BS 7448-4:1997

Incorporating
Corrigendum No. 1

Fracture mechanics toughness tests —

Part 4: Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials

ICS 77.040.10

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee ISE/NFE/4, Mechanical testing of metals, upon which the following bodies were represented:

British Non-ferrous Metals Federation
British Railways Board
Copper Development Association
Electricity Association
ERA Technology Ltd.
GAMBICA (BEAMA Ltd.)
Institute of Materials
Ministry of Defence
National Physical Laboratory
Society of British Aerospace Companies Limited
The Welding Institute
UK Steel Association
United Kingdom Accreditation Service
University College London
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The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

BEAMA Ltd.
Castings Development Centre
Lloyds Register of Shipping

This British Standard, having been prepared under the direction of the Engineering Sector Board, was published under the authority of the Standards Board and comes into effect on 15 December 1997

Amendments issued since publication

Amd. No.	Date	Comments
12017 Corrigendum No. 1	July 2001	Corrections to Figure 9 and **9.3.1**.

The following BSI references relate to the work on this standard:
Committee reference ISE/NFE/4
Draft for comment 93/301852 DC

ISBN 0 580 28630 4

Contents

Foreword

This Part of BS 7448 has been prepared by Technical Committee ISE/NFE/4.

It gives a method for the determination of fracture resistance curves and initiation values for stable crack extension in metallic materials.

BS 7448 is being published in four Parts.

Part 1 describes a method for determining K_{Ic}, critical crack tip opening displacement (CTOD) and critical J values of fracture toughness for metallic materials under displacement controlled monotonic loading at quasistatic rates.

Part 2 describes a method for determining the fracture toughness of weldments in metallic materials.

A further Part of BS 7448 is in preparation as follows.

Part 3 describes a method for determining dynamic fracture toughness.

It has been assumed in the drafting of this standard that the execution of its provisions is entrusted to appropriately qualified and experienced people.

CAUTION. It is important to note that tests of the type described involve the use of large forces, and may involve the rapid movement of machine parts and fractured test specimens. Therefore it is important to consider the safety of machine operators.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 46, an inside back cover and a back cover.

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1 Scope

This Part of BS 7448 gives a method for determining the resistance to stable crack extension of metallic materials. The method uses fatigue precracked specimens. These are tested in displacement controlled loading at a constant rate of increase in stress intensity factor within the range 0.5 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ to 3.0 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ [1] during the initial elastic deformation. Resistance to crack extension is characterized in terms of the variation in crack tip opening displacement (CTOD) and/or J with stable crack extension. These characterizations are referred to in this standard as δ and J R-curves, respectively.

The method is only suitable for tests on specimens that exhibit stable crack extension. If unstable fracture or crack arrest occurs in any of the tests in an R-curve determination it is necessary also to assess the test results in accordance with BS 7448-1.

Testing requirements and analysis procedures are given which enable crack extension resistance curves to be calculated from both straight notch and stepped notch compact specimens and single edge notch bend specimens. Individual fracture parameters are also defined for CTOD and J at a point where stable crack extension is close to the onset of initiation.

The definition of fracture toughness values relevant to particular structural integrity assessments is outside the scope of this British Standard.

NOTE Publications of relevance to the subject matter covered by this Part of BS 7448 are listed in the bibliography in Annex A. A system of crack plane identification is given in Annex B.

2 References

2.1 Normative references

This Part of BS 7448 incorporates, by dated or undated reference, provisions from other publications. These normative references are made at the appropriate places in the text and the cited publications are listed on the inside back cover. For dated references, only the edition cited applies; any subsequent amendments to or revisions of the cited publication apply to this Part of BS 7448 only when incorporated in the reference by amendment or revision. For undated references, the latest edition of the cited publication applies, together with any amendments.

2.2 Informative references

This Part of BS 7448 refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

3 Definitions

For the purposes of this Part of BS 7448 the following definitions apply.

3.1

stress intensity factor (K)

the magnitude of the elastic stress field singularity for a homogeneous, linear-elastic body

NOTE It is a function of applied force, crack length and specimen geometry, and is expressed in units of $\text{MPa}\cdot\text{m}^{0.5}$.

3.2

crack tip opening displacement (CTOD)

the relative displacement of the surfaces of a crack normal to the original (undeformed) crack plane at the tip of the fatigue precrack, expressed in millimetres

3.3

***J*-integral**

a line or surface integral that encloses the crack front from one crack surface to the other, which characterizes the local stress-strain field at the crack tip, expressed in MJ/m^2 [2]

3.4

J

an experimental equivalent of the J-integral as determined by the method given in the present standard

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[1] $0.0316\ \text{MPa}\cdot\text{m}^{0.5} = 1\ \text{N}\cdot\text{mm}^{-1.5} = 0.0316\ \text{MN}\cdot\text{m}^{-1.5}$.

[2] $1\ \text{MJ/m}^2 = 1\ \text{MN/m}$.

3.5

unstable crack extension

an abrupt crack extension which occurs with or without prior stable crack extension

3.6

pop-in

an abrupt discontinuity in the force versus displacement record, featured as a sudden increase in displacement and, generally, a decrease in force

NOTE Subsequently displacement and force generally increase to above their values at pop-in.

3.7

stable crack extension

crack extension which, in displacement control, stops when the applied displacement is held constant

3.8

stretch zone width (SZW)

the length of crack extension that occurs during crack tip blunting; that is, prior to the onset of slow stable crack extension, and which occurs in the same plane as the fatigue precrack

4 Symbols and designations

For the purposes of this Part of BS 7448 the following symbols and designations apply.

a	nominal crack length (see Figure 2 to Figure 5) or, for the purposes of fatigue precracking (see **7.4.4** and **7.4.5**), an assumed value $\leq a_o$, in millimetres
a_o	measured original crack length (see **9.9.2**), in millimetres
B	thickness of test specimen, in millimetres
B_{min}	minimum test specimen net thickness, in millimetres
B_N	test specimen net thickness between sidegroove tips, in millimetres
C	specimen elastic compliance, in millimetres per kilonewton
E	Young's modulus of elasticity at the temperature of interest, in gigapascals
F	applied force, in kilonewtons
F_L	collapse force, calculated using R_m, in kilonewtons
F_f	maximum fatigue precracking force during the final stages of fatigue crack extension (see **7.4.4** and **7.4.5**), in kilonewtons
J	experimental equivalent of the J-integral, in megajoules per square metre
J_o	resistance to crack extension expressed in terms of J, not allowing for stable crack extension, in megajoules per square metre
J_{corr}	resistance to crack extension expressed in terms of J, corrected for stable crack extension, in megajoules per square metre
$J_{0.2BL}$	resistance to crack extension expressed in terms of J, at 0.2 mm crack extension offset to the blunting line, in megajoules per square metre
$J_{0.2}$	resistance to crack extension expressed in terms of J, at 0.2 mm crack extension including blunting, in megajoules per square metre
J_{max}	resistance to crack extension expressed in terms of J, at the limit for J controlled crack extension, in megajoules per square metre
K	stress intensity factor, in $MPa \cdot m^{0.5}$
$\dot{K}$	rate of change of K with time, in $MPa \cdot m^{0.5} s^{-1}$
q	displacement of bend specimen or stepped notch compact specimen along the load-line, in millimetres
S	span between outer loading points in a three point bend test, in millimetres
T	test temperature, in degrees celsius
U_p	plastic component of area under plot of force (F) versus specimen displacement along the load-line (see Figure 16), in joules

V	notch opening displacement at or near to notch mouth, in millimetres
V_e	elastic component of V, in millimetres
V_p	plastic component of V, in millimetres
W	width of test specimen, in millimetres
W_t	total width of compact specimen, in millimetres
z	for bend and straight notch compact specimens, distance of the notch opening gauge location above the surface of the specimen [see Figure 6 b)], or, in the case of a stepped notch compact specimen the distance of the notch opening gauge location above the load line, in millimetres
δ	crack tip opening displacement (CTOD)
δ_o	resistance to crack extension expressed in terms of CTOD, not allowing for stable crack extension, in millimetres
δ_{corr}	resistance to crack extension expressed in terms of CTOD corrected for stable crack extension, in millimetres
$\delta_{0.2}$	resistance to crack extension expressed in terms of CTOD at 0.2 mm crack extension including blunting, in millimetres
$\delta_{0.2BL}$	resistance to crack extension expressed in terms of CTOD at 0.2 mm crack extension offset to the blunting line, in millimetres
δ_{max}	CTOD limit for CTOD controlled crack extension, in millimetres
Δa	stable crack extension, including SZW (see **9.9.3**), in millimetres
Δa_{max}	crack extension limit for CTOD/J controlled crack extension, in millimetres
v	Poisson's ratio
η_p	J calibration function
R_{mB}	tensile strength at the temperature of fatigue precracking, in megapascals
R_m	tensile strength at the temperature of the fracture test[3], in megapascals
$R_{p0.2B}$	0.2 % proof strength at the temperature of fatigue precracking, in megapascals
$R_{p0.2}$	0.2 % proof strength at the temperature of the fracture test[3] in megapascals

5 Principle

A fatigue crack is extended in a single edge notched bend or compact specimen by applying an alternating force within controlled limits. The specimen is then subjected to an increasing force.

One of two techniques is used to determine crack extension: the multiple specimen method or the single specimen method. The multiple specimen method is regarded as the definitive approach.

In the multiple specimen method a minimum of six nominally identical specimens are monotonically loaded to different displacements.

NOTE If a multiple specimen R-curve is required in terms of both δ and J fracture toughness parameters, it may be necessary to test more than six specimens in order to satisfy the various spacing requirements (see **12.3**).

Measurements are made of forces and displacements up to the point of termination of the test. The specimen crack fronts are marked after testing thus enabling measurement of stable crack extension after the specimens have been broken open.

Alternatively, a single specimen method based on, for example, the unloading compliance or potential drop technique is used (see clause **10**).

The tests are then analysed to obtain resistance to crack extension curves (R-curves) i.e. a plot of fracture resistance, in terms of δ or J, against stable crack extension Δa. These can then be further analysed to obtain estimates of fracture toughness at the initiation of stable crack extension.

This procedure is summarized in a flow chart in Figure 1.

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[3] At present no British Standard exists for the measurement of tensile properties below ambient temperature. In these cases the values to be used are subject to agreement between interested parties.

6 Test specimens

6.1 General

6.1.1 Each specimen shall be of one of the following designs (see **6.3**):

a) rectangular cross-section single edge notch three point bend (see Figure 2);

b) straight notch compact (see Figure 3);

c) stepped notch compact (see Figure 4).

NOTE Specimens having W/B ratios greater than 2 will have an increased tendency to buckle.

6.1.2 The notch profile shall be such that it is within the envelope shown in Figure 5. In order to expedite fatigue precracking the machined notches in the test specimens are normally produced by milling, sawing or disc grinding.

When a milled notch is used the notch root radius shall be not greater than 0.10 mm. When a sawn, disc ground or spark eroded notch is used, the notch tip shall have a width not greater than 0.15 mm.

Because it is generally impractical to machine 0.15 mm wide notches to depths greater than 2.5 mm, it is allowable to machine a stepped width notch.

The plane of the notch shall be perpendicular to the specimen surfaces to within ± 2°.

When required, knife edges shall either be machined into the specimen or be attached separately as shown in Figure 6 and Figure 7. The dimension $2x$ shall be within the working range of the notch opening displacement gauge. The knife edges shall be square with the specimen surfaces and parallel to within 0.5°. For all types of knife edge, the notch opening displacement gauge shall be free to rotate about the points of contact between the gauge and knife edge.

NOTE For this reason, when inward pointing knife edges or razor blades are used, it may be necessary to use an enlarged notch mouth, as shown in Figure 5 and Figure 7 (see **8.3**).

6.2 Sidegrooving

For a multi-specimen test method, sidegrooving (see Figure 8) is optional in the case of specimens with a thickness equal to the structural thickness under consideration and which are of the correct orientation to test the crack plane under consideration. For all other specimens and test methods, the specimens shall be sidegrooved.

NOTE 1 Fatigue precracking after sidegrooving (see **7.4**) can result in an uneven fatigue crack front.

NOTE 2 Sidegrooving is required to promote uniform crack extension along the crack front and can result in lower, hence more conservative, R-curves than if plane sided specimens of the same nominal dimensions are used.

If a specimen is sidegrooved, both sides of the specimen shall have sidegrooves which are equal in depth and which have an included angle, α, of 30° to 90° with a root radius of 0.4 mm ± 0.2 mm. The total depth of sidegrooving, $B - B_N$, shall be equal to $0.20B$ ($0.10B$ each side) where B_N is the net section thickness.

NOTE It is recommended that sidegrooves with an included angle of 90° are used for austenitic specimens. This is because of the large compressive strains that occur at the back face of such specimens which can result in partial or complete closure of the sidegrooves at the back face.

6.3 Choice of specimen design

The choice of specimen design shall take into consideration any preference for δ or J R-curve testing and the crack orientation to be used in the test (see **7.2**).

NOTE All three designs (see Figure 2 to Figure 4) are suitable for the determination of δ R-curves. Determination of J R-curves requires the measurement of load-line displacement (q). The stepped notch compact specimen (see Figure 4) allows direct measurement of load-line displacement (q). Methods for measuring load-line displacement directly and indirectly are outlined in Annex C for the bend specimen (see Figure 2). Straight notch compact specimens require the establishment of a relationship between load-line and notch opening displacement (see Annex C).

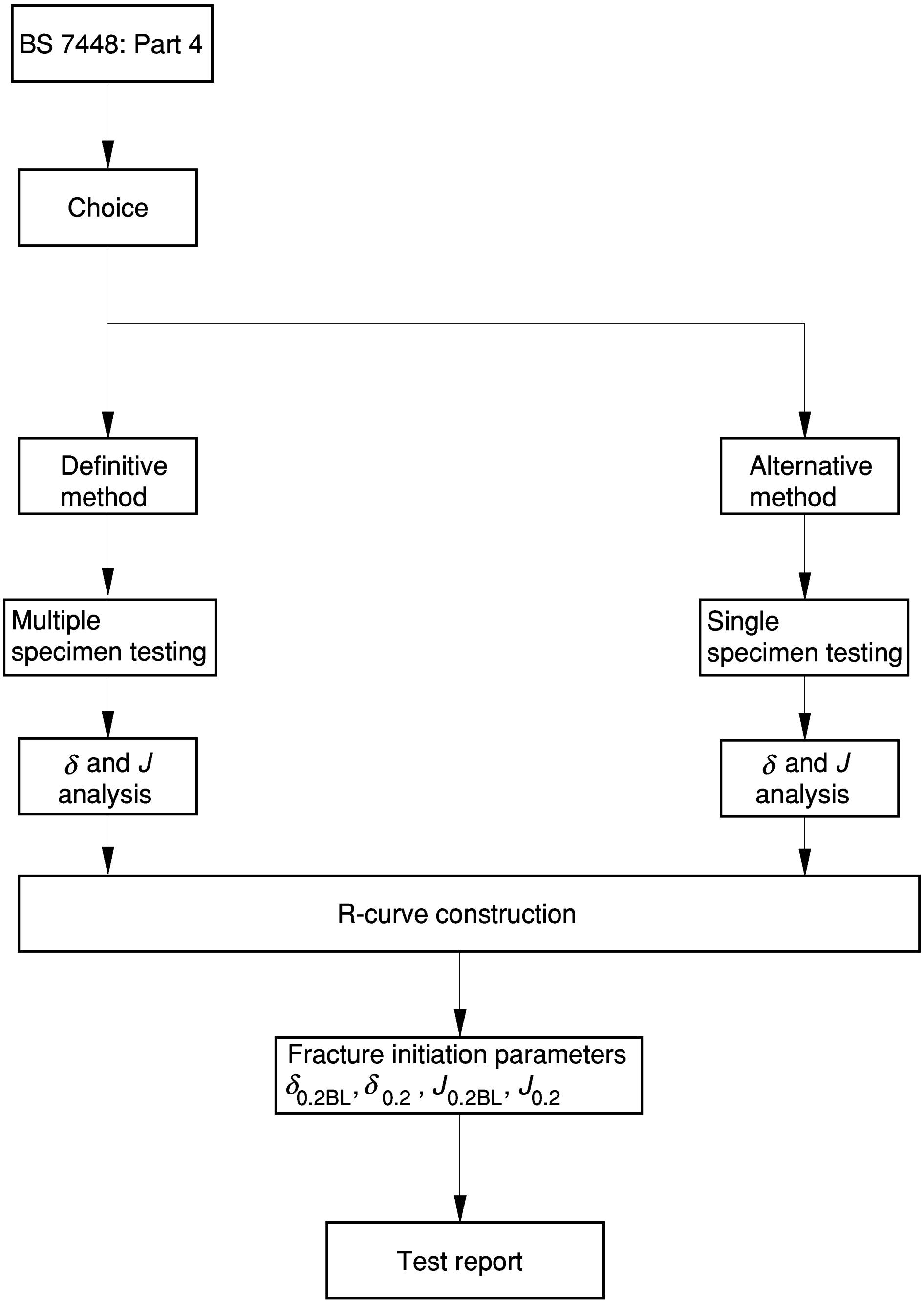
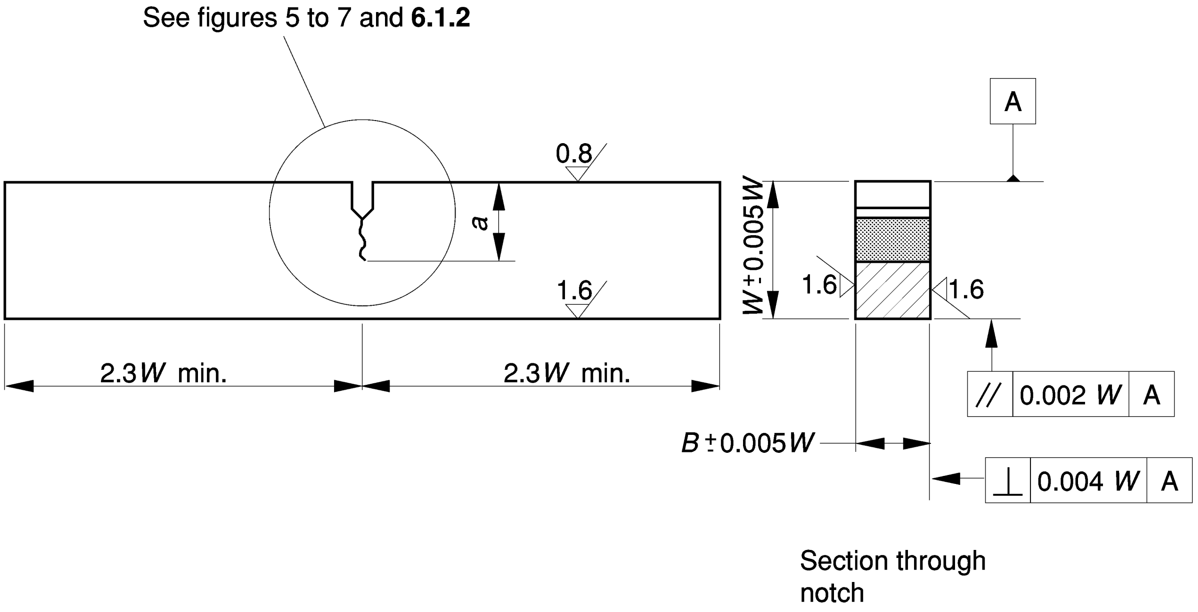


Figure 1 — Flow chart for the test method



NOTE 1 The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within $0.005W$.

