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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 hoop tensile properties of tubes

Céramiques techniques (céramiques avancées, céramiques techniques avancées) — Propriétés mécaniques des céramiques composites à température ambiante et à pression atmosphérique — Détermination des propriétés en traction circonférentielle 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 of 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 www.iso.org/iso/foreword.html.

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

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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

1 Scope

This document specifies the conditions for the determination of hoop tensile properties of ceramic matrix composite (CMC) 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 in composite tubes are distinctly different from those in flat specimens.

This document provides information on the hoop tensile properties and stress-strain response, such as hoop tensile strength, hoop tensile strain at failure and elastic constants. The information can 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 (*x*D, with $2 < x < 3$), subjected to an internal pressure.

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

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

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

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

3 Terms and definitions

For the purpose 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* (3.3)

3.2
gauge length
L_0
initial distance between reference points on the test specimen in the *calibrated length* (3.1)

3.3
external diameter
d_o
outer distance through the centre of the tube from one side to the other in the *gauge length* (3.2)

3.4
internal diameter
d_i
inner distance through the centre of the tube from one side to the other in the *gauge length* (3.2)

3.5
wall thickness
h
distance between the *internal* (3.4) and *external diameters* (3.3) in the *gauge length* (3.2)

3.6
hoop tensile strain
$\varepsilon_{\theta\theta}$
relative change in circumferential direction in the *gauge length* (3.2)

3.7
axial strain
ε_{zz}
relative change in the axial (or longitudinal) direction in the *gauge length* (3.2)

3.8
hoop tensile stress
$\sigma_{\theta\theta}$
stress supported by the test specimen in circumferential direction at any time in the test

3.9
burst pressure
P_F
highest recorded internal pressure undergone by the test specimen when tested to failure

3.10
hoop tensile strength
$\sigma_{\theta\theta,m}$
hoop tensile stress (3.8) calculated at the *burst pressure* (3.9)

3.11
proportionality ratio or pseudo-elastic modulus in the circumferential direction
$EP_{\theta\theta}$
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 in 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 in the circumferential direction, $E_{\theta\theta}$, in the single case where the linearity starts near the origin.

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

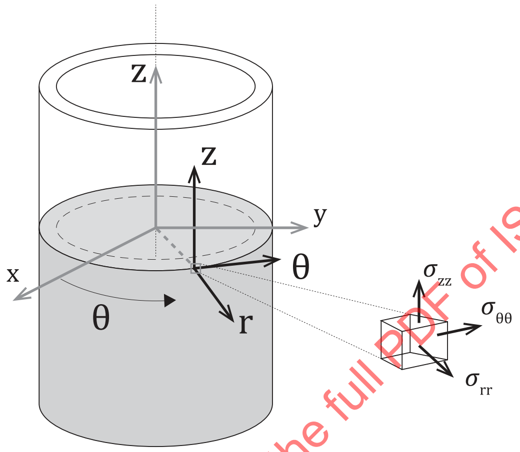
In this case only stress-strain couples can be fixed.

3.12
Poisson's ratio
$\nu_{\theta z}$
negative ratio of circumferential to *axial strain* (3.7)

3.13
coordinate system
system used to determine location in space

Note 1 to entry: Cylindrical coordinates are adopted in this 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 inserted into an appropriate test fixture assembly and subjected to monotonic loading via indirect internal pressure up to fracture. Uniform radial pressure is produced using hydraulic oil injection with a piston through an elastomeric bladder located inside the tubular test specimen. The elastomeric bladder mates to the inner diameter of the tubular test specimen, thus causing its expansion under pressure. The test is performed at constant piston displacement or constant strain (or constant loading rate). Both the applied pressure and resulting hoop tensile strain are measured and recorded simultaneously. The hoop tensile strength and corresponding strain are determined from the burst pressure while the various other hoop 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 The resulting force from internal pressure loading is applied in the radial direction. Monotonic refers to a continuous non-stop test rate with no reversals from test initiation to final fracture.

NOTE 2 The method described in this document does not cover the possibility of applying pressurization via a dense rubber material in compressive without fluid.

5 Apparatus

5.1 Pressurizing system

The pressurizing system shall be able to apply a continuously increasing and uniform internal pressure to the tubular test specimen.

