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AMENDMENT 1
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Plastics — Determination of fracture toughness (G_{IC} and K_{IC}) — Linear elastic fracture mechanics (LEFM) approach

AMENDMENT 1: Guidelines for the testing of injection-moulded plastics containing discontinuous reinforcing fibres

Plastiques — Détermination de la ténacité à la rupture (G_{IC} et K_{IC}) — Application de la mécanique linéaire élastique de la rupture (LEFM)

AMENDEMENT 1: Lignes directrices relatives à l'essai des matériaux plastiques moulés par injection contenant des fibres de renfort discontinues

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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.org
Web www.iso.org

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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 2.

The main task of technical committees is to prepare International Standards. 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 document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

Amendment 1 to ISO 13586:2000 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*. It is based on guidelines originally developed by Technical Committee TC 4 of the European Structural Integrity Society (ESIS).

Plastics — Determination of fracture toughness (G_{IC} and K_{IC}) — Linear elastic fracture mechanics (LEFM) approach

AMENDMENT 1: Guidelines for the testing of injection-moulded plastics containing discontinuous reinforcing fibres

Page 1

Update Clause 2 (normative references) as follows:

Replace ISO 604:1993 by ISO 604:2002 (same title).

Replace ISO 5893:1993 by ISO 5893:2002, *Rubber and plastics test equipment — Tensile, flexural and compression types (constant rate of traverse) — Specification.*

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Add the following references to the Bibliography:

[8] FOLKES, M. *Short fibre reinforced thermoplastics*, Research Studies Press, J. Wiley (1992)

[9] LOWE, A.C., MOORE, D.R., RUTTER, P.M. *Impact and dynamic fracture of polymers and composites*, ESIS Publication 19, edited by J.G. Williams and A. Pavan, p. 383, MEP Ltd (London) (1995)

[10] MOORE, D.R., *Experimental Methods in the Application of Fracture Mechanics Principles to the Testing of Polymers and Composites*, Chapter 1, p. 59, *The Measurement of K_C and G_C at Slow Speeds for Discontinuous Fibre Composites*, edited by B.R.K. Blackman, D.R. Moore, A. Pavan and J.G. Williams, ISBN 008 043689 7, Elsevier Science (2001)

[11] DAVIS, M., MOORE, D.R. *Composites Science & Technology*, **40**, p. 131 (1991)

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Add the following annex before the Bibliography.

Annex B
(informative)

Guidelines for the testing of injection-moulded plastics containing discontinuous reinforcing fibres

B.1 General

ISO 13586 was developed for non-reinforced plastics. However, with the proliferation of injection-moulded products made from fibre-reinforced plastics, it was considered appropriate that some guidelines be given to users who want to apply this International Standard to measure the toughness of reinforced composite materials. Whilst the theoretical basis which underpins the standard cannot be rigorously applied to reinforced plastics, informative results can be obtained.

When applying this International Standard to injection-moulded plastics containing discontinuous reinforcing fibres, three issues arise. The first of these relates to sample morphology stemming from the injection-moulding manufacturing method. The second relates to a feature involved in crack initiation and the third concerns the application of LEFM to this class of anisotropic, heterogeneous material and the validity of the toughness values.

B.2 Effect of injection moulding on fibre alignment

During the injection moulding of plastics containing discontinuous reinforcing fibres, the melt is delivered into a mould tool under a shear stress field. This causes the fibres to be aligned in the direction of mould fill. However, the melt strikes a cold mould surface and quickly solidifies. Therefore, the fibres aligned in the direction of mould fill are generally near to the mould surface. The melt that enters the central or core region of the mould is then subjected to a stress field where the deformations are extensional, i.e. a diverging stress field [8]. This aligns the fibres in this core region at approximately right angles to the direction of mould fill. In simplistic terms, a skin-core-skin structure is established through the thickness of the moulding. Of course, in reality this is an over-simplification of a much more complex fibre orientation, but an adequate approximation for an assessment of toughness. The mould thickness will then determine which layer will be dominant, with thin mouldings being skin-dominated and thicker mouldings being core-dominated.

B.3 Guidelines for the preparation of samples

These guidelines require that the direction of mould fill from the injection-moulding process be known for the material to be tested. An injection moulding will have in-plane anisotropy and through-thickness heterogeneity. The moulding will have three mutually perpendicular directions, as follows:

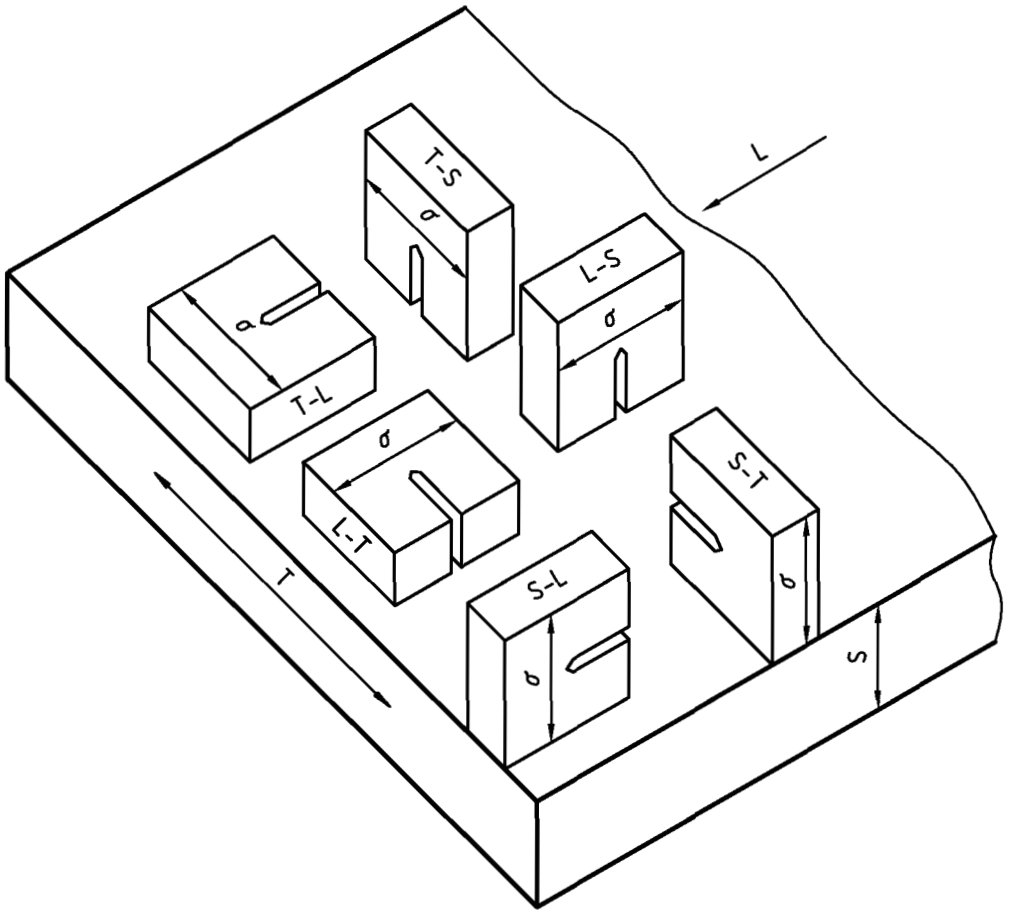
L Longitudinal, i.e. in the processing direction;

T Transverse, i.e. in the mould width direction;

S Short transverse, i.e. in the through-thickness direction.

