INTERNATIONAL STANDARD

ISO 15733

First edition
2001-02-01

Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for tensile stress-strain behaviour of continuous, fibre-reinforced composites at room temperature

Céramiques techniques — Méthode d'essai de comportement à la contrainte en traction des composites renforcés de fibres continues, à température ambiante

Reference number
ISO 15733:2001(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.ch
Web www.iso.ch

Printed in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 15733 was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

Annex A forms a normative part of this International Standard, annex B is for information only.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for tensile stress-strain behaviour of continuous, fibre-reinforced composites at room temperature

1 Scope

This International Standard specifies the determination of in-plane tensile behaviour including stress-strain response under monotonic uniaxial testing of continuous fiber-reinforced ceramic matrix composites (CFRCMCs) at ambient temperature.

This International Standard addresses, but is not restricted to, various suggested test piece geometries, test piece fabrication methods, testing modes, testing rates, allowable bending, data collection and reporting procedures. This International Standard applies primarily to ceramic and/or glass matrix composites with continuous fiber reinforcement: uni-directional (1-D), bi-directional (2-D) and tri-directional (3-D) or other multi-directional reinforcements. Carbon fiber-reinforced carbon matrix (C/C) composites may also be tested using this International Standard, although caution is advised since this International Standard was developed primarily for CFRCMCs and any accommodations unique to C/C composites have not been included.

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

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 286-1:1988, *ISO system of limits and fits — Part 1: Bases of tolerances, deviations and fits.*

ISO 3611:1978, *Micrometer callipers for external measurement.*

ISO 6892:1998, *Metallic materials — Tensile testing at ambient temperature.*

ISO 7500-1:1999, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system.*

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

3 Terms and definitions

For the purposes of this International Standard, the following terms and definitions apply.

3.1
fine ceramic (advanced ceramic, advanced technical ceramic)
highly-engineered, high-performance predominately non-metallic, inorganic, ceramic material having specific functional attributes

3.2
axial strain
average longitudinal strain measured at the surface on opposite sides of the longitudinal axis of symmetry of the test piece by strain-sensing devices located at the mid length of the reduced section

3.3
bending strain
difference between the strain at the surface and the axial strain

NOTE In general, the bending strain varies from point to point around and along the reduced section of the test piece.

3.4
breaking force
force at which fracture occurs

3.5
ceramic matrix composite
material consisting of two or more materials (insoluble in one another), in which the major, continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, glass, metal or organic in nature; these components are combined on a macroscale to form a useful engineering material possessing certain properties or behaviour not possessed by the individual constituents

3.6
continuous fiber-reinforced ceramic matrix composite (CFRCMC)
ceramic matrix composite in which the reinforcing phase consists of a continuous fiber, continuous yarn or a woven fabric

3.7
fracture strength
tensile stress which the material sustains at the instant of fracture

NOTE Fracture strength is calculated from the force at fracture during a tensile test carried to rupture and the original cross-sectional area of the test piece.

3.8
gauge length
original length of that portion of the test piece over which strain or change of length is determined

3.9
irrecoverable cumulative damage energy (also known as, modulus of toughness)
strain energy per unit volume required to stress the material from zero to final fracture indicating the ability of the material to absorb energy beyond the elastic range (i.e., inherent damage tolerance of the material)

3.10
matrix-cracking stress
the applied tensile stress at which the matrix cracks into a series of roughly parallel blocks perpendicular to the tensile stress

3.11
modulus of elasticity
the ratio of stress to corresponding strain less than the proportional limit

3.12
proportional limit stress
the greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law)

3.13
percent bending
the bending strain times 100 divided by the axial strain

3.14
recoverable elastic energy (also known as, modulus of resilience)
strain energy per unit volume required to elastically stress the material from zero to the proportional limit indicating the ability of the material to absorb energy when deformed elastically and return it when the force is removed

3.15
slow crack growth
sub-critical crack growth (extension) which may result from, but is not restricted to, such mechanisms as environmentally-assisted stress corrosion or diffusive crack growth

3.16
tensile strength
the maximum tensile stress which a material is capable of sustaining

NOTE Tensile strength is calculated from the maximum force during a tensile test carried to rupture and the original cross-sectional area of the test piece.

3.17
test series
a discrete group of tests on individual test pieces conducted within a discrete period of time on a particular material configuration, test piece geometry, test condition or other uniquely definable qualifier (e.g., a test series composed of material A comprising ten test pieces of geometry B tested at a fixed rate in strain control to final fracture in ambient air)

4 Symbols and designations

Symbols used throughout this International Standard and their designations are given in Table 1.

Table 1 — Symbols and designations

Symbol	Designation	Unit	References
A	Surface area	mm^2	9.5.1 equations 1, 2a, 2b
d	Thickness	mm	Tables 2, 3 Figures 3, 4
E	Elastic modulus (Young's modulus)	MPa	9.5.7 equation 6, Figure 6
E_R	Recoverable elastic energy (modulus of resilience)	J/m^3	9.5.10 equation 7
E_T	Irrecoverable cumulative damage energy (modulus of toughness)	J/m^3	9.5.11 equations 8, 9
F	Force	N	9.5.1 equation 1
F_f	Force at fracture	N	9.5.5 equation 5
F_m	Maximum force	N	9.5.3 equation 4
l	Length, extensometer or test piece at any time	mm	9.5.2 equation 3
l_0	Length, original extensometer or test piece	mm	9.5.2 equation 3

Table 1 *(continued)*

Symbol	Designation	Unit	References
L	Length, total for straight-sided test piece geometry	mm	Table 3 Figure 4
L_1	Length, gauge for contoured test piece geometry	mm	Table 2 Figure 3
L_2	Length, total for contoured test piece geometry	mm	Table 2 Figure 3
n	Number of valid tests	1	10.1, g)
n_T	Number of total tests	1	10.1, g)
R	Radius, blend for contoured test piece geometry	mm	Table 2 Figure 3
SD	Standard deviation	var.	equation 11
R_f	Tensile strength at fracture	MPa	9.5.5 equation 5
R_m	Ultimate tensile strength	MPa	9.5.3 equation 4
V	Coefficient of variation	var.	equation 12
W	Width, total for straight-sided test piece geometry	mm	Table 2 Figure 4
W_1	Width, gauge for contoured test piece geometry	mm	Table 2 Figure 3
W_2	Width, grip for contoured test piece geometry	mm	Table 2 Figure 3
$\overline{X}$	Mean	1	equation 10
ε	Strain, normal	mm/mm	9.5.2 equation 3
ε_f	Strain, corresponding to R_f	mm/mm	9.5.6 Figure 6
ε_m	Strain, corresponding to R_m	mm/mm	9.5.4
ε_0	Strain, corresponding to σ_0	mm/mm	9.5.9 Figure 6
σ	Stress, normal	MPa	9.5.1 equation 1
σ_0	Stress, proportional limit	MPa	9.5.8 Figures 6, 7

5 Principle

This International Standard is for material development, material comparison, quality assurance, characterization, reliability and design data generation. Dissimilar material response of CFRCMCs in tension and compression prevents unambiguous characterization of material behaviour from flexural tests. Therefore, uniaxially-tested and uniformly-stressed tensile tests can provide information on fundamental material behaviour including stress-strain response, proportional limit and ultimate strengths, elastic constants, and strain-energy absorption.