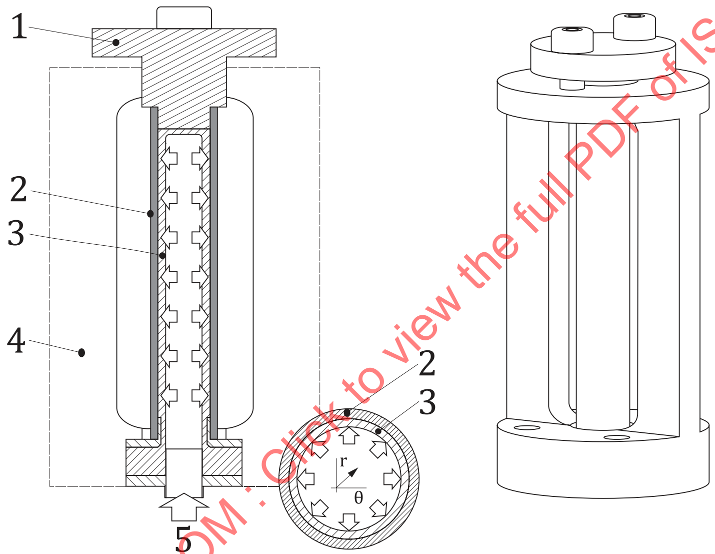
The following equipment is recommended for this test:

a) an oil (or other fluid) bath maintained at uniform temperature;

b) an annular and leak-tight elastomeric bladder surrounding the inner periphery of the tubular test specimen able to transmit a uniform pressure loading by its elasticity expansion;

c) a test machine (or a press) capable of applying a determined compressive force on a piston free to move vertically to increase oil pressure in the elastomeric bladder.

Figure 2 shows a schematic example to illustrate the principle of a satisfactory pressurizing system.



Key

1 cover plate

2 tubular test specimen

3 elastomeric bladder

4 space flange

5 oil inlet for pressurization (*P*)

Figure 2 — Example of hydrostatic pressurizing system for CMC tubular test specimen

5.2 Test specimen gripping and end closure

The gripping device shall be able to maintain the tubular test specimen in position to withstand internal pressure induced by the expansion of the elastomeric bladder while allowing it to move radially. An example of construction detail is shown in Figure 2 for which the tubular test specimen is mounted on a spacer flange. A cover plate is clamped on the flange with two screws to obtain a correct alignment.

The brittle nature of the CMCs requires particular attention to minimize crack initiation and fracture. Therefore, it is recommended that the attachment screws are released and then the adjustment screw adjusted to push the mating flanges back slightly until they come into contact with the tube, but without applying any axial force to it.

Specimen end closure shall be able to withstand the maximum test pressure. Closure shall be designed so that it does not cause failure of the specimen.

5.3 Strain measurement

5.3.1 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 bonded resistance strain gauges or digital image correlation (DIC). If Poisson's ratio is to be determined, the tubular test specimen shall be instrumented to measure strain in both longitudinal and circumferential directions.

5.3.2 Strain gauges

5.3.2.1 Strain gauge selection

The strain gauges, the surface preparation of the tubular test specimen and the bonding agents should be chosen to provide adequate performance on the tested materials.

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

Unless it can be shown that strain gauge readings are not unduly influenced by localized strain events such as fibre crossovers, strain gauges should have an active gauge length greater than three characteristic unit cells (repeating units) of the reinforcement in both longitudinal and circumferential directions. This averages the localized strain effects of the fibre crossovers.

Under internal pressure loading, a single-grid gauge pattern would normally be used with the gauge axe aligned to coincide with the circumferential 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 circumferential and longitudinal directions.

5.3.2.2 Surface preparation

The relatively rough surface of composites usually requires some preparation prior to strain gauge bonding. The basic steps shall 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 requires alternative techniques.

NOTE A typical method is to apply an epoxy precoat to fill the surface irregularities and finish by polishing.

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

5.3.3 Digital image correlation

5.3.3.1 General

The DIC method can also be used to determine local strain of CMC tubular test specimens loaded under internal pressure 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 CMC tubes are as follows.

5.3.3.2 Experimental set-up

The experimental set-up for DIC measurements requires a digital charge-coupled device (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 shall be selected to ensure that the entire coupon surface is in the best focal plane of the camera and that the highest possible magnification is attained. Annular illumination with white or monochromanic 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 tests, 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.

5.3.3.3 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 by 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 having a pronounced roughness average are expected to naturally produce highly micro-textured images.

5.3.3.4 Calculation

Correlation may then be 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 circumferential strain.