The anisotropic sheet shown in Figure B.1 will have six different directions of toughness for which six specimens designated T-S, L-S, S-T, T-L, L-T and S-L can be used for measurement purposes. The first letter designates the direction normal to the crack plane, i.e. the direction of the stress applied to generate a colinear crack. The second letter is the expected direction of crack propagation. However, in practice the specimens have to be cut with a thickness equal to the thickness of the moulding, so only the T-L and L-T specimens can be used and it is recommended that both T-L and L-T specimens be prepared. Thus both the

T-L and L-T specimens will have a thickness h equal to the mould thickness. Either SENB or CT specimens may be used. Specimens should not be cut from close to the edge of the moulding. The notch tip radius should be sharp and it is recommended that it should be less than 50 µm.



Key

L longitudinal direction (direction of mould fill)

T long transverse direction (mould width direction)

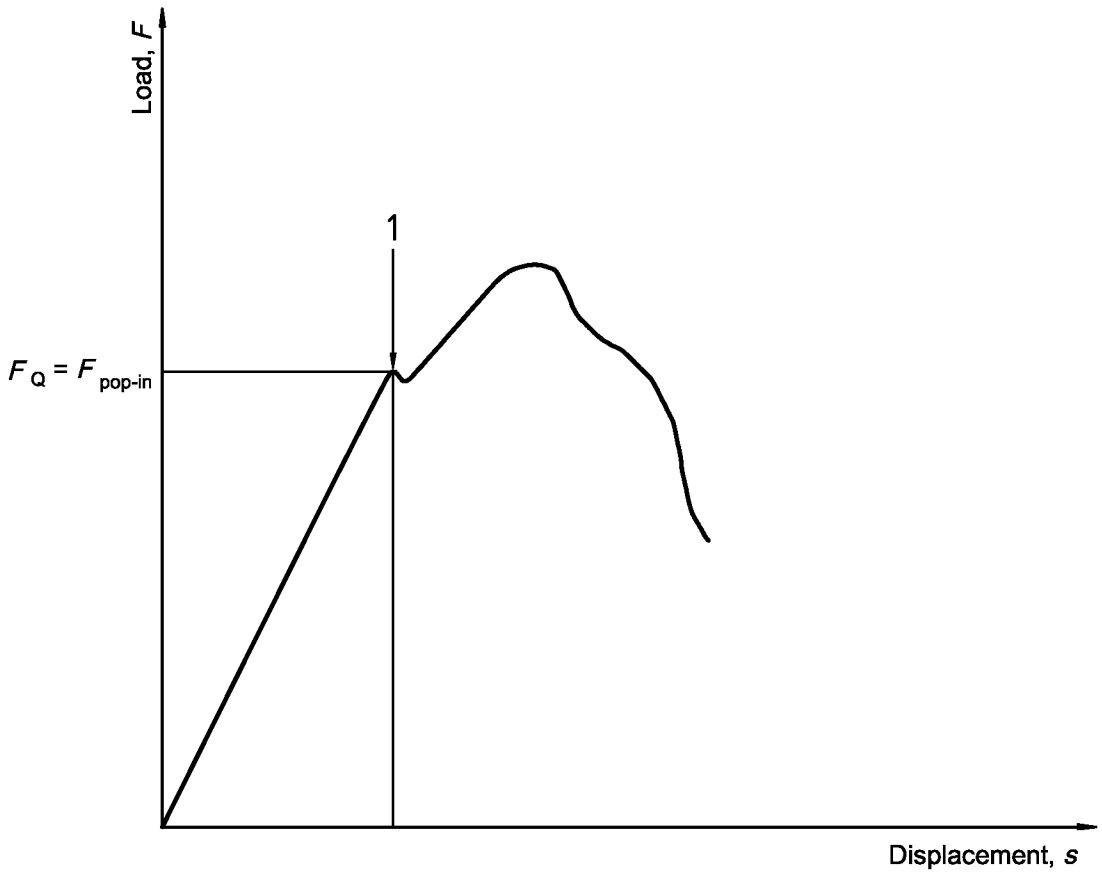
S short transverse direction (through-thickness direction)

σ direction of stress

Figure B.1 — Specimen configuration for an anisotropic sheet (illustrated for a CT specimen)

B.4 Guidelines for the interpretation of the load-displacement curve when "pop-in" occurs

When testing injection-moulded plastics containing discontinuous reinforcing fibres, a force decrease (termed "pop-in") is sometimes observed [9] on the load-displacement curve prior to the main peak as shown in Figure B.2. This initial peak force is followed by a drop which can then be followed by a further, often significant, rise. If the stiffness, i.e. the slope of the force-displacement curve, reduces after the drop in the force, then it is likely that the crack has initiated. When this is observed, the value of the force at which the "pop-in" occurs should be taken as F_Q. When "pop-in" does not occur, the trace should be interpreted as described in Clause 6 and shown in Figure 7.



Key

1 "pop-in"

Figure B.2 — Load-displacement curve for a notched test specimen made from injection-moulded plastic containing discontinuous reinforcing fibres when "pop-in" occurs

B.5 Guidelines for assessing the colinearity of the crack growth

The crack growth in homogeneous polymeric materials should be colinear and grow in the direction at right angles to the direction of the applied stress. However, for a discontinuous-fibre-reinforced composite the crack growth will usually not be colinear. It is informative to assess the extent of non-colinearity of each specimen after the test. It is recommended that this be done by firstly observing the fractured surface side-on to the crack growth and then by examination of the plane of the crack. A visual observation of the side-on view will provide information on the degree of colinearity at the edge of the specimen, i.e. in the "skin" layer. Then, by microscopic examination of the plane of the crack, an estimation can be made of the skin thickness t_S and of the core thickness t_C. These regions can be identified due to the preferential alignment of the fibres during injection moulding as described in Clause B.2. When the crack grows through a region of the moulding where

the fibres are aligned parallel to the crack, a smooth fracture surface is observed. However, when the crack grows through a region of the moulding where the fibres are aligned perpendicular to the crack, then a rough fracture surface is observed. It follows therefore that the fracture surface of the L-T specimen will have a smooth core layer and rough skin layers. However, the fracture surface of the T-L specimens will have a rough core layer and smooth skin layers.