This test consists of testing a test piece to fracture using a uniaxial tensile force for the purpose of determining tensile stress-strain response, various tensile strengths and corresponding strains, elastic constants and various deformation energies. Generally, this test is carried out under conditions of ambient temperature and environment.

6 Apparatus

6.1 Testing machine

The testing machine shall be verified in accordance with ISO 7500-1 and shall be of at least grade 1,0 unless otherwise specified.

6.2 Test piece gripping

Various types of gripping device may be used to transmit the measured force applied by the testing machine to the test piece. The brittle nature of the matrices of CFRCMCs requires a uniform interface between the grip components and the gripped section of the test piece in order to minimize crack initiation and fracture of the test piece in the gripped section. Gripping devices can be classified generally as those employing active and those employing passive grip interfaces.

6.2.1 Active grip interfaces

Active grip interfaces require continuous application of a mechanically-, hydraulically- or pneumatically-derived force (pressure) to transmit the force applied by the test machine to the test piece. Sufficient lateral pressure shall be applied to prevent slippage between the grip face and the test piece. Grip surfaces that are scored or serrated with a pattern similar to that of a single-cut file have been found to be satisfactory. See Figure 1.

NOTE Generally, these types of grip interface cause a force to be applied perpendicular to the surface of the gripped section of the test piece. Transmission of the uniaxial force applied by the test machine is then accomplished by friction between the test piece and the grip faces.

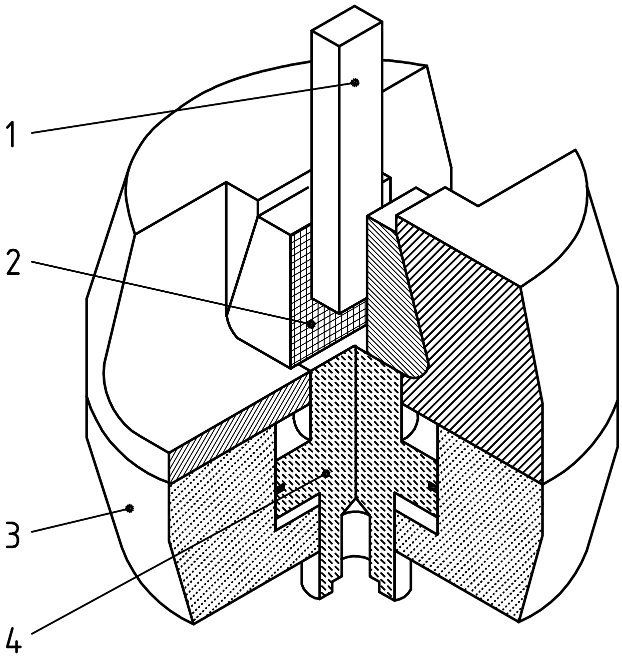
6.2.2 Passive grip interfaces

Passive grip interfaces transmit the force applied by the test machine to the test piece through a direct mechanical link. These mechanical links transmit the test forces to the test piece via geometrical features of the test pieces such as shank shoulders or holes in the gripped head. See Figure 2.

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

6.2.3 Test train couplers

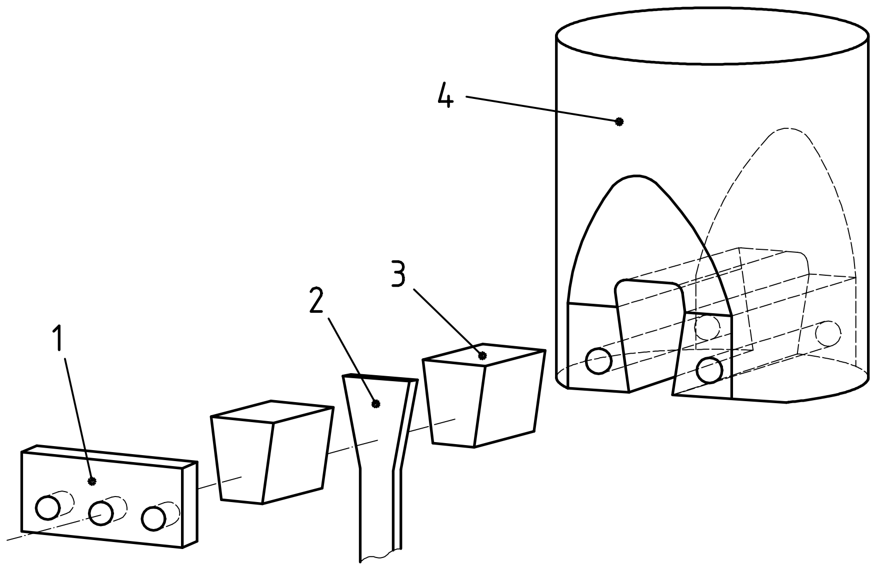
Various types of device (test-train couplers) may be used to attach the active or passive grip interface assemblies to the testing machine. The test-train couplers in conjunction with the type of gripping device play major roles in the alignment of the test train and subsequent bending imposed in the test piece. The efficacy of the test train couplers and grip interfaces is verified through the procedure discussed in 8.1 and Annex A.



Key

1 Test piece
2 Wedge grip
3 Grip body
4 Grip mechanism

Figure 1 — Example of an active grip interface



Key

1 Retaining plate
2 Test piece
3 Inserts for lateral centring of test piece
4 Grip attachment

Figure 2 — Example of a passive grip interface

6.3 Strain measurement

Strain measurement is required for tensile testing of CFRCMC test pieces in accordance with this International Standard.

Extensometers shall be of class 1 in accordance with ISO 9513. The extensometer gauge length shall be not less than 10 mm (25 mm preferred) and shall be centrally located in the mid region of the parallel length of the gauge section of the test piece.

Extensometers which are in mechanical contact with the test piece shall not cause damage to the test piece surface such that a detrimental effect on tensile behaviour is produced. Ensure that the extensometer does not introduce bending greater than that allowed in 8.1. Extensometers shall preferably be of a type that is capable of measuring elongation on both sides of a test piece (for averaging of strain and/or determination of in-situ percent bending).

Strain gauges may also be used to measure strain in tensile tests of CFRCMCs. Unless it can be shown that strain gauge readings are not unduly influenced by localized strain events such as fiber 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 transverse direction. The strain gauges, surface preparation and bonding agents should be chosen to provide adequate performance on the subject materials and suitable strain-recording equipment should be used.

6.4 Data acquisition

Obtain at least an autographic record of applied force and gauge section elongation or strain versus time using either analogue chart recorders or digital data acquisition systems. Recording devices shall be accurate to within 1 % of the selected range for the testing system including readout unit and should have a minimum data acquisition rate of 10 Hz with a response of 50 Hz deemed more than sufficient.

6.5 Dimension measurement

Micrometers and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured and shall be in accordance with ISO 3611. To obtain consistent measurements of cross sectional dimensions, use a flat, anvil-type micrometer. Ball-tipped or sharp anvil micrometers are not recommended for woven CFRCMCs because the resulting measurements may be affected by the peaks and troughs of the weave. Measure cross-sectional dimensions to within 0,02 mm using dimension-measuring devices with accuracies of 0,01 mm.