The provider's software instructions shall 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 longitudinal strain on a close working area.

5.4 Pressure and data recording systems

A pressure sensor shall be used to measure the pressure applied to the tubular test specimen versus time and a calibrated recorder shall be used to record elongation (or strain) in the gauge length. The use of digital data recording systems is recommended for this purpose.

The measuring range of the pressure sensor shall be selected in accordance with the expected burst pressure. It shall be located in the test system at a location such that it only indicates the pressure on the test specimen.

Recording devices shall be accurate 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.

5.5 Measurement of dimensions

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 micrometers 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 CMCs 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 the 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 specimen

6.1 Specimen specifications

6.1.1 General

CMC 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 CMC tubes also has a broad range of configurations with different fibre loadings and directional variations. Therefore, it is currently not practicable to define a single test specimen geometry that is applicable to all CMC tubes.

The selection and definition of a tubular test specimen geometry depends on the purpose of the hoop tensile test. In addition, the pressurizing system and the grip devices may influence the design of the test specimen geometry.

6.1.2 Dimension

The as-described test method applies to CMC tubes with external diameters greater than 7 mm and a minimum of 0,5 mm in wall thickness roughly corresponding to a minimum of one single layer. The ratio between the external diameter and wall thickness (d_o/h) is commonly extended on the range from 5 to 30.

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

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

6.1.3 Geometry

A straight-sided tube geometry that often does not require machining to obtain proper dimensions is required to carry out the test. Figure 3 represents a tubular test specimen with straight-sided geometry. Dimensional requirements for an acceptable specimen are contained in Table 1.

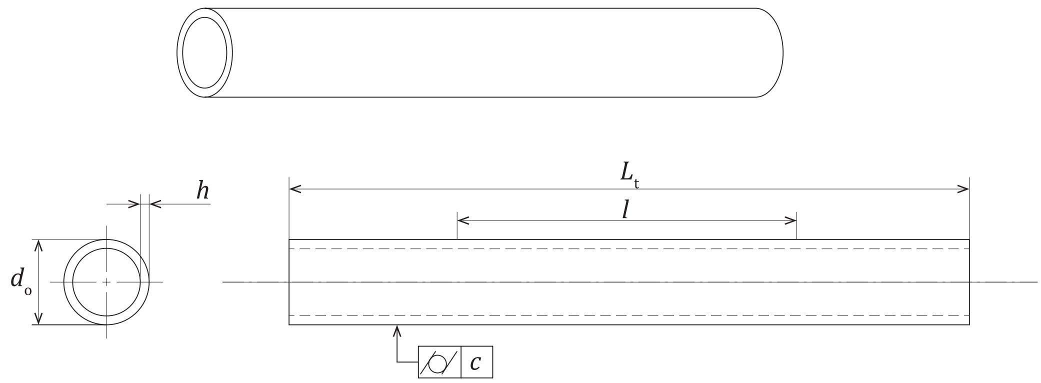


Figure 3 — Straight-sided tube test specimen

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

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
Cylindricity	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 CMC application. It is common for CMC tubes to have a relative diametral variability, particularly for larger diameter tubes.

The gauge section might or might 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 a “3 points internal micrometer” or an “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 could be necessary for two purposes: (i) to develop a controlled diameter in the gauge section and/or (ii) to produce a uniform diameter at the extremities to facilitate specimen holding and alignment. Depending on the use made of the hoop tensile data, apply one of the following test specimen preparation procedures.

6.2.2 As-fabricated

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

6.2.3 Application-matched machining

The tubular 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 should apply to prepare the tubular test specimens.

All grinding or cutting should 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 shall 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 could be necessary for specific CMC systems.

6.3 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 could be necessary, if estimates regarding the form of the strength distribution are required.

Test specimens should be selected and prepared from representative CMC 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 reported 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 pressure or piston-displacement control. The recommended rate of testing shall be sufficiently fast to obtain the maximum hoop tensile stress at the burst pressure of the tubular test specimen. Typically, fracture should occur within 60 s of the start of the test.

The test mode and the pressurizing 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 a pressure-controlled mode due to the cumulative damage process of the CMCs, a piston-displacement control is preferred.

7.3 Testing technique

7.3.1 Measurement of test specimen dimensions

The external and internal radii are 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 preferably measured with a micrometer, as described in 5.5. The arithmetic means of the measurements shall be used for the hoop stress calculation.