B.6 Estimation of the smooth fraction for L-T and T-L specimens

If the thickness of the skin layer t_S and the thickness of the core layer t_C are measured optically, then the amount of smooth fracture, termed the smooth fraction, can be estimated. In T-L specimens, the smooth fraction is the value of $2t_S/h$ and for the L-T specimens it is the value of t_C/h, where h is the thickness of the specimen as defined in Figure 1 for the SENB specimen and Figure 3 for the CT specimen.

A smooth fraction of unity implies a completely smooth fracture surface (as would typically be obtained when fracturing an unreinforced polymer) and a smooth fraction of zero implies a completely rough fracture surface. Round-robin results [10] obtained by ESIS TC 4 on a 50 % by mass glass polyamide composite are shown in Figure B.3. Reference [4] discusses in detail the nature of the results, the interpretation of the fracture surface and the shape of the curve in Figure B.3. Further discussion is beyond the scope of this test method. The results show that, as the smooth fraction tends towards unity, then the K_C value should tend towards the plane strain value for the resin. From these data, an anticipated resin K_C value of around 3,5 MPa·m$^{1/2}$ would be suggested, which does seem reasonable. When the smooth fraction tends towards zero, the fracture process is dominated by fibre pull-out and breaking fibres, so a large K_C would be expected, as was indeed observed.

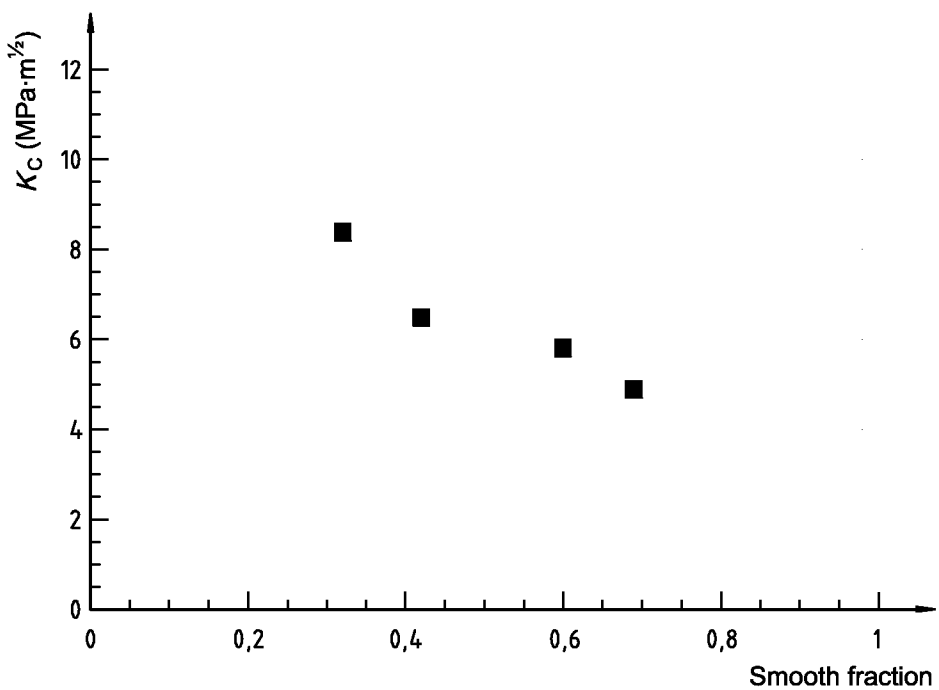


Figure B.3 — K_C plotted against the smooth fraction of the fracture surface for 50 % by mass glass-fibre-reinforced polyarylamide injection mouldings of thickness 2 mm and 5 mm

B.7 Guidelines for comparing the toughness of two different reinforced materials

When comparing toughness values measured for different discontinuous-fibre-reinforced composites, it is recommended that values of K_C versus smooth fraction be plotted for each composite. The values of K_C at a common smooth fraction can then be compared. The larger K_C value will infer the higher toughness. The

quality of the comparison will be improved if a mid-range value for the smooth fraction is chosen for the comparison.

B.8 Guidelines for measuring the yield strength

To apply the size criteria, a value of the tensile yield strength σ_y is required. However, for discontinuous-fibre-reinforced composites this should not be measured in tension because tensile failure will be accompanied by other processes such as fibre pull-out, fibre fracture, debonding and matrix cracking [11]. Therefore, it is recommended that a value of 0,7 times the compressive yield stress be used. This can be measured using the standard method for compressive testing, ISO 604. During compressive testing, the stress should be aligned in the T direction for T-L specimens and in the L direction for L-T specimens so that an appropriate value of the compressive yield stress, and hence σ_y, can be determined.

B.9 Validity of the data

The size criteria outlined in 6.4 are rigorous, and give validity criteria for the measured toughness values. It has been shown that this rigorous approach cannot be applied to injection-moulded discontinuous-fibre-reinforced composites. The size criteria can, however, be considered as quality criteria for these materials and informative (though non-rigorous) values of K_C and G_C can be obtained. In addition, when plotted against the smooth fraction of the fracture surface, these parameters can provide a powerful means of comparing materials.

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Tel. + 41 22 749 01 11
Fax + 41 22 734 10 79
E-mail copyright@iso.ch
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Foreword

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International Standard ISO 13586 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*.

Annex A forms a normative part of this of ISO 13586.

INTERNATIONAL STANDARD ISO 13586:2000(E)

Plastics — Determination of fracture toughness (G_{IC} et K_{IC}) — Linear elastic fracture mechanics (LEFM) approach

1 Scope

This International Standard specifies the principles for determining the fracture toughness of plastics in the crack-opening mode (mode I) under defined conditions. Two test methods with cracked specimens are defined, namely three-point-bending tests and compact-specimen tensile tests in order to suit different types of equipment available or different types of material.

The methods are suitable for use with the following range of materials:

— rigid and semi-rigid thermoplastic moulding, extrusion and casting materials;

— rigid and semi-rigid thermosetting moulding and casting materials.

Certain restrictions on the linearity of the load-displacement diagram, on the specimen width and on the thickness are imposed to ensure validity (see 6.4) since the scheme used assumes linear elastic behaviour of the cracked material and a state of plane strain at the crack tip. Finally, the crack must be sharp enough so that an even sharper crack will not result in significantly lower values of the measured properties.