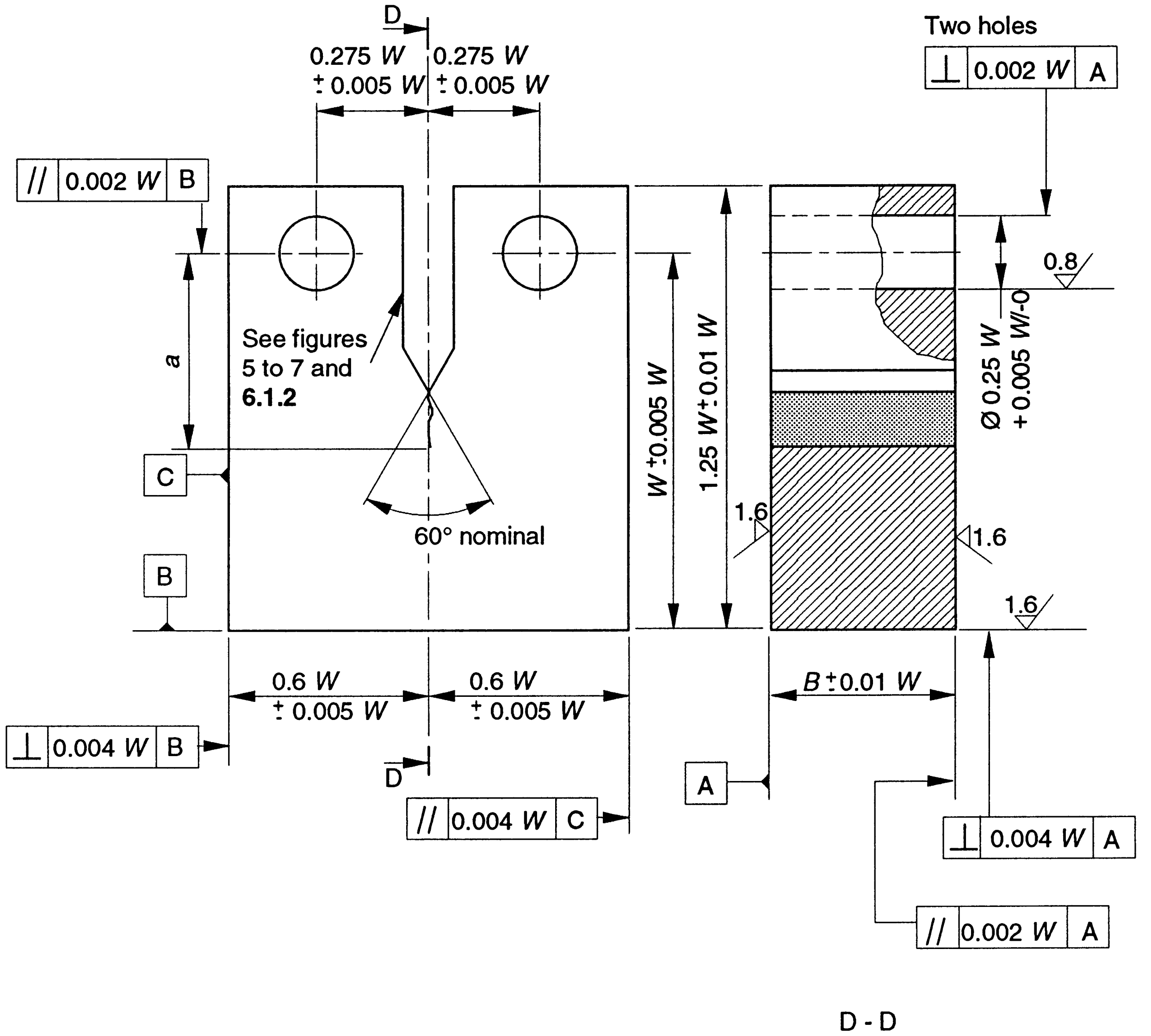
NOTE 2 Integral or attachable knife edges for clip gauge attachment may be used (see Figure 6 and Figure 7).

NOTE 3 For starter notch and fatigue crack configurations see Figure 5.

NOTE 4 $1.0 \le W/B \le 4.0$ ($W/B = 2$ preferred).

NOTE 5 $0.45 \le a/W \le 0.70$.

Figure 2 — Proportional dimensions and tolerances for a single edge notch bend specimen



NOTE 1 The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within $0.005W$.

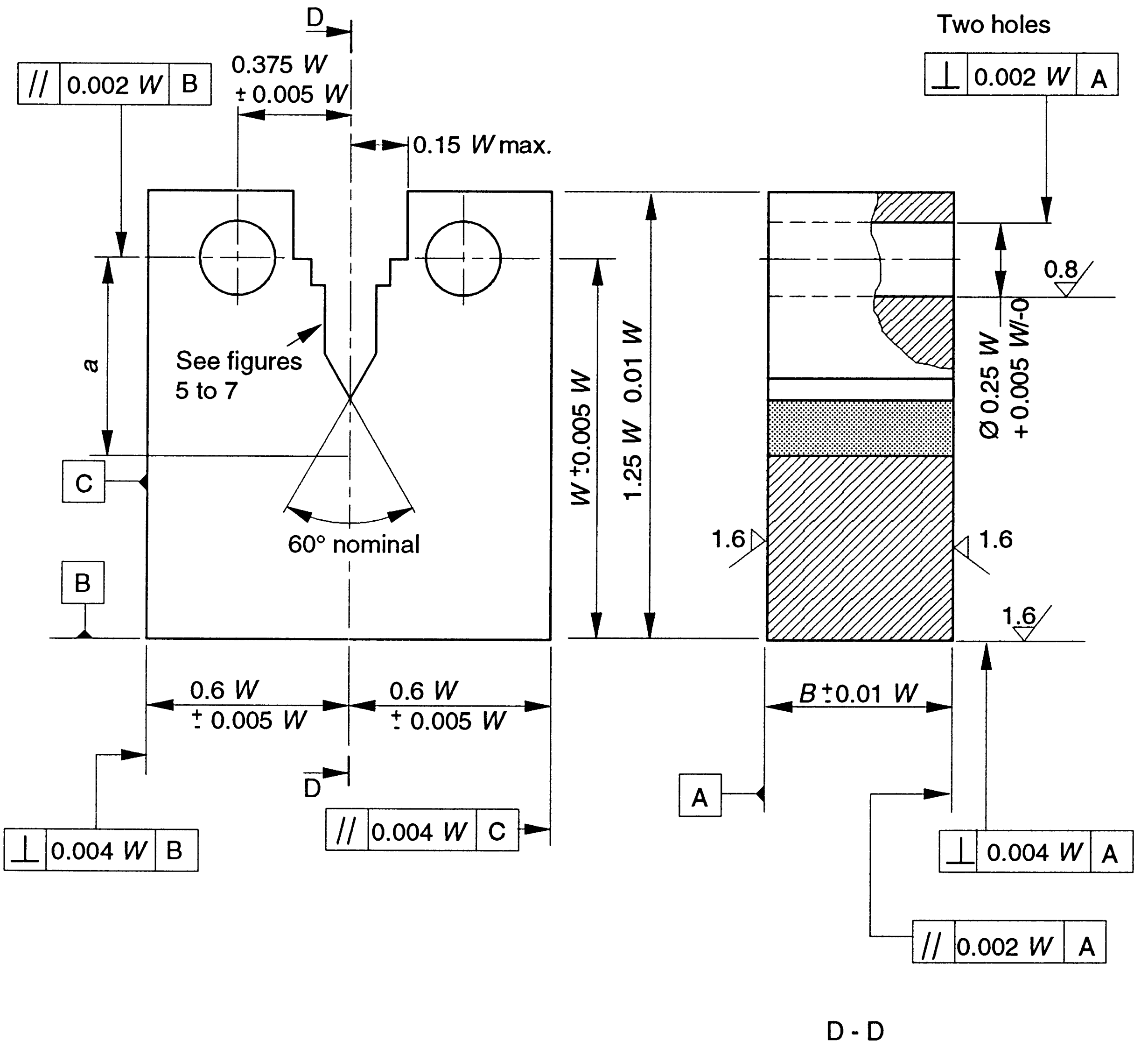
NOTE 2 Integral or attachable knife edges for clip gauge attachment may be used (see Figure 6 and Figure 7).

NOTE 3 For starter notch and fatigue crack configurations see Figure 5.

NOTE 4 $0.8 \leq W/B \leq 4.0$ ($W/B = 2$ preferred).

NOTE 5 $0.45 \leq a/W \leq 0.70$.

Figure 3 — Proportional dimensions and tolerances for a straight notch compact specimen



NOTE 1 The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within $0.005W$.

NOTE 2 Integral or attachable knife edges for clip gauge attachment may be used (see Figure 6 and Figure 7).

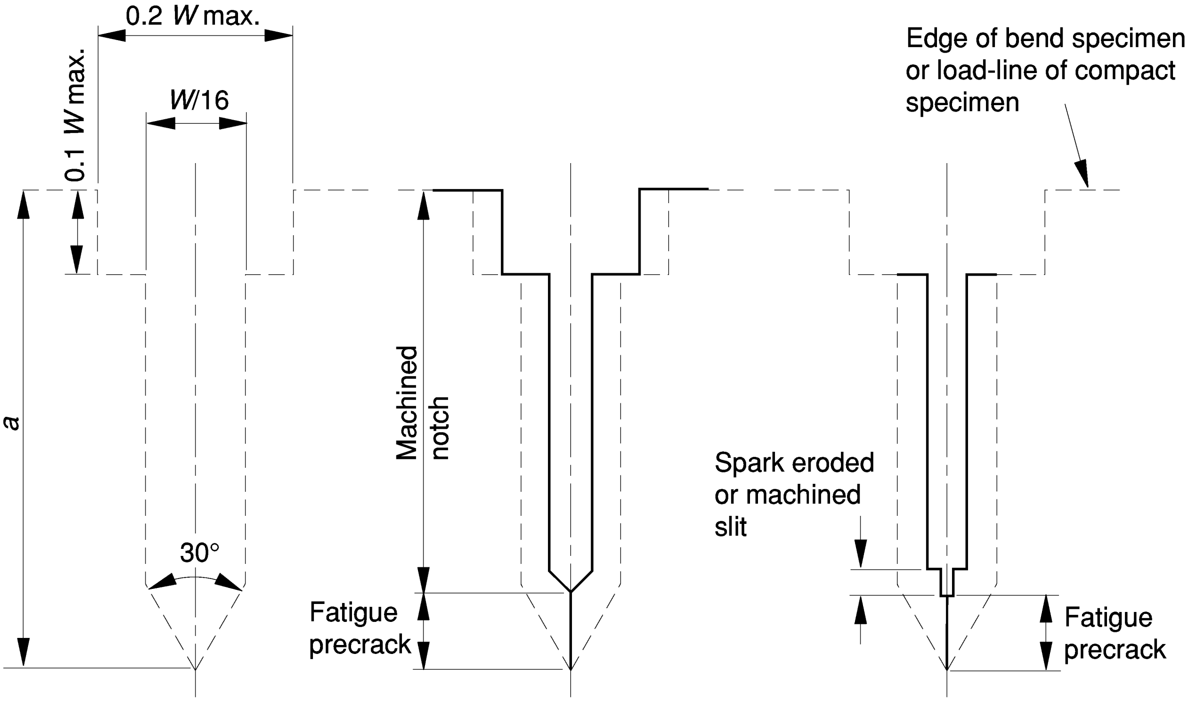
NOTE 3 For starter notch and fatigue crack configurations see Figure 5.

NOTE 4 $0.8 \leq W/B \leq 4.0$ ($W/B = 2$ preferred).

NOTE 5 $0.45 \leq a/W \leq 0.70$.

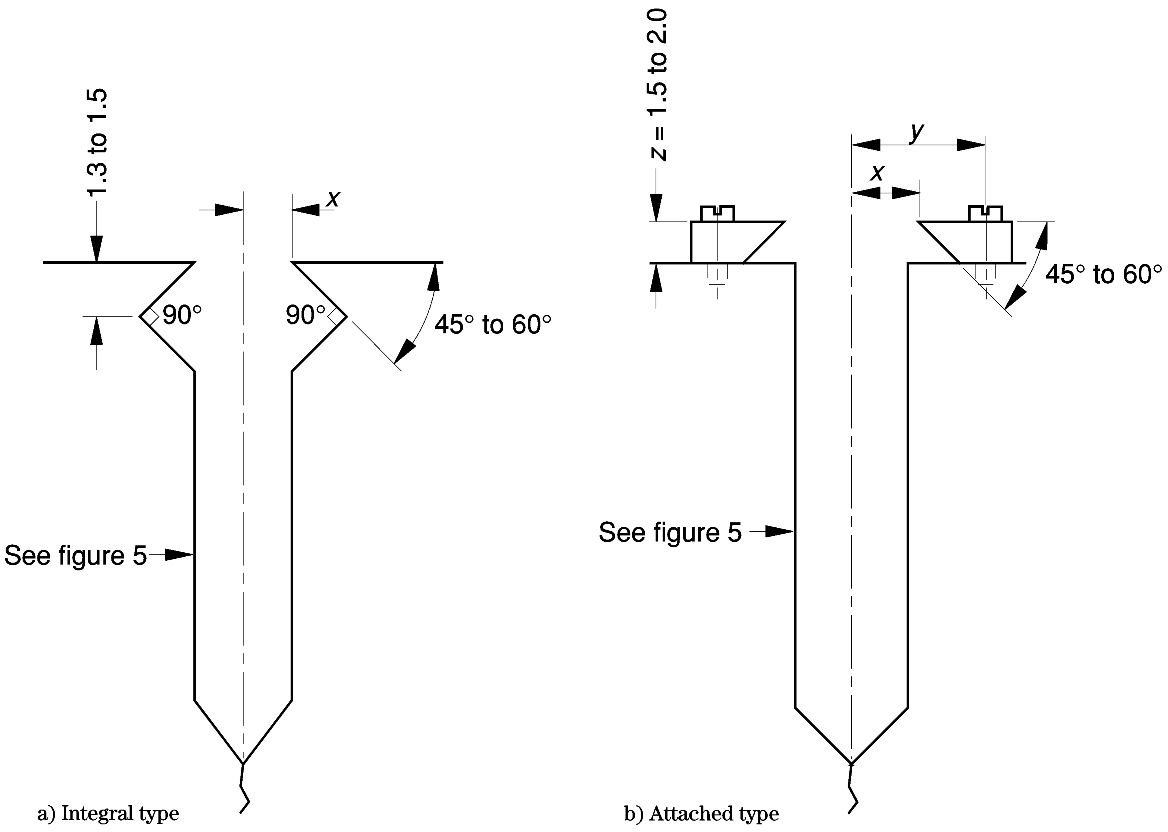
NOTE 6 A second step may not be necessary for some clip gauges; configuration optional providing fatigue crack starter notch and fatigue crack fit within the envelope shown in Figure 5.

Figure 4 — Proportional dimensions and tolerances for a stepped notch compact specimen



a) Envelope b) Notch geometries

Figure 5 — Acceptable fatigue crack starter notches and fatigue crack configurations
(see Figure 6)



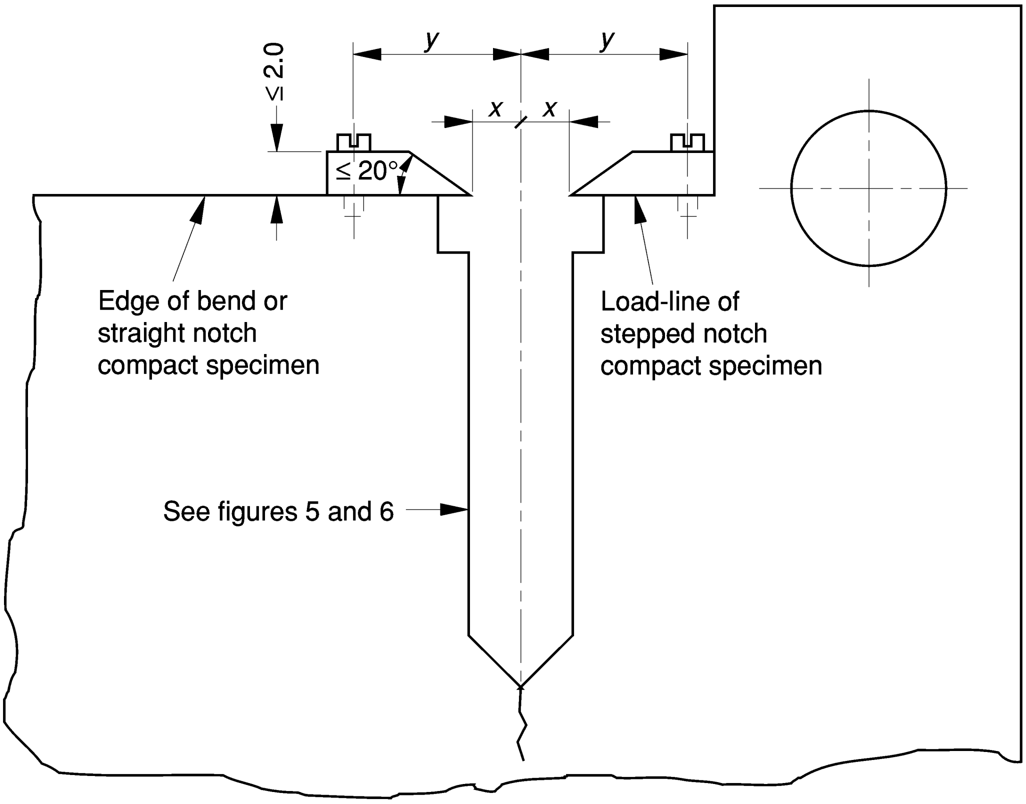
For $2x$ see **6.1.2**

$2y$ + screw thread diameter $\leq W/2$

All linear dimensions are in millimetres

NOTE If the knife edges are glued or similarly attached to the edges of the specimen, $2y$ = distance between extreme points of attachment.

Figure 6 — Outward pointing knife edges and corresponding notch geometries (see Figure 7)



For $2x$ see **6.1.2**

$2y$ + screw thread diameter ≤ $W/2$

All linear dimensions are in millimetres

NOTE 1 If the knife edges are glued or similarly attached to the edges of the specimen, $2y$ = distance between extreme points of attachment.

NOTE 2 If razor blades are used instead of inward pointing knife edges, the displacement will normally be measured at a point half the razor blade thickness above the load line (see **9.2.4**).