7 Test piece

7.1 Test piece geometry

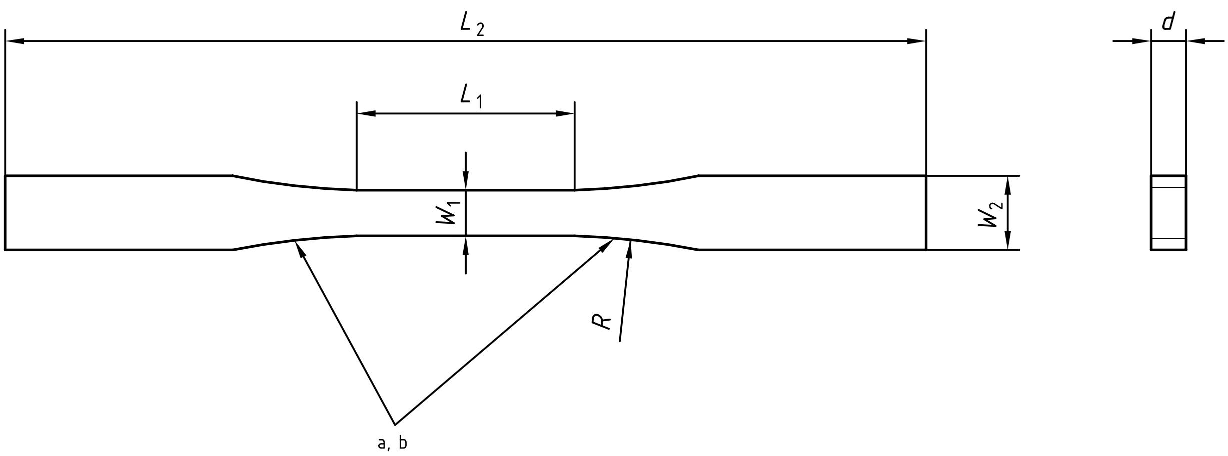
The choice of geometry of a tensile test piece is dependent on the ultimate use of the tensile behaviour data. For example, if the tensile strength of an as-fabricated component is required, the dimensions of the resulting test piece may reflect the thickness, width and length restrictions of the component. If it is desired to evaluate the effects of interactions of various constituent materials for a particular CFRCMC manufactured via a particular processing route, then the size of the test piece and resulting gauge section will reflect the desired volume or surface area to be sampled.

Therefore, no single test piece geometry can be recommended or prescribed to meet all the requirements of a particular testing programme or apparatus. Annex B contains further information on test piece geometries including a figure showing examples of successful test piece geometries used for CFRCMCs.

Certain dimensional requirements are contained in Tables 2 and 3 depending on whether contoured (Figure 3) or straight-sided geometries (Figure 4) are used, respectively.

Table 2 — Minimum dimensions of contoured test piece geometries (see Figure 3)

Dimension	Minimum value mm	Tolerance mm
Total length, L_2	⩾ 100	± 0,5
Gauge Length, L_1	⩾ 30	± 0,2
Thickness, d	⩾ 2 and at least a) three plies for simply woven materials or b) one unit cell width for complex woven materials	± 0,2
Gauge width, W_1	⩾ 6 and at least a) three fibre bundles for simply woven materials or b) one unit cell width for complex woven materials	± 0,2
Grip width, W_2	⩾ 10 and at least 1,4 × W_1	± 0,2
Blend radius, R	⩾ 35	± 2
Parallelism of machined part	0,05	



a Smooth and blend at intersection with width, W_1, of gauge section.

b Simple intersection (no steps of jogs) with width, W_2, of grip section.

Figure 3 — "Generic" countered test piece geometry (see Table 2)

Table 3 — Minimum dimensions of straight-sided test piece geometries (see Figure 4)

Dimension	Minimum value mm	Tolerance mm
Length, *L*	⩾ 100	± 0,5
Thickness, *d*	⩾ 2 and at least a) three plies for simply woven materials or b) one unit cell width for complex woven materials	± 0,2
Width, *W*	⩾ 6 and at least a) three fibre bundles for simply woven materials or b) one unit cell width for complex woven materials	± 0,2
Parallelism of machine part	0,05	

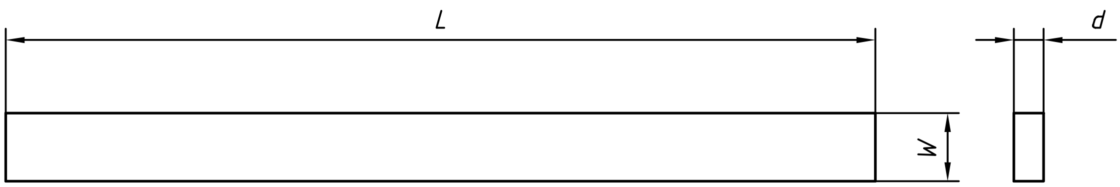


Figure 4 — "Generic" straight-sided test piece geometry (see Table 3)

7.2 Test piece preparation

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

7.2.1 As-fabricated

The test piece shall simulate the surface/edge conditions and processing route of an application where no machining is used; e.g., as-cast, sintered or injection molded part. No additional machining specifications are relevant. As-processed test pieces may possess rough surface textures and non-parallel edges and as such may cause excessive misalignment and/or be prone to non-gauge section fractures.

7.2.2 Application-matched machining

Finish the test piece as close to the same surface/edge preparation as that applied to the component. Unless the process is proprietary, report specifics about the stages of material removal, wheel grits, wheel bonding, amount of material removed per pass and type of coolant used.

7.2.3 Customary practices

In instances where a customary machining procedure has been developed that is completely satisfactory for a class of materials (i.e., it induces no unwanted surface/subsurface damage or residual stresses), use this procedure.

7.2.4 Recommended procedure

Perform all grinding or cutting with an ample supply of appropriate filtered coolant to keep the workpiece and grinding wheel constantly flooded and particle flushed. Grind in at least two stages, ranging from coarse to fine rate of material removal. Cut in one stage appropriate for the depth of cut. Remove stock in the order of 0,03 mm per pass using diamond tools that have between 320 and 600 grit. Remove equal quantities of stock from each face where applicable.

7.3 Number of test pieces

A minimum of five valid tests is required for the purpose of estimating a mean. A greater number of tests may be necessary if estimates regarding the form of the strength distribution are required. If material cost or test piece availability limit the number of tests to be conducted, fewer tests can be conducted to determine an indication of material properties.

7.4 Valid test

A valid individual test is one which meets the following requirements:

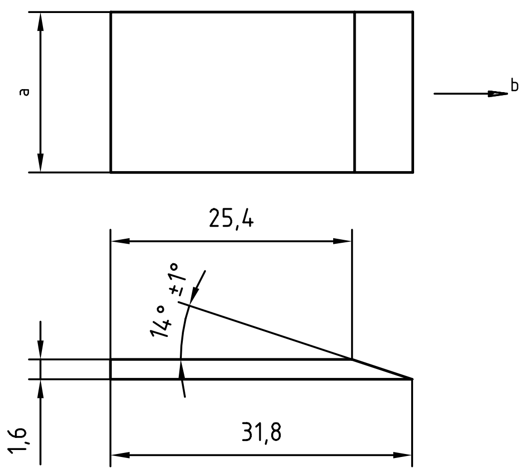
a) all the testing requirements of this International Standard;

b) failure occurs in the uniformily-stressed gauge section unless those tests failing outside the gauge section are interpreted as interrupted tests for the purpose of censored test analyses.