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 291:1997, *Plastics — Standard atmospheres for conditioning and testing.*

ISO 527-1:1993, *Plastics — Determination of tensile properties — Part 1: General principles.*

ISO 604:1993, *Plastics — Determination of compressive properties.*

ISO 2818:1994, *Plastics — Preparation of test specimens by machining.*

ISO 5893:1993, *Rubber and plastics test equipment — Tensile, flexural and compression types (constant rate of traverse) — Description.*

3 Terms and definitions

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

3.1
energy release rate
G
the change in the external work δU_{ext} and strain energy δU_S of a deformed body due to enlargement of the cracked area δA

$$G = \frac{\delta U_{ext}}{\delta A} - \frac{\delta U_S}{\delta A} \quad (1)$$

It is expressed in joules per square metre, J/m^2.

3.2
critical energy release rate
G_{IC}
the value of the energy release rate G in a precracked specimen under plane-strain loading conditions, when the crack starts to grow

It is expressed in joules per square metre, J/m^2.

3.3
stress intensity factor
K
the limiting value of the product of the stress $\sigma(r)$ perpendicular to the crack area at a distance r from the crack tip and of the square root of $2\pi r$, for small values of r

$$K = \lim_{r \to 0} \sigma(r) \times \sqrt{2\pi r} \quad (2)$$

It is expressed in Pa·√m.

The term factor is used here because it is common usage, even though the value has dimensions.

3.4
critical stress intensity factor
K_{IC}
the value of the stress intensity factor when the crack under load actually starts to enlarge under a plane-strain loading condition around the crack tip

It is expressed in Pa·√m.

The critical stress intensity factor K_{IC} of a material is related to its critical energy release rate G_{IC} by the equation

$$G_{IC} = K_{IC}^2 / E \quad (3)$$

where E is the modulus of elasticity, determined under similar conditions of loading time (up to crack initiation) and temperature.

In the case of plane-strain conditions:

$$E = \frac{E_t}{1 - \mu^2} \quad (4)$$

where

E_t is the tensile modulus (see ISO 527-1);

μ is Poisson's ratio (see ISO 527-1-).

3.5
displacement
s_a
the displacement of the loading device, corrected as specified in 5.4

It is expressed in metres, m.

3.6
stiffness
S
the initial slope of the force-displacement diagram

$$S = \left(\frac{dF}{ds}\right)_{s \to 0}$$

It is expressed in newtons per metre, N/m.

3.7
force
F_Q
the applied load at the initiation of crack growth

It is expressed in newtons, N.

See also subclause 6.1.

3.8
energy
W_B
the input energy when crack growth initiates

It is expressed in joules, J.

W_B is based upon the corrected load-displacement curve.

3.9
crack length
a
the crack length up to the tip of the initial crack prepared as specified in 4.3.

It is expressed in metres, m.

For three-point-bending test specimens, the crack length is measured from the notched face. For compact tensile-test specimens, the crack length is measured from the load line, i.e. from the centres of the holes for the loading pins (see Figures 1 and 3).

The crack length a is normalized by the width w of the test specimen ($\alpha = a/w$).

3.10
energy calibration factor
ϕ

$$\phi(a/w) = -S\left(\frac{\mathrm{d}S}{\mathrm{d}\alpha}\right)^{-1} \quad (5)$$

where

S is the stiffness of the specimen;

$\alpha\,(= a/w)$ is the normalized crack length (see 3.9).

Values of $\phi\,(a/w)$ are given in annex A for both types of specimen.

3.11
geometry calibration factor
f

Values of $f\,(a/w)$ are given in annex A for both types of specimen.

3.12
characteristic length
$\bar{r}$
the size of the plastic deformation zone around the crack tip

It is required for checking fulfilment of the size criteria (see 6.4).

4 Test specimens

4.1 Shape and size

Test specimens for three-point-bending tests (also called single-edge-notch bending, SENB) and for compact tensile (CT) tests shall be prepared in accordance with Figures 1 and 3, respectively. It is usually convenient to make the thickness h of the test specimens equal to the thickness of a sheet sample and to make the test specimen width w equal to $2h$. The crack length a should preferably be in the range given by $0{,}45 \leqslant a/w \leqslant 0{,}55$.

4.2 Preparation

Test specimens shall be prepared in accordance with the relevant material International Standard for the material under test and with ISO 2818. In the case of anisotropic specimens, take care to indicate the reference direction on each test specimen.

4.3 Notching

Method a), b) or c) can be used for notching:

a) Machine a sharp notch into the test specimen and then generate a natural crack by tapping on a new razor blade placed in the notch (it is essential to practice this since, in brittle test specimens, a natural crack can be generated by this process, but some skill is required in avoiding too long a crack or local damage). The length of the crack thus created shall be more than four times the original notch tip radius.

b) If a natural crack cannot be generated, as in tough test specimens, then sharpen the notch by sliding a razor blade across the notch. Use a new razor blade for each test specimen. The length of the crack thus created shall be more than four times the original notch tip radius.

c) Cooling tough test specimens and then performing razor tapping is sometimes successful.

Pressing the blade into the notch is not recommended because of induced residual stresses.

4.4 Conditioning

Condition test specimens as specified in the International Standard for the material under test. In the absence of this information, select the most appropriate set of conditions from ISO 291, unless otherwise agreed upon by the interested parties.

5 Testing

5.1 Test machine

The machine shall satisfy the requirements of ISO 5893. The load indicator shall show the total load carried by the test specimen. This device shall be essentially free from inertia lag at the test speeds used. It shall indicate the load with an accuracy of at least 1 % of the actual value.

5.2 Displacement transducer

The displacement is recorded during the test. The transducer shall be essentially free from inertia lag at the test speeds used. It shall measure the displacement with an accuracy of 2 % of the relevant length or better. The effects of the transducer on the load measurements shall either be negligible (that is < 1 %) or they shall be corrected.

5.3 Loading rigs

A rig with moving rollers is used for three-point-bending (SENB) tests, as shown in Figure 2. Indentation into the test specimen is minimized by the use of rollers with a large diameter ($> w/2$). The measurement of the displacement shall be taken at the centre of the span L (see Figure 2).

For the compact tensile test, the test specimen is loaded by means of two pins in holes in the specimen. The displacement of the load points during the test is measured, for example by a clip gauge near the pins (see 5.2).

