



BSI Standards Publication

Guide to methods for assessing the acceptability of flaws in metallic structures

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© The British Standards Institution 2025
Published by BSI Standards Limited 2025

ISBN 978 0 539 33282 7

ICS 25.160.40

The following BSI references relate to the work on this standard:

Committee reference WEE/37

Draft for comment 19/30369477 DC

Amendments/corrigenda issued since publication	
Date	Text affected
January 2025	C1. See Foreword for details

Contents

Foreword *ix*

0	Introduction	0/1
1	Scope	1/1
2	Normative references	1/1
3	Symbols and definitions	1/1
4	Types of flaw	4/1
5	General guidance on assessment	5/1
5.1	Modes of failure and material damage mechanisms	5/1
5.2	Sequence of assessment	5/2
5.3	Fracture assessment options	5/3
6	Information required for assessment	6/1
6.0	Symbols and definitions	6/1
6.1	General	6/1
6.2	Essential data	6/2
6.3	Non-destructive testing	6/2
6.4	Stresses to be considered	6/4
7	Assessment for fracture resistance	7/1
7.0	Symbols and definitions	7/1
7.1	Background	7/4
7.2	Procedure	7/32
7.3	Assessment (Options 1 to 3)	7/34
7.4	Further points	7/39
8	Assessment for fatigue	8/1
8.0	Symbols and definitions	8/1
8.1	Assessment procedures	8/3
8.2	Data required for assessment	8/7
8.3	Probability of survival	8/14
8.4	General procedure for fracture mechanics assessment of planar flaws	8/15
8.5	Basis of procedure for assessing flaws using quality categories	8/16
8.6	Assessment of planar flaws using quality categories	8/19
8.7	Assessment of embedded non-planar flaws using quality categories	8/37
8.8	Assessment of shape imperfections using quality categories	8/39
8.9	Estimation of tolerable sizes of flaws	8/41
9	Assessment of flaws under creep and creep/fatigue conditions	9/1
9.0	Symbols and definitions	9/1
9.1	General	9/3
9.2	Background to methods	9/4
9.3	Background to assessments	9/4
9.4	Factors involved in the safe use of the procedure	9/5
9.5	Creep exemption criteria	9/5
9.6	Creep-fatigue exemption criteria	9/8
9.7	Crack behaviour at high temperature	9/9
9.8	Assessment of components containing a known or postulated defect	9/11
9.9	Further guidance on the assessment procedure	9/15
9.10	Basic calculations	9/17
9.11	Material data for predicting crack initiation and growth under creep and creep/fatigue	9/19
9.12	Guidance on performing assessment calculations	9/20
9.13	Assess significance of results	9/22
10	Assessment for other modes of failure	10/1
10.0	Symbols and definitions	10/1
10.1	Yielding due to overloading of remaining cross-section	10/1
10.2	Leakage in pressure, liquid or vacuum containing equipment	10/2

10.3 Environmental effects 10/2

10.4 Instability (buckling) 10/7

Annexes

Annex A (informative) Evaluation under mode I, II and III loads A/1

Annex B (informative) Assessment procedures for tubular joints in offshore structures B/1

Annex C (informative) Assessment procedures for pressure vessels and pipelines C/1

Annex D (informative) Stress due to misalignment D/1

Annex E (informative) Flaw recharacterization E/1

Annex F (informative) Procedure for leak-before-break (LbB) assessment F/1

Annex G (informative) The assessment of locally thinned areas (LTAs) G/1

Annex H (informative) Reporting of assessments H/1

Annex I (informative) The significance of strength mismatch on the fracture behaviour of welded joints I/1

Annex J (informative) Use of Charpy V-notch impact tests to estimate fracture toughness J/1

Annex K (informative) Probabilistic assessment K/1

Annex L (informative) Fracture toughness determination for welds L/1

Annex M (informative) Stress intensity factor solutions M/1

Annex N (informative) Allowance for constraint effects N/1

Annex O (informative) Consideration of proof testing and warm prestressing O/1

Annex P (informative) Compendium of reference stress and limit load solutions for homogeneous and strength mismatched structures P/1

Annex Q (informative) Residual stress distributions in as-welded joints Q/1

Annex R (informative) Determination of plasticity interaction effects with combined primary and secondary loading R/1

Annex S (informative) Information for making high temperature crack growth assessments S/1

Annex T (informative) Guidance on the use of NDT with ECA T/1

Annex U (informative) Worked examples in fatigue assessment using the quality category approach U/1

Annex V (informative) Strain-based assessment (SBA) V/1

List of figures

Figure 0.1 – Example of integrity management procedure for flaws 0/2

Figure 6.1 – Linearization of stress distributions 6/5

Figure 6.2 – Procedure for resolving flaws normal to principal stress 6/8

Figure 7.1 – General flowchart for fracture assessment 7/5

Figure 7.2 – Flowchart for Option 1 fracture assessment 7/6

Figure 7.3 – Flowchart for Option 2 fracture assessment 7/7

Figure 7.4 – Flowchart for Option 3 fracture assessment 7/8

Figure 7.5 – Flowchart for flaw characterization 7/10

Figure 7.6 – Definitions of flaw dimensions 7/11

Figure 7.7 – Flaw alignment rules for non-coplanar flaws 7/12

Figure 7.8 – Flaw interaction rules for coplanar flaws 7/13

Figure 7.9 – Definition of terms used in tensile testing 7/15

Figure 7.10 – De-rating values for yield/proof strength and tensile strength at temperatures above room temperature in C-Mn steels and duplex stainless steels 7/17

Figure 7.11 – Treatment of sets of between three and five tests 7/25

Figure 7.12 – Treatment of sets of more than six tests 7/26

Figure 7.13 – Example of a Failure Assessment Diagram 7/34

Figure 7.14 – Ductile tearing assessment 7/38

Figure 7.15 – Example of non-unique solutions 7/40

Figure 8.1 – Schematic crack growth relationships 8/6

Figure 8.2 – Recommended fatigue crack growth laws 8/11

Figure 8.3 – Quality category S-N curves 8/17

- Figure 8.4 – Quality category approach: assessment of surface flaws in plates under axial loading 8/22
- Figure 8.5 – Quality category approach: assessment of surface flaws in plates (no weld toe or other stress raiser) in bending 8/24
- Figure 8.6 – Quality category approach: assessment of embedded flaws in axially loaded joints 8/26
- Figure 8.7 – Quality category approach: assessment of weld toe flaws in axially loaded joints 8/28
- Figure 8.8 – Quality category approach: assessment of weld toe flaws in joints loaded in bending 8/34
- Figure 9.1 – Determination of temperature T_c at which 0.2% creep strain is accumulated at a stress level equal to the proof strength 9/7
- Figure 9.2 – Insignificant creep curves for austenitic steels 9/8
- Figure 9.3 – Insignificant creep curves for ferritic steels 9/8
- Figure 9.4 – Schematic behaviour of crack subjected to steady loading at elevated temperature 9/10
- Figure 9.5 – Schematic representation of crack propagation and failure conditions 9/11
- Figure 9.6 – Flowchart for overall creep assessment procedure described in 9.8.2 9/12
- Figure 10.1 – Schematic diagrams of typical relationships between crack velocity and stress intensity factor during SCC 10/4
- Figure 10.2 – Types of corrosion fatigue crack growth behaviour 10/6
- Figure A.1 – Definitions of loading modes A/2
- Figure B.1 – Assessment method for fatigue crack growth in tubular joints B/4
- Figure E.1 – Flowchart for recharacterization of flaws E/2
- Figure E.2 – Rules for recharacterization of flaws E/3
- Figure F.1 – The leak-before-break diagram F/4
- Figure F.2 – Flowchart for LbB procedure F/6
- Figure G.1 – Flowchart of assessment procedure G/4
- Figure G.2 – Dimensions of an LTA G/5
- Figure G.3 – Dimensions of a bend G/6
- Figure G.4 – Dimensions of a sphere and vessel end G/7
- Figure G.5 – Interaction between LTAs G/9
- Figure I.1 – Idealized weld geometry – the parent and weld metals have yield strengths of σ_Y^W and σ_Y^P respectively I/4
- Figure I.2 – Idealized definition of mismatch ratio, M , and construction of the equivalent stress-strain curve (weighted average of the other two curves) I/5
- Figure J.1 – Flowchart for selecting an appropriate correlation for estimating fracture toughness from Charpy data J/3
- Figure M.1 – Through-thickness flaw geometry M/5
- Figure M.2 – Edge flaw geometry M/5
- Figure M.3 – Surface flaw M/6
- Figure M.4 – Stress intensity magnification factor M_m for surface flaws in tension M/8
- Figure M.5 – Stress intensity magnification factor M_b for surface flaws in bending M/10
- Figure M.6 – Finite surface flaw in an infinite width plate M/11
- Figure M.7 – Extended flaw geometry M/15
- Figure M.8 – Extended surface flaw in an infinite width plate M/16
- Figure M.9 – Embedded flaw M/17
- Figure M.10 – Stress intensity magnification factor M_m for embedded flaws in tension (at point nearest material surface) M/18
- Figure M.11 – Stress intensity magnification factor M_b for embedded flaws in bending M/20
- Figure M.12 – Corner flaw geometry M/21
- Figure M.13 – Corner flaw at hole geometry M/23
- Figure M.14 – Through-thickness flaw in cylinder oriented axially M/27
- Figure M.15 – Internal surface flaw in cylinder oriented axially M/32