7.5 End tabs

End tabs may be required to provide a compliant layer for gripping for active grip interfaces. Balanced 0/90° cross-ply E-glass fiber-reinforced epoxy, PM, and carbon fiber-reinforced resins are satisfactory tab materials. Each bevelled tab (bevel angle ⩽ 15°) should be a minimum of 30 mm long, the same width of the test piece with the total thickness of the tabs in the order of the thickness of the test piece. Any high-elongation (tough) adhesive system may be used with the length of the tabs determined by the shear strength of the adhesive, size of the test piece, and estimated strength of the composite. In any case, a significant fraction (e.g., ⩾10 % to 20 %) of fractures within one test piece width of the tab shall be cause to re-examine the tab materials and configuration, gripping method and adhesive, and to make necessary adjustments to promote fracture within the gauge section. Figure 5 shows an example of a successful tab design.

Dimensions in millimetres



[a] Width of specimen

[b] Toward longitudinal midpoint of specimen

NOTE 1 Surface finish 0,5 µm to 1,0 µm all over except end faces which may be 1 µm to 2 µm.

NOTE 2 Final grind of gauge section to be longitudinal.

Figure 5 — Example of a tapered end tab

8 Test conditions

8.1 Verification of axial alignment

Verify the alignment of the testing system at a minimum at the beginning and end of a test series using either a dummy or actual test piece and the procedures listed in annex A or similar procedures as listed in annex C. Bending shall not exceed 5 % at a mean strain equal to either one half the anticipated strain at the onset of the cumulative fracture process (e.g. matrix cracking stress) or a strain of 0,000 5 (i.e. 500 micro strain) whichever is greater.

8.2 Test modes and rates

Test modes may involve force, displacement (stroke) or strain control. The test should be sufficiently rapid so as to be completed in less than 30 s thereby obtaining the maximum possible tensile strength on fracture of the material. However, test rates may also be used to evaluate rate effects. In all cases report the test mode and rate.

NOTE Strain rates in the order of 50×10^{-6} s^{-1}, stress rates in the order of 35 MPa s^{-1} to 50 MPa s^{-1}, and cross-head displacement rates on the order of 0,001 mm s^{-1} to 0,05 mm s^{-1} are recommended in order to minimize environmental effects when testing in ambient air.

9 Procedure

9.1 Test piece dimensions

Determine the thickness and width of the gauge section of each test piece to within 0,02 mm. Obtain measurements from at least three different cross-sectional planes in the gauge section. Report the measured dimensions and locations of the measurements for use in the calculation of the tensile stress. Use the average of the multiple measurements in the stress calculations.

9.2 Preparation for testing

Report any special components required for each test. Mark top and bottom of the ungripped part of the test piece with an indelible marker — if testing vertically or left and right if testing horizontally — and front (side facing the operator) in relation to the test machine. Set the test mode and test rate on the test machine. Secure one end of the test piece in the gripping device. With no force applied to the test piece either mount the extensometer on the test piece gauge section and zero the output or attach the lead wires of the strain gauges to the signal conditioner and zero the outputs. Secure the other end of the test piece in the gripping device and apply an initial force to the test piece to remove the "slack" from the test train. Ready the autograph data acquisition systems for data logging. Initiate the data acquisition. Initiate the test mode.

9.3 Completion of testing

After test piece fracture, disable the action of the test machine and the data collection of the data acquisition system. Record the breaking force to an accuracy of 1 % of the force range. Carefully remove the test piece from the grip interfaces. Take care not to damage the fracture surfaces by preventing them from coming into contact with each other or other objects. Place the test piece, along with any fragments from the gauge section, in a suitable, non-metallic container for later analysis.

9.4 Post test

Determine and report ambient temperature and relative humidity. Measure and report the fracture location relative to the midpoint of the gauge section. Use the convention that the midpoint of the gauge section is 0 mm with positive (+) measurements toward the top of the test piece as tested (and marked) and negative (–) measurements toward the bottom of the test piece as tested (and marked). For fracture surfaces which are not perpendicular to the longitudinal axis the average fracture location may be reported. Report the orientation of the fracture locations. If fracture has occurred outside the uniformly-stressed gauge section, the result should not be used in the calculations of mechanical properties.

9.5 Calculation of results

CFRCMC materials may exhibit different stress-strain responses as illustrated schematically in Figures 6 a) b) and c). Therefore, interpretation of the test results will depend on the type of response exhibited. Points corresponding to the following calculated values are shown on the appropriate diagrams.

9.5.1 Engineering stress

The engineering stress is calculated as follows:

$$\sigma = \frac{F}{A} \tag{1}$$

where

σ is the engineering stress in megapascals;

F is the applied, uniaxial tensile force in newtons;

A is the original cross-sectional area in square millimetres.

The cross-sectional area, A, is calculated as follows:

for contoured test piece geometry cross section

$$A = W_1\, d \tag{2a}$$

for straight-sided test piece geometry cross sections

$$A = W\, d \tag{2b}$$

where

W_1 is the average width of the gauge section for the contoured test pieces in millimetres;

W is the average width of the gauge section for the straight-sided test pieces in millimetres;

d is the average thickness of the gauge section in millimetres.

9.5.2 Engineering strain

The engineering strain is calculated as follows:

$$\varepsilon = \frac{(l - l_0)}{l_0} \quad (3)$$

where

ε is the engineering strain;

l is the gauge length (test piece or extensometer gauge length) at any time in millimetres;

l_0 is the original gauge length in millimetres.

NOTE If strain gauges are used, strain is determined directly.

In some cases the initial portion of the stress versus strain (σ-ε) curve shows a non-linear region or "toe" followed by a linear region as shown in Figure 6 c). This toe may be an artifact of the tensile test and may not represent a property of the material. The σ-ε curve can be corrected for this toe by extending the linear region of the curve to the zero stress point on the strain axis as shown in Figure 6 c). The intersection of this extension with the strain axis is the toe correction which is subtracted from all values of strain greater than the toe correction strain. The resulting σ-ε curve is used for all subsequent calculations. Report the original σ-ε curve with the non-linear toe region in uncorrected as well as corrected form.

9.5.3 Tensile strength

The tensile strength is calculated as follows:

$$R_m = \frac{F_m}{A} \quad (4)$$

where

R_m is the ultimate tensile strength in megapascals;

F_m is the maximum force in newtons.

9.5.4 Strain at tensile strength (optional)

Determine strain at tensile strength, ε_m, as the strain corresponding to the tensile strength measured during the test.