5.4 Displacement correction

The measured displacement s_a shall be corrected for the indentation of the loading pins, compression of the test specimen and the machine compliance in order to determine properly the stiffness S of the specimen and the work W_B at crack growth initiation. The calibration of the test system shall be performed as follows:

The load-displacement correction curve (see Figure 4) is generated by analogy with the fracture test but by using unnotched test specimens, as indicated in the Figures 5 and 6. The rollers of the three-point-bending rig are moved together to reduce even further the small flexing of the unnotched test specimen under load. The displacement correction shall be performed for each material and at each different temperature and test speed since polymers are generally sensitive to temperature and test speed. The degree of loading-pin penetration and specimen compression can vary with changes in these variables. The indentation tests shall be performed such that the loading times are the same as in the fracture tests. This will involve lower test speeds to reach the same load in the same time, for example about half the speed.

In practice, a linear correction curve is usually obtained up to loads even exceeding the fracture load of cracked test specimens (see Figure 4). Any initial non-linearity due to penetration of the loading pins into the specimen is observed during both the calibration test and the actual fracture test. Therefore, the initial non-linearity is effectively corrected for by the following proposed method:

At corresponding load, the displacement s_j taken from the correction curve is subtracted from the displacement s_a in the actual fracture test with a notched test specimen. In this way, the corrected load-displacement curve is constructed. The stiffness S and the work W_B at crack growth initiation are derived from this curve (see Figure 7). The corrections s_j of the displacements usually amount to less than 20 % of the measured displacement s_a.

5.5 Test atmosphere

Conduct the test in the same atmosphere as used for conditioning, unless otherwise agreed upon by the interested parties, for example for testing at elevated or low temperatures.

5.6 Thickness, width and crack length of test specimens

Measure the thickness h and width w of each test specimen to the nearest 0,02 mm. Record an approximate reading of the crack length a which will be corrected on completion of the test. Usually crack tip lines are visible on the two fracture surfaces. Calculate the mean value of five readings of the crack length taken along the original crack front. These shall be taken at the edges, the centre and half way between. The crack length shall differ by no more than 10 % over the entire crack front. If differences larger than 10 % are found, reject the test. Care shall be taken that it is the original crack tip which is being observed since slow growth can occur.

5.7 Test conditions

It is recommended that 23 °C and a test speed of 10 mm/min be used as the basic test conditions. In all cases, the loading time and the test temperature shall be measured. Speeds greater than 0,1 m/s and loading times less than 10 ms should preferably be avoided since dynamic effects may cause errors.

Carry out at least three tests for each set of conditions. If it is not possible to obtain valid results at 23 °C (see 6.4), it is often possible to do so by decreasing the temperature. Usually, a reduction in the test temperature does not change K_{IC} greatly but increases the yield stress of the polymer, rendering the fractures more brittle. If this procedure is used, both temperature and loading time shall be stated in the test report.

6 Expression of results

6.1 Determination of F_Q

In an ideal material, the load-displacement curve is a linear one with an abrupt drop in the load at the instant of crack growth initiation. In such rather rare cases, F_Q can be identified with the maximum load.

In most cases, there is some non-linearity in the curve and this can be due to plastic deformation at the crack tip, non-linear elasticity, general visco-elasticity or stable crack growth after initiation but prior to instability. The first three effects violate the LEFM assumption and the fourth one means that the true initiation load is not defined by the maximum. In order to circumvent a doubtful definition of initiation, an arbitrary rule is used here. The zero-point tangent is drawn to the curve in Figure 7 to determine the initial stiffness S. This stiffness is reduced by 5 % and a further line is drawn accordingly. If the maximum of the load-displacement curve falls within these two lines, then F_{max} shall be called F_Q (the load at crack growth initiation). If the second line intersects the load curve at F_5 prior to the maximum, then F_5 shall be called F_Q. Referring to Figure 7, the conditions of LEFM are assumed to be met if

$$\frac{F_{max}}{F_5} < 1{,}1$$

If this condition of 10 % non-linearity is violated, the test shall be rejected.

6.2 Provisional result G_Q

Calculate the critical energy release rate from the energy W_B up to the instant of crack growth initiation, where the load is F_Q and the original crack length is a:

$$G_Q = \frac{W_B}{h \times w \times \phi(a/w)} \tag{6}$$

where

W_B is the energy to break;

h is the test specimen thickness;

w is the test specimen width;

$\phi(a/w)$ is the energy calibration factor, depending on the crack length a.

Calculate ϕ as shown in annex A. Tables with values of $\phi(a/w)$ for both types of test specimen are also given in annex A.

6.3 Provisional result K_Q

Calculate the critical stress intensity factor K_Q from the load F_Q at crack growth initiation and the original crack length a:

$$K_Q = f(a/w)\frac{F_Q}{h\sqrt{w}} \tag{7}$$

where

F_Q is the load at crack growth initiation;

h is the test specimen thickness;

w is the test specimen width;

$f(a/w)$ is the geometry calibration factor, depending on the crack length a.

Calculate f as shown in annex A. Tables with values of $f(a/w)$ for both types of test specimen are also given in annex A.

6.4 Size criteria and validation of results

The test is valid only if the dimensions of the test specimen are significantly larger than the plastic zone around the crack tip, characterized by the length $\bar{r}$. Appropriate test specimens for plane-strain fracture tests shall meet the following size criteria:

thickness h	$> 2{,}5 \times \bar{r}$
crack length a	$> 2{,}5 \times \bar{r}$
ligament width $(w - a)$	$> 2{,}5 \times \bar{r}$

With the specimen dimensions proposed in this International Standard, all the criteria are usually satisfied simultaneously. The criteria cover two limitations in that h must be sufficient to ensure plane strain but $(w - a)$ has to be sufficient to avoid excessive plasticity in the ligament. If $(w - a)$ is too small, the test will usually violate the

linearity criterion, but will not necessarily do so. If the linearity criterion is violated, a possible option is to increase w for the same h. Values of w/h of up to 4 are permitted.

Calculate the characteristic length $\bar{r}$ from either of the two provisional results G_Q or K_Q:

$$\bar{r} = \frac{2f^2 \phi S G_Q}{h\sigma_y^2} \tag{8}$$

or

$$\bar{r} = \frac{K_Q^2}{\sigma_y^2} \tag{9}$$

where

h is the test specimen thickness;

f is the geometry calibration factor;

ϕ is the energy calibration factor;

S is the test specimen stiffness, derived from the corrected curve (see 5.4);

σ_y is the uniaxial tensile yield stress (determined in accordance with ISO 527-1) or, alternatively, 0,7 times the compressive yield stress (determined in accordance with ISO 604).