- Figure M.16 – Extended internal surface flaw in cylinder orientated axially M/34
- Figure M.17 – External surface flaw in cylinder oriented axially M/35
- Figure M.18 – Extended axial external surface flaw in cylinder M/36
- Figure M.19 – Through-thickness flaw in cylinder oriented circumferentially M/38
- Figure M.20 – Internal surface flaw in cylinder oriented circumferentially M/43
- Figure M.21 – Extended internal surface flaw in cylinder M/45
- Figure M.22 – Extended external surface flaw in cylinder M/46
- Figure M.23 – Through-thickness flaw in spherical shell M/49
- Figure M.24 – Flaws in bars and bolts M/50
- Figure M.25 – Fully circumferential flaw in a round bar M/54
- Figure M.26 – Welded joint geometries M/55
- Figure M.27 – Transverse load-carrying cruciform joint M/56
- Figure N.1 – Schematic showing curve fitting of low constraint test data to obtain a and k N/9
- Figure N.2 – Modifications to the Option 1 failure assessment curve (continuous yielding) for various values of the material parameter, a , and constraint levels, β (< 0) N/11
- Figure N.3 – FAD analysis for (a) fracture initiation and (b) ductile tearing N/12
- Figure O.1 – Schematic illustration of a proof test argument O/4
- Figure O.2 – Typical warm prestress cycles O/6
- Figure P.1 – Double edge cracked plate under tension P/8
- Figure P.2 – Extended embedded flaw in a plate P/10
- Figure P.3 – Circumferential internal and external surface flaws in thick-walled cylinders under combined tension and bending P/19
- Figure P.4 – Classification of plasticity deformation patterns for mismatched structures P/22
- Figure P.5 – Centre cracked plate under tension P/26
- Figure P.6 – Double edge cracked plate under tension P/29
- Figure P.7 – Single edge cracked plate under in-plane bending P/33
- Figure P.8 – Fully circumferential internal flaw in thin-walled pipe/cylinder under tension P/35
- Figure P.9 – Centre through-thickness crack in a clad plate under tension P/36
- Figure Q.1 – Components of longitudinal residual stress distribution for plate butt welds and pipe axial seam welds (austenitic steel) Q/4
- Figure Q.2 – Components of transverse stress distribution for plate butt welds and axial seam welds (austenitic and ferritic steels) Q/5
- Figure Q.3 – Components of longitudinal stress distribution for pipe butt welds (ferritic and austenitic steels) Q/6
- Figure Q.4 – Components of transverse stress distribution for pipe butt welds (ferritic steels) Q/7
- Figure Q.5 – Components of longitudinal stress distribution for plate to plate T-butt welds (ferritic steels) Q/10
- Figure Q.6 – Components of transverse stress distribution for plate to plate T-butt welds (austenitic and ferritic steels) Q/12
- Figure Q.7 – Components of longitudinal stress distribution for tubular T-butt welds (ferritic steels) Q/13
- Figure Q.8 – Components of transverse stress distribution for tubular T-butt welds (ferritic steels) Q/14
- Figure Q.9 – Residual stress profile for repair welds (transverse and longitudinal) Q/15
- Figure S.1 – General form of a creep curve defining the average and secondary creep strain rates S/2
- Figure S.2 – General form of a creep curve defining the average and secondary creep strain rates S/3
- Figure T.1 – Assessment of flaw tolerance using ECA T/5
- Figure T.2 – Assessment of detected flaw T/6
- Figure U.1 – Butt weld containing embedded flaw U/2
- Figure U.2 – Derivation of actual quality category for a flaw U/3

Figure U.3 – Fillet weld containing a surface flaw U/4

Figure U.4 – Derivation of actual quality category for a flaw U/5

Figure U.5 – Obtaining the quality category for the flaw U/6

Figure V.1 – Flowchart for a strain-based assessment (SBA) using the methods of Annex V V/7

Figure V.2 – Distribution of stress and strain across the location of the flaw being assessed from an uncracked stress analysis V/8

Figure V.3 – Derivation of the reference stress, σ_{ref} , and the reference strain, ϵ_{ref} , from the applied nominal strain, ϵ_{nom} , and the material true stress-true strain curve V/8

Figure V.4 – Derivation of the flow strain, ϵ_f , from the material flow strength, σ_f , using the true stress-true strain curve V/9

Figure V.5 – Single edge-notched tension (SENT) specimen V/10

Figure V.6 – SBA FAL together with tearing lines used to determine the instability load level for a 0.4 mm deep flaw in a SENT specimen loaded in tension. V/12

List of tables

Table 7.1 – Engineering definitions of yield and tensile strengths for Options 1, 2, 3 7/14

Table 7.2 – Coefficient of variation (COV) for tensile properties for ferritic steels 7/16

Table 7.3 – Elastic modulus 7/16

Table 7.4 – Guidance for determining whether yielding is continuous or discontinuous in rolled steel plate 7/19

Table 7.5 – Minimum of three equivalent (MOTE) 7/27

Table 7.6 – Values of $k_{0.90}$ at the lower 20th percentile for the one-sided tolerance limit for a normal distribution 7/28

Table 7.7 – Limits for slag inclusions and porosity 7/40

Table 8.1 – Procedure for assessment of known flaws 8/4

Table 8.2 – Stress ranges used in fatigue assessments 8/8

Table 8.3 – Recommended fatigue crack growth laws for steels in air 8/10

Table 8.4 – Recommended fatigue crack growth laws for steels in a marine environment 8/12

Table 8.5 – Recommended fatigue crack growth threshold, ΔK_0 , values for assessing welded joints 8/14

Table 8.6 – Details of quality category S-N curves 8/17

Table 8.7 – Minimum values of $\Delta\sigma_j$ for assessing non-planar flaws and shape imperfections 8/38

Table 8.8 – Limits for non-planar flaws in as welded steel and aluminium alloy weldments 8/39

Table 8.9 – Limits for non-planar flaws in steel weldments stress-relieved by PWHT 8/39

Table 8.10 – Acceptance levels for misalignment expressed in terms of stress magnification factor, k_m 8/40