Figure 7 — Inward pointing knife edges and corresponding notch geometries (see Figure 6)

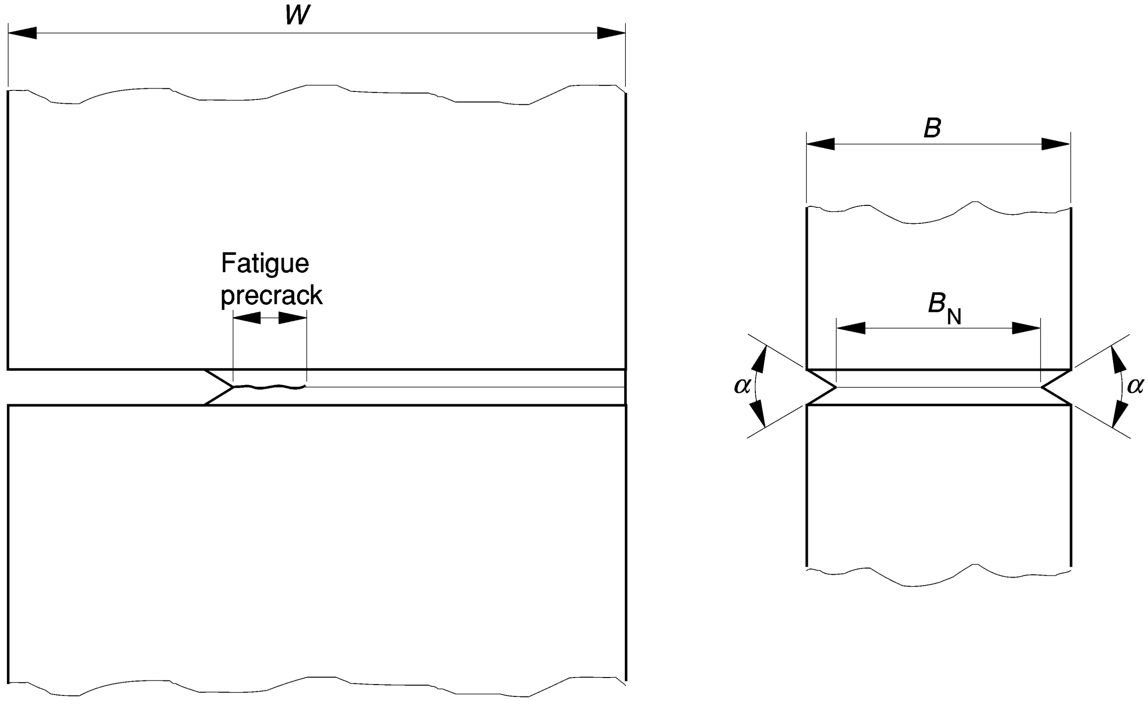


Figure 8 — Typical sidegrooved specimen (see **6.2**)

7 Specimen preparation and fatigue precracking

7.1 Material condition

All specimens shall be tested in the finally heat-treated, mechanically worked and environmentally conditioned state. Specimens shall be machined in this final state. However, for materials having a hardness greater than 600 HV30 (see BS 427), for which machining is difficult, the final treatment may be carried out after machining, provided that the required dimensions and tolerances on specimen size, shape and overall surface finish are met (see **7.3**), and that full account is taken of the effects of specimen size on metallurgical condition induced by certain heat treatments e.g. water quenching of steels.

7.2 Crack plane orientation

The orientation of the crack plane shall be decided before machining (see **7.3**), identified in accordance with one of the co-ordinate systems given in Annex B, and recorded in the test report (see clause **15**).

NOTE The fracture toughness of a material is usually dependent on the orientation and direction of propagation of the crack in relation to the principal directions of mechanical working or grain flow.

7.3 Machining

The sizes, shapes, dimensional tolerances and surface finishes for the specimens shall be as given in Figure 2 to Figure 4. Details of notches shall be as given in Figure 5, Figure 6 and Figure 7.

7.4 Fatigue precracking

7.4.1 Fatigue precracking shall be done at room temperature with the material already in the finally heat-treated, mechanically worked and environmentally conditioned state unless particular fatigue precracking temperatures, and intermediate treatments between fatigue precracking and testing, are required to simulate the conditions for a specific structural application.

7.4.2 Measure the specimen thickness (B) and width (W) as described in **9.2.2** and **9.2.3** respectively. The measured values of specimen thickness (B) and width (W) shall be recorded and used to determine the maximum fatigue precracking force (F_f) according to **7.4.4** or **7.4.5**.

7.4.3 The fatigue precracking force shall be measured to an accuracy within ± 2.5 %.

7.4.4 For the three point bend specimen illustrated in Figure 2, the maximum fatigue precracking force (F_f) during the final 1.3 mm or 50 % of precrack extension, whichever is less, [see **7.4.6**a)], shall be the lower of:

a)

$$F_\mathrm{f} = \frac{0.8B\,(W - a_\mathrm{o})^2}{S} \times R_\mathrm{p0.2B} \tag{1}$$

b)

$$F_\mathrm{f} = 1.6 \times 10^{-4} E \left\{\frac{(WBB_\mathrm{N})^{0.5}}{g_1\,(a_\mathrm{o}/W)}\right\} \times \frac{W}{S} \tag{2}$$

where

$$g_1\,(a_\mathrm{o}/W) = \frac{3\,(a_\mathrm{o}/W)^{0.5}\,[1.99 - (a_\mathrm{o}/W)\,\{1 - (a_\mathrm{o}/W)\}\,\{2.15 - 3.93\,(a_\mathrm{o}/W) + 2.7\,(a_\mathrm{o}/W)^2\}]}{2\,\{1 + 2\,(a_\mathrm{o}/W)\}\,\{1 - (a_\mathrm{o}/W)\}^{1.5}} \tag{3}$$

Specific values of $g_1\,(a_\mathrm{o}/W)$ are given in Table 1.

7.4.5 For the compact specimens illustrated in Figure 3 and Figure 4, the maximum precracking force (F_f) during the final 1.3 mm or 50 % of precrack extension, whichever is less, [see **7.4.6** a)], shall be the lower of:

a)

$$F_\mathrm{f} = \frac{0.6B(W - a_\mathrm{o})^2}{(2W + a_\mathrm{o})} \times R_\mathrm{p0.2B} \tag{4}$$

b)

$$F_\mathrm{f} = 1.6 \times 10^{-4} E \left\{\frac{(WBB_\mathrm{N})^{0.5}}{g_2\,(a_\mathrm{o}/W)}\right\} \times \frac{W}{S} \tag{5}$$

where

$$g_2(a_\mathrm{o}/W) = \frac{\{2 + (a_\mathrm{o}/W)\}\{0.886 + 4.64\,(a_\mathrm{o}/W) - 13.32\,(a_\mathrm{o}^2/W^2) + 14.72\,(a_\mathrm{o}^3/W^3) - 5.6\,(a_\mathrm{o}^4/W^4)\}}{\{1 - (a_\mathrm{o}/W)\}^{1.5}}$$

Specific values of $g_2\,(a_\mathrm{o}/W)$ are given in Table 2.

7.4.6 A fatigue precrack shall be developed from the tip of the machined notch in the specimen as specified in a) to d).

a) The ratio of the minimum to the maximum force in the fatigue cycle shall be in the range 0 to 0.1.

NOTE To expedite crack initiation (see **6.1.2**) one or more cycles of opposite sign and equal or lower magnitude force may be applied first.

b) For all designs of specimen (see Figure 2 to Figure 4), the ratio a_o/W shall be in the range 0.45 to 0.70 (see **9.9**).

c) The minimum fatigue precrack extension shall be the larger of 1.3 mm or 2.5 % of the specimen width (W) (see **9.9**).

d) The difference between the two initial crack length measurements on the surfaces of the specimen, measured to ± 0.05 mm, shall not exceed 15 % of the average of the two measurements.

Table 1 — Values of g_1 (a_o/W) for three-point bend specimens

a_o/W	g_1 (a_o/W)	a_o/W	g_1 (a_o/W)
0.450	2.29	0.630	4.25
0.455	2.32	0.635	4.34
0.460	2.35	0.640	4.43
0.465	2.39	0.645	4.53
0.470	2.43	0.650	4.63
0.475	2.46	0.655	4.73
0.480	2.50	0.660	4.84
0.485	2.54	0.665	4.95
0.490	2.58	0.670	5.06
0.495	2.62	0.675	5.18
0.500	2.66	0.680	5.30
0.505	2.70	0.685	5.43
0.510	2.75	0.690	5.57
0.515	2.79	0.695	5.71
0.520	2.84	0.700	5.85
0.525	2.89	0.705	6.00
0.530	2.94	0.710	6.16
0.535	2.99	0.715	6.32
0.540	3.04	0.720	6.50
0.545	3.09	0.725	6.67
0.550	3.14	0.730	6.86
0.555	3.20	0.735	7.06
0.560	3.25	0.740	7.27
0.565	3.31	0.745	7.48
0.570	3.37	0.750	7.71
0.575	3.43	0.755	7.95
0.580	3.50	0.760	8.20
0.585	3.56	0.765	8.47
0.590	3.63	0.770	8.75
0.595	3.70	0.775	9.04
0.600	3.77	0.780	9.35
0.605	3.85	0.785	9.68
0.610	3.92	0.790	10.04
0.615	4.00	0.795	10.41
0.620	4.08	0.800	10.80
0.625	4.16		

Table 2 — Values of g_2 (a_0/W) for compact specimens

a_0/W	g_2 (a_0/W)	a_0/W	g_2 (a_0/W)
0.450	8.34	0.630	15.44
0.455	8.46	0.635	15.77
0.460	8.58	0.640	16.12
0.465	8.70	0.645	16.48
0.470	8.83	0.650	16.86
0.475	8.96	0.655	17.25
0.480	9.09	0.660	17.65
0.485	9.23	0.665	18.07
0.490	9.37	0.670	18.52
0.495	9.51	0.675	18.97
0.500	9.66	0.680	19.44
0.505	9.81	0.685	19.94
0.510	9.96	0.690	20.45
0.515	10.12	0.695	20.99
0.520	10.29	0.700	21.55
0.525	10.45	0.705	22.14
0.530	10.63	0.710	22.75
0.535	10.80	0.715	23.40
0.540	10.98	0.720	24.07
0.545	11.17	0.725	24.77
0.550	11.36	0.730	25.51
0.555	11.56	0.735	26.29
0.560	11.77	0.740	27.10
0.565	11.98	0.745	27.96
0.570	12.20	0.750	28.86
0.575	12.42	0.755	29.80
0.580	12.65	0.760	30.80
0.585	12.89	0.765	31.86
0.590	13.14	0.770	32.97
0.595	13.39	0.775	34.15
0.600	13.65	0.780	35.40
0.605	13.93	0.785	36.72
0.610	14.21	0.790	38.12
0.615	14.50	0.795	39.61
0.620	14.80	0.800	41.20
0.625	15.11		

8 Test equipment

8.1 Calibration

The calibration of measuring apparatus shall be traceable to the National Physical Laboratory either directly or indirectly through a hierarchical chain such as that provided by the United Kingdom Accreditation Service (UKAS) accredited Calibration Laboratories in accordance with the accuracy demanded by the test.

This includes automatic equipment used for the determination of any one of the parameters described in this standard.

8.2 Force application

8.2.1 The test machine shall be capable of applying a force at a constant displacement rate.

8.2.2 A load-cell of nominal capacity exceeding $1.2F_L$ shall be used, where F_L is as given by one of the following equations, as applicable.

a) For the bend specimens:

$$F_L = \frac{4B\,(W-a)^2}{3S} \times R_m \tag{7}$$

b) For the compact specimens:

$$F_L = \frac{B\,(W-a)^2}{(2W+a)} \times R_m \tag{8}$$

8.2.3 The system for force application and recording shall allow the force signal to be recorded against the displacement of the test specimen. The combination of force sensing and recording device shall conform to grade 1.0 of BS 1610-1:1992 and BS EN 10002-2:1992 for the compressive and tensile force calibrations respectively.

8.3 Displacement measuring devices

A notch opening displacement gauge shall have an electrical output that represents the displacement (V) of two precisely located gauge positions spanning the notch. The design of the displacement gauge, knife edges and specimen shall allow free rotation of the points of contact between the gauge and knife edges.

Displacement gauges for both notch opening displacement and load-line displacement shall be calibrated in accordance with BS EN 10002-4:1995, as interpreted in relation to this method, and shall be of at least class 1; however, calibration shall be performed at least weekly during the time the gauge is in use.

NOTE Periodic verification at greater frequency may be necessary depending on use and agreement between contractual parties.

Verification of the displacement gauge shall be performed at the temperature of test ± 5 °C. The response of the gauge shall be true within ± 0.003 mm for displacements up to 0.3 mm and ± 1 % of the recorded value for larger displacements.

8.4 Test fixtures

8.4.1 The three point bend specimen (see Figure 2) shall be tested using a loading fixture designed to reduce friction at the loading points to a minimum. Achieve this by allowing the rollers to rotate and move apart slightly, thus maintaining rolling contact throughout the test. The diameter of the rollers shall be between W and $W/2$ (see Figure 9).

The length of the rollers shall be greater than the specimen thickness (B). The rollers shall be supported by the test fixture along their full length.

NOTE A design that has proved satisfactory is shown in Figure 9.

8.4.2 The compact specimens shall be loaded in tension using a clevis and pin arrangement, as shown in Figure 10 and Figure 11, that has been designed to minimize friction.

For multi-specimen testing either arrangement may be used. However, for single specimen unloading compliance testing only a clevis with a flat bottomed hole (see Figure 11) shall be used.

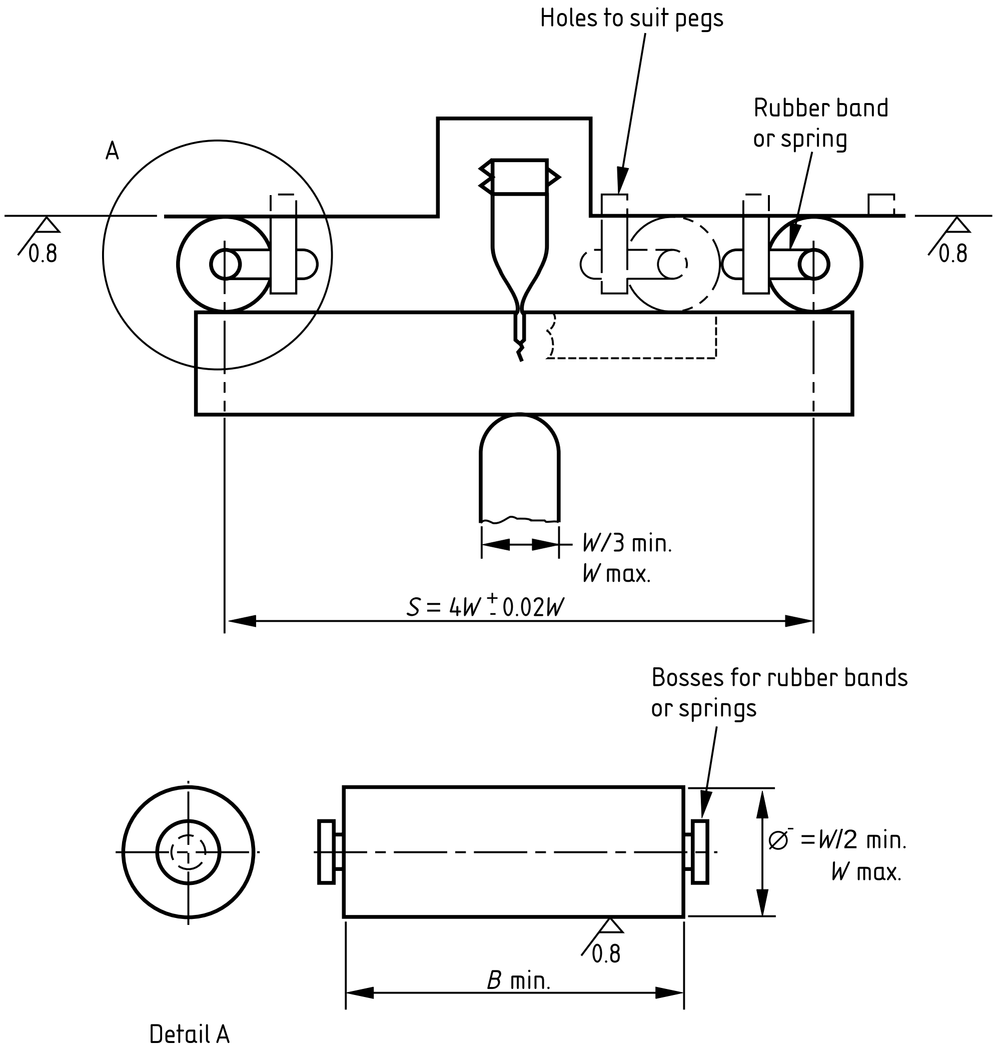
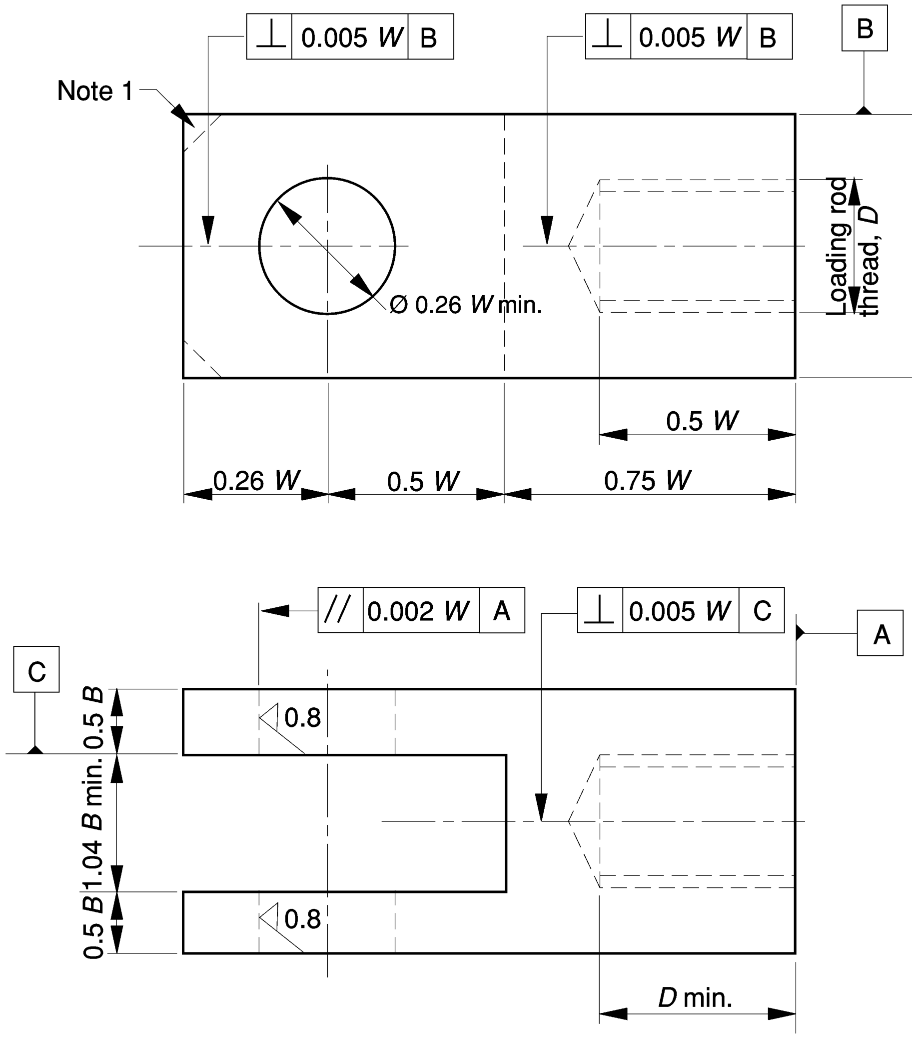


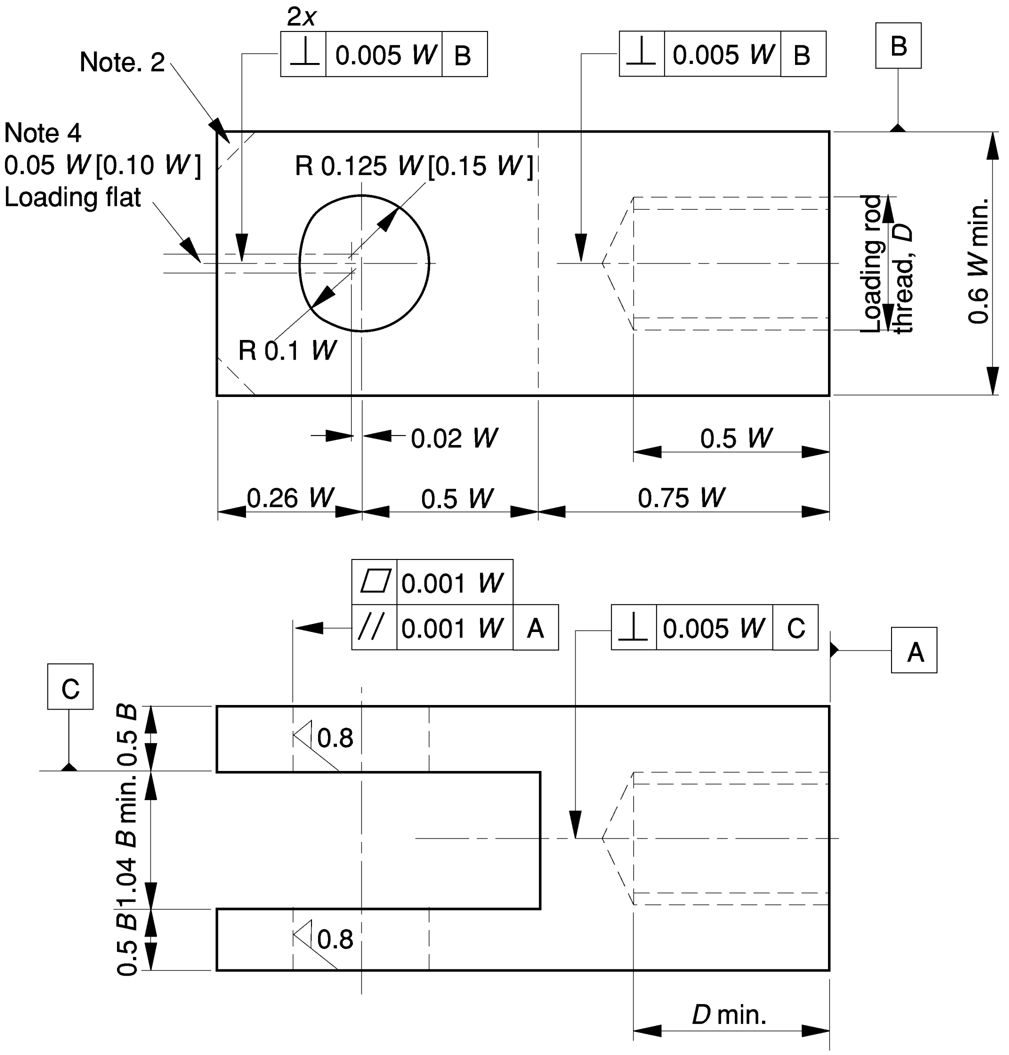
Figure 9 — Fixture for three-point bend tests



NOTE 1 Corners of clevis may be removed if necessary to accommodate the clip gauge.