9.5.5 Fracture strength

The fracture strength is calculated as follows:

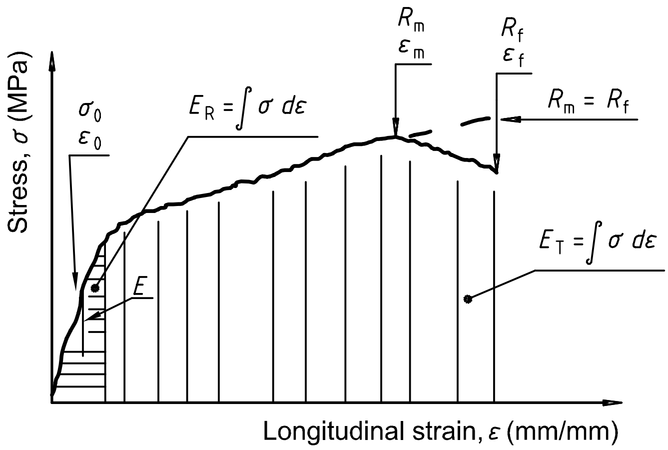
$$R_f = \frac{F_f}{A} \quad (5)$$

where

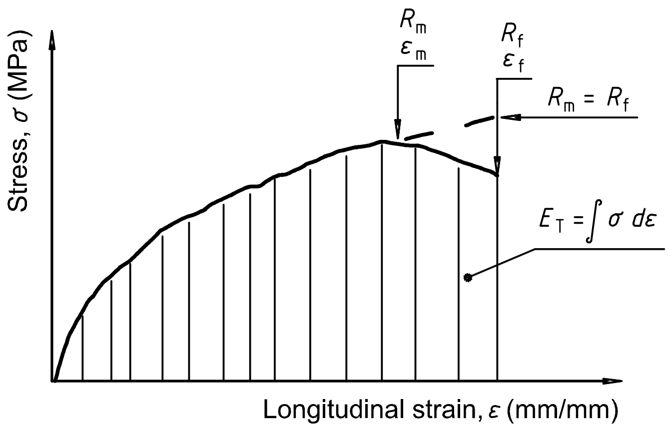
R_f is the tensile strength in units of megapascals;

F_f is the fracture force (breaking force), in newtons when the test piece separates into two or more pieces.

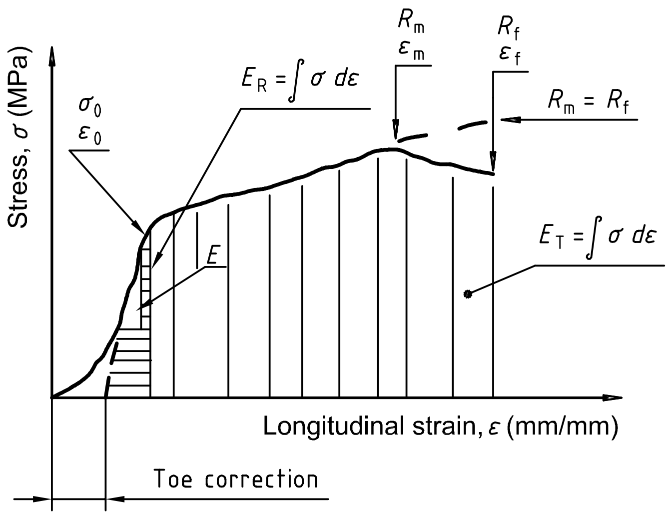
In some instances as shown by the dashed line in Figures 6 a) to 6 c), $R_m = R_f$.



a) Stress-strain curve with a linear region



b) Non linear stress-strain curve



c) Stress-strain curve with a linear region and toe

NOTE At the high-strain portions of the σ-ε curves, two different types of behaviour are depicted: where stress drops prior to fracture (solid line) and where stress increases up to the point of fracture (dashed line).

Figure 6 — Schematic diagrams of stress-strain (σ-ε) curves for CFRCMCs

9.5.6 Strain at fracture strength

Determine strain at fracture strength, ε_f, as the engineering strain corresponding to the fracture strength measured during the test. In some instances as shown in Figures 6 a) to 6 c), $\varepsilon_m = \varepsilon_f$.

9.5.7 Modulus of elasticity

The modulus of elasticity is calculated as follows:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (6)$$

$\Delta\sigma/\Delta\varepsilon$ is the slope of the σ-ε curve within the linear region as shown in Figures 6 a) to 6 c). The modulus of elasticity may not be defined for materials which exhibit entirely non-linear σ-ε curves as shown in Figure 6 b).

9.5.8 Proportional limit stress

9.5.8.1 General

By definition the proportional limit stress, σ_0, may not exist for materials which exhibit an entirely non-linear σ-ε curve.

Determine the proportional limit stress, σ_0, by one of the following methods (see Figure 7)

9.5.8.2 Offset method

Determine by generating a line (5) running parallel to the same part of the linear part of the σ-ε curve used to determine the modulus of elasticity (3). The line so generated shall be at a specified strain offset (1). The proportional limit stress is the stress level at which the offset line intersects the σ-ε curve (4).

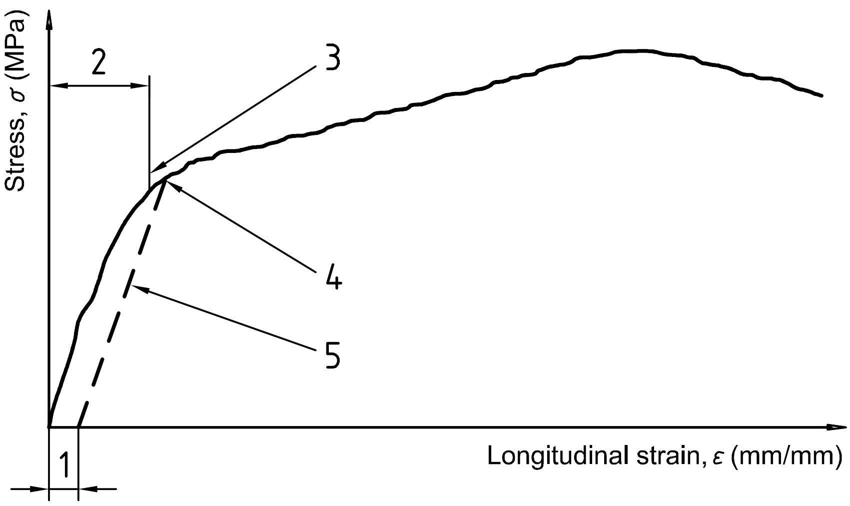


Figure 7 — Schematic diagram of methods for determining proportional limit stress

9.5.8.3 Extension under force method

Determine σ_0 by noting the stress on the curve which corresponds to a specified strain (2). The specified strain may or may not be in the linear region of the σ-ε curve but the specified strain at which σ_0 is determined shall be constant and reported for all tests in a set.

NOTE A strain of 0,000 5 m/m (500 µm/m) has been used successfully in the past for either the specified strain offset of the offset method or the specified strain for the extension under force method.

9.5.8.4 User-defined method

Determine σ_0 by any clearly-defined and described method which shall be reported and used consistently for all tests in a test series.

9.5.9 Strain at proportional limit stress (optional)

Determine strain at proportional limit stress, ε_0, as the strain corresponding to proportional limit stress, determined for the test.

9.5.10 Recoverable elastic energy (optional)

Calculate the recoverable elastic energy (modulus of resilience), E_R in joules per cubic millimetre as the area under the linear part of the σ-ε curve or alternatively estimated as:

$$E_R = \int_0^{\varepsilon_0} \sigma d\varepsilon \approx \tfrac{1}{2} \sigma_0 \varepsilon_0 \qquad (7)$$

σ_0 and ε_0 are as used in Figure 7 in pascals (N/m^2) and millimetres respectively.