Table 8.11 – Acceptance levels for weld toe undercut in material thicknesses from 10 mm to 40 mm 8/40

Table 9.1 – Temperature below which creep is negligible in 200,000 h for carbon manganese and ferritic steels 9/6

Table D.1 – Formulae for calculating the bending stress due to misalignment in butt joints D/4

Table D.2 – Formulae for calculating the bending stress due to misalignment in cruciform joints D/7

Table F.1 – Guidance on selection of assessment sites around a pipe system F/5

Table F.2 – Crack opening area methods for simple geometries and loading F/8

Table F.3 – Summary of short wave length surface roughness values F/12

Table F.4 – Particulates in primary system water F/16

Table K.1 – Examples of target reliabilities specified by codes and standards K/6

Table K.2 – Paris Law parameters including uncertainty in A for a one-stage model (N, mm) K/12

Table K.3 – Paris Law parameters including uncertainty in A for a two-stage model (N , mm)	K/13
Table M.1 – Geometry functions for a finite surface flaw in an infinite width plate – deepest point of flaw	M/13
Table M.2 – Geometry functions for a finite surface flaw in an infinite width plate – intersection of flaw with free surface	M/14
Table M.3 – Geometry functions for an extended surface flaw in an infinite width plate	M/16
Table M.4a) – M_1 for axial through-thickness in cylinders: membrane loading	M/28
Table M.4b) – M_2 for axial through-thickness in cylinders: membrane loading	M/29
Table M.4c) – M_3 for axial through-thickness in cylinders: bending loading	M/30
Table M.4d) – M_4 for axial through-thickness in cylinders: membrane loading	M/31
Table M.5 – M_m and M_b for axial internal surface flaw in cylinder	M/33
Table M.6 – M_m and M_b for extended axial internal surface flaw in cylinder	M/34
Table M.7 – M_m and M_b for axial external surface flaw in cylinder	M/35
Table M.8 – M_m and M_b for extended axial external surface flaw in cylinder	M/36
Table M.9a) – M_1 for circumferential through-thickness in cylinders: membrane loading	M/39
Table M.9b) – M_2 for circumferential through-thickness flaws in cylinders: membrane loading	M/40
Table M.9c) – M_3 for circumferential through-thickness flaws in cylinders: bending loading	M/41
Table M.9d) – M_4 for circumferential through-thickness flaws in cylinders: bending loading	M/42
Table M.10 – M_m and M_b for circumferential internal surface flaw in cylinder	M/44
Table M.11 – M_m and M_b for extended circumferential internal surface flaw in cylindrical shell	M/45
Table M.12 – Influence coefficients at points A and B for an equatorial through-thickness flaw in a sphere	M/47
Table M.13 – M_m for semi-elliptical flaw in a round bar under tension loading	M/51
Table M.14 – M_b for semi-elliptical flaw in a round bar under bending loading	M/51
Table M.15 – Values of v and w for axial and bending loading	M/56
Table N.1 – Polynomial coefficients defining β_T for CCP	N/13
Table N.2 – Polynomial coefficients defining β_T for CCPB	N/14
Table N.3 – Polynomial coefficients defining β_T for DENT	N/14
Table N.4 – Polynomial coefficients defining β_T for SENT	N/15
Table N.5 – Polynomial coefficients defining β_T for SEB	N/15
Table N.6 – Polynomial coefficients defining β_T for SENB	N/16
Table N.7 – Polynomial coefficients defining β_T for CT	N/16
Table N.8 – Polynomial coefficients defining β_T for SCP: uniaxial tension	N/17
Table N.9 – Polynomial coefficients defining β_T for SCPB	N/18
Table N.10 – Polynomial coefficients defining β_T for extended internal circumferential surface flaw in a cylinder	N/19
Table N.11 – Polynomial coefficients defining β_T for internal circumferential surface flaw in a cylinder (biaxial tension)	N/20
Table N.12 – Polynomial coefficients defining β_T for internal circumferential surface flaw in a cylinder (uniaxial tension)	N/21
Table N.13 – a and k defined with respect to T/σ_Y for $n = 5$	N/23
Table N.14 – a and k defined with respect to T/σ_Y for $n = 6$	N/24
Table N.15 – a and k defined with respect to T/σ_Y for $n = 7$	N/25
Table N.16 – a and k defined with respect to T/σ_Y for $n = 8$	N/26

Table N.17 – a and k defined with respect to T/σ_Y for $n = 9$	N/27
Table N.18 – a and k defined with respect to T/σ_Y for $n = 10$	N/28
Table N.19 – a and k defined with respect to T/σ_Y for $n = 11$	N/29
Table N.20 – a and k defined with respect to T/σ_Y for $n = 12$	N/30
Table N.21 – a and k defined with respect to T/σ_Y for $n = 13$	N/31
Table N.22 – a and k defined with respect to T/σ_Y for $n = 14$	N/32
Table N.23 – a and k defined with respect to T/σ_Y for $n = 15$	N/33
Table N.24 – a and k defined with respect to T/σ_Y for $n = 16$	N/34
Table N.25 – a and k defined with respect to T/σ_Y for $n = 17$	N/35
Table N.26 – a and k defined with respect to T/σ_Y for $n = 18$	N/36
Table N.27 – a and k defined with respect to T/σ_Y for $n = 19$	N/37
Table N.28 – a and k defined with respect to T/σ_Y for $n = 20$	N/38
Table P.1 – Calculation of bending stresses as functions of moments	P/5
Table P.2 – Values of χ for bending loading	P/21
Table Q.1 – Assessment ranges for as-welded residual stress distributions in ferritic steels	Q/2
Table Q.2 – Assessment ranges for as-welded residual stress distributions in austenitic stainless steels (pipe butt welds only)	Q/2
Table Q.3 – Components of longitudinal stress and K_{sb}^{max} for plate butt welds and pipe axial seam welds (austenitic steel)	Q/4
Table Q.4 – Components of transverse stress and K_{sb}^{max} for plate butt welds and axial seam welds (austenitic and ferritic steel)	Q/5
Table Q.5 – Components of longitudinal stress and K_{sb}^{max} for pipe butt welds (ferritic and austenitic steels)	Q/6
Table Q.6 – Components of transverse stress and K_{sb}^{max} for pipe butt welds (ferritic steel)	Q/9
Table Q.7 – Components of transverse stress and K_{sb}^{max} for pipe butt welds (austenitic steel)	Q/9
Table Q.8 – Components of longitudinal stress and K_{sb}^{max} for plate to plate T-butt welds (ferritic steels)	Q/11
Table Q.9 – Components of transverse stress and K_{sb}^{max} for plate to plate T-butt welds (ferritic and austenitic steels) and longitudinal stress and K_{sb}^{max} for plate to plate T-butt welds (austenitic steels)	Q/12
Table Q.10 – Components of longitudinal stress and K_{sb}^{max} for tubular T-butt welds (ferritic steels)	Q/13
Table Q.11 – Components of transverse stress and K_{sb}^{max} for tubular T-butt welds (ferritic steels)	Q/14
Table Q.12 – Components of transverse and longitudinal stress distribution for repair welds (ferritic and austenitic steels)	Q/15
Table S.1 – Mean uniaxial creep properties for different steels for short (<10 000 h) and long-term tests	S/5
Table S.2 – Mean uniaxial creep properties for different steels for short (<10 000 h) and long-term tests	S/7
Table T.1 – Examples of inspection capabilities for sub-surface flaws	T/8
Table T.2 – Examples of inspection capabilities for back surface flaws	T/8
Table T.3 – Examples of inspection capabilities for flaws at the accessible surface	T/9
Table T.4 – Capabilities for detection and length measurement of surface-breaking flaws by MPI	T/15
Table T.5 – Flaw detection capability for liquid penetrant testing	T/16

Summary of pages

This document comprises a front cover, an inside front cover, pages i to x, pages 0/1 to V/14, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 December 2019. It was prepared by Technical Committee WEE/37, *Acceptance levels for flaws in welds*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This British Standard supersedes BS 7910:2013+A1:2015, which is withdrawn.