NOTE 2 Clevis and pin hardness ≥ 40 HRC.

Figure 10 — Typical design of clevis for applying a tensile force to a compact specimen



NOTE 1 Pin diameter = $0.24W$ (+ 0.000W/– $0.005W$).

NOTE 2 Corners of clevis may be removed if necessary to accommodate the clip gauge.

NOTE 3 Clevis and pin hardness ≥ 40 HRC.

NOTE 4 For specimens showing large displacements, clevis hole dimensions shall be enlarged to the values shown in square brackets.

Figure 11 — Typical design of clevis for applying a tensile force to a compact specimen
(suitable for the single specimen method employing the unloading compliance technique)

9 Multiple specimen test procedure

9.1 General

The multiple specimen method requires the testing of several nominally identical specimens to different crack extensions as specified in **12.3**. A minimum of six specimens are required.

9.2 Specimen measurement

9.2.1 The dimensions of the specimens shall conform to the requirements of Figure 2 to Figure 6. Measurements shall be made before testing in accordance with **9.2.2**, **9.2.3**, **9.2.4** and **9.2.5**, and after testing in accordance with **9.9**. The measurements shall be recorded and used for the calculations in accordance with clause **11**.

9.2.2 Measure the specimen thickness to ± 0.025 mm or ± 0.1 %, whichever is larger, at not less than three equally spaced positions along the anticipated crack extension path. The average of these measurements shall be taken as the thickness (B). For sidegrooved specimens, measure the specimen net thickness to ± 0.025 mm or ± 0.1 %, whichever is larger, at not less than three equally spaced positions along the anticipated crack extension path between the sidegroove tips. The average of these three measurements shall be taken as the specimen net section thickness (B_N).

9.2.3 Measure the specimen width to the nearest ± 0.025 mm or ± 0.1 %, whichever is larger, at not less than three equally spaced positions across the specimen thickness on a line not further than 10 % of the nominal width away from the crack plane. The average of these measurements shall be taken as the width (W).

9.2.4 When outward pointing attached knife edges [see Figure 6b)] are used, the knife edge thickness, which is equal to z, shall be measured. If razor blades are used for the knife edges, the half thickness of these shall be taken as equal to the dimension z.

NOTE 1 If z is less than $0.002a$, it may be ignored.

NOTE 2 When integral or inward pointing attached knife edges are used [see Figure 6a) and Figure 7], the dimension z is equal to zero.

9.2.5 When straight notch compact specimens are used, measure the dimension ($W_t - W$) to ± 0.025 mm or± 0.1 %, whichever is larger.

9.3 Three point bend testing

9.3.1 *Specimen fixture alignment*

Set up the test fixture (see Figure 9) so that the line of action of the applied force passes midway between the centres of the rollers within ± 1 % of the distance between these centres. Adjust the span (S) to $4W \pm 0.02W$, and record the actual span to ± 0.5 %. Locate the bend specimen with the crack tip midway between the rollers to ± 1 % S, and square to the roller axes to within ± 2°.

9.3.2 *Notch opening displacement*

For tests to calculate δ R-curves, the value of δ is determined from the notch opening displacement V. Seat the notch opening gauge on the knife edges after squeezing the gauge beams together to maintain spring contact between the knife edges and beam seats.

9.3.3 *Load-line displacement*

For tests to calculate J R-curves, J is evaluated from the load-line displacement q. Suitable methods for measuring load-line displacements directly or indirectly are described in Annex C.

9.4 Compact tension testing

9.4.1 *Specimen and fixture alignment*

The centre-lines of the upper and lower clevises shall be within the smaller of $0.03B$ or 1 mm of each other and within the smaller of $0.03B$ or 1 mm of both the specimen hole centre-line and the specimen mid-thickness centre-line.

NOTE If the single specimen unloading compliance method is employed using clevises with flat bottomed holes (see **8.4.2** and Figure 11) specimen and fixture alignment will vary during testing due to the rolling contact.

9.4.2 *Notch opening displacement*

For tests to calculate δ R-curves, the value of δ is determined from the notch opening displacement V. This is measured at the load-line for stepped notch compact specimens as shown in Figure 7. For straight notch compact specimens the knife edges are located at a distance $\{z + (W_t - W)\}$ from the load-line in the direction away from the crack tip. Seat the notch opening gauge on the knife edges as described in **9.3.2**.

9.4.3 *Load-line displacement*

For tests to calculate J R-curves, J is evaluated from the load-line displacement q. For tests using the stepped notch compact specimen shown in Figure 4 with inward pointing or integral knife edges (see Figure 6 and Figure 7) seat the notch opening gauge on the knife edges on the load-line of the specimen, as described in **9.3.2**.

For tests using the straight notch compact specimen, which do not permit direct measurement of load-line displacement, the relationship between the measured displacement and the load-line displacement shall be established so that load-line values may be inferred (see Annex C).

9.5 Specimen test temperature

The temperature of the test specimen shall be controlled and recorded to an accuracy of ± 2.0 °C. Place a thermocouple or platinum resistance thermometer in contact with the surface of the specimen in a region not further than 5 mm from the crack tip. Tests shall be made in situ in suitable low or high temperature media.

Before testing in a liquid medium, the specimen shall be retained in the liquid for at least 30 s/mm of thickness (B) after the specimen surface has reached the test temperature. When using a gaseous medium, a soaking time of at least 1 min/mm of thickness shall be used.

The recorded temperature of the test specimen shall remain within ± 2 °C of the nominal test temperature, T, throughout the test. The time at test temperature prior to testing shall be recorded in the test report (see clause **15**).

9.6 Testing rates

Using displacement control, apply a machine displacement such that a constant $\dot{K}$ is achieved within the range 0.5 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ to 3.0 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ during linear elastic specimen deformation.

Record the value of $\dot{K}$ achieved (see clause **15**). Each specimen in the same series shall be loaded at the same nominal rate which shall be recorded in the test report (see clause **15**).

9.7 Recording

Make a record of the output of the force sensing device (see **8.2.3**) versus the output from the notch opening displacement gauge (see **8.3**) and/or the load-line displacement of a three point bend specimen (see **8.3** and Annex C).

NOTE 1 If unstable fracture is a possibility (see clause **11**) and an autographic record is made for a subsequent manual analysis it should be noted that BS 7448-1 requires the initial slope of the force versus notch opening displacement, or force versus load-line displacement record to be between 0.85 and 1.5.

NOTE 2 Non-linearity often occurs at the beginning of a record. Since this may make it difficult to analyse the record, it is advisable to minimize this non-linearity by a preliminary loading and unloading with a force not exceeding F_f (see **7.4.4** and **7.4.5**).

9.8 Extent of loading

Load the first specimen to a displacement just beyond that associated with the maximum force attainable. Reduce the force to zero allowing no further increase in displacement.

Mark the extent of stable crack extension as described in **9.9.1** and measure the original crack length and stable crack extension as described in **9.9.2** and **9.9.3**. Calculate values of J or δ as described in clause **11**.

Repeat the test procedure with further specimens terminating each test at the displacement judged to give crack extension conforming to the requirements in **12.3**.

9.9 Crack measurement

9.9.1 *Marking stable crack extension*

Mark the extent of stable crack extension by either heat tinting or additional fatigue cracking. The fatigue cracking shall be performed at room temperature at a fatigue: force ratio greater than 0.6 to avoid damage to the fracture surfaces from crack closure effects. The maximum fatigue force shall not exceed three-quarters of the final force measured during the test. If the fracture test was performed below ambient temperature then subsequent fatigue cracking shall be performed so as to avoid additional plastic deformation.

Break open the specimen at or below room temperature to reveal the fracture surfaces.

9.9.2 *Original crack length*

Measure the crack length (a) from the specimen surface (for single edge notch bend specimens) or pinhole centreline (for compact specimens) to the tip of the fatigue precrack to ± 0.25 %a or ± 0.05 mm, whichever is the greater. The measurements shall be made at nine equally spaced points where the outer points are located at 1 %B in from the minimum net thickness B_{min} (see Figure 12 and Figure 13). The original crack length (a_0) shall be obtained by firstly averaging the two measurements at the outer points (a_1 and a_9) and then averaging this value with the seven inner points in accordance with the following equation:

$$a_0 = \frac{1}{8}\left(\frac{a_1 + a_9}{2} + \sum_{i=2}^{i=8} a_i\right) \tag{9}$$

The original crack length (a_0) shall meet the following requirements.

a) The ratio a_0/W shall be within the range 0.45 to 0.70.

b) The difference between a_0 and any of the nine crack length measurements (a_1 to a_9) contributing to a_0 shall not exceed 10 %a_0.

c) No part of this fatigue precrack front shall be closer to the crack starter notch than 1.3 mm or 2.5 %W whichever is the larger.

d) The fatigue precrack and machined notch shall be within the appropriate envelope for the corresponding a_0/W value (see Figure 5).

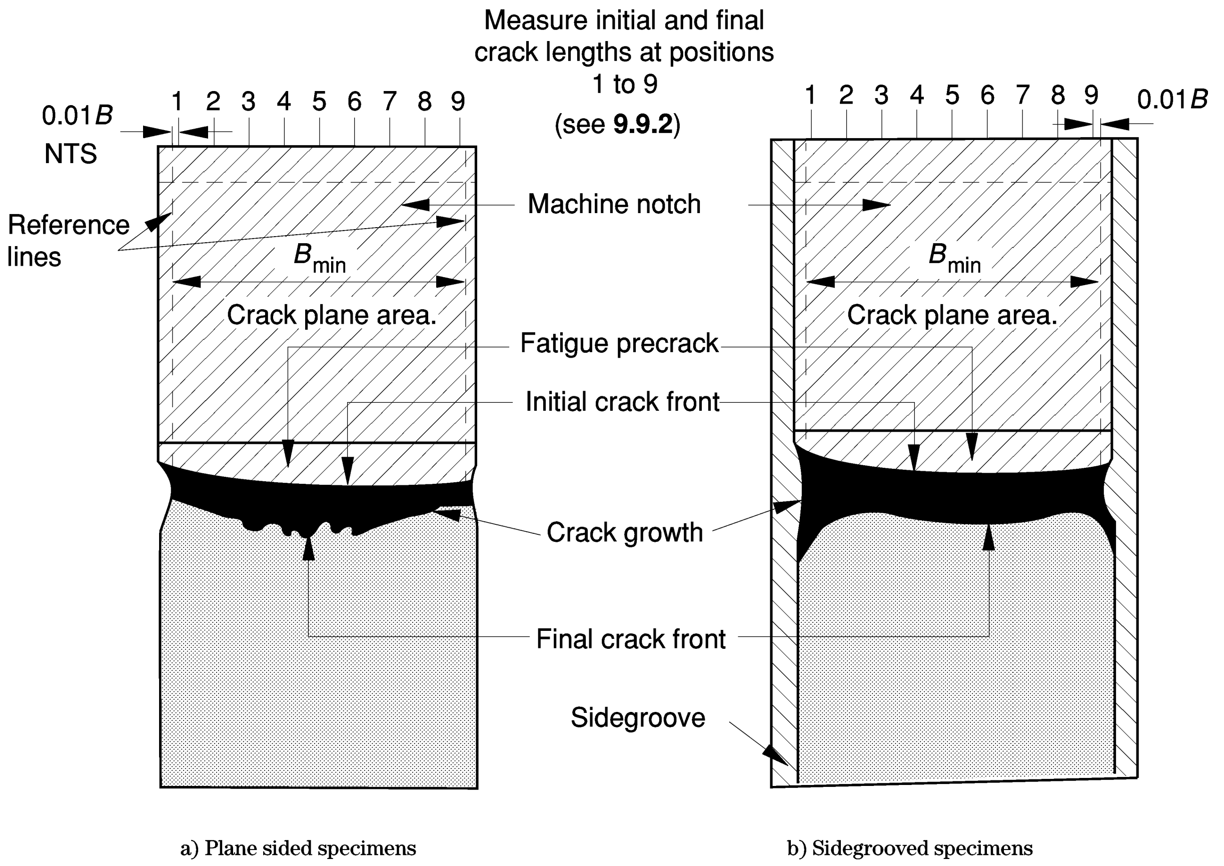
If the requirements given in a) to d) are not satisfied then the initial crack length shall be deemed not to conform to the requirements of this test method. These results shall be identified in the test report [see clause **15**, item t)].

9.9.3 *Stable crack extension*

Determine the mean crack extension, mean Δa, between the fatigue precrack front and the final heat tinted or fatigue marked crack front using the nine point averaging procedure described in **9.9.2**. If the difference between minimum and maximum values of crack extension at positions 1 to 9 exceeds 20 % of the mean Δa, or 0.15 mm, whichever is the greater, then record non-uniform crack extension in the test report [see clause **15**, item u)].

Any irregularities in crack extension, such as spikes and isolated "islands" of crack extension, shall be recorded in the test report (see clause **15**).

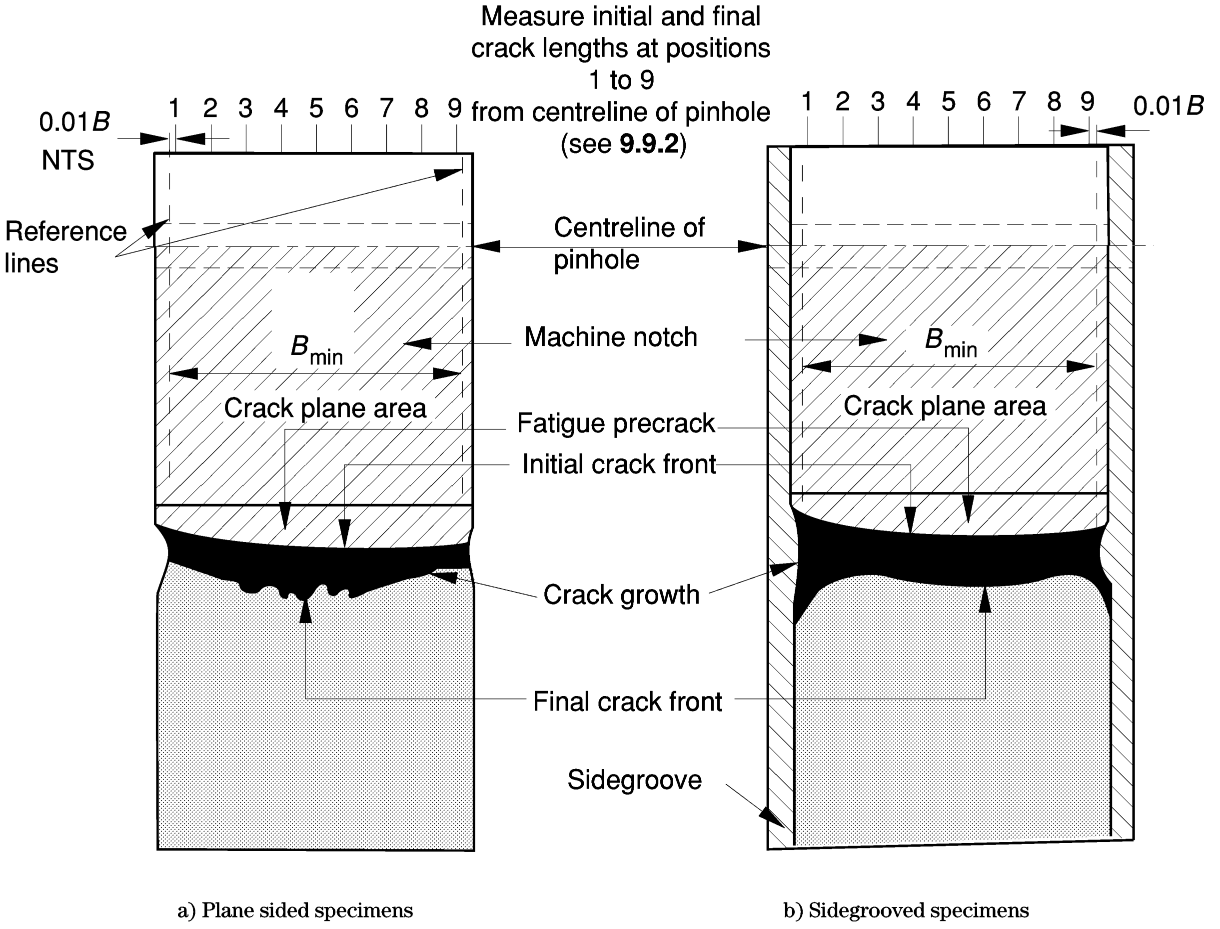
NOTE Difficulties may arise in measuring highly irregular crack fronts such as spikes or regions of disconnected crack extension. For these situations, it may only be practicable to estimate the crack length by ignoring the spikes or subjectively averaging the crack extension region. Care should be exercised when the results derived from highly irregular crack fronts are used to assess structural integrity.



a) Plane sided specimens

b) Sidegrooved specimens

Figure 12 — Measurement of crack lengths on single edge notch bend specimens



a) Plane sided specimens b) Sidegrooved specimens

Figure 13 — Measurement of crack lengths on compact specimens

10 Single specimen test procedure

10.1 General

There is no restriction on the single specimen methods which may be used, providing that the data can be qualified (see **10.3**). The method used shall be documented and referred to in the test report (see clause **15**).

Publications describing some techniques for single specimen testing are listed in the bibliography in Annex A.

10.2 Specimens

10.2.1 Test specimens shall conform to clause **6** and to **10.2.2**.

10.2.2 If crack extension is monitored using the unloading compliance technique (see Annex D) all specimens shall be sidegrooved. If the crack extension is monitored using a potential drop technique, then the requirements of **6.2** shall apply.