If the criteria are met, the results of the test are valid, and thus

$G_Q = G_{IC}$ and $K_Q = K_{IC}$

6.5 Cross-check of results

A cross-check on the accuracy of the results can be made since the modulus of elasticity E is related to the stiffness S and to the mechanical fracture properties G_{IC} and K_{IC} as follows:

$$E_{stiff} = \frac{2f^2 \phi S}{h} \tag{10}$$

$$E_{fract} = \frac{K_{IC}^2}{G_{IC}} \tag{11}$$

where

E is the modulus of elasticity (see 3.4);

f is the geometry calibration factor (see annex A);

ϕ is the energy calibration factor (see annex A);

h is the test specimen thickness;

S is the test specimen stiffness;

K_{IC} is the critical stress intensity factor;

G_{IC} is the critical energy release rate.

Usually, E_{stiff} is slightly larger than E_{fract}. If the difference exceeds 15 %, the results obtained for G_{IC} and K_{IC} shall be examined for possible errors.

7 Precision

Table 1 gives a set of data obtained by nine groups on a nylon. Most of the data was obtained in SENB testing, and two forms of notching were used: razor sliding and razor tapping. The means of five tests are given together with the standard deviations. The average standard deviations are 5 % for K_{IC} and 12 % for G_{IC}.

Table 1 — K_{IC} and G_{IC} measurements on a nylon

Group No.	Specimen type	Notching	K_{IC} (mean) MPa·√m	G_{IC} (mean) kJ/m²	E_{stiff}	E_{fract}
1	SENB	RS	4,14 ± 0,17	4,76 ± 0,98	3,65	3,65
		RT	4,03 ± 0,10	3,92 ± 0,15	4,14	4,14
2	SENB	RT	3,79 ± 0,08	4,01 ± 0,17	2,24 [a]	3,58
3	SENB	RS	3,84 ± 0,17	4,48 ± 0,70	3,32	3,33
		RT	4,21 ± 0,26	4,82 ± 0,73	3,64	3,71
4	SENB	RT	4,10 ± 0,35	5,14 ± 0,67	3,30	3,28
5	SENB	RS	3,82 ± 0,21	4,20 ± 0,41	3,63	3,32
6	CT	RT	4,46 ± 0,13	5,82 ± 0,24	3,57	3,42
7	SENB	RT	3,99 ± 0,10	4,80 ± 0,46	—	3,32
8	SENB	RT	3,9 ± 0,3	4,7 ± 0,8	3,22	3,21
9	SENB	RT	4,10 ± 0,22	6,40 ± 0,8 [b]	—	2,63 [b]
		Mean	4,03 ± 0,19	4,82 ± 0,56		

[a] Error suspected
[b] Without indentation correction
RS Razor sliding
RT Razor tapping

8 Test report

The test report shall contain the following:

a) a reference to this International Standard;

b) all details necessary for complete identification of the material tested, including source and history;

c) the test specimen shape (SENB or CT) and dimensions;

d) the notching method used;

e) the test temperature and speed;

f) one example of a load-displacement curve;

g) the number of specimens tested;

h) the ratio F_{max}/F_5, if relevant (see 6.1), and the loading time;

i) the yield stress determination procedure used and the loading time;

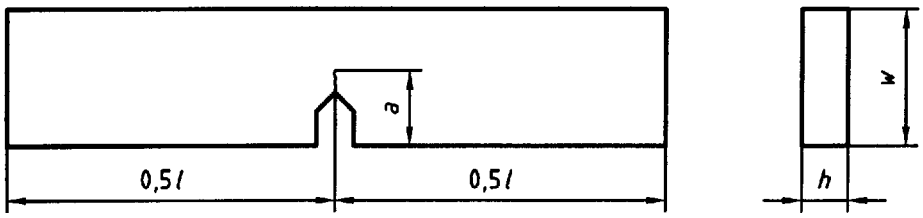
j) the results of the size criteria assessment;

k) the critical energy release rate G_{IC} and critical stress intensity factor K_{IC};

l) the values of E_{stiff} and E_{fract};

m) any deviations from the requirements of this International Standard;

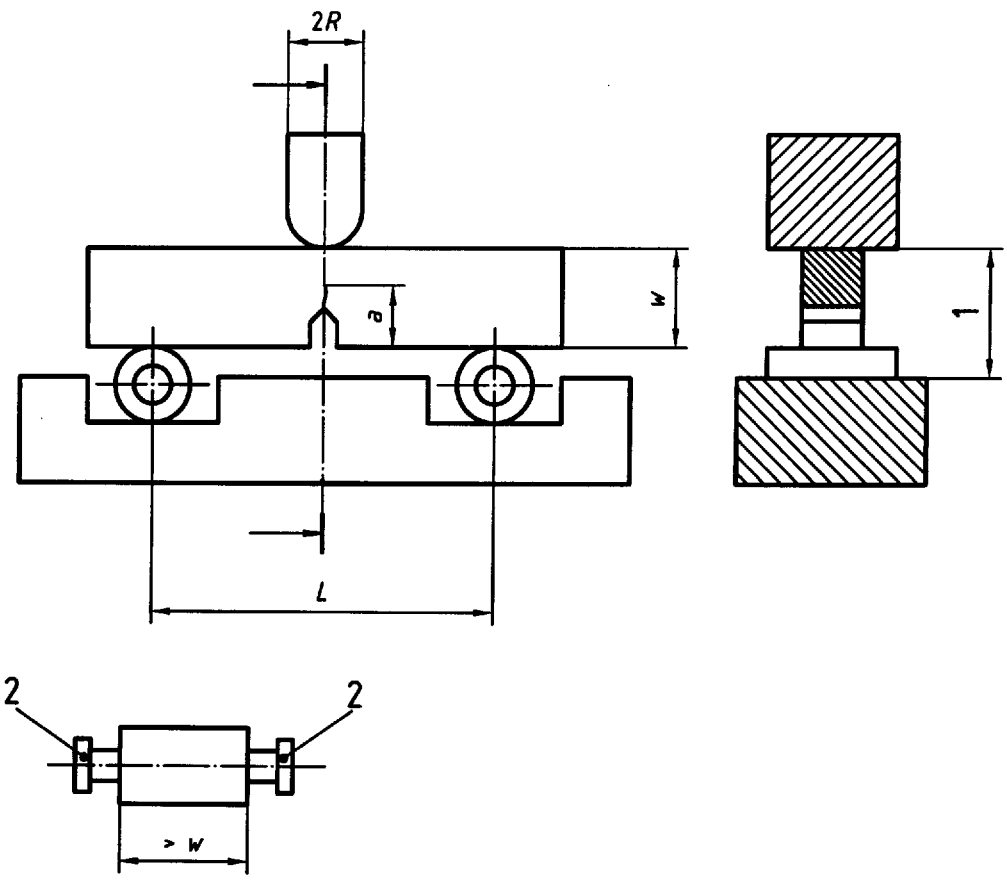
n) the date of testing.