Information about this document

This is a full revision of the standard. It introduces the following principal changes, which reflect both advances in structural integrity technology and feedback from users.

- Annex A to Annex U are now all designated as “informative” (in earlier editions they were classified as either “informative” or “normative”. This minor change reflects the nature of the document, i.e. it provides guidance rather than prescribing a particular set of rules.
- A new Annex V has been added, addressing strain-based assessment and design.
- The document has been broken down into self-contained clauses and annexes, each with its own bibliography, tables, equations, figures and symbols. This has inevitably introduced an element of repetition, e.g. of key reference documents, but is intended to improve the flexibility and agility of the document in years to come.
- New bibliographic references have been added, in particular to a series of papers published in a special BS 7910-focussed issue of the *International Journal of Pressure Vessels and Piping*. These cover the major damage/failure mechanisms covered by BS 7910 (fracture, fatigue, creep, corrosion), plus specific topics related to the annexes (residual stress, constraint, reliability, NDT, strain-based assessment) and the application of BS 7910 to pipelines. Whilst the background papers are based mainly on BS 7910:2013, the information is equally applicable to BS 7910:2019 in most cases.
- New rules for flaw interaction criteria and some new materials property clauses have been introduced in Clause 7.
- Annex F [Procedure for leak-before-break (LbB) assessment] has been simplified; the detectable leakage procedure has been retained and the full LbB removed.
- In Annex J (Use of Charpy V-notch impact tests), a new subclause addresses interpretation of incomplete transition curves and gives more guidance on use of the Master Curve approach.
- Annex K (Probabilistic assessment) has been updated; the tables of generic partial safety factors (PSFs) for use with fracture assessment have been removed.
- Annex M (Stress intensity factor solutions) contains solutions for finite and extended surface-breaking flaws in plates subjected to non-linear stress fields. These were previously included in Annex Q (Residual stress distributions in as-welded joints) but have been moved to Annex M in the interests of consistency and to underline their potential use with primary, as well as secondary, stresses.

- Annex N (Allowance for constraint effects) has been simplified by removing the look-up tables based on the Q parameter.
- Annex P (Compendium of reference stress and limit load solutions) includes additional information on the source of the solutions, in particular on the distinction between global and local solutions. Limit load solutions for offshore tubular joints and clad plates containing a repair weld have been removed. As a result of this change, Equation (P.31) has been removed; however, in order to maintain continuity with the 2013 edition, subsequent equations have not been renumbered.
- Annex R (Determination of plasticity interaction effects) has been simplified. In the interests of continuity with earlier revisions, both plasticity interaction factors (ρ and V) have been retained; the simplified approach has been kept and the alternative approaches described in the 2013 edition have been removed. Moreover, the simplified approach to the calculation of V has been revised to reflect the most recent amendments to the R6 procedure.

Text introduced or altered by Corrigendum No. 1 is indicated in the text by tags  . Minor editorial corrections are not tagged.

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As a guide this British Standard takes the form of guidance and advisory recommendations. It should not be quoted as if it were a specification or a code of practice.

Presentational conventions

The guidance in this standard is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Additional commentary, explanation and general informative material is presented in smaller italic type.

Where words have alternative spellings, the preferred spelling of the *Shorter Oxford English Dictionary* is used (e.g. "organization" rather than "organisation").

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0 Introduction

The background to the development of BS 7910 is given in reference [0.1].

Where it is necessary to examine critically the integrity of new or existing structures by the use of non-destructive testing (NDT) methods, acceptance levels are required for any flaws that might be revealed. These often already exist as quality control levels (for example in a construction code); however, in this British Standard the derivation of acceptance levels for flaws is based upon the principle of fitness-for-service.

By this principle a structure is considered to be adequate for its purpose, provided the conditions to cause failure are not reached. A distinction has to be made between acceptance based on quality control and acceptance based on fitness-for-service.

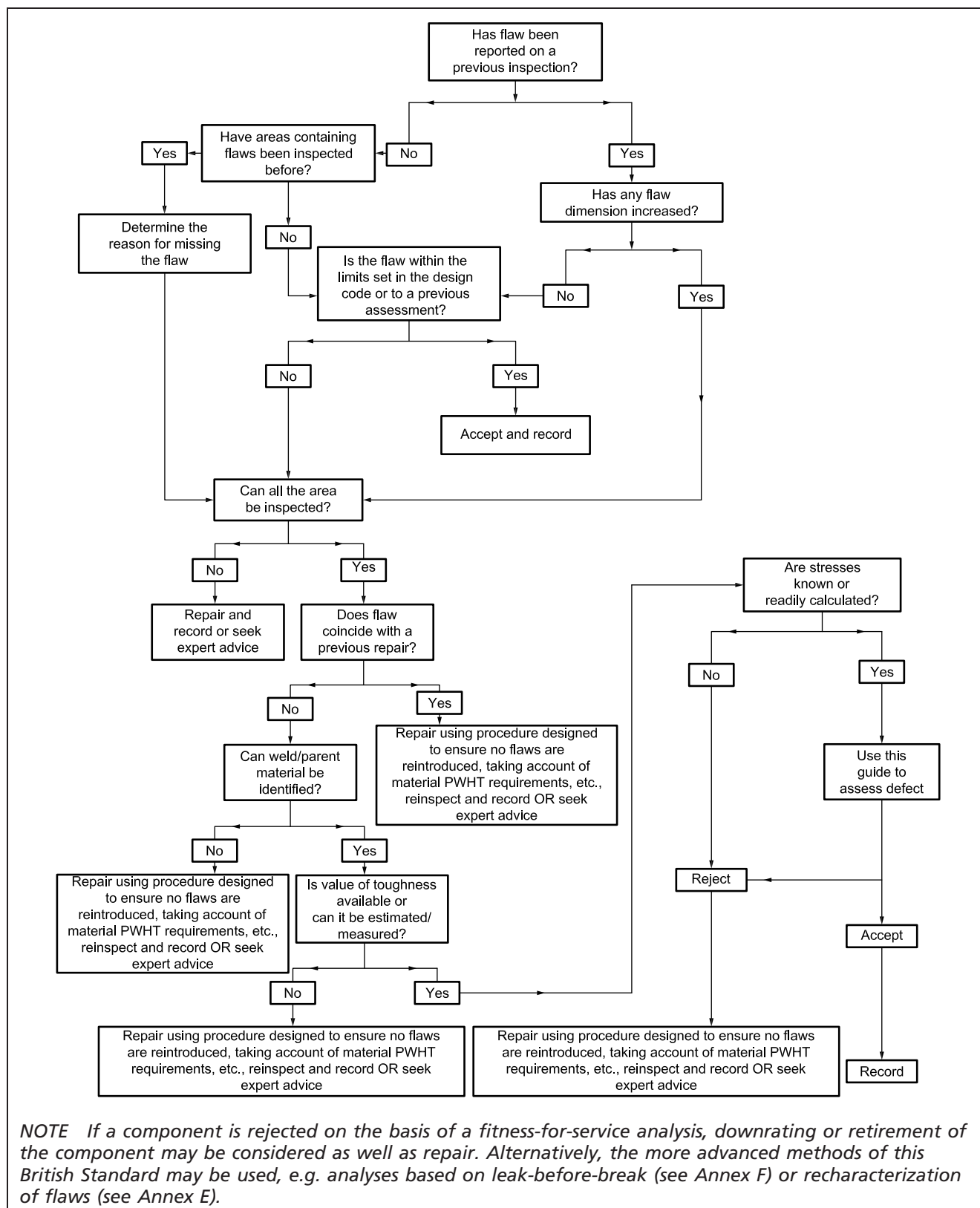
Quality control levels are usually both arbitrary and conservative, but are of considerable value in the monitoring and maintenance of quality during production. Flaws that are less severe than such quality control levels as given, for example, in current construction codes, are acceptable without further consideration. If flaws are more severe than the quality control levels, rejection is not necessarily automatic. Decisions on whether rejection, down rating and/or repairs are required may be based on fitness-for-service, either in the light of previously documented experience with similar material, stress and environmental combinations or on the basis of an engineering critical assessment (ECA) (see Figure 0.1). It is with the latter that this document is concerned. It is emphasized, however, that a proliferation of flaws, even if shown to be acceptable by an ECA, is regarded as indicating that quality is in need of improvement. The use of an ECA is not intended to be viewed as an alternative to good workmanship. The response to flaws not conforming to workmanship criteria needs to be the correction of the fault in the process causing the non-conformity. The methods covered by this British Standard are complementary to, and not a replacement for, good quality workmanship.

