active grips commonly use circular end tabs that encircle the external circumference of the tubular test specimen. Sufficient lateral pressure must be applied to prevent slippage between the grip side and the tubular test specimen.

Grip sides including a V-shaped notch either scored or serrated with a pattern similar to that of a single-cut file have been found to be satisfactory. An example of active gripping device for tubular test specimen is shown in Figure A.1.

NOTE These types of grip interface cause a force to be applied perpendicular to the face of the grip section of the tubular test specimen. Transmission of the uniaxial force applied by the testing machine is then accomplished by friction between the tubular test specimen and the grip faces.

A.2 Passive grip interfaces

A.2.1 General

Passive grip interfaces transmit the uniaxial force applied by the testing machine to the tubular test specimen either through an adhesive bond into the grips or by a direct mechanical link. Generally, this mechanical link transmits the test forces to the tubular test specimen via geometric features on the specimen such as tapered shoulders. Several possibilities are presented and discussed in A.2.2.

A.2.2 Mechanical gripping

In passive mechanical gripping, there is no active gripping of the test sample and gripping does not depend on frictional forces. Two examples of passive mechanical bonding grips are shown in Figure A.2.

The first example uses the flared ends of the tubular test specimen (as fabricated or prepared by means of tapered collars bonded, see 6.3) to load the sample in tension thanks to two split collets with a tapered centre core. The second example uses a hanging device comprising an imprint designed to receive the tubular specimen surmounted by an adapted collar. For these two gripping types, the critical geometry factors are a good fit and uniform contact between the tapered shoulders or the end tabs of the specimen and the grip parts.

NOTE Generally, the uniaxial force is transmitted to the tubular test specimen through contact along the entire specimen/grip interface, thus minimizing eccentric forces.

The use of passive mechanical gripping is not recommended to carry out cycled tests because of the possibility of uncoupling between the tubular test specimen and the grip in the absence of loading.

A.2.3 Adhesive bonding

Adhesive bonding can also be employed to grip the tubular test specimen to the load train couplers through the use of grip fixtures, as illustrated in Figures A.3 and A.4.

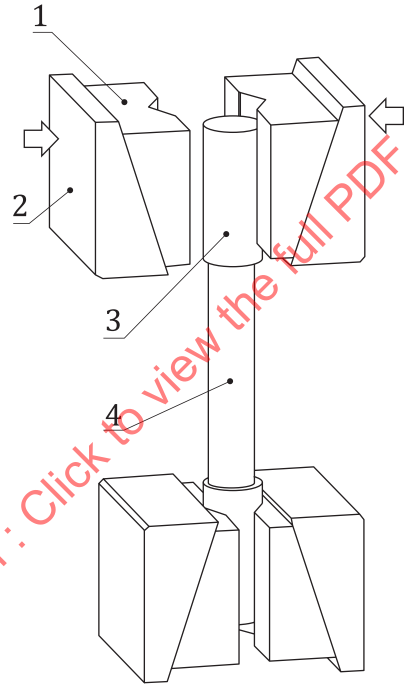
An adhesive with high shear strength is commonly used to bond the tubular test specimen into the fixtures. A commonly used adhesive is a two-part room-temperature curing, tough, high-strength [20 MPa to 35 MPa] epoxy.

A.3 Load train couplers

Fixed couplers usually employ concentricity (*x*, *y* alignment) and angularity adjusters to minimize load train misalignments (see example in Figure A.3), although non-fixed couplers produce self-alignment of the load train during the movement of the crosshead (see example in Figure A.4).

NOTE 1 Although alignment closely depends on the load train configuration, the procedure for end collars bonding on the specimen described in 6.3 is also an important feature to be considered for proper alignment.

NOTE 2 Fixed load train couplers are preferred in monotonic testing of CFCC tubes because they maintain the tubular test specimen in an aligned position, and thus provide a uniform stress across the remaining ligament of the gauge section.



Key

1 grip body

2 wedge grip

3 upper cylindrical end tab

4 tubular test specimen

Figure A.1 — An active grip interface for CFCC tubes