Key

w	Width	
l	Overall length	$l > 4{,}2w$
h	Thickness	$w/4 < h < w/2$
a	Crack length	$0{,}45w \leqslant a \leqslant 0{,}55w$

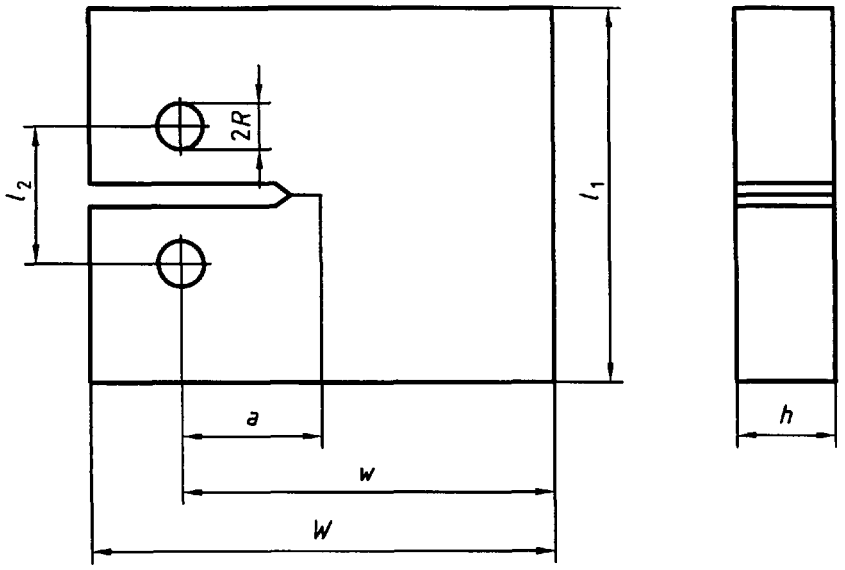
Figure 1 — Three-point-bending (SENB) test specimen as specified in 4.1



Key

L	Span between rollers	$L = 4w \pm 0{,}1w$	1	Distance monitored by displacement transducer
R	Radius	$w/8 < R < w/2$	2	Bosses for rubber bands
h	Thickness			

Figure 2 — Rig as specified in 5.3 with two rollers and displacement transducer for three-point-bending (SENB) tests



Key

w	Width	
W	Overall width	$W = 1{,}25w \pm 0{,}01w$
l_1	Length	$l_1 = 1{,}2w \pm 0{,}01w$
l_2	Distance between centres of two holes located symmetrically to the crack plane ± 0,005w	$l_2 = 0{,}55w \pm 0{,}000\ 5w$
R	Radius	$R = 0{,}125w \pm 0{,}005w$
h	Thickness	$0{,}4w < h < 0{,}6w$
a	Crack length	$0{,}45w \leqslant a \leqslant 0{,}55w$

(The loading pins and holes shall be smooth and a loose fit to minimize friction.)

Figure 3 — Compact tensile (CT) test specimen as specified in 4.1

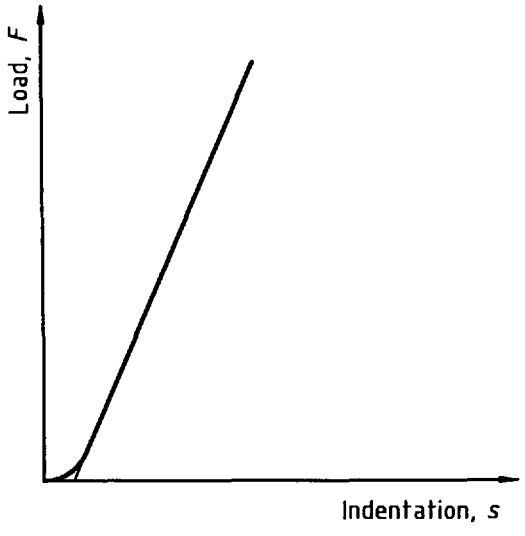


Figure 4 — Load-indentation curve determined on an unnotched test specimen (see 5.4)

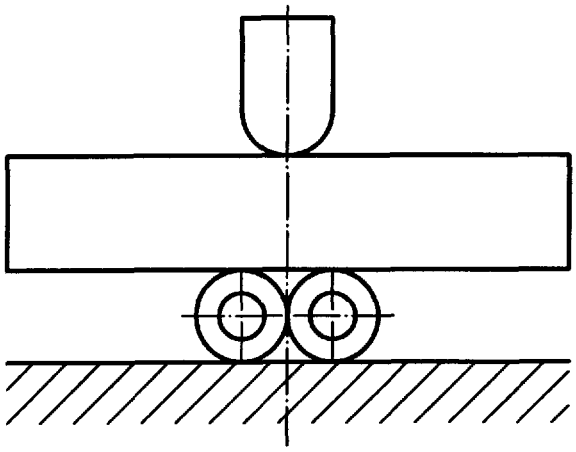


Figure 5 — Arrangement for determining the indentation displacement of a bending-test specimen (see 5.4)