A procedure for an ECA is described throughout whereby the significance of flaws under a particular set of circumstances can be determined. All parties need to agree to its use.

It is impossible to provide a single list of flaws that are known not to cause premature failure, as a large number of variables are involved as enumerated in this British Standard. Where relevant experience and data already exist it is possible to dispense with the full ECA procedure and to use authenticated previous assessments as a basis for the establishment of acceptability limits. An ECA may also be used as a basis for deferring necessary repairs to a time mutually agreeable to the contracting parties. Unsatisfactory repair of innocuous flaws can result in the substitution of more harmful and/or less readily detectable flaws.

Flaw assessment on a fitness-for-service basis requires thorough examination by non-destructive testing (NDT) using techniques capable of locating and sizing flaws in critical areas. This British Standard may be used to identify such areas and to assist in optimizing the NDT procedures by identifying those aspects of flaw characterization, size and position that need to be determined. Such NDT is normally carried out after any post-weld heat treatment (PWHT) and/or proof test. However, since a major objective of this British Standard is to reduce costs by eliminating unnecessary repair, careful consideration needs to be given to the level of inspection required to implement this British Standard, and to the limitations of NDT methods.

Figure 0.1 Example of integrity management procedure for flaws



Where NDT has revealed the presence of flaws, the following options apply.

- If the flaws do not exceed the quality control levels in the appropriate application standard, no further action is required.
- If acceptance limits have already been established on the basis of an ECA for the appropriate combination of materials, fabrication procedure, welding

consumables, stress and environmental factors, flaws need to be assessed on that basis.

- If no relevant documented experience exists, then an ECA based on the guidance given in this document may be carried out.

An ECA helps to identify the limiting conditions for failure or the limiting design conditions. It is emphasized that some aspects of an ECA are based on new concepts that could be subject to review.

The application of ECA principles means that “safe” results are obtained. The option of using appropriate safety factors has been incorporated or is inherent throughout the standard. If the accuracy of the input information employed (e.g. stress levels, materials properties at the appropriate temperature, flaw size determination) is in question, appropriate additional safety factors need to be agreed. Equally a flaw is not necessarily unacceptable when it is found initially to exceed the acceptance levels that are derived from this standard. A further assessment may be made following the principles given in this standard incorporating more precise input data or analysis methods or by testing structurally relevant components.

This British Standard also gives guidance on the use of probabilistic methods. These factors and methods do not constitute a full risk analysis of the component undergoing assessment as they do not quantify the consequences of a failure. Where failure of the structure under assessment could pose an unjustifiable or intolerable risk to the surrounding environment or population, a full risk analysis might be needed, with due recognition of both individual and societal risk [0.2].

The assessment methods given in this British Standard provide a quantitative measure of the acceptability of a flaw in a structure. They are not to be used in isolation but are to be used as part of an overall process for the management of flaws. The management of flaws is part of a wider integrity management plan for the structure or system. The management processes for flaws address factors such as:

- the cause of the flaw and remedial action to prevent further occurrences or growth;
- whether a previous inspection failed to detect this flaw. If so, the reasons for not detecting the flaw need to be determined. The inspection technique or assumptions about sub-critical crack growth rates might need to be reviewed;
- the previous history of the structure and whether it is consistent with the nature, location and size of the flaw;
- whether an inspection suggests that the flaw has grown and the observed growth is consistent with assumptions about loading and sub-critical crack growth rates after allowing for uncertainty in the inspection results;
- the implications for other structures of the same or similar design and whether modifications to the structure or a change in the service conditions might be required;
- whether there is a pattern of this flaw being detected in other structures of the same design.

An example algorithm for managing the assessment of flaws is shown in Figure 0.1. Alternative approaches may be developed.

Bibliography for Introduction

Standards publications

There are no standards publications in the Introduction.

Other documents

- [0.1] HADLEY, I. BS 7910:2013 in brief. *In: International Journal of Pressure Vessels and Piping*, August 2018, 165, 263–269.
<<https://doi.org/10.1016/j.ijpvp.2018.07.010>>
- [0.2] ROYAL SOCIETY. *Risk analysis, perception, management*.
London: The Royal Society, 1992.

1 Scope

This British Standard gives guidance and recommendations for assessing the acceptability of flaws in all types of structures and components. Although emphasis is placed on welded fabrications in ferritic and austenitic steels and aluminium alloys, the procedures can be used for analysing flaws in structures made from other metallic materials and in non-welded components or structures. The methods described are applicable at the design, fabrication and operational phases of the life of a structure.

Specific applications include:

- assessing a known flaw in order to determine the fitness-for-service of a flawed structure;
- calculating the defect-tolerance of a structure in order to inform materials selection, load capacity or inspection requirements;
- justifying waiver of post-weld heat-treatment in thick-walled steel structures.

2 Normative references

There are no normative references in this document.

NOTE Informative references are listed in individual clauses and annexes.

3 Symbols and definitions

For the purposes of this British Standard, the symbols, definitions and units given in individual clauses and annexes apply.

4 Types of flaw

The effects of the following flaws may be assessed using methods given in this British Standard:

- a) planar flaws:
 - 1) cracks;
 - 2) lack of fusion or penetration;
 - 3) undercut, root undercut, concavity and overlap (on some occasions, undercut and root undercut in welds are treated as shape imperfections);
- b) non-planar flaws:
 - 1) cavities;
 - 2) solid inclusions (on some occasions cavities and solid inclusions are treated as planar flaws);
 - 3) local thinning (e.g. due to corrosion);
 - 4) porosity;
- c) shape imperfections:
 - 1) misalignment;
 - 2) imperfect profile.

Flaws of the type given in c) include some that may be treated as planar flaws, which are listed in a), and others that give rise to stress concentration effects. A comprehensive classification of the various types of weld flaw which can be encountered is given in BS EN ISO 6520-1.

Bibliography for Clause 4

Standards publications

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS EN ISO 6520-1, *Welding and allied processes – Classification of geometric imperfections in metallic materials*

Other documents

There are no other references in this clause.

5 General guidance on assessment

5.1 Modes of failure and material damage mechanisms

The influence of the flaws listed in Clause 4 may be assessed, using methods given in this British Standard, for the following modes of failure and damage mechanisms:

- a) failure by fracture and plastic collapse (see Clause 7);
- b) damage by fatigue (see Clause 8);
- c) damage by creep and creep fatigue (see Clause 9);
- d) failure by leakage of containment vessels (see 10.2);
- e) damage by corrosion and/or erosion (see 10.3.2);
- f) damage by environmentally assisted cracking (see 10.3.3);
- g) failure by instability (buckling) (see 10.4).

For each flaw or flaw type the following points should be assessed:

- 1) the potential modes of final failure; and
- 2) any possible material damage mechanisms leading to property degradation or sub-critical flaw growth.