10.2.3 Specimen measurement and testing shall be carried out in accordance with **9.2** to **9.7** and **9.9**.

10.3 Acceptance criteria for single specimen test methods

10.3.1 *General*

At least three nominally identical specimens shall be tested using the same single specimen technique. One of these specimens shall be tested up to the crack extension limit (see clause **12**) so as to satisfy the data point spacing requirement given in **12.3**.

The test on one of the remaining two specimens should be terminated when there is between 0.1 mm and 0.3 mm of crack extension beyond the blunting line (see **12.2.2**). The test on the other specimen should be terminated midway in the crack extension range (see Figure 14 and clause **12**).

10.3.2 ***Crack length***

The difference between the initial estimate of crack length, determined from the single specimen technique, and a_o (see **9.9.2**) shall not exceed 2 % of a_o.

10.3.3 ***Crack extension***

The final crack extension estimated by the single specimen technique shall not exceed ± 15 % of the measured crack extension, Δa, (see **9.9.3**) or ± 0.15 mm, whichever is the greater.

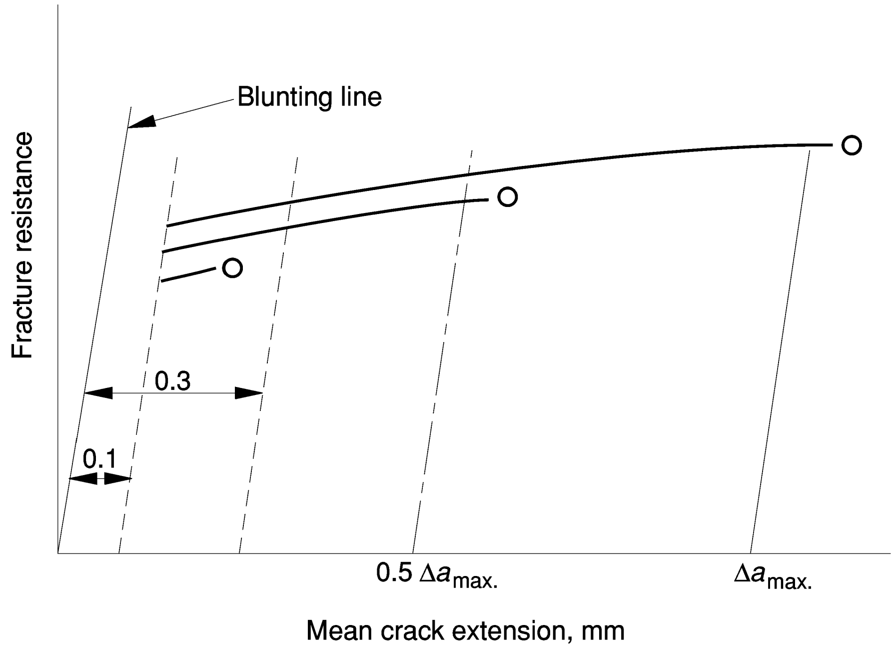


Figure 14 — Single specimen crack extension termination requirement

11 Analysis of test data

11.1 General

The analysis procedures for determining values of δ and J for R-curves from multiple specimen data are given in **11.2** and **11.3**.

If any test, from a multiple or single specimen R-curve determination, exhibits unstable crack extension or pop-in, then that test and all other tests forming the R-curve determination shall be analysed using Part 1 of this standard. If sufficient stable crack extension data (see clause **12**) are generated, then an R-curve and initiation parameters can still be calculated in accordance with this Part of the standard; however any unstable crack extension and associated values of fracture toughness calculated in accordance with Part 1 shall also be reported (see clause **15**).

11.2 Crack tip opening displacement, δ

11.2.1 ***Determination of*** V_p

Refer to Figure 15. Determine and record the plastic component of the notch opening displacement (V_p) from the test record, i.e. that corresponding to the appropriate notch opening displacement at the termination of the test.

Determine V_p either graphically or analytically. The graphical method can be performed either manually from the test record, or using computer techniques. The analytical method is based on elastic compliance techniques, and involves subtracting the theoretical elastic notch opening displacement (V_e) from the total notch opening displacement (V) (see Annex E).

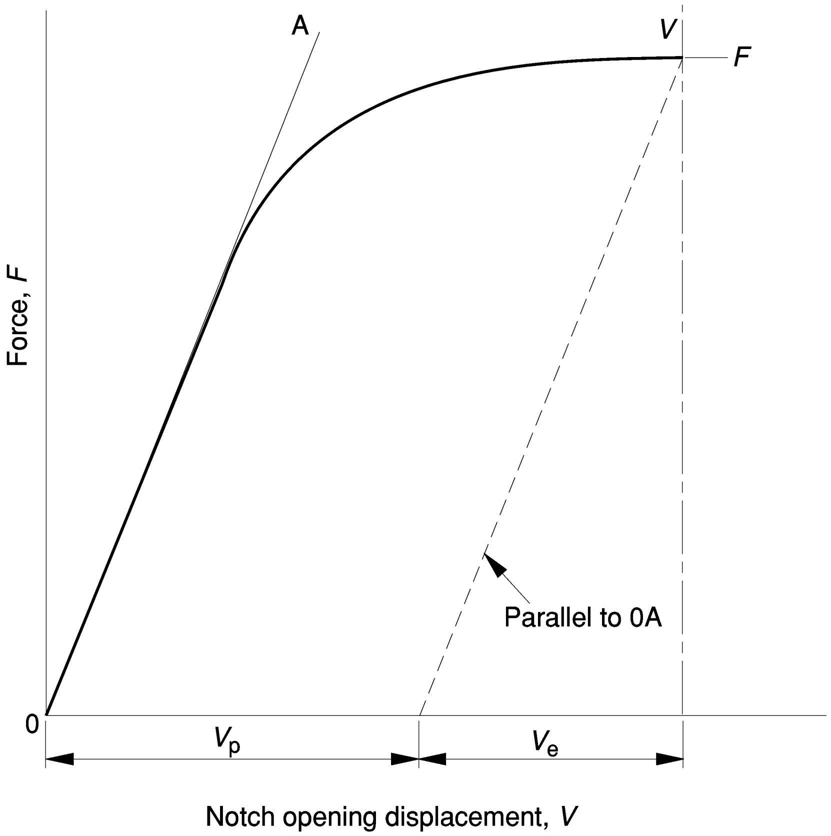


Figure 15 — Graphical determination of V_p

11.2.2 *Bend specimens*

Calculate δ_{corr} for each specimen using the relationship:

$$\delta_{corr} = \frac{K^2 (1 - \nu^2)}{2ER_{p0.2}} + \frac{0.6\Delta a + 0.4 (W - a_o)}{0.6 (a_o + \Delta a) + 0.4W + z} \times V_p \qquad (10)$$

where

$$K = \frac{FS}{W^{1.5} (BB_N)^{0.5}} \times g_1 (a_o/W) \qquad (11)$$

and

F	is the force at termination of the test;
$g_1 (a_o/W)$	is the stress intensity function given in **7.4.4**;
z	is equal to the knife edge thickness as given in **9.2.4**;
V_p	is the plastic component of the notch opening displacement at the termination of the test as shown in Figure 15 (see **11.2.1**).

For non-sidegrooved specimens replace B_N with B.

11.2.3 *Stepped notch compact specimens*

Calculate δ_{corr} for each specimen using the relationship:

$$\delta_{\mathrm{corr}} = \frac{K^2 (1 - \nu^2)}{2ER_{\mathrm{p0.2}}} + \frac{0.54\Delta a + 0.46 (W - a_{\mathrm{o}})}{0.54 (a_{\mathrm{o}} + \Delta a) + 0.46W + z} \times V_{\mathrm{p}} \tag{12}$$

where

$$K = \frac{F}{(BB_{\mathrm{N}}W)^{0.5}} \times g_2 (a_{\mathrm{o}}/W) \tag{13}$$

$g_2 (a_{\mathrm{o}}/W)$ is the stress intensity function as given in **7.4.5**

and F, z, and V_{p} are as given in **11.2.2**.
For non-sidegrooved specimens replace B_{N} with B.

11.2.4 *Straight notch compact specimens*

Calculate δ_{corr} for each specimen using the relationship:

$$\delta_{\mathrm{corr}} = \frac{K^2 (1 - \nu^2)}{2ER_{\mathrm{p0.2}}} + \frac{0.54\Delta a + 0.46 (W - a_{\mathrm{o}})}{0.54 (a_{\mathrm{o}} + \Delta a) + 0.46W + (W_{\mathrm{t}} - W) + z} \times V_{\mathrm{p}} \tag{14}$$

where

$$K = \frac{F}{(BB_{\mathrm{N}}W)^{0.5}} \times g_2 (a_{\mathrm{o}}/W) \tag{15}$$

and $g_2 (a_{\mathrm{o}}/W)$, F, z and V_{p} are as given in **11.2.2** and **11.2.3**.
For non-sidegrooved specimens replace B_{N} with B.

11.3 Resistance to crack extension expressed in terms of *J*

11.3.1 *Determination of* U_{p}

Refer to Figure 16. Determine and record the plastic component of the work done (U_{p}) by measuring the area indicated in Figure 16. The area corresponding to U_{p} in Figure 16 may be determined either directly from the test record (e.g. by using a polar planimeter), or by numerical integration by computer techniques, or by combination of the latter and an analytical method based on elastic compliance, which involves the subtraction of the theoretical elastic area (U_{e}) from the total area (U) (see Annex E).

11.3.2 *Calculation of* J_{corr}

Calculate J_{corr} for each sidegrooved specimen using the relationship:

$$J_{\mathrm{corr}} = J_{\mathrm{o}} \left\{ 1 - \frac{(0.75\eta_{\mathrm{p}} - 1)}{(W - a_{\mathrm{o}})} \Delta a \right\} \tag{16}$$

where

$$J_{\mathrm{o}} = \frac{K^2 (1 - \nu^2)}{E} + \frac{\eta_{\mathrm{p}} U_{\mathrm{p}}}{B_{\mathrm{N}} (W - a_{\mathrm{o}})} \tag{17}$$

$\eta_{\mathrm{p}} = 2$ for single edge notch bend specimens;

$\eta_{\mathrm{p}} = 2 + 0.522 (1 - a_{\mathrm{o}}/W)$ for compact specimens;

$$K = \frac{FS}{W^{1.5} (BB_{\mathrm{N}})^{0.5}} \times g_1 (a_{\mathrm{o}}/W) \tag{18}$$

for single edge notch bend specimens;

$$K = \frac{F}{(BB_N W)^{0.5}} \times g_2\,(a_o/W) \qquad (19)$$

for compact specimens;

F is the force being applied immediately prior to unloading at termination of the test;

and $g_1\,(a_o/W)$ and $g_2\,(a_o/W)$ are as given in **11.2.2** and **11.2.3** respectively.

For non-sidegrooved specimens replace B_N with B.

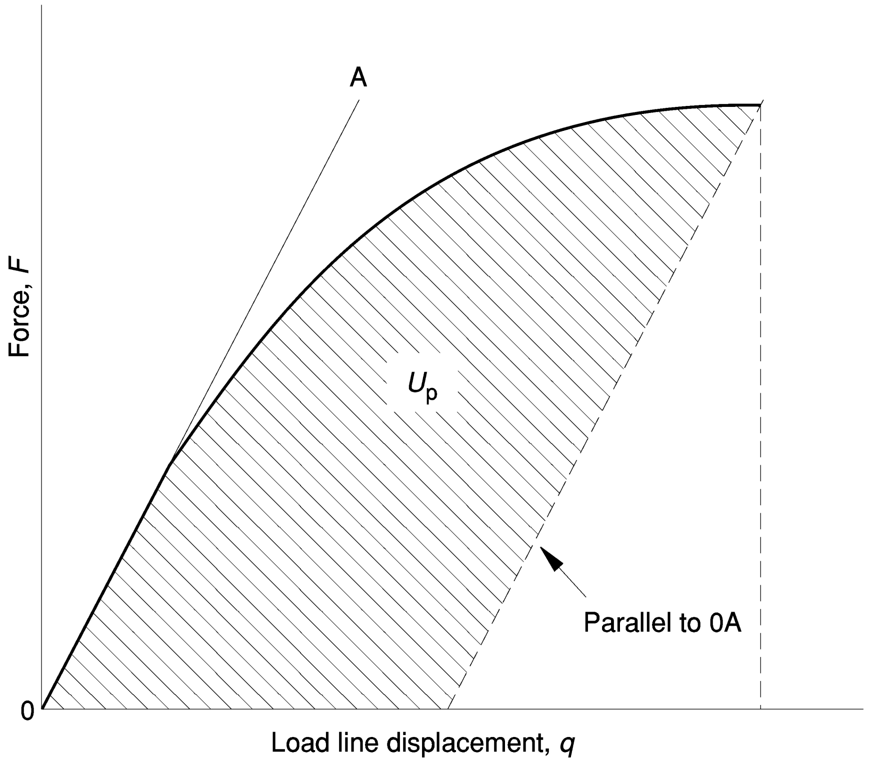


Figure 16 — Determination of U_p

12 Construction of R-curves

12.1 General

Use the experimental data obtained to plot the points for a δ or J R-curve (see Figure 17 to Figure 20). Calculate the limits of applicability for the δ or J R-curve in accordance with **12.2** to **12.6**.

12.2 Δa_{max} crack extension limit

12.2.1 For each specimen, calculate the crack extension limit Δa_{max} from either:

$$\Delta a_{max} = 0.25\,(W - a_o) \text{ for } \delta\text{; or} \qquad (20)$$

$$\Delta a_{max} = 0.10\,(W - a_o) \text{ for } J. \qquad (21)$$

12.2.2 Determine the slope of the blunting line from either of the following relationships:

$$\delta = 1.87\left(\frac{R_m}{R_{p0.2}}\right)\Delta a \quad \text{for } \delta\text{; or} \qquad (22)$$

$$J = 3.75 R_m \Delta a \quad \text{for } J. \qquad (23)$$

Plot the blunting line on the graph containing the experimental data.

12.2.3 Construct the crack extension limit exclusion line, parallel to the blunting line at an offset corresponding to the minimum value of Δa_{max} calculated in **12.2.1** (see Figure 17).

12.2.4 Construct an exclusion line parallel to the blunting line at an offset of 0.10 mm (see Figure 17).

12.3 Data spacing requirement

A minimum of six data points shall be used to describe the crack extension fracture resistance behaviour. Ideally the data points should be evenly spaced. At least one data point is required in each of the four equal crack extension regions shown in Figure 17.

12.4 Curve fit

Determine the best fit curve through the data points which lie between the 0.1 mm and Δa_{max} exclusion lines (see Figure 17), using the equation:

$$\delta \text{ or } J = m + l\,(\Delta a)^{x} \tag{24}$$

where l, m and x are constants determined in accordance with Annex F; and

where m and $l \geq 0$ and $0 \leq x \leq 1$.

If m or l is negative then additional data points shall be obtained.

12.5 Limits to δ-controlled crack extension

12.5.1 For each specimen calculate δ_{max} from the smaller of:

$$\delta_{\text{max}} = \frac{(W - a_{\text{o}})}{30} \text{ ; and} \tag{25}$$

$$\delta_{\text{max}} = \frac{B}{30} \tag{26}$$

12.5.2 Construct a horizontal exclusion line to the δ-Δa data at the minimum calculated δ_{max} value (see Figure 18).

12.5.3 Examples of R-curves for two different materials are shown in Figure 18 (case 1 and case 2). The intersection of the best fit curve (see **12.4**) with the δ_{max} exclusion line (case 1 in Figure 18) gives the point (δ_{g1}, Δa_{g1}, which defines the upper limit for the R-curve. The intersection of the best fit curve (see **12.4**) with the Δa_{max} exclusion line (case 2 in Figure 18) gives the point δ_{g2}, Δa_{g2}, which defines the upper limit for the R-curve.

12.6 Limits to J controlled crack extension

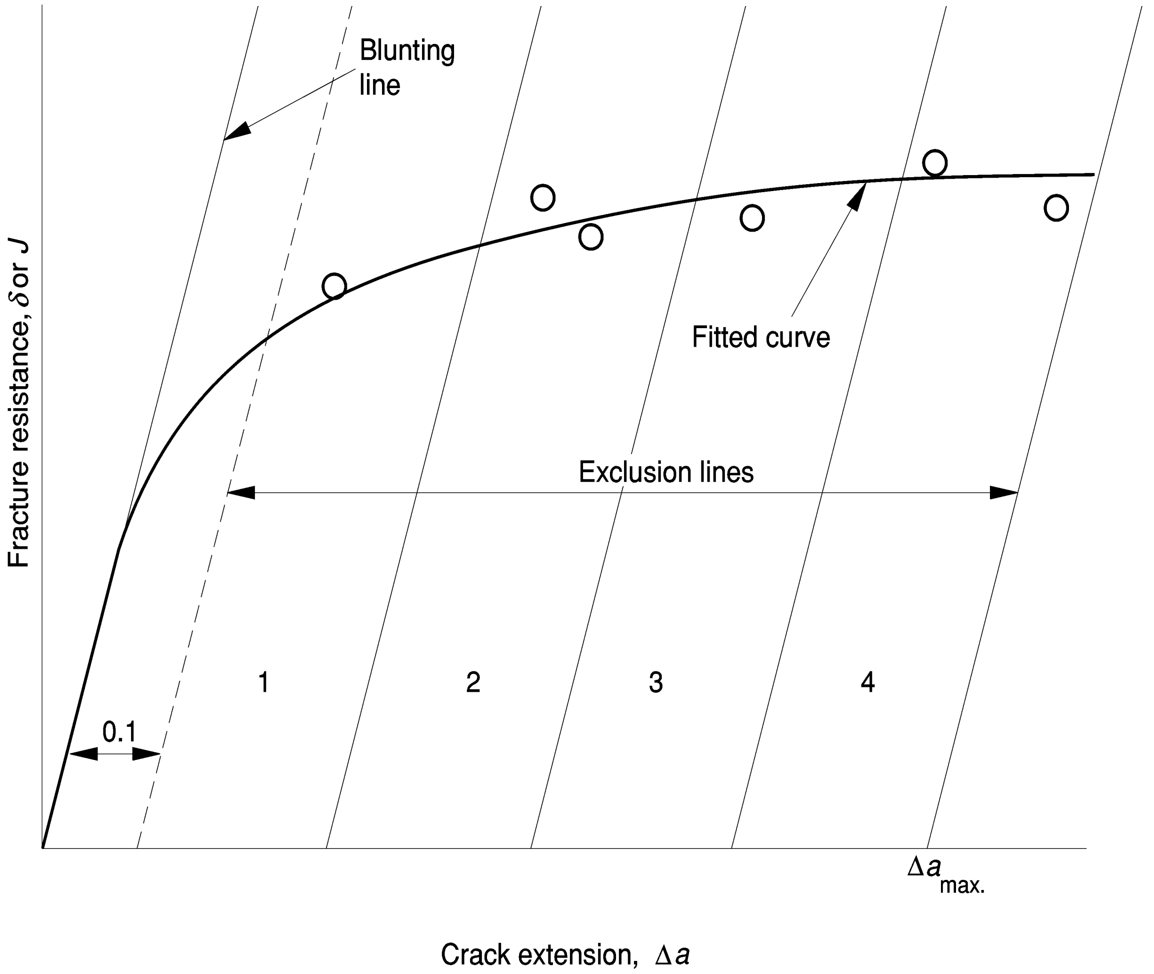
12.6.1 For each specimen, calculate J_{max} from the smaller of:

$$J_{\text{max}} = (W - a_{\text{o}})\,\frac{(R_{\text{p0.2}} + R_{\text{m}})}{40} \text{ ; and} \tag{27}$$

$$J_{\text{max}} = B\,\frac{(R_{\text{p0.2}} + R_{\text{m}})}{40} \tag{28}$$

12.6.2 Construct a horizontal exclusion line to the J-Δa data at the minimum calculated J_{max} value (see Figure 18).

12.6.3 Examples of R-curves for two different materials are shown in Figure 18 (case 1 and case 2). The intersection of the best fit curve (see **12.4**) with the J_{max} exclusion line (case 1 in Figure 18) gives the point J_{g1}, Δa_{g1}, which defines the upper limit for the R-curve. The intersection of the best fit curve (see **12.4**) with the Δa_{max} exclusion line (case 2 in Figure 18) gives the point J_{g2}, Δa_{g2}, which defines the upper limit for the R-curve.