9.5.11 Irrecoverable cumulative damage energy (optional)

Calculate the irrecoverable cumulative damage energy (modulus of toughness) E_T in joules per cubic millimetre as the area under the entire σ-ε curve or alternatively estimated as:

$$E_T = \int_0^{\varepsilon_f} \sigma d\varepsilon \approx \frac{\sigma_0 + R_m}{2} \varepsilon_f \qquad (8)$$

σ_0 and S_u are as used in Figures 8 and 9 pascals (N/m^2) and ε_0 is in m/m. E_T can be estimated as follows for materials for which σ_0 is not calculated and which have a σ-ε curve which can be a parabola.

$$E_T = \int_0^{\varepsilon_f} \sigma d\varepsilon \approx \tfrac{2}{3} R_m \varepsilon_f \qquad (9)$$

9.5.12 Mean, standard deviation and coefficient of variation

For each series of tests calculate the mean, standard deviation and coefficient of variation for each measured value as follows:

Mean $$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{10}$$

Standard deviation $$\text{SD} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n-1}} \tag{11}$$

Coefficient of variation $$V = \frac{100(\text{SD})}{\overline{X}} \tag{12}$$

where X represents the measured values and n is the number of valid tests.

10 Test report

10.1 Test set

For the test set, the following information shall be reported.

a) Date and location of testing.

b) Tensile test piece geometry used (including engineering drawing). For end-tabbed test pieces include a drawing of the tab as well as the tab material and specify the adhesive used.

c) Type and configuration of the test machine (include drawing or sketch if necessary). If a commercial test machine was used, the manufacturer and model number are sufficient for describing the test machine.

d) Type, configuration, and resolution of strain measurement equipment used (include drawing or sketch if necessary). If a commercial extensometer or strain gauges and strain gauge conditioner were used, the manufacturer and model number are sufficient for describing the strain measurement equipment.

e) Type, configuration and surface finish of grip interface used (include drawing or sketch if necessary). If a commercial grip interface was used, the manufacturer and model number are sufficient for describing the grip interface.

f) Type and configuration of test-train couplers (include drawing or sketch if necessary). If a commercial test-train coupler was used, the manufacturer and model number are sufficient for describing the coupler.

g) Number (n) of test pieces used in valid tests (e.g. fracture in the gauge section). In addition, report the total number of test pieces tested (n_T) to provide an indication of the expected success rate of the particular test piece geometry and test apparatus.

h) All relevant material data including vintage or billet identification. As a minimum, report the date the material was manufactured. For commercial materials, report the commercial designation. A short description of reinforcement (type, lay up, etc.), fibre volume fraction and bulk density shall be included.

i) Description of the method of test piece preparation including all stages of machining.

j) If any heat treatments, coatings or pre-test exposures were applied, whether to the as-processed material or to the as-fabricated test piece.

k) Test environment including relative humidity, ambient temperature and atmosphere (e.g. ambient air, dry nitrogen, silicon oil, etc.), partial pressure (or percentage) of oxygen (if known).

l) Test mode (force, displacement or strain control) and actual test rate (force rate, displacement rate or strain rate). Report calculated strain rate, s^{-1}, if appropriate.

m) Percent bending and corresponding average strain in the test piece recorded during the verification as measured at the beginning and end of the test series.

n) Mean, standard deviation and coefficient of variation for each test series.

o) The following properties, if measured:

   1) tensile strength, R_m;

   2) strain at tensile strength, ε_m (if measured);

   3) fracture strength, R_f;

   4) strain at fracture strength, ε_f;

   5) modulus of elasticity, E;

   6) proportional limit stress, σ_o and method of determination;

   7) strain at proportional limit stress, ε_o (if measured);

   8) recoverable elastic energy (modulus of resilience), E_R (if measured);

   9) irrecoverable cumulative damage energy (modulus of toughness), E_T (if measured).

p) Any significant deviation from the procedures and requirements of this International Standard.

Figure 8 shows a sample reporting table for a test set.

10.2 Individual tests

For each test piece tested the following information shall be reported.

a) Pertinent overall test piece dimensions, if measured, such as total length, length of gauge section, gripped section dimensions, etc.

b) Average surface roughness, if measured, of gauge section measured in the longitudinal direction.

c) Average cross-sectional dimensions, if measured, or cross-sectional dimensions at the plane of fracture.

d) Plot of the entire stress-strain (σ-ε) curve.

e) Ultimate tensile strength, R_m

f) Strain at tensile strength, ε_m (if measured)

g) Fracture strength, R_f

h) Strain at fracture strength, ε_f

i) Modulus of elasticity, E

j) Proportional limit stress, σ_0, and method of determination

k) Strain at proportional limit stress, (if measured) ε_0

l) Recoverable elastic energy (modulus of resilience), E_R (if measured)

m) Irrecoverable cumulative damage energy (modulus of toughness), E_T (if measured)

n) Fracture location relative to the gauge section midpoint in units of mm (+ is toward the top of the test piece as marked and – is toward the bottom of the test piece as marked with 0 being the gauge section midpoint).

o) Any significant deviation from the procedures and requirements of this International Standard.

Figure 9 shows a sample reporting table for an individual test.

Test record identifier	
Test piece identification	
Date of test	
Location of test	
Name of person conducting test	
Type of test piece, contour or straight sided (attach drawing)	
Test piece dimensions total length, L_2 or L (mm)	
gauge length, L_1 (mm)	
thickness, d (mm)	
gauge width, W_1 or W (mm)	
grip width, W_2 (mm)	
End tab (if used) (attach drawing) end tab material	
end tab adhesive	
Type and configuration of test machine (attach drawing and/or make/manufacturer)	
Type and configuration of strain measurement (attach drawing and/or make/manufacturer)	
Type and configuration of grip interface (attach drawing and/or make/manufacturer)	
Type and configuration of test train couplers (attach drawing and/or make/manufacturer)	
Number of valid tests (n)	
Total number of tests (n_T)	
Material data vintage (date of manufacture) (if known)	
commercial designation (if known)	
reinforcement type and fibre (if known)	
fibre volume fraction (if known)	
bulk density (if known)	
matrix material (if known)	
interphase material (if known)	
Test piece fabrication	
Heat treatment, coating, etc.	
Test environment relative humidity (%)	
ambient temperature (^{o}C)	
atmosphere	
Test mode (force, displacement, or strain)	
Test rate [N/s, mm/s, or (mm/mm)/s]	
Test train verification	
Initial percent bending and average strain	
Final percent bending and average strain	
Mean ultimate tensile strength, R_m (MPa)	
Standard deviation tensile strength, R_{SD} (MPa)	
Mean strain at tensile strength, ε_m (mm/mm) (if measured)	
Standard deviation strain at tensile strength, ε_{SD} (mm/mm) (if measured)	
Mean tensile strength at fracture, R_f (MPa)	
Mean strain at fracture strength, ε_f (mm/mm)	
Standard deviation strain at fracture strength, ε_{fSD} (mm/mm)	
Mean modulus of elasticity, E (GPa)	
Standard deviation modulus of elasticity, E_{SD} (GPa)	
Mean proportional limit stress, σ_o (MPa)	

Standard deviation proportional limit stress, σ_{0SD} (MPa)	
Method of determination of σ_0	
Mean strain at proportional limit stress, ε_p (mm/mm) (if measured)	
Standard deviation strain at proportional limit stress, ε_{pSD} (mm/mm) (if measured)	
Mean recoverable elastic energy (modulus of resilience), E_R (J/m^3) (if measured)	
Standard deviation recoverable elastic energy (modulus of resilience), E_R (J/m^3) (if measured)	
Mean irrecoverable cumulative damage energy (modulus of toughness), E_T (J/m^3) (if measured)	
Standard deviation irrecoverable cumulative damage energy (modulus of toughness), E_T (J/m^3) (if measured)	