NOTE Material damage and sub-critical flaw growth can be affected by the material itself, design features, stress levels, time, cyclic loading, composition and concentration of process fluids and additives, flow rates, operating temperatures, external environment, etc., though not all these considerations apply to any given material damage mechanism.

The following are examples of some of the most common material damage mechanisms.

- i) Embrittlement: this type of damage can be caused in some materials by irradiation, temper embrittlement, or by caustic, hydrogen or hydrogen sulfide rich environments.
- ii) Fatigue: this is a damage process whereby embedded or surface cracks can initiate and grow under fluctuating stress (e.g. due to applied loads, thermal stress variations and vibrations). Members containing stress concentrations (e.g. flaws, geometric discontinuities) are particularly susceptible. For these reasons, welded components can give much lower fatigue lives than plain material under the same loading.
- iii) Corrosion fatigue: this is a type of damage similar to fatigue, but the onset of cracking and crack growth rates are accelerated by the corrosive medium.
- iv) Creep cracking: this is internal and/or external cracking due to operating temperatures greater than the creep threshold temperature, which is a function of the material. Components subjected to creep conditions have a finite life and the damage rate is a function of temperature, stress and time. For this reason, the finite life of highly stressed components and welds within a structure can be much lower than the plain areas subject to membrane stress alone.
- v) Internal corrosion: material loss can take many forms, such as pitting corrosion, crevice corrosion, localized corrosion, general corrosion, etc., and is mainly due to the contents of the system, including any impurities.
- vi) External corrosion and under lagging corrosion: depending on the material, its loss from exposed areas can be similar to internal corrosion. This damage mechanism is mainly caused by a wet and dry environmental sequence such

as exposure to rain or the local environment surrounding the component (e.g. leaking fluids, emissions from surrounding plant).

- vii) Stress corrosion cracking (SCC): in some materials internal and/or external cracking can occur due to chemical action on a stressed component. Generally as-welded components are more susceptible than those that have been post-weld heat-treated. Crack initiation and propagation rates are a function of material, stress, temperature, and the concentration of the corrosive medium.
- viii) Hydrogen and hydrogen sulfide related cracking: the damage rate is a function of material, pressure, temperature, concentration of H_2 or H_2S , etc.
- ix) Erosion: the internal loss of material is mainly due to rapid flow of process fluid and to abrupt changes in fluid flow direction or the presence of other liquid or solid impurities.
- x) Cavitation: the most common areas affected are pump impellers and components where high flow rates occur with significant pressure drop, such as might occur across control valves in process fluid piping or pipelines.

These failure modes and damage mechanisms are not relevant in all applications. At the outset all operating conditions should be taken into account, including start-up, shut-down, process upset and external environment, to establish which are relevant to the particular component under consideration. Possible interaction between the various damage mechanisms should also be taken into account. The detailed assessment of the various modes of failure and material damage mechanisms is given in Clause 7, Clause 8, Clause 9 and Clause 10.

The likelihood of failure from the operation of these failure modes and damage mechanisms can be predicted with varying degrees of confidence and accuracy. The behaviour of components subject to fatigue loading, creep, brittle fracture and general volumetric corrosion forming locally thinned areas (LTAs) is well understood. It is not practical to attempt to provide treatments for the other mechanisms listed in the same depth and generality as is provided for failure by fracture, fatigue, creep or corrosion, but they should all be addressed in an ECA, since failure can arise through their operation. Brief guidelines are offered in Clause 10 for the assessment of these mechanisms. If it is established that a risk of failure from these mechanisms exists, a specific assessment should be undertaken. This should incorporate the assumptions and approaches used, which should be fully documented and agreed by all parties.

5.2 Sequence of assessment

The following is the recommended sequence of operations for carrying out an assessment for a known flaw.

- a) Identify the flaw type, i.e. planar, non-planar or shape (Clause 4).
- b) Establish the cause of the flaw.
- c) Establish the essential data, relevant to the particular structure (see 6.2).
- d) Determine the size of the flaw.
- e) Assess possible material damage mechanisms and damage rates.
- f) Determine the limiting size for the final modes of failure.
- g) Based on the damage rate, assess whether the flaw would grow to this final size within the remaining life of the structure or the in-service inspection interval, by sub-critical crack growth.
- h) Assess the consequences of failure.
- i) Carry out sensitivity analysis.

- j) If the flaw would not grow to the limiting size, including appropriate factors of safety, it is acceptable. The safety factors should take account both of the confidence in the assessment and of the consequences of failure.

Estimation of tolerable planar flaw sizes may be made by starting from a series of limiting flaw sizes as determined in f) and determining the initial flaw sizes that would grow to these within the remaining life as in g). Procedures for calculating such tolerable final flaw sizes are given in Clause 7, Clause 8, Clause 9 and Clause 10.

5.3 Fracture assessment options

Several levels of treatment of flaws are possible, depending on the application and materials data available. Three options for dealing with fracture are included in Clause 7.

- Option 1 is a conservative procedure that is relatively simple to employ and does not require detailed stress/strain data for the materials being analysed.
- Option 2 is based on the use of a material-specific stress-strain curve.
- Option 3 uses numerical analysis to generate a failure assessment diagram (FAD).

Procedures are given in Clause 8 and Clause 9 for estimating fatigue and creep crack growth respectively, when specific materials data is provided. Guidance is also given in these clauses on making assessments when specific information is not available. Where appropriate, guidance is included on the probability of survival and on the desirability of conducting a sensitivity analysis.

Bibliography for Clause 5

There are no references in this clause.

6 Information required for assessment

6.0 Symbols and definitions

For the purposes of this clause, the following symbols, definitions and units apply, unless otherwise indicated at the point of use.

Symbol	Definition	Units
a	Half flaw length for through-thickness flaw, flaw height for surface flaw or half height for embedded flaw	mm
B	Section thickness in plane of flaw	mm
c	Half flaw length for surface and embedded flaws	mm
K_I	Applied tensile (mode I) stress intensity factor (SIF)	N/mm ^{3/2}
K_{Ic}	Plane strain fracture toughness	N/mm ^{3/2}
K_{ISCC}	Critical stress intensity factor for stress corrosion cracking	N/mm ^{3/2}
k_m	Stress concentration factor due to misalignment	—
k_t	Stress concentration factor due to local structural discontinuities (e.g. holes, notches, sharp corners)	—
k_{tb}	Bending stress concentration factor	—
k_{tm}	Membrane stress concentration factor	—
P_b	Primary bending stress	N/mm ²
P_m	Primary membrane stress	N/mm ²
Q	Secondary stress	N/mm ²
Q_b	Secondary bending stress	N/mm ²
Q_m	Secondary membrane stress	N/mm ²
R	Stress ratio, i.e. ratio of minimum to maximum stress (or stress intensity factor) during fatigue cycling	—
ΔK_I	Cyclic range of K_I	N/mm ^{3/2}
$\Delta\sigma$	Applied stress range	N/mm ²
$\Delta\sigma_b$	Bending component of stress range	N/mm ²
$\Delta\sigma_m$	Membrane component of stress range	N/mm ²
$\Delta\sigma_1, \Delta\sigma_2$	Linearized values of primary or secondary stress ranges	N/mm ²
σ	Stress	N/mm ²
σ_{max}	Maximum value of stress distribution across a section	N/mm ²
σ_1, σ_2	Linearized values of primary or secondary stresses	N/mm ²

6.1 General

The ECA requires assumptions to be made about input parameters. Therefore, if there is any likelihood that an ECA will be required during the life of a structure, relevant materials properties should be generated at the construction stage, or appropriate materials should be retained for later testing. Accurate fracture toughness data are particularly important, and tests on weld procedure qualification samples are advisable. Similarly, fatigue crack growth, creep and SCC data may be obtained from the actual materials of construction. Any such tests should be performed in accordance with the appropriate standard from the following list:

- BS ISO 12108 for fatigue crack growth;
- BS ISO 12108 for fatigue crack growth threshold;
- BS 7448, BS EN ISO 15653 and ISO 12135 for fracture toughness;

- BS 8571 for low-constraint fracture toughness;
- BS EN ISO 7539 for SCC.