Linear dimension in millimetres.

NOTE At least six data points are required. Each crack sector shall contain at least one data point. See **12.3** and **12.4**.

Figure 17 — Data spacing and curve fit

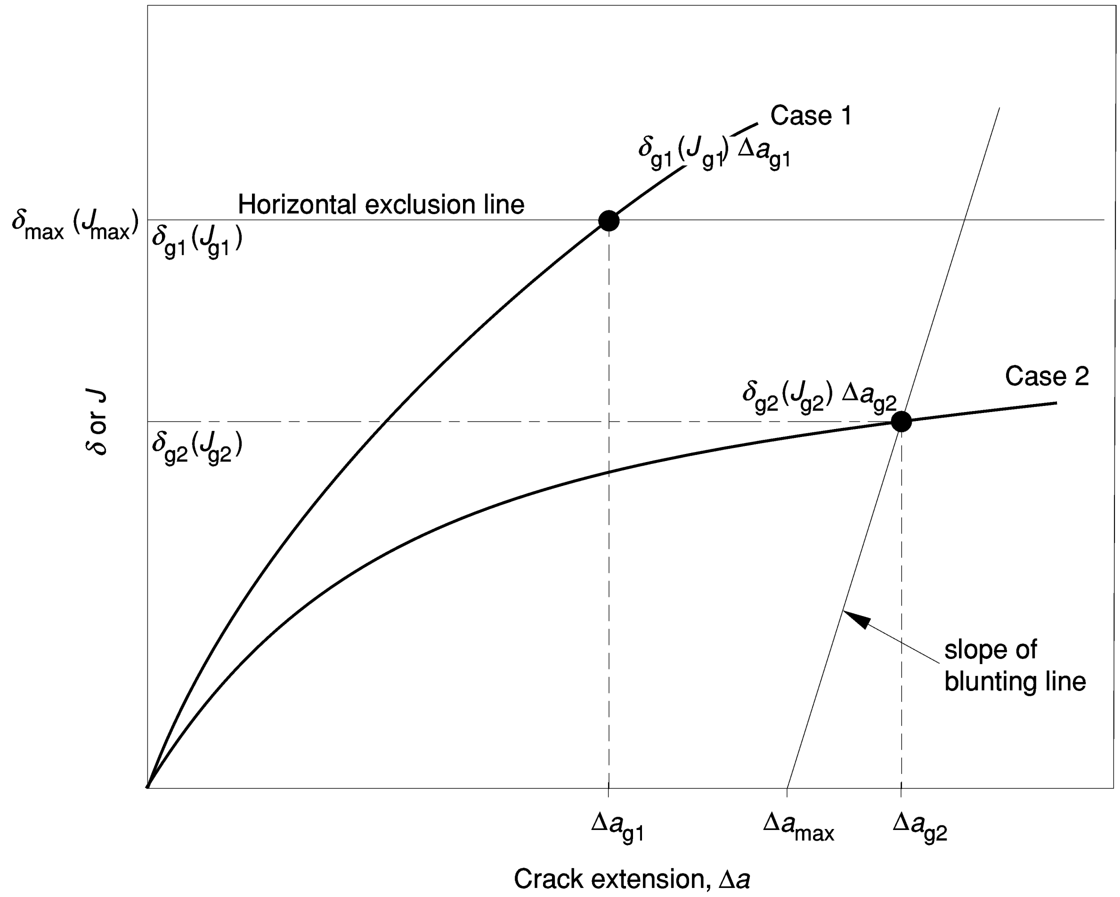


Figure 18 — Limits to δ or J controlled crack extension

13 Determination of fracture parameters

13.1 General

Methods are given in **13.2** and **13.3** respectively which can be used to obtain two fracture parameters for estimating δ and J close to the onset of crack initiation from crack extension fracture resistance data.

These parameters are as follows.

a) $\delta_{0.2BL}$ or $J_{0.2BL}$ which measure the fracture resistance at 0.2 mm crack extension offset to the blunting line. They provide an engineering definition of initiation and avoid the use of a scanning electron microscope for defining SZW. These parameters can be used to rank materials covering a wide range of crack extension fracture resistance behaviour with respect to crack initiation.

b) $\delta_{0.2}$ or $J_{0.2}$ which measure the fracture resistance at 0.2 mm of total crack extension including crack tip blunting. In many areas these parameters provide a useful engineering estimate of initiation which are lower bound values compared with $\delta_{0.2BL}$ and $J_{0.2BL}$. For high toughness materials, they may be ranked unduly low.

NOTE The choice of, and the decision regarding the applicability of, these fracture parameters for structural integrity assessments and materials characterization is at the discretion of the user.

13.2 δ fracture parameters

13.2.1 $\delta_{0.2BL}$

13.2.1.1 Construct a plot of the blunting line and the best fit curve through the δ-Δa data in accordance with **12.2.2** and **12.4**, respectively.

13.2.1.2 Construct a parallel line, offset to the blunting line by 0.2 mm (see Figure 19). The intersection of the best fit curve with this offset line defines $\delta_{0.2\text{BL}}$.

13.2.1.3 If $\delta_{0.2\text{BL}}$ exceeds δ_{max} determined in accordance with **12.5.1**, then the value of $\delta_{0.2\text{BL}}$ calculated in accordance with this method is not acceptable.

13.2.1.4 Determine the slope of the δ-Δa curve, $(\mathrm{d}\delta/\mathrm{d}a)_{0.2\text{BL}}$, at the intersection point from the equation given in **12.4**. If the slope of the blunting line, $(\mathrm{d}\delta/\mathrm{d}a)_{\text{BL}}$, is less than $2(\mathrm{d}\delta/\mathrm{d}a)_{0.2\text{BL}}$ then the value of $\delta_{0.2\text{BL}}$ calculated in accordance with this method is not acceptable.

13.2.2 $\delta_{0.2}$

13.2.2.1 Construct a line corresponding to constant total crack extension of 0.2 mm on a plot of the δ-Δa data. The intersection of this line with the best fit curve through the data as given in **12.4** defines $\delta_{0.2}$ (see Figure 20). At least one data point shall be between 0.2 mm and 0.4 mm.

13.2.2.2 If $\delta_{0.2}$ exceeds δ_{max} determined in accordance with **12.5.1**, then the value of $\delta_{0.2}$ calculated in accordance with this method is not acceptable.

13.3 J fracture parameters

13.3.1 $J_{0.2\text{BL}}$

13.3.1.1 Construct a plot of the blunting line, as given in **12.2.2**, and the best fit curve, as given in **12.4**, through the J-Δa data.

13.3.1.2 Construct a parallel line, offset to the blunting line by 0.2 mm (see Figure 19). The intersection of the best fit curve with this offset line defines $J_{0.2\text{BL}}$.

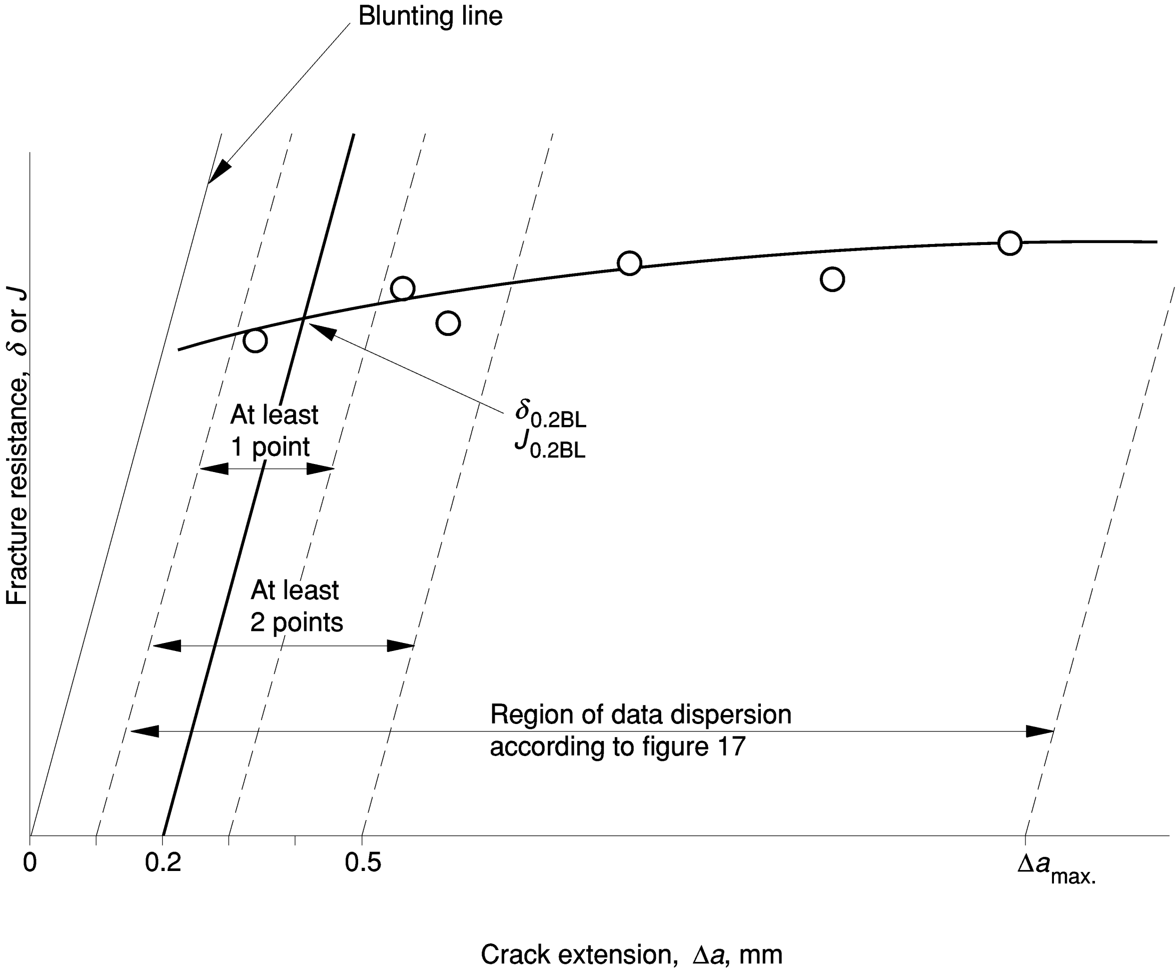
13.3.1.3 If $J_{0.2\text{BL}}$ exceeds J_{max} determined in **12.6.1**, then the value of $J_{0.2\text{BL}}$ calculated in accordance with this method is not acceptable.

13.3.1.4 Determine the slope of the J-Δa curve, $(\mathrm{d}J/\mathrm{d}a)_{0.2\text{BL}}$, at the intersection point from the equation given in **12.4**. If the slope of the blunting line, $(\mathrm{d}J/\mathrm{d}a)_{\text{BL}}$, is less than $2(\mathrm{d}J/\mathrm{d}a)_{0.2\text{BL}}$ then the value of $J_{0.2\text{BL}}$ calculated in accordance with this method is not acceptable.

13.3.2 $J_{0.2}$

13.3.2.1 Construct a line corresponding to constant total crack extension of 0.2 mm on a plot of the J-Δa data. The intersection of this line with the best fit curve through the data obtained as given in **12.4** defines $J_{0.2}$ (see Figure 20). At least one data point shall be between 0.2 mm and 0.4 mm crack extension.

13.3.2.2 If $J_{0.2}$ exceeds J_{max} determined in accordance with **12.6.1**, then the value of $J_{0.2}$ calculated in accordance with this method is not acceptable.



NOTE At least six data points are required.

Figure 19 — Derivation of $\delta_{0.2BL}$ and $J_{0.2BL}$

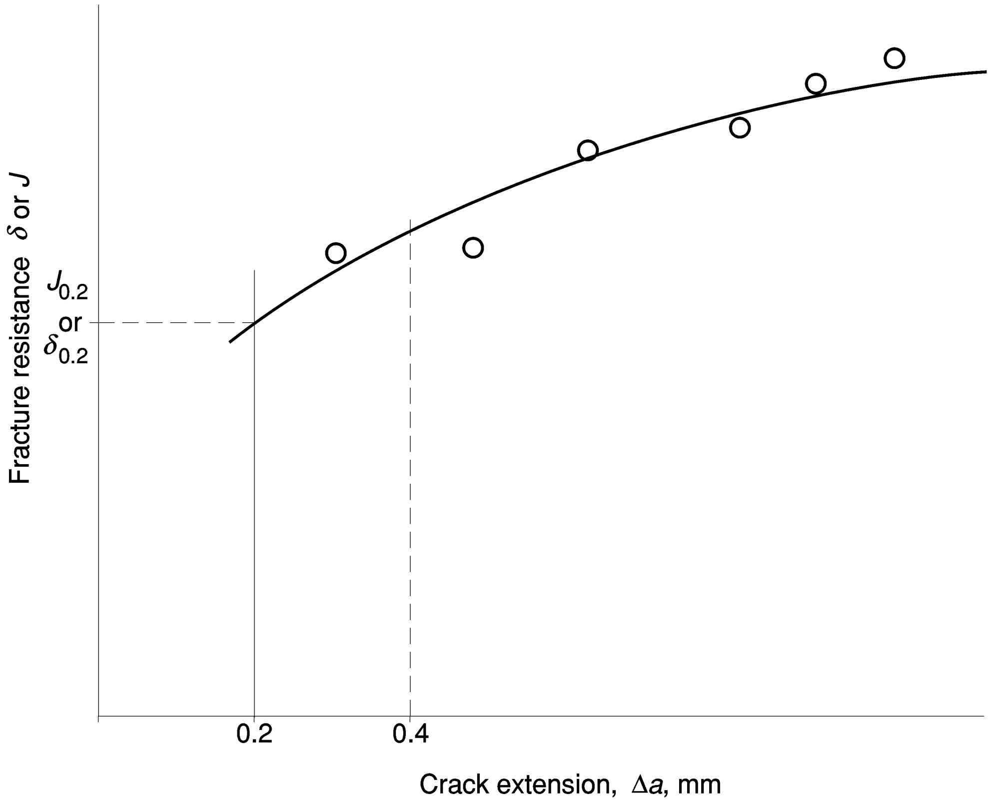


Figure 20 — Derivation of $\delta_{0.2}$ and $J_{0.2}$

14 Check lists for qualification of data

14.1 General

For a determination to be qualified the requirements in **14.2** and **14.3** shall be complied with.

14.2 Specimen dimensions

14.2.1 Before fatigue precracking check that the specimen has the dimensions and tolerances specified in **6.1**.

14.2.2 For specimens that are sidegrooved, check that the dimensions and tolerances are as specified in **6.2**.

14.2.3 For plain sided specimens or specimens fatigue precracked before sidegrooving, check that:

a) the minimum surface crack length (a) is at least 0.45 of the specimen width (W);

b) both ends of the fatigue crack have extended for at least 1.3 mm or 2.5 % of the specimen width (W) from the root of the machined notch, whichever is the greater [see **7.4.6** c)];

c) the difference between the two surface crack length measurements is not greater than 15 % of the average of these two measurements [see **7.4.6** d)];

d) the fatigue precrack is within the appropriate envelope (see Figure 5) on both surfaces of the specimen [see **7.4.6** e)];

14.2.4 After breaking open the specimen following completion of the test, check that:

a) multi-plane fatigue precracking and fracture is not present at the fatigue precrack front;

b) the original crack length (a_0) to specimen width (W) ratio is between 0.45 and 0.70 [see **9.9.2** a)];

c) the difference between a_0 and any of the nine crack length measurements (a_1 to a_9) contributing to a_0 is less than 10 % of a_0 [see **9.9.2**b)];

d) no part of the fatigue precrack front is closer to the crack starter notch than 1.3 mm or 2.5 %W, whichever is the larger [see **9.9.2**c)];

e) the fatigue precrack is within the appropriate envelope for the corresponding a_0/W value [see Figure 5 and **9.9.2**d)].

14.3 Other items

14.3.1 Before starting to analyse the data in accordance with clause **11**, check that:

a) behaviour was fully stable. If unstable fracture or pop-in occurred, then the test and all other nominally identical tests shall be analysed in accordance with BS 7448-1. In such cases, determination of fracture toughness tearing resistance in accordance with this Part of BS 7448 may also be performed, if sufficient R-curve data points are generated prior to the unstable fracture or pop-in. Any specimen which exhibits unstable fracture or pop-in shall be reported in accordance with clause **15**;

b) the fatigue precracking force (F_f) has not exceeded the limits given in **7.4**;

c) the fatigue : force ratio is within the range 0 to 0.1 as specified in **7.4.6** a).

14.3.2 During the R-curve analysis, check that a minimum of one data point lies within each of the four crack extension intervals between Δa = 0.1 mm and $\Delta a_{\max}$ beyond the blunting line (see Figure 17 and **12.3**).

14.3.3 During derivation of the fracture parameters $\delta_{0.2\mathrm{BL}}$ and $J_{0.2\mathrm{BL}}$ check that:

a) one data point is within 0.1 mm crack extension of the 0.2 mm offset line (see **13.2.1.2** and **13.3.1.2**);

$\delta_{0.2\mathrm{BL}} \leq \delta_{\max}$ (see **13.2.1.3**); and/or $J_{0.2\mathrm{BL}} \leq J_{\max}$ (see **13.3.1.3**);

b) $2(\mathrm{d}\delta/\mathrm{d}a)_{0.2\mathrm{BL}} < (\mathrm{d}\delta/\mathrm{d}a)_{\mathrm{BL}}$ (see **13.2.1.4**); and/or

$2(\mathrm{d}J/\mathrm{d}a)_{0.2\mathrm{BL}} < (\mathrm{d}J/\mathrm{d}a)_{\mathrm{BL}}$ (see **13.3.1.4**).

14.3.4 During derivation of the fracture parameters check that:

$\delta_{0.2} \leq \delta_{\max}$ (see **13.2.2.2**); and/or
$J_{0.2} \leq J_{\max}$ (see **13.3.2.2**).