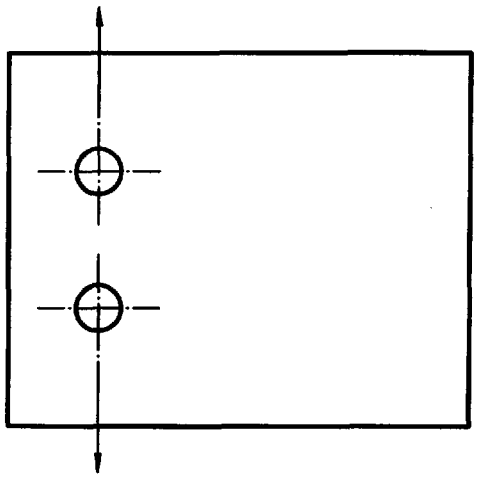
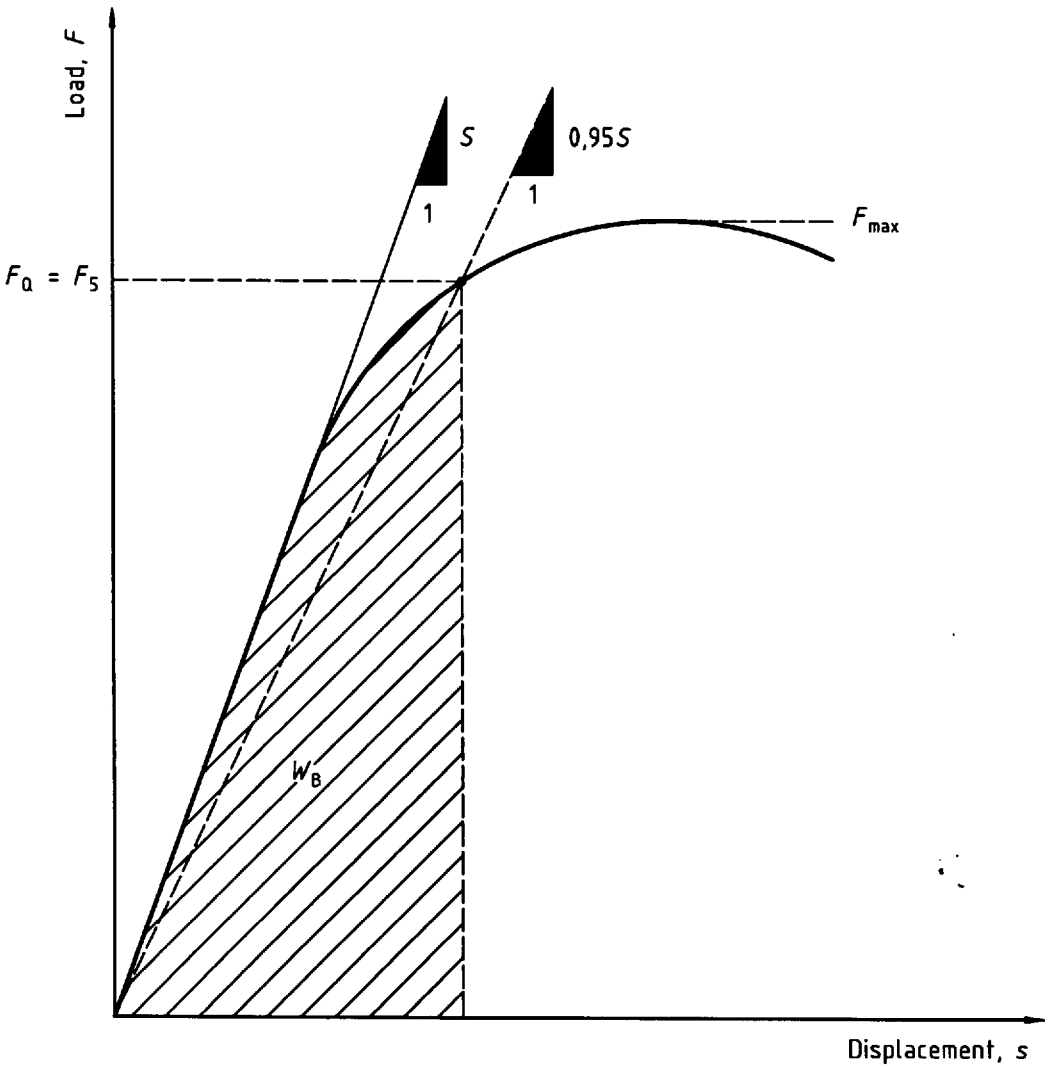


Figure 6 — Arrangement for determining the indentation displacement of a compact tensile specimen (see 5.4)



F_Q is the load at crack growth initiation;
W_B is the energy to break.

Figure 7 — Load-displacement curve for a notched test specimen
(The displacement has been corrected for indentation effects — see 5.4)

Annex A
(normative)

Calibration factors

Table A.1 — Calibration factors f and ϕ for single-edge-notch bending (SENB) test specimens: $L/w = 4$
(values calculated using reference [6])

L is the span
$\alpha = a/w$
where
a is the crack length
w is the width

Interpolation is recommended.

α	f	ϕ
0,05	2,50	1,502
0,10	3,39	0,857
0,15	4,07	0,641
0,20	4,70	0,526
0,25	5,36	0,449
0,30	6,09	0,391
0,35	6,93	0,345
0,40	7,93	0,307
0,45	9,14	0,275
0,50	10,65	0,246
0,55	12,57	0,220
0,60	15,09	0,195
0,65	18,51	0,170
0,70	23,40	0,145
0,75	30,84	0,120
0,80	43,21	0,096
0,85	66,76	0,072
0,90	123,30	0,049
0,95	351,62	0,025

Equations used for the calculation (SENB): $0 < \alpha < 1$

$$f = 6\alpha^{1/2}\frac{1{,}99 - \alpha(1-\alpha)\left(2{,}15 - 3{,}93\alpha + 2{,}7\alpha^2\right)}{(1+2\alpha)(1-\alpha)^{3/2}}$$

$$\phi = \frac{A + 18{,}64}{\mathrm{d}A/\mathrm{d}\alpha}$$

$$A = \frac{16\alpha^2}{(1-\alpha)^2}\left(8{,}9 - 33{,}717\alpha + 79{,}616\alpha^2 - 112{,}952\alpha^3 + 84{,}815\alpha^4 - 25{,}672\alpha^5\right)$$

$$\frac{\mathrm{d}A}{\mathrm{d}\alpha} = \frac{16\alpha^2}{(1-\alpha)^2}\left(-33{,}717 + 159{,}232\alpha - 338{,}856\alpha^2 + 339{,}26\alpha^3 - 128{,}36\alpha^4\right) +$$

$$+ 16\frac{\left[2\alpha(1-\alpha) + 2\alpha^2\right]}{(1-\alpha)^3}\left(8{,}9 - 33{,}717\alpha + 79{,}616\alpha^2 - 112{,}952\alpha^3 + 84{,}815\alpha^4 - 25{,}672\alpha^5\right)$$

Table A.2 — Calibration factors f and ϕ for compact tensile (CT) test specimens
(values calculated using reference [7])

$\alpha = a/w$
where
a is the crack length
w is the width

Interpolation is recommended.

α	f	ϕ
0,25	4,92	0,199
0,30	5,62	0,208
0,35	6,39	0,213
0,40	7,28	0,213
0,45	8,34	0,208
0,50	9,66	0,199
0,55	11,36	0,186
0,60	13,65	0,170
0,65	16,86	0,152
0,70	21,55	0,133
0,75	28,86	0,112

Equations used for the calculation (CT): $0,2 < \alpha < 0,8$

$$f = \frac{(2+\alpha)}{(1-\alpha)^{3/2}}\left(0,886 + 4,64\alpha - 13,32\alpha^2 + 14,72\alpha^3 - 5,6\alpha^4\right)$$

$$\phi = \frac{A(1-\alpha)}{B+2A}$$

$$A = \left(1,9118 + 19,118\alpha - 2,5122\alpha^2 - 23,226\alpha^3 + 20,54\alpha^4\right)$$

$$B = \left(19,118 - 5,0244\alpha - 69,678\alpha^2 + 82,16\alpha^3\right)(1-\alpha)$$

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