The information should take account of the material strain and thermal history and the appropriate environment. The assessment should cover all loadings, including, as appropriate, those arising during transport, construction, installation and testing, and, where necessary, take account of fault and accident conditions. The effects of local loads and misalignment should also be taken into account. Any assumptions should be justified to the satisfaction of all parties and appropriate documentation, including material specification and details of actual material used, should be appended to the ECA.

6.2 Essential data

Relevant data from the following list should be obtained:

- a) nature, position and orientation of flaw;
- b) structural and weld geometry, fabrication procedure;
- c) stresses (pressure, thermal, residual or resulting from any other type of mechanical loading) and temperatures including transients;
- d) yield or 0.2% proof strength, tensile strength and elastic modulus (in certain cases, a complete engineering stress/strain curve is required);
- e) fatigue/corrosion fatigue $S-N$ and crack propagation data;
- f) fracture toughness (K_{Ic} or values of J -integral or CTOD) data [in certain cases fracture toughness may be estimated from relevant Charpy V-notch data (see Annex J)];
- g) creep rupture, creep crack propagation and creep fatigue data; and
- h) bulk corrosion and SCC (K_{ISCC}) data.

6.3 Non-destructive testing

6.3.1 General

NDT is an essential aspect of a fitness-for-service assessment. The NDT technique(s) used for flaw evaluation should be chosen to provide the type of information required to an acceptable degree of accuracy. Such information should include some or all of the following items:

- a) flaw length;
- b) flaw height;
- c) flaw position;
- d) flaw orientation with respect to the principal stress direction; and
- e) whether the flaw cross-section is planar or non-planar.

6.3.2 Methods for surface-breaking flaws

The following methods (in no order of preference) may be used for the detection of surface-breaking flaws:

- a) visual;
- b) liquid penetrant;
- c) magnetic particle (for ferromagnetic materials);
- d) eddy current [including AC field measurement (ACFM)];

- e) electrical potential drop (AC or DC);
- f) radiography; and
- g) ultrasonics.

These methods are also suitable for measuring the surface length of such flaws, but only ultrasonic, eddy current (including ACFM) and potential drop methods are capable of providing a measurement of their height. Further guidance on the use of NDT is given in Annex T.

6.3.3 Methods for embedded flaws

The following methods (in no order of preference) may be used for the detection of embedded flaws:

- a) radiography;
- b) ultrasonics;
- c) eddy current (including ACFM); and
- d) electrical potential drop (DC only).

Radiography and ultrasonics are both capable of providing a measurement of flaw length, but ultrasonic testing is the only NDT method that is routinely used to measure flaw height. Eddy current, ACFM and potential drop methods tend to provide a measurement of the cross-sectional area of the flaw.

6.3.4 Applicable standards and treatment of uncertainties

NDT should be carried out in accordance with the appropriate standards from the following list:

- ultrasonics, including Time of Flight Diffraction (TOFD): BS EN 17640, BS EN ISO 22825, BS EN ISO 10863, BS EN ISO 13588, BS EN ISO 11666, BS EN ISO 15626 and BS EN ISO 19285;
- radiography: BS EN ISO 10675, BS EN ISO 17636-1 and BS EN ISO 17636-2;
- magnetic particle: BS EN ISO 17638 and BS EN ISO 23278;
- liquid penetrant: BS EN ISO 3452 and BS EN ISO 23277;
- eddy current: BS EN ISO 15548, BS EN ISO 15549 and BS EN ISO 17643;
- visual: BS EN ISO 17637 and BS EN 1370.

Any inspection procedure which deviates from or is not covered by an appropriate standard should be appended to the ECA. Suitable allowances should be incorporated in the assessment of flaw sizes to cover intrinsic and measurement errors involved and thereby ensure conservative assessment of flaw severity. These allowances and their bases should be quoted in the ECA. Guidance on the measurement error and reliability of commonly used inspection methods is given in Annex T.

Standard inspection techniques, which are suitable and economically viable for examining long lengths of weld, are not necessarily appropriate for the accurate flaw measurement required for an ECA. In such cases, supplementary techniques or additional test methods should be employed.

6.3.5 Treatment of uninspectable areas

Where a region of a structure cannot be inspected, the size of flaw that could exist in the uninspectable region should be estimated based on flaw distributions in areas of the structure which could be inspected. When assessing the likelihood of the presence of such flaws, account may be taken of

knowledge of the weld preparations, the welding process and procedures, and the general quality of welding attained. Account may also be taken of the operating applied loads, process fluid parameters and any significant external environment relevant to the region.

6.4 Stresses to be considered

6.4.1 General

Stresses used in the ECA should be justified and tabulated and form an integral part of the assessment. When complete stress information is not available, the basis for any estimate should be agreed with all parties and included in the assessment. The methods in this British Standard relate predominantly to stress-based assessment, i.e. when the nominal stress is lower than the yield strength of the flawed section. A method for strain-based assessment is given in Annex V.

The stresses to be considered in the assessment are those which would be calculated by a stress analysis of the unflawed structure. The actual stress distributions may be used, or the stresses (or stress ranges) may be linearized, as shown in Figure 6.1. Linearization may be carried out across the flaw [Figure 6.1a)] or across the section containing the flaw [Figure 6.1b)]. The latter method normally provides overestimates, but has the advantage that linearization does not need to be repeated with crack growth. Account should be taken of the primary membrane and bending stresses, the secondary stresses and the magnification of the primary stresses caused by local or gross discontinuities or by misalignment, as described in 6.4.2, 6.4.3 and 6.4.4. Typical schematic representations of these are given in Figure 6.1. In an assessment of the effect of a single or steady state applied load, it is important to distinguish between primary and secondary stresses, as only the former contribute to plastic collapse. In a fatigue assessment, the important distinction is between static and fluctuating stresses and all fluctuating stresses are treated in the same way as primary stresses. In the special case when allowance is made for R (8.2.1.4), steady state primary stresses and secondary stresses should also be taken into account, in order to determine the actual values of the maximum and minimum applied stresses. The stress categories described below do not necessarily coincide with those used in other documents (for example, PD 5500). In the fracture assessment routes described in Clause 7, shear stresses are not included. If shear stresses are significant, the guidance in Annex A may be used.

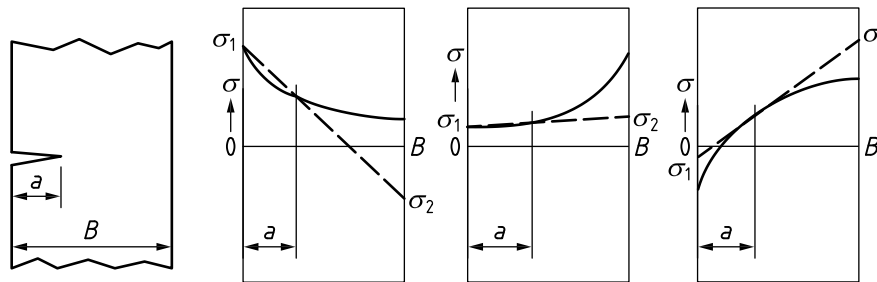
6.4.2 Primary stress (P)

Primary stresses are stresses that can, if sufficiently high, contribute to plastic collapse (secondary stresses do not) (see 6.4.3). They can also contribute to failure by fracture, fatigue, creep or SCC. They include all stresses arising from internal pressure and external loads. Some stresses classified as secondary by design codes and guidance documents, e.g. ASME Boiler and Pressure Vessel Code, Section III, and PD 5500, are regarded as primary in this British Standard, e.g. certain thermal and residual stresses (see 7.1.6). The primary stresses are divided into membrane, P_m , and bending, P_b , components as follows.