NOTE Alternatively, in cases where it is not possible to infer or determine external and internal diameters with a micrometer, measurements can be performed by the optical profilometry method.

7.3.2 Instrumentation of test specimen

Depending on the method selected for 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 5.3.2).

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 5.3.3).

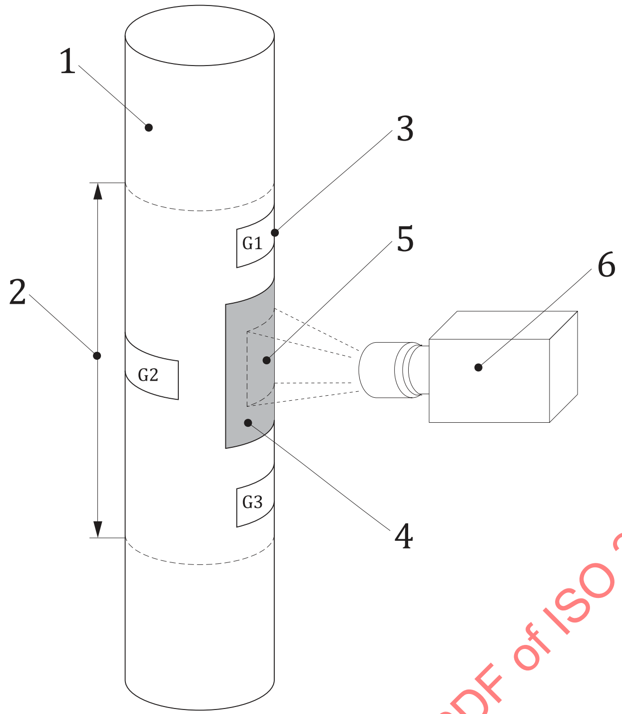
7.3.3 Setting-up of strain measurement means

The selected strain measurement means shall be installed and/or calibrated without any pressure applied into the 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 at an appropriate rate.

An example of successful configuration for hoop tensile testing on a CMC tubular test specimen is shown in Figure 4.



Key

1 tubular test specimen
2 calibrated length
3 strain gauge “G1” (G2, G3)
4 high-contrast speckle pattern
5 camera observation area
6 digital CCD camera with telecentric lens

Figure 4 — Example of successful configuration for hoop tensile testing of tubular test specimen

7.3.4 Measurements

The hoop tensile test shall be conducted in the following sequence:

— Activate and adjust the testing machine (or press) to its initial position, zero load and desired test rate.

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

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

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

— Load the tubular test specimen up to burst pressure.

After specimen fracture, disable the action of the test machine (or press) and the data acquisition systems. Carefully remove the tubular test specimen fragments from the pressurizing device and wipe the spilled oil with a cloth. Take care not to damage the fracture surfaces through contact with each other or other objects. Place the test specimen fragments into a suitable and protective package for later analysis.

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

A protective guard can be installed to prevent oil projection and stop high-speed projectiles. The protective guard should not influence the strain measurement when using the DIC method.

7.3.5 Post-test analyses

Fracture location shall be measured and reported in relation to the principal directions of the fibrous architecture.

For fracture surfaces which are not parallel 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 CMC 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 outside the designated gauge section;

— oil leakage in the hydraulic system.

The main factors of concern that can produce invalid tests include manufacturing or technical defects of the elastomeric bladder and hydraulic system failure.

Results from tubular test specimens fracturing outside the uniformly stressed gauge section are considered anomalous and invalid. Under no circumstances should the calculation of an average hoop 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 (±θ) between the reinforcement directions and the tube axis shall be specified.

8.2 Hoop tensile stress and strain

The hoop tensile stress is calculated according to Formula (1):

$$\sigma_{\theta\theta} = 2\times10^4 \frac{PR_i^2}{\left(R_o^2 - R_i^2\right)} \quad (1)$$

where

$\sigma_{\theta\theta}$ is the hoop tensile stress on the outer surface in megapascals (MPa);

P is the applied internal pressure at any time in pascals (Pa);

R_i is the average internal radius in the gauge length in millimetres (mm);

R_o is the average external radius in the gauge length in millimetres (mm).

The average internal (R_i) and external (R_o) radius of the tubular test specimen are determined, respectively, according to Formula (2) and Formula (3):

$$R_i = \frac{d_i}{2} \tag{2}$$

$$R_o = \frac{d_o}{2} \tag{3}$$

where

d_i is the inner distance through the centre of the tube from one side to the other one in the gauge length in millimetres (mm);

d_o is the outer distance through the centre of the tube from one side to the other one in the gauge length in millimetres (mm).