Figure 8 — Sample reporting sheet for a test set

Test record identifier	
Test piece identification	
Date of test	
Location of test	
Name of person conducting test	
Type of test piece, contour or straight sided	
Test piece dimensions	
total length, L_2 or L (mm)	
gauge length, L_1 (mm)	
thickness, d (mm)	
gauge width, W_1 or W (mm)	
grip width, W_2 (mm)	
Average surface roughness (m)	
Stress-strain (ε-σ) curve	Attached
Ultimate tensile strength, R_m (MPa)	
Strain at ultimate tensile strength, ε_m (if measured) (m/m)	
Fracture strength, R_f	
Strain at fracture strength, ε_f (m/m)	
Modulus of elasticity, E	
Proportional limit stress, σ_0 (MPa)	
Method of determination	
Strain at proportional limit stress, ε_0 (m/m) (if measured)	
Recoverable elastic energy (modulus of resilience), E_R (J/m^3)	
Irrecoverable cumulative damage energy (modulus of toughness), E_T (J/m^3)	
Fracture location (mm)	

Figure 9 — Sample reporting sheet for an individual test

Annex A
(normative)

Alignment verification

Alignment of the testing system shall be measured at least at the beginning and end of a test series using either a dummy or actual test piece and the procedures listed in ASTM Practice E1012 or similar procedures as described in 8.1. Applicable details of the alignment procedure for square or circular cross sections are given below.

For simplicity, mount a minimum of eight foil resistance strain gauges on the verification test piece as shown in Figure A.1. Separate the strain gauge planes by 3/4 l_0 where l_0 is the length of the reduced or designated gauge section. Mount four strain gauges, equally spaced (90° apart) around the circumference of the gauge section (i.e. one strain gauge on each face), at each of two planes at either end of the gauge section. These planes shall be symmetrically located about the longitudinal midpoint of the gauge section. Use suitable strain recording equipment. Mount the top of the test piece in the grip interface. Connect the lead wires of the strain gauges to the conditioning equipment. Zero the strain gauges before mounting the bottom of the test piece in the grip interface. Apply sufficient force to the test piece in order to achieve a main strain equal to either one-half the anticipated strain in the test material at the onset of the cumulative fracture process (e.g. matrix cracking stress) or a strain of 0,000 5 (i.e. 500 micro strain) whichever is greater. Calculate percent bending as follows for square or circular cross sections referring to Figure A.1 for the strain gauge numbers. Calculate percent bending at the upper and lower planes of the gauge section using equations A.1 and A.2, respectively.

$$B_u = \frac{\left[\left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right)^2 + \left(\frac{\varepsilon_2 - \varepsilon_4}{2}\right)^2\right]^{1/2}}{\left[\frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4}{4}\right]} 100 \qquad \text{(A.1)}$$

$$B_l = \frac{\left[\left(\frac{\varepsilon_5 - \varepsilon_7}{2}\right)^2 + \left(\frac{\varepsilon_6 - \varepsilon_8}{2}\right)^2\right]^{1/2}}{\left[\frac{\varepsilon_5 + \varepsilon_6 + \varepsilon_7 + \varepsilon_8}{4}\right]} 100 \qquad \text{(A.2)}$$

where

B_u is percent upper bending;

B_l is percent lower bending;

ε_1, ε_2, ε_3 and ε_4 are strain readings for strain gauges located at the upper planes of the gauge sections;

ε_5, ε_6, ε_7 and ε_8 are strain readings for strain gauges located at the lower planes of the gauge sections;

Strain gauge readings are in units of strain (i.e. m/m) and compressive strains are negative.

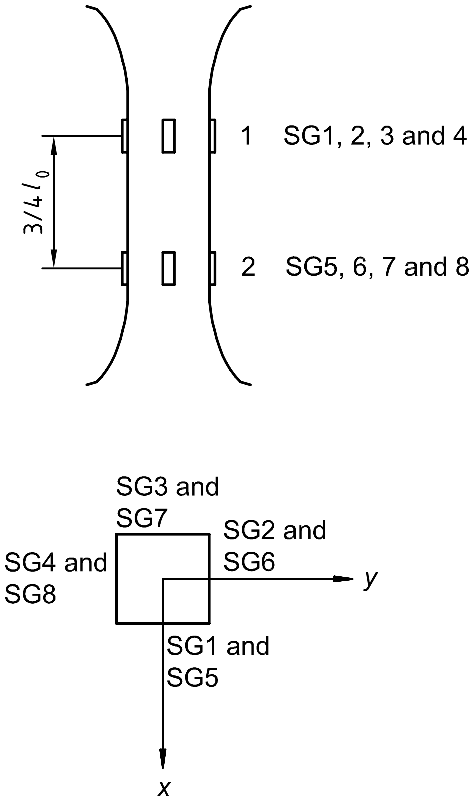


Figure A.1 — Illustration of strain gauge placement on gauge section planes and strain gauge numbering

Annex B
(informative)

Test piece geometries

B.1 General

Test piece geometries can be categorized in general as contoured and straight-sided as discussed below and as shown in Figure B.1.