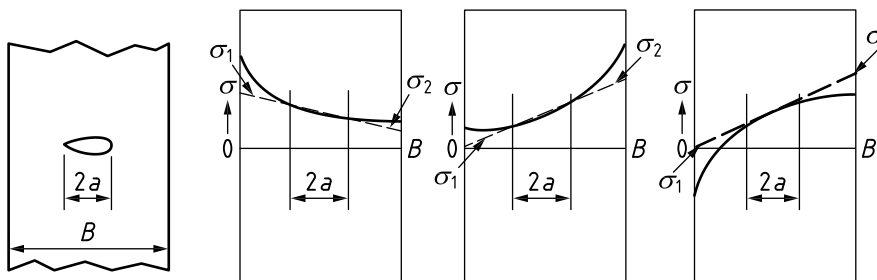
- Membrane stress (P_m) is the mean stress through the section thickness that is necessary to ensure the equilibrium of the component or structure.
- Bending stress (P_b) is the component of stress due to imposed loading that varies linearly across the section thickness. The bending stresses are in equilibrium with the local bending moment applied to the component. For the purpose of this British Standard, P_b is regarded as a stress superimposed upon P_m .

Figure 6.1 Linearization of stress distributions

a) Linearization of stress distributions across flaw



1) Examples of linearization of primary or secondary stress distributions for surface flaws



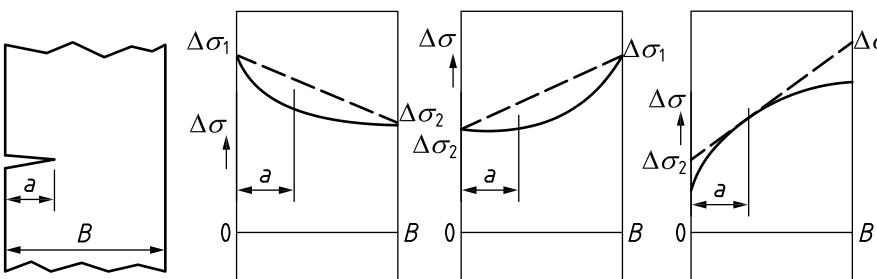
2) Examples of linearization of primary or secondary stress distributions for embedded flaws

P_m, Q_m and P_b, Q_b can be determined from the distributions in a)1) and a)2) using the following equations:

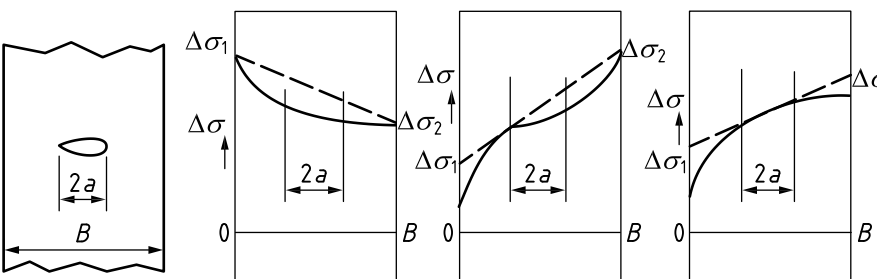
$$P_m, Q_m = \frac{\sigma_1 + \sigma_2}{2} \quad \text{and} \quad P_b, Q_b = \frac{\sigma_1 - \sigma_2}{2}$$

NOTE Any linearized distribution of stress is acceptable provided that it is greater than or equal to the magnitude of the real distribution over the flaw surface.

b) Linearization of stress range distributions across section



1) Examples of linearization of stress range distributions for surface flaws



2) Examples of linearization of stress range distributions for embedded flaws

$\Delta\sigma_m$ and $\Delta\sigma_b$ can be determined from the distributions in b)1) and b)2) using the following equations:

$$\Delta\sigma_m = \frac{\Delta\sigma_1 + \Delta\sigma_2}{2} \quad \text{and} \quad \Delta\sigma_b = \frac{\Delta\sigma_1 - \Delta\sigma_2}{2}$$

6.4.3 Secondary stress (Q)

The secondary stresses, Q , are self-equilibrating stresses necessary to satisfy compatibility in the structure. An alternative description is that they can be relieved by local yielding, heat treatment, etc.

Thermal and residual stresses are usually secondary.

NOTE Fluctuating thermal stresses are treated as primary in a fatigue assessment.

Secondary stresses do not cause plastic collapse as they arise from strain/displacement limited phenomena. They do however contribute to the severity of local conditions at a crack tip, and, when it is necessary to include them in an assessment, they should be included in calculations of K_I and ΔK_I . Thermal stresses (primary and secondary) should also be multiplied by appropriate stress concentration and misalignment factors, k_t and k_m .

The secondary stresses may be divided into membrane, Q_m , and bending, Q_b , components as for primary stresses (see 7.1.8).

6.4.4 Stresses at structural discontinuities

6.4.4.1 General

Stress concentrations occur at structural discontinuities under applied primary or thermal stresses. Secondary stresses are not influenced by structural discontinuities except that thermal stresses, when considered primary (see 7.1.8), are affected by structural discontinuities. Their effects are quantified by calculating peak stresses at the discontinuities, as described in 6.4.4.2 to 6.4.4.4. The bending component may be obtained by subtracting the membrane component from the peak stress.

6.4.4.2 Gross structural discontinuities

Typical gross structural discontinuities are those occurring at pressure vessel nozzles and at the major intersections in tubular structures. For such situations, the stress at the discontinuity is calculated by multiplying the applied stress by the appropriate stress concentration factor, for the purposes of calculating crack driving force, K_I . For nominal stress, membrane stress and bending stress, the stress concentration factors are k_t , k_{tm} , and k_{tb} , respectively. Where stress information is available in the form of membrane and bending stresses, separate stress concentration factors, k_{tm} and k_{tb} , should be applied to each. Further guidance for tubular joints and for pressure vessel nozzles is given in Annex B and Annex C respectively. This type of stress concentration usually decays over distances greater than the section thickness, and can lead to a plastic hinge across the full section thickness over local regions.

6.4.4.3 Discontinuities due to misalignment or deviation from intended shape

Discontinuities due to misalignment or deviation from intended shape cause bending stresses. This is calculated by multiplying the applied membrane stress by a stress magnification factor k_m (see Annex D). This type of stress magnification also decays over distances greater than the section thickness and can lead to a plastic hinge across the full thickness over local regions. If additional bending stresses due to misalignment occur within a region of stress concentration due to a gross structural discontinuity, both effects should be taken into account.

6.4.4.4 Local structural discontinuities

Stress concentrations due to local structural discontinuities (e.g. holes, notches, sharp corners) usually decay over distances less than the hole or notch radius, which might be a small proportion of the wall thickness. If the flaw lies within this region, then the effect of the stress concentrations on both fracture/fatigue and plastic collapse should be taken into account and the peak stress may be calculated by multiplying the applied stress by k_t .

Stress concentration effects due to weld toes do not contribute to plastic collapse. However, they increase the stress intensity factor (see Annex M). For sharp corners, the theoretical stress concentration factor is infinite, and cracks at such regions should be treated by a stress intensity magnification factor. Local structural discontinuities can be located within zones of stress concentration caused by gross discontinuities and/or by misalignment, and all these effects should be taken into account in the stress analysis.

Different methods of incorporating peak stresses are used in various different assessment methods within this British Standard, as detailed in 7.1.6, 7.2.3, Clause 8 and Clause 9.