15 Test report

The test report shall show:

a) the number of this British Standard (i.e. BS 7448-4);

b) the identity of the test specimens;

c) the method of single specimen testing used, if applicable;

d) the identity and form of the material tested (e.g. forging, plate, casting), and its condition (see **7.1**);

e) the geometry and main dimensions of the specimens tested (see clause **6** and **9.2**);

f) whether the specimens were full thickness or sub-size;

g) the crack plane orientation (see **7.2**);

h) the fatigue precracking details, including the final F_f and fatigue : force ratio (see **7.4**);

i) the tensile strength (R_{mB}) and 0.2 % proof strength ($R_{p0.2B}$) of the specimen material at the temperature of fatigue precracking;

j) the span (S) used in three-point bend tests (see **9.3.1**), if applicable;

k) the knife edge thickness (which is equal to z) (see **9.2.4**), if applicable;

l) the rate of increase in initial stress intensity factor ($\dot{K}$) (see **9.6**);

m) the force (F) versus notch opening displacement (V) records (see **9.7**), if applicable;

n) the force (F) versus load-line displacement (q) records, (see **9.7**), if applicable;

o) the temperature (T) of the specimen at the time of the test (see **9.5**) and the time period at the test temperature;

p) the tensile strength (R_m) and 0.2 % proof strength ($R_{p0.2}$) of the specimen material at the temperature of the test;

q) any unusual feature of the fracture surface (see **9.9**);

r) a sketch or photograph of the fracture surface showing the original shape and size of the fatigue precrack, the extent of stable crack extension, and any unusual features of the fracture surface (see **9.9.3**);

s) measured original crack length (a_o);

t) non-uniform fatigue precrack if applicable (see **9.9.2**);

u) non-uniform crack extension, if applicable (see **9.9.3**);

v) the J-Δa and/or δ-Δa curves and all data points including details of the exclusion lines and constructional procedure;

w) fracture parameters, $\delta_{0.2BL}$, $\delta_{0.2}$, δ_g, $J_{0.2BL}$, $J_{0.2}$, J_g and Δa_g, as applicable, and their derivation (see clause **12**);

x) any unstable fracture or pop-in behaviour and the appropriate associated fracture toughness in terms of J and/or δ, as applicable, determined in accordance with BS 7448-1;

y) details of any of the above items that fail to conform to the requirements listed in clause **14**;

z) any departure from this standard and the justification for that departure. All resulting data shall be clearly identified.

Annex A (informative)
Bibliography

General

BUZZARD, R.J. and FISHER, D.M. Load displacement measurement and work determination in three point bend tests of notched or pre-cracked specimens. *Journal of Testing and Evaluation*. 1978, **6**(1), 35-39.

DAWES, M.G. Elastic-plastic fracture toughness based on the COD and J-contour integral concepts. *In: Symposium on elastic-plastic fracture,* 1977, ASTM Special Technical Publication 668, p. 307.

EGF P1-92, ESIS (European Structural Integrity Society) *Recommendations for Determining the Fracture Resistance of Ductile Materials*, January 1992.

HELLMANN, D., ROHWERDER, G., and SCHWALBE, K.H. Development of a test set up for measuring deflection of single edge notched bend (SENB) specimens. *Journal of Testing and Evaluation.* 1984, **12**(1), 62-64.

RICE, J.R. A path independent integral and the approximate analysis of strain concentration by notches and cracks. *Journal of Applied Mechanics*. 1968, **35**, 379.

SAXENA, A. and HUDAK, S.J. Review and extension of compliance information for common crack extension specimens. *International Journal of Fracture*. 1978, **14**(5), 453-468.

WILLOUGHBY, A.A. and GARWOOD, S.J. On the unloading compliance method of deriving a single-specimen R-curve in three-point bending. *In: 2nd symposium on elastic-plastic fracture*, 1983, ASTM Special Technical Publication 803, Vol. 2, p. 372.

Single specimen methods (see Annex D)

General

EGF P1-92, 1992, ESIS (European Structural Integrity Society) *Recommendations for Determining the Fracture Resistance of Ductile Materials*, January 1992.

Unloading compliance technique

ASTM Standards, 1992, E813-89, J_{Ic} *a measure of fracture toughness*, Section 3, Vol. 03.01, 732-746.

ASTM Standards, 1992, E1152-87, *Standard test method for determining J-R curves*, Section 3, Vol. 03.01, 847-859.

FUTATO, R.J., AADLAND, J.D., VAN DER SLUYS, W.A. and LOWE, A.L. *A sensitivity study of the unloading compliance single specimen J-test technique*. ASTM Special Technical Publication 856, 1985, pp. 84-103.

GORDON, J.R. *The Welding Institute procedure for the determination of the fracture resistance of fully ductile steels*. TWI Report 275/1985[4].

GORDON, J.R. *An assessment of the accuracy of the unloading compliance method for measuring crack extension resistance curves.* TWI Report 325/1986[4].

HELLMANN, D., ROHWERDER, G., and SCHWALBE, K.-H. Development of a test set up for measuring the deflection of single-edge notch bend (SENB) specimens. *Journal of Testing and Evaluation.* 1984, **12**, 42-44.

MORLAND, E. Validation of fracture mechanics data used in structural integrity assessments. *Nuclear Energy*. 1985, **24**(3), 181-186.

NEALE, B.K., CURRY, D.A., GREEN, G., HAIGH, J.R., and AKHURST, K.N. A procedure for the determination of the fracture resistance of ductile steels. *International Journal of Pressure Vessels and Piping*. 1985, **20**(3), 155-179.

STEENKAMP, P.A.J.M. *J*-R Curve testing of three point bend specimens by the unloading compliance method. *In: 18th National Symposium on Fracture Mechanics*, 1985, ASTM Special Technical Publication 945, 1988.

VOSS, B. 1983, On the problem of “Negative Crack extension” and “Load Relaxation” in single specimen partial unloading compliance tests, CSNI Workshop on Ductile Fracture Test Methods, Paris, 210-219.

---

[4] Enquiries to TWI, Abington Hall, Abington, Cambridge CB1 6AL.

Potential change techniques

BERGER, C. and VAHLE, F., 1982, Application of the DC potential method to prediction of crack initiation, Proceedings of a CSNI Workshop, OECD, Paris, 1-3 December.

DEBEL, C. P. and ADRIAN, F., 1982, Experience with ductile crack extension measurements applying the DC-PD technique to compact tension fracture specimens, Proceedings of a CSNI Workshop, OECD, Paris, 1-3 December.

DIETZEL, W., and SCHWALBE, K.-H. Monitoring stable crack extension using a combined a.c./d.c. potential drop technique. *Material Prufung*. 1986, **28**, 368-372.

DOVER, W.D., and COLLINS, R. Recent advances in the detection and sizing of cracks using alternating current field measurement (A.C.F.M.). *British Journal of Non-destructive Testing.* 1980, **22**, 291-295.

HOLLSTEIN, T., BLAUEL, J.G., and VOSS, B. On the determination of elastic-plastic fracture material parameters: A comparison of different test methods. ASTM Special Technical Publication 856, 1985, 104-116.

JOHNSON, H.H. Calibrating the electric potential method for studying slow crack extension. *Materials Research and Standards.* 1965, **5**, 442-445.

OKOMURA, K., VENKATASUBRAMANIAN, T.V., UNVALA, B.A., and BAKER, T.J. Application of the AC potential drop technique to the determination of R-curves of tough ferritic steels. *Engineering Fracture Mechanics.* 1981, **14**, 617-625.

PRANTL, G: 1982, Assessment of crack extension of different methods, Proceedings of a CSNI Workshop, OECD, Paris, 1-3 December.

ROO, DE P and MARANDET, B 1982, Application of the AC potential method to the detection of initiation in static and dynamic testing, in: *Ductile Fracture Test Methods*, Proceedings of a CSNI Workshop, OECD, Paris, 1-3 December.

SCHWALBE, K.-H., HELLMANN, D., HEERENS, J., KNAACK, J., and MULLER-ROOS, J.: 1985, Measurement of stable crack extension including detection of initiation of growth using the DC potential drop and the partial unloading methods. ASTM Special Technical Publication 856, 1985, 338-362.

SCHWALBE, K.-H., and HELLMANN, D. Application of the electrical potential method to crack length measurements using Johnson's formula. *Journal of Testing and Evaluation.* 1981, **9**, 218-221.

WILKOWSKI, G. M., 1982, Elastic plastic fracture studies using the DC-EP method In: *Ductile Fracture Test Methods,* Proceedings of a CSNI Workshop, OECD, Paris, 1-3 December.

Analytical methods for the determination of V_p and U_p (see Annex E)

GARWOOD, S.J., and WILLOUGHBY, A.A. Fracture toughness measurements on materials exhibiting stable ductile crack extension. In: *Proceedings of the International Conference on Fracture toughness testing— Methods, Interpretation and Application* pp 261-281, The Welding Institute, London, June 1982.

GORDON, J.R. *The Welding Institute procedure for the determination of the fracture resistance of fully ductile metals.* TWI Report No. 275/1985. June 1985.

Offset power law fit to crack extension fracture resistance data (see Annex F)

NEALE, B.K. On the best fit curve through crack growth fracture resistance data. *Fatigue and Fracture of Engineering Materials and Structures.* 1993, **16**(4), 465-472.

Annex B (normative) Crack plane identification

The system of crack plane identification described in this annex shall be used in order to avoid ambiguous interpretation. It is based on an arrangement of three reference axes related to the main stressing direction which are as follows:

X is longitudinal, i.e. parallel to the grain flow.

Y is transverse, i.e. normal to the X and Z axes.

Z is short transverse i.e. coincident with the thickness direction.

Using a two-letter code, the first letter indicates the direction perpendicular to the crack plane and the second the direction of crack front movement. Thus X-Z represents a crack in a longitudinal specimen moving in a short transverse direction. Figure B.1 shows the system applied to a rectangular section.

In order to identify crack planes in cylindrical sections the same code system shall be applied. This system is illustrated in Figure B.2.

Cracks orientated in planes not coincident with two of the reference axes shall be similarly referenced. When the plane of the crack is coincident with a primary reference with direction of propagation at an angle to the other two, the combination can be written X-YZ where the specimen is longitudinal and the direction transverse/short transverse. Similarly a skewed plane but primary direction could be represented by YZ-X. Examples are shown in Figure B.3.

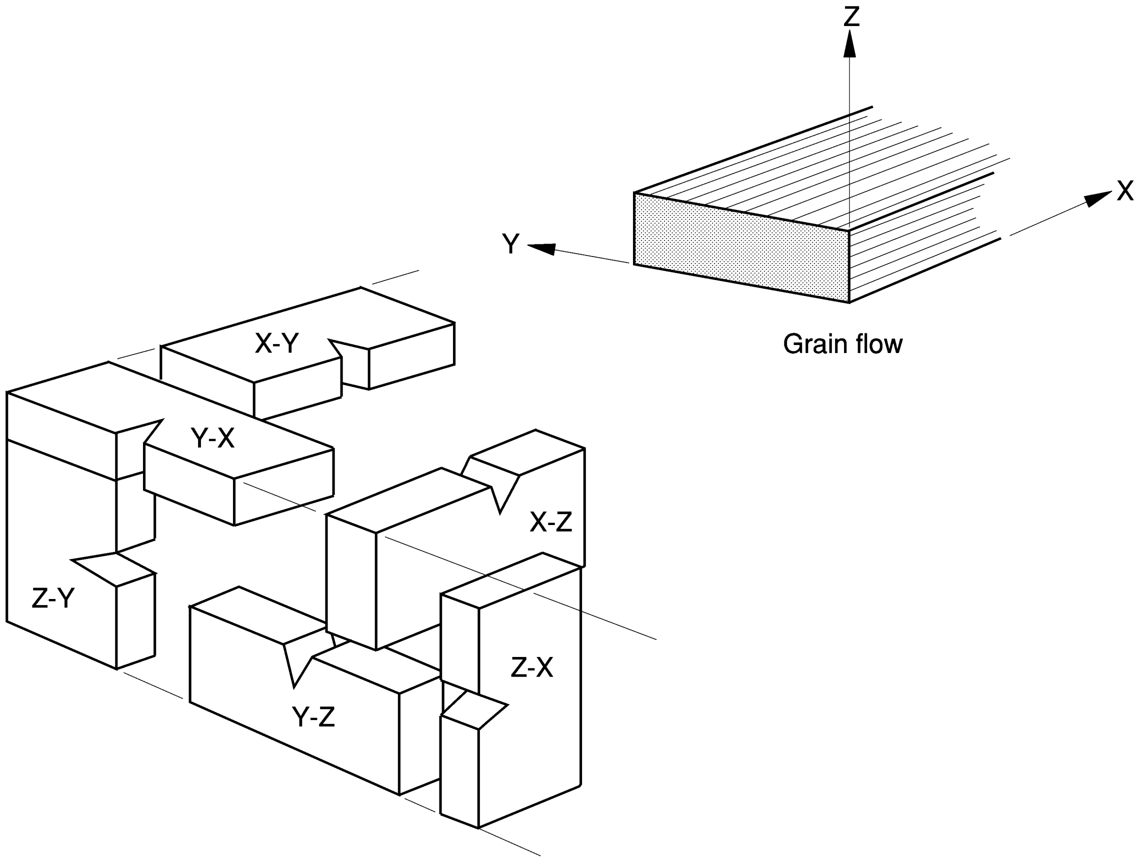
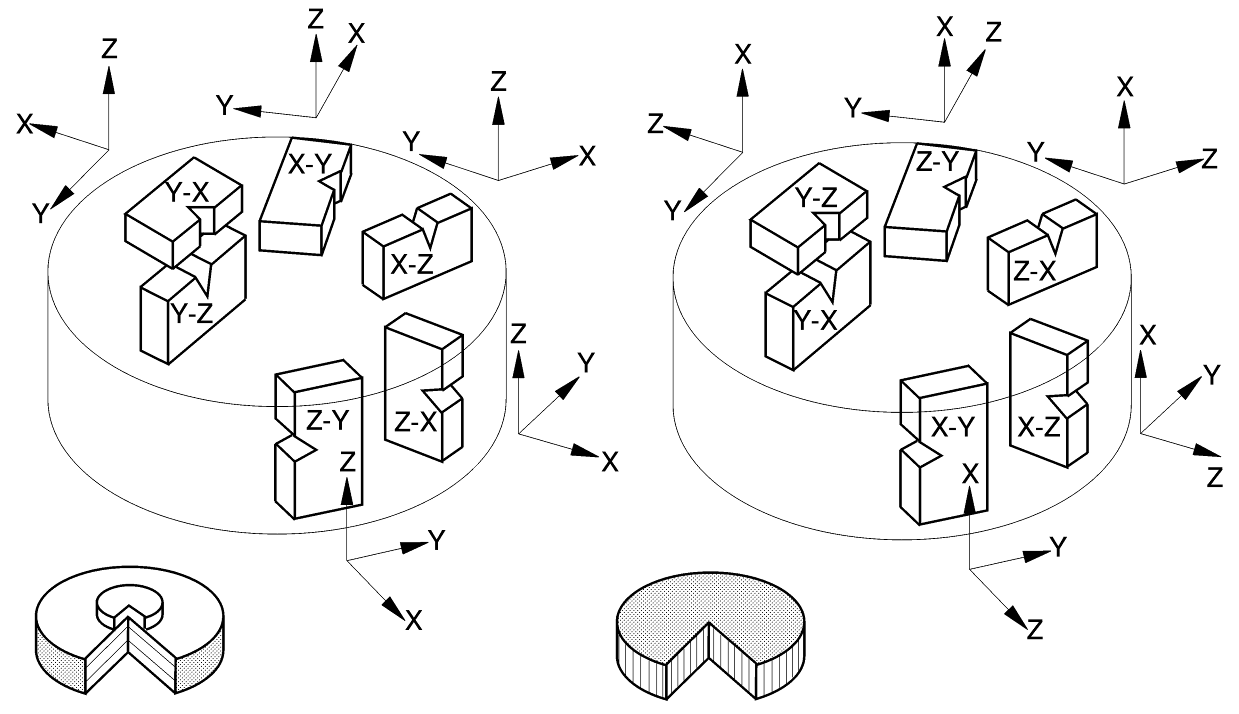


Figure B.1 — Basic fracture plane identification: rectangular section



a) Radial grain flow, axial working direction

b) Axial grain flow, radial working direction

Figure B.2 — Basic fracture plane identification: cylindrical sections

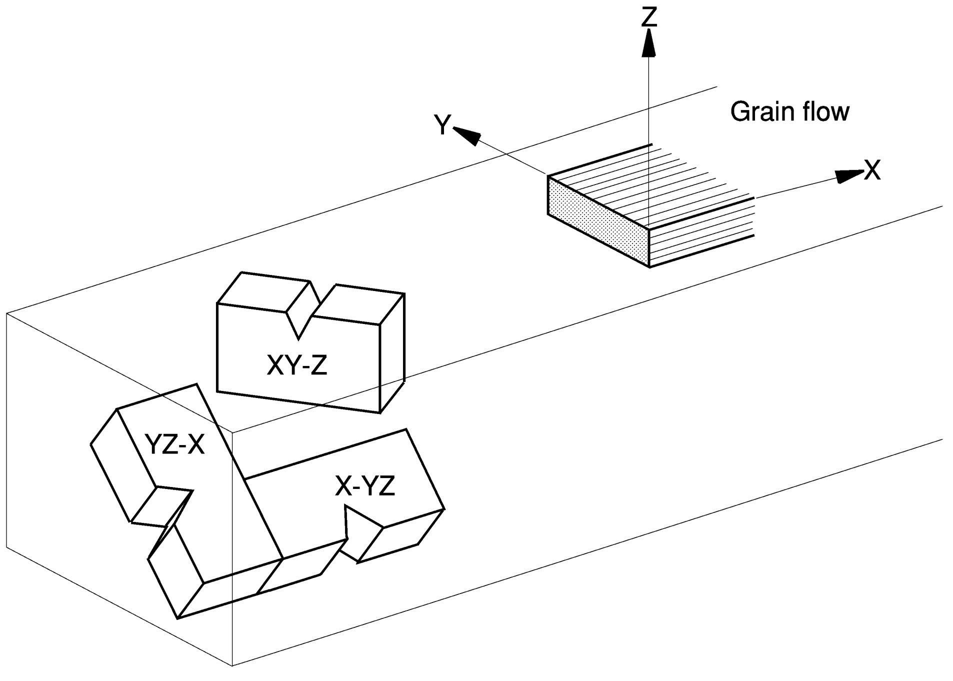


Figure B.3 — Non-basic fracture plane identification

Annex C (informative) Measurement of load-line displacement, q, in a three-point bend test

As described in **11.3**, the method of calculating critical J values requires the measurement of the area under a force (F) versus load-line displacement (q) record (see Figure 16). However, unlike the situation when testing a stepped notch compact specimen (see Figure 4 and **9.4**), it is difficult to obtain direct measurements of load-line displacement for a three-point bend specimen (see Figure 2 and **9.3**). The difficulty is in separating the true load-line displacements of the specimen from the elastic plastic displacements in the specimen under the three loading points, and also the elastic displacements in the loading fixtures and testing machine. These extraneous displacements are additive, so that measurements of machine ram or crosshead displacement, or relative displacements between the specimen and testing machine will overestimate the true load-line displacement. The extent of such an overestimate will vary with the specimen material, condition and temperature and also the dimensions of the specimen, loading fixtures and testing machine.

The only way to obtain load-line displacement directly, is to measure the relative movement of appropriate points on the specimen. This can be done for example, by measuring the vertical displacement of the notch tip relative to a horizontal line that is a fixed distance from the undeformed edge of the specimen near the outer loading points. This type of direct measurement may be obtained by using a horizontal “comparator” bar [1], [2], and measuring the vertical displacement of the bar relative to the notch tip, or notch mouth as shown schematically in Figure C.1.

NOTE Measurements to the notch mouth (see Figure C.1) represent the load-line displacement (q) to an accuracy of better than ± 2 % for q equal to or less than $0.14W$, which corresponds to a total notch opening angle of 8°.

An indirect measurement of load-line displacement can be obtained by measuring the extraneous displacements separately, and then subtracting them from the machine crosshead displacement. Thus, referring to the measurements in Figure C.2, it can be seen that the load-line displacement (q) at any particular force (F) will be given by $q = \Delta - \Delta_1 - \Delta_2$. If preferred, the total extraneous displacement ($\Delta_1 + \Delta_2$) can be measured with the loading points close together, as shown in Figure C.3.