Indications for the measurement of d_o and d_i are detailed in 5.5 and 7.3.1.

The hoop strain ($\varepsilon_{\theta\theta}$) is directly determined by strain gauges or the DIC method on the outer surface of the specimen (no dimension).

NOTE 1 Calculation of the hoop tensile stress on the outer surface of the specimen considers the linear isotropic case. The relation applies for tubular CMC since the attainable deformation levels remain very low for such ceramic materials.

NOTE 2 Depending on the orientation of the measure, the axial strain (ε_{zz}) can also be determined on the outer surface from DIC measurements or even from gauge measurements if used.

8.3 Hoop tensile strength and corresponding strain

The hoop tensile strength is calculated according to Formula (4):

$$\sigma_m = 2 \times 10^4 \frac{P_F R_i^2}{\left(R_o^2 - R_i^2\right)} \tag{4}$$

where

σ_m is the hoop tensile strength on the outer surface in megapascals (MPa);

P_F is the burst pressure in pascals (Pa);

R_i, R_o are the average internal and external radii, respectively, as defined in 8.2, in millimetres (mm).

The corresponding hoop strain (ε_m) is directly determined by strain gauges or the DIC method on the outer surface of the specimen (no dimension).

8.4 Proportionality ratio or pseudo-elastic modulus in circumferential direction

8.4.1 Stress-strain curves with a linear region

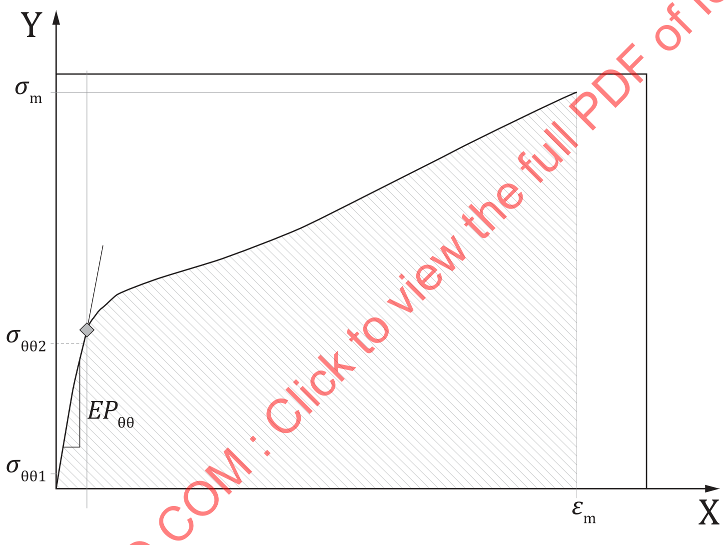
Calculate the proportionality ratio or pseudo-elastic modulus $EP_{\theta\theta}$ defined between two points, A_1 ($\sigma_{\theta\theta 1}$, $\varepsilon_{\theta\theta 1}$) and A_2 ($\sigma_{\theta\theta 2}$, $\varepsilon_{\theta\theta 2}$), measured near the lower and upper limits of the linear part of the stress-strain measured curve, according to Formula (5):

$$EP_{\theta\theta}\left(A_1, A_2\right)=\left(\frac{\sigma_{\theta\theta 2}-\sigma_{\theta\theta 1}}{\varepsilon_{\theta\theta 2}-\varepsilon_{\theta\theta 1}}\right) \tag{5}$$

where $EP_{\theta\theta}$ is the pseudo-elastic modulus, in gigapascals (GPa).

When the material has a linear behaviour at the origin, the proportionality ratio or pseudo-elastic modulus in the circumferential direction is termed the hoop tensile elastic modulus ($E_{\theta\theta}$). Any point on the linear section of the stress-strain recorded curve may be used for its determination.

A schematic diagram of methods for determining proportional limit stress on a characteristic hoop tensile curve with linear region is illustrated in Figure 5.



Key

X hoop tensile strain $\varepsilon_{\theta\theta}$ (%)

Y hoop tensile stress $\sigma_{\theta\theta}$ (MPa)

Figure 5 — Methods for determining proportional limit stress

8.4.2 Nonlinear stress-strain curves

The hoop tensile elastic modulus might not be defined for materials that exhibit entirely nonlinear 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.