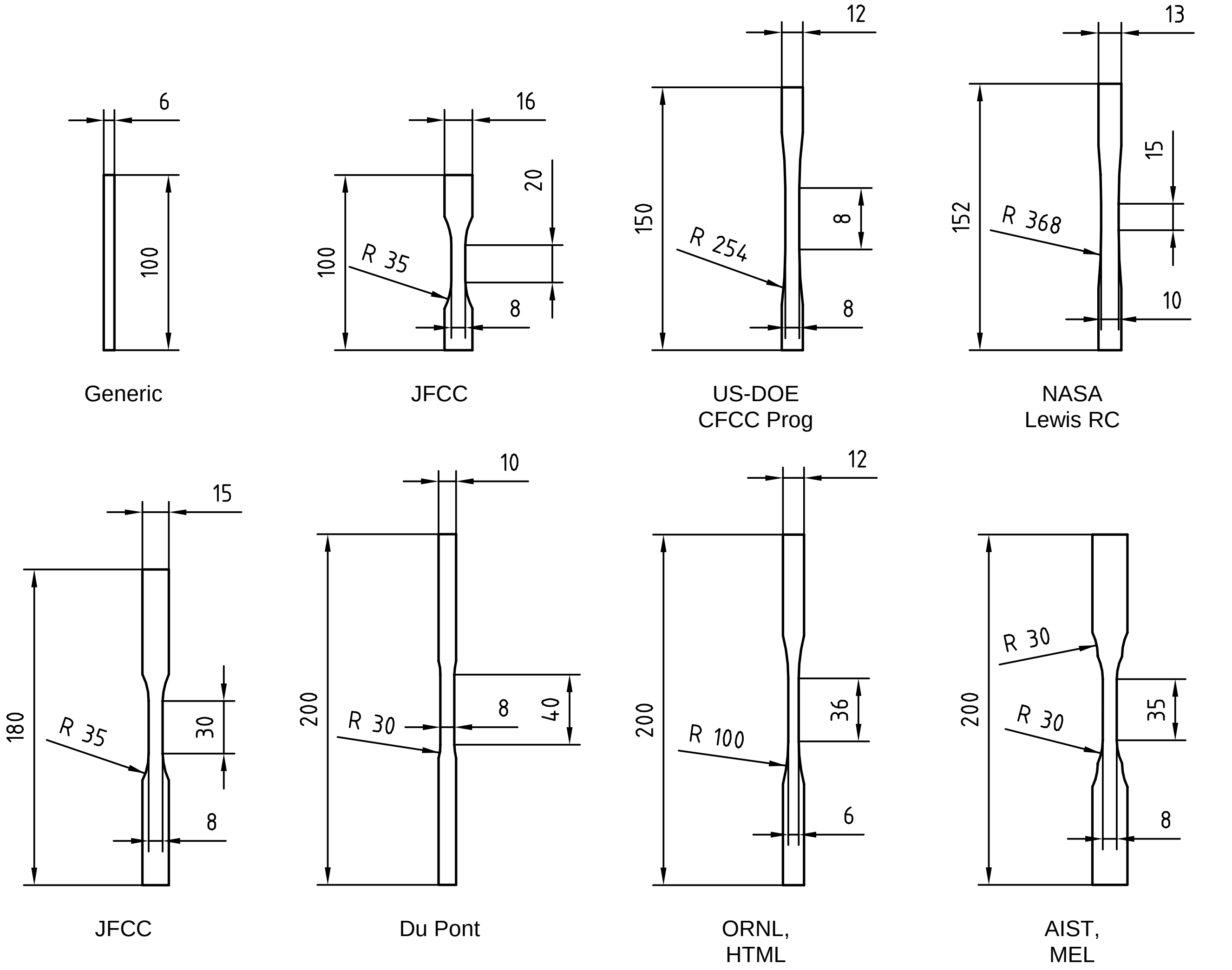
B.2 Contoured test piece

Generally, test piece geometries with contoured gauge sections (transition radii of > 50 mm) are preferred in order to give rise to tensile stresses with the greatest values in the uniformly-stressed gauge section while minimizing the stress concentration due to the geometrical transition of the radius. Often stress analyses (e.g. finite element analysis) of untried test piece geometries are conducted to ensure that stress concentrations which can lead to undesired fractures outside the gauge sections do not exist. Contoured test piece geometries by their nature contain inherent stress concentrations due to geometric transitions. Stress analyses can indicate the magnitude of such stress concentrations while revealing the success of producing a uniform tensile stress state in the gauge section of the test piece.

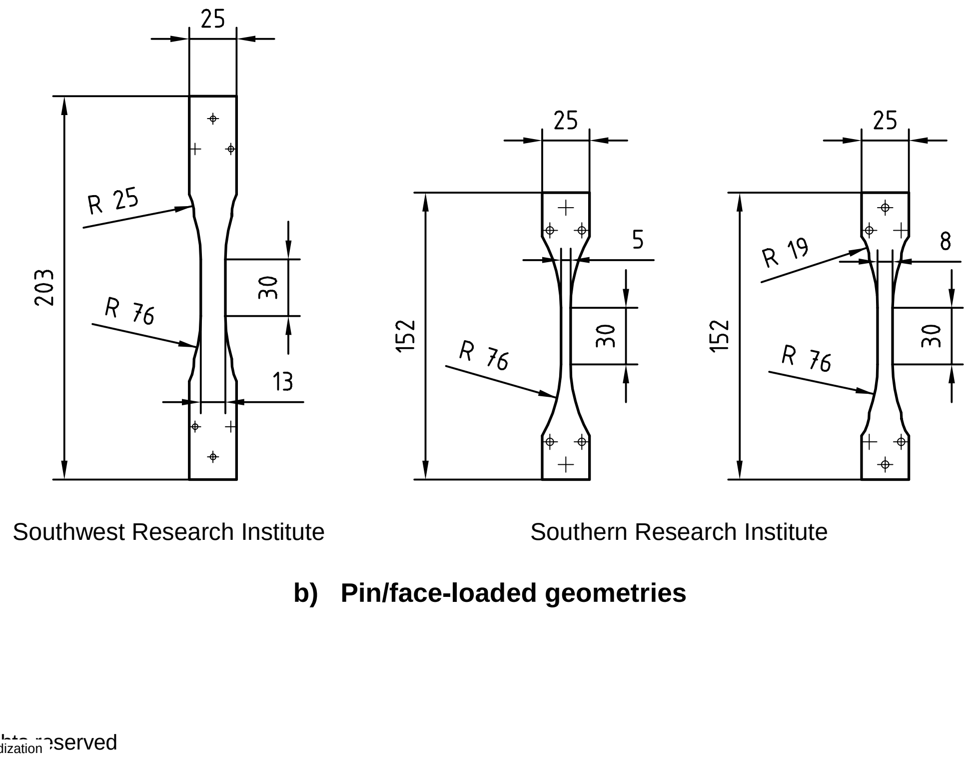
B.3 Straight-sided test pieces

In certain instances, (e.g., 1-D CFRCMCs tested along the direction of the fibres) low interfacial shear strength relative to the tensile strength in the fibre direction will cause splitting of the test piece. This split will initiate at the transition region between the gauge section and the gripped section of a contoured test piece and will propagate along the fibre direction leading to fracture of the test piece. In such cases, straight-sided (i.e. non-contoured) test pieces may be required for determining the tensile strength behaviour of the CFRCMC. In other instances, a particular fibre weave or processing route will preclude fabrication of test pieces with reduced gauge section, thus requiring implementation of straight-sided test pieces. Straight-sided test pieces may be gripped using any of the methods discussed in this International Standard although active gripping systems are recommended for minimizing non-gauge section fractures.

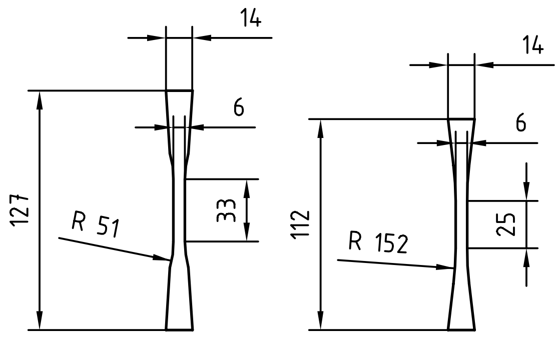
Dimensions in millimetres



a) Face-loaded geometries



b) Pin/face-loaded geometries



University of Michigan

c) Edge-loaded geometries

Figure B.1 — Examples of various tensile test piece geometries

Bibliography

[1] ASTM C1275-00, *Standard Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Specimens at Ambient Temperatures.*

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

[3] HSR/EPM-D001-93, *Monotonic Tensile Testing of Ceramic Matrix, Intermetallic Matrix, and Metal Matrix Composite Materials.*

[4] PEC-TS CMC 01, *Test method for tensile stress-strain behaviour of continuous fibre-reinforced ceramic matrix composites at room and elevated temperatures.*

[5] RIMCOF-S-001-92, *Test Method for Ultra-high Temperature Tensile Properties of Advanced C/C Composites.*

[6] ASTM E1012-99, *Standard Practice for Verification of Specimen Alignment Under Tensile Loading.*

[7] CEN (EUR 16138), *Bending in Uniaxially Loaded Tension/Compression Test Pieces* (ISBN 92-826-9681-2).

[8] NPL (NPL MMS001:1995), *Code of Practice for the Measurement of Bending in Uniaxial Low Cyclic Fatigue Testing* (ISBN 0 946754 16 0).

ICS 81.060.30

Price based on 27 pages