An alternative indirect measurement of load-line displacement can be obtained from two measurements of notch opening displacement. For example, using one notch opening displacement gauge located near the notch mouth, and a second located above the notch mouth (see Figure C.4), the load-line displacement may be determined from the following equation [3]:

$$q = \frac{S(V_2 - V_1)}{4(z_2 - z_1)} \qquad \text{(C.1)}$$

Equation (C.1) assumes that the bend specimen deforms as two rigid halves about a centre of rotation, and that S is the actual span (this may vary during a test), under these conditions equation (C.1) would underestimate q by less than 1 % for $\theta < 8°$. For $\theta \geq 8°$, the load line displacement may be estimated with similar accuracy from:

$$q = \frac{S}{2}\tan\left(\arcsin\left[\frac{(V_2 - V_1)}{2\,(z_2 - z_1)}\right]\right) \qquad \text{(C.2)}$$

Reference [4] also gives further details on a suitable method of measuring extraneous displacement for single edge notch bend specimens.

If the displacement is measured on the front face of a compact specimen, a suitable relationship to determine load-line displacement is given in reference [5].

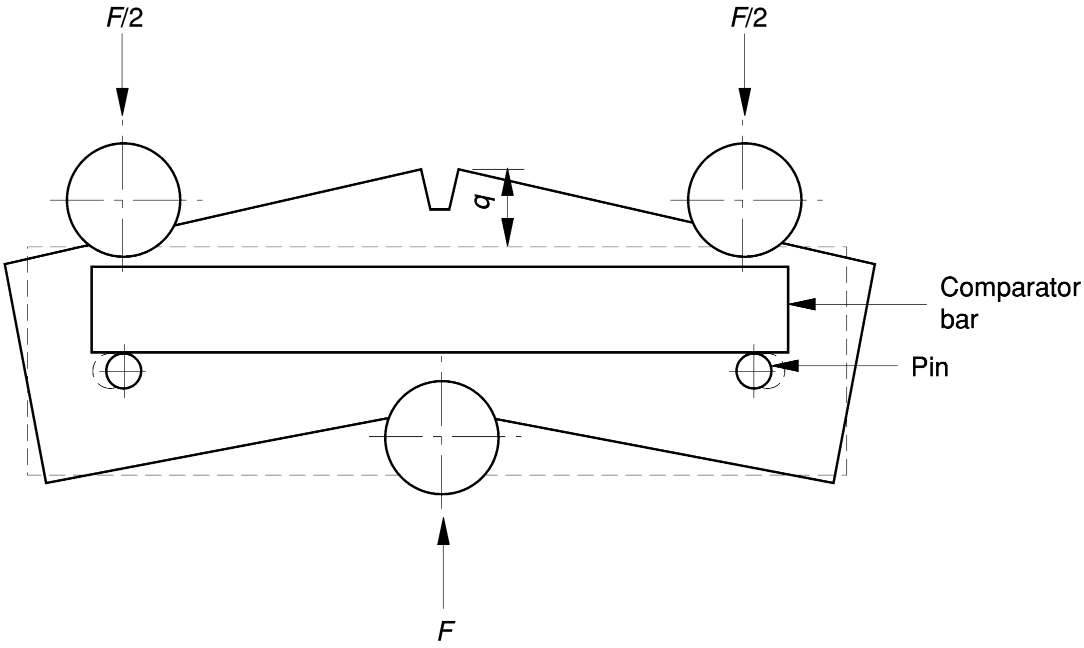
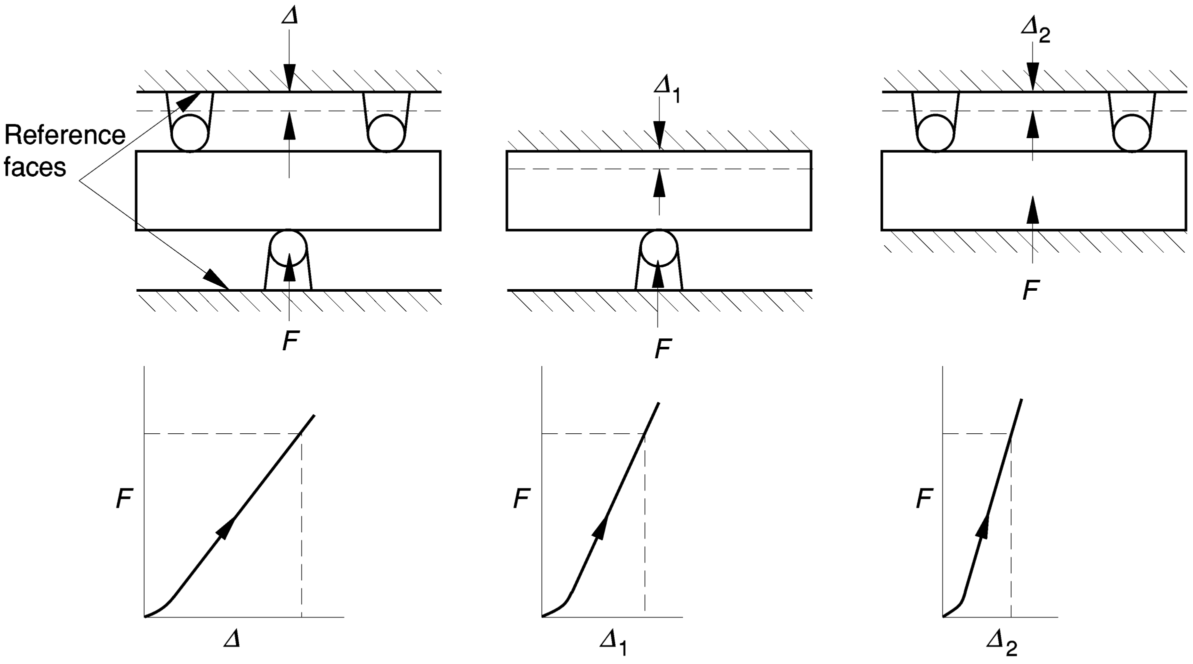


Figure C.1 — Schematic representation of the "comparator" bar



a) Crosshead displacement, Δ

b) Elastic plastic indentation of specimen and compression of central roller and anvil, Δ_1

c) Elastic plastic indentation of specimen and compression of outer rollers and anvils, Δ_2

Figure C.2 — Displacements associated with single edge notch bend specimens

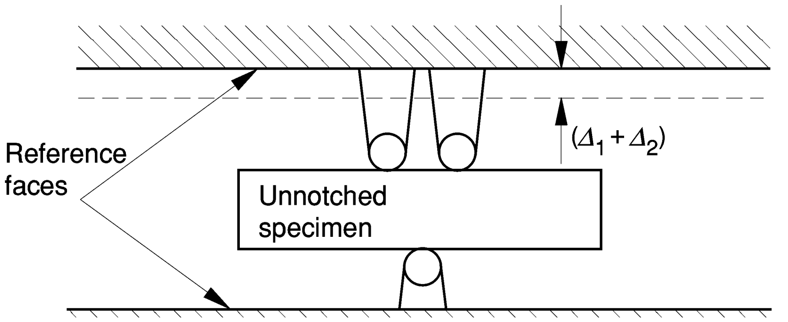


Figure C.3 — Determination of extraneous displacements for single edge notch bend specimens

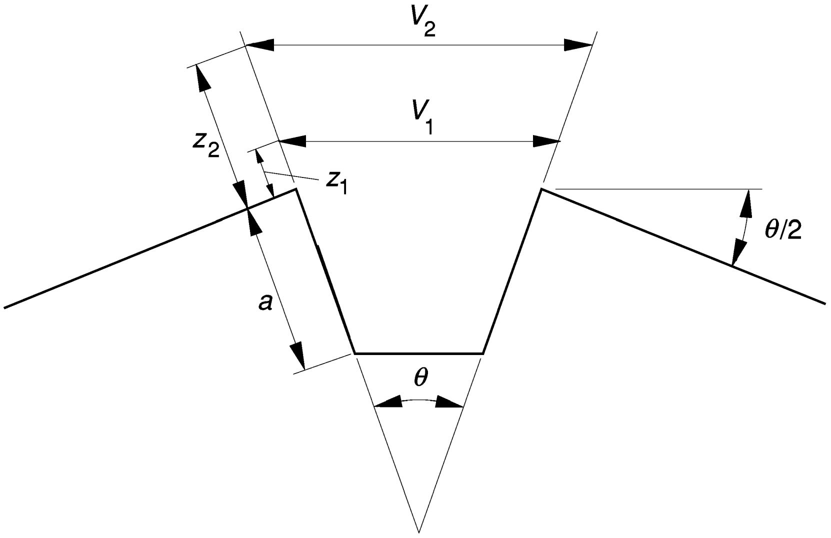


Figure C.4 — Location of two notch opening displacement measurements (V_1 and V_2) for the determination of load-line displacement

Annex D (informative) Single specimen methods

NOTE References giving methods for measuring crack extension in a specimen based on the unloading compliance and potential change techniques are listed in the bibliography in Annex A.

Any single specimen test method may be used provided it conforms to the qualification requirements given in **10.3** and the test requirements given in clause **8**.

In the unloading compliance technique, a specimen is partially unloaded and then reloaded at specified intervals during the test. The unloading slopes, which tend to be linear and independent of prior plastic deformation, are used to estimate the crack length at each unloading from analytical elastic compliance relationships.

The potential change technique relies on the fact that the potential distribution in the vicinity of a crack changes with crack extension. With suitable instrumentation, the changes in potential can be detected and calibrated to provide an estimate of increase in the crack length. The applied potential is either direct or alternating and the technique is referred to as either the d.c. or the a.c. potential change technique, respectively.

Both techniques are ideally suited to computer control and subsequent analysis of the test data. However, it should be noted that they require careful experimentation and sophisticated test equipment in order to realize their full potential. The tests should be controlled using either the transducer monitoring notch mouth opening or load line displacement.

There is a fundamental difference between multiple and single specimen test methods. The multiple specimen method gives only an average of the crack extension resistance behaviour and of the initiation parameters. The single specimen method gives individual results which can provide information on material homogeneity.

Annex E (normative)
Analytical methods for the determination of V_p and U_p

E.1 The analytical methods are based on elastic compliance relationships.

E.2 The plastic component of notch opening displacement, V_p, (see Figure 15) can be determined from the total notch opening displacement, V, at the point of interest using the relationship:

$$V_p = V - V_e \tag{E.1}$$

where

V_e is given by one of the following equations, as applicable.

a) For three point single edge notch bend specimens:

$$V_e = V_{e1}\left\{1 + \left(\frac{z}{0.8a + 0.2W}\right)\right\} \text{ for cases where } \frac{z}{a} \leq 0.2 \tag{E.2}$$

where V_{e1} is the elastic component of the notch mouth opening displacement and is given by the following equation:

$$V_{e1} = \frac{FS\,(1 - \nu^2)}{EB_{\text{eff}}W} \times 6\left(\frac{a}{W}\right)\left[0.76 - 2.28\left(\frac{a}{W}\right) + 3.87\left(\frac{a}{W}\right)^2 - 2.04\left(\frac{a}{W}\right)^3 + \frac{0.66}{\{1 - (a/W)\}^2}\right] \tag{E.3}$$

where

$$B_{\text{eff}} = B - \frac{(B - B_N)^2}{B} \tag{E.4}$$

b) For stepped notch compact specimens:

$$V_e = q_{e2}\left\{1 + \left(\frac{z}{0.8a + 0.2W}\right)\right\} \text{ for cases where } \frac{z}{a} \leq 0.2 \tag{E.5}$$

where q_{e2} is the elastic component of the load-line displacement, and is given by the following equation:

$$q_{e2} = \frac{F\,(1 - \nu^2)}{EB_{\text{eff}}} \times \left(\frac{W + a}{W - a}\right)^2 \times \left\{2.163 + 12.219\left(\frac{a}{W}\right) - 20.065\left(\frac{a}{W}\right)^2 - 0.9925\left(\frac{a}{W}\right)^3 + 20.609\left(\frac{a}{W}\right)^4 - 9.9314\left(\frac{a}{W}\right)^5\right\} \tag{E.6}$$

where

B_{eff} is as given in equation (E.4).

c) For straight notch compact specimens:

$$V_e = V_{e2}\left\{1 + \left(\frac{z}{0.8a + 0.45W}\right)\right\} \text{ for cases where } \frac{z}{a + 0.45W} \leq 0.2 \qquad \text{(E.7)}$$

where V_{e2} is the elastic component of the notch mouth opening displacement, and is given by the following equation:

$$V_{e2} = \frac{F\,(1 - \nu^2)}{EB_{\text{eff}}} \times \left\{\frac{19.75}{1 - (a/W)^2}\right\}\left\{0.5 + 0.192\left(\frac{a}{W}\right) + 1.385\left(\frac{a}{W}\right)^2 - 2.919\left(\frac{a}{W}\right)^3 + 1.842\left(\frac{a}{W}\right)^4\right\} \qquad \text{(E.8)}$$

where

B_{eff} is as given in equation (E.4).

E.3 The plastic component of the area under the plot of force versus specimen displacement along the load-line, U_p, (see Figure 16) shall be determined from the total area U up to the point of interest using the relationship:

$$U_p = U - U_e \qquad \text{(E.9)}$$

where

U_e is given by one of the following equations, as applicable.

a) For three point single edge notch bend specimens:

$$U_e = \frac{F \times q_{e1}}{2} \qquad \text{(E.10)}$$

where q_{e1} is the elastic component of the load-line displacement, and is given by the following equation:

$$q_{e1} = \frac{F\,(1 - \nu^2)}{EB_{\text{eff}}} \times \left(\frac{S}{W - a}\right)^2 \times \left\{1.193 - 1.980\left(\frac{a}{W}\right) + 4.478\left(\frac{a}{W}\right)^2 - 4.443\left(\frac{a}{W}\right)^3 + 1.739\left(\frac{a}{W}\right)^4\right\} \qquad \text{(E.11)}$$

where B_{eff} is as given in equation (E.4).

b) For stepped notch compact specimens:

$$U_e = \frac{Fq_{e2}}{2} \qquad \text{(E.12)}$$

where q_{e2} is as given in equation (E.6).

Annex F (normative)
Offset power law fit to crack extension fracture resistance data

NOTE A reference regarding the use of the offset power law is given in the bibliography in Annex A.

F.1 General

The offset power law to be fitted to crack extension fracture resistance data is of the general form:

$$y = m + l(\Delta a)^x \qquad \text{(F.1)}$$

where

y	is either J or δ;
Δa	is the crack extension;
l, m and x	are constants the values of which have to be determined.

The advantage of the offset power law is that it can simplify to either a straight line when x is 1 or a power law when m is zero. If l, m and x are all non-zero the fitted line is of the form shown in Figure F.1.

F.2 Determination of constants l, m and x

F.2.1 The constants l, m and x can be determined using the methods given in **F.2.2** and **F.2.3**.

F.2.2 Take values of x from 0.01 up to and including 1.00 in steps of 0.01. For each value of x calculate the correlation coefficient r from the following equation:

$$r = \left[\sum \{y_i\ (\Delta a_i)^x\} - \frac{\sum \Delta a_i^x \sum y_i}{k}\right]\left[\left\{\sum y_i^2 - \frac{(\sum y_i)^2}{k}\right\}\left\{\sum \Delta a_i^{2x} - \frac{(\sum a_i^x)^2}{k}\right\}\right]^{-0.5} \tag{F.2}$$

where

k is the number of data points.

The best fit is given by the value of x which maximizes the correlation coefficient.

F.2.3 Having determined x, calculate m and l from the following equations:

$$l = \left\{\sum y_i^2 - \frac{(\sum y_i)^2}{k}\right\}^{0.5}\left\{\sum \Delta a_i^{2x} - \frac{(\sum \Delta a_i^x)^2}{k}\right\}^{-0.5} \tag{F.3}$$

and

$$m = \frac{(\sum y_i - l \sum \Delta a_i^x)}{k} \tag{F.4}$$

The slope l minimizes the sum of the squares of the perpendicular distances from the best fit line.

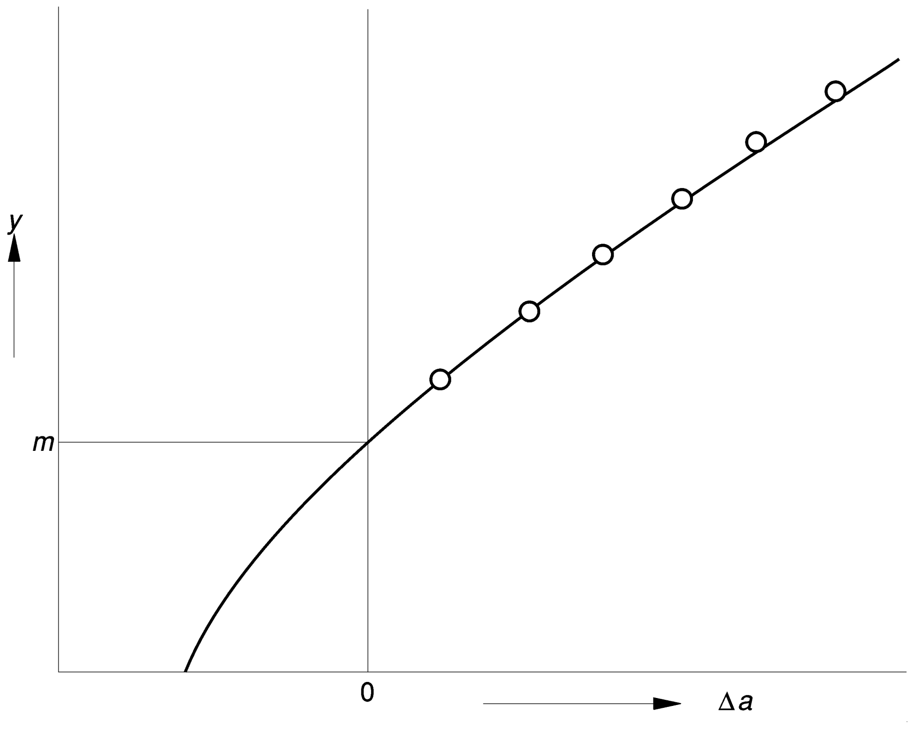


Figure F.1 — General form of the offset power law expression $y = m + l(\Delta a)^x$

List of references (see clause **2**)

Normative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 1610, *Materials testing machines and force verification equipment.*

BS 1610-1:1992, *Specification for the grading of the forces applied by materials testing machines when used in the compression mode.*

BS 7448, *Fracture mechanics toughness tests.*

BS 7448-1:1991, *Method for determination of* K_{Ic}, *critical CTOD and critical J values of metallic materials.*

BS EN 10002, *Tensile testing of metallic materials.*

BS EN 10002-2:1992, *Verification of the force measuring system of the tensile testing machine.*

BS EN 10002-4:1995, *Verification of extensometers used in uniaxial testing.*

Informative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 427:1990, *Method for Vickers hardness test and for verifications of Vickers hardness testing machines.*

Other references

[1] DAWES, M. G. Elastic-plastic fracture toughness based on the COD and J-contour integral concepts. In: *Symposium on elastic-plastic fracture*, 1977, ASTM Special Technical Publication 668 p.307.

[2] HELLMANN, D., ROHWERDER, G. and SCHWALBE, K. H. Development of a test set up for measuring deflection of single edge notched bend (SENB) specimens. *Journal of Testing and Evaluation*, 1984, **12**(1), 62-64.

[3] WILLOUGHBY, A. A. and GARWOOD, S. J. On the unloading compliance method of deriving a single-specimen R-curve in three-point bending. In: *2nd symposium on elastic-plastic fracture*, 1983, ASTM Special Technical Publication 803, Vol.2, p.372.

[4] BUZZARD, R. J. and FISHER, D.M. Load displacement measurement and work determination in three point bend tests of notched or pre-cracked specimens. *Journal of Testing and Evaluation*, 1978, **6**(1), 35-39.

[5] SAXENA, A. and HUDAK, S. J. Review and extension of compliance information for common crack extension specimens *International Journal of Fracture*. 1978, **14**(5), 453-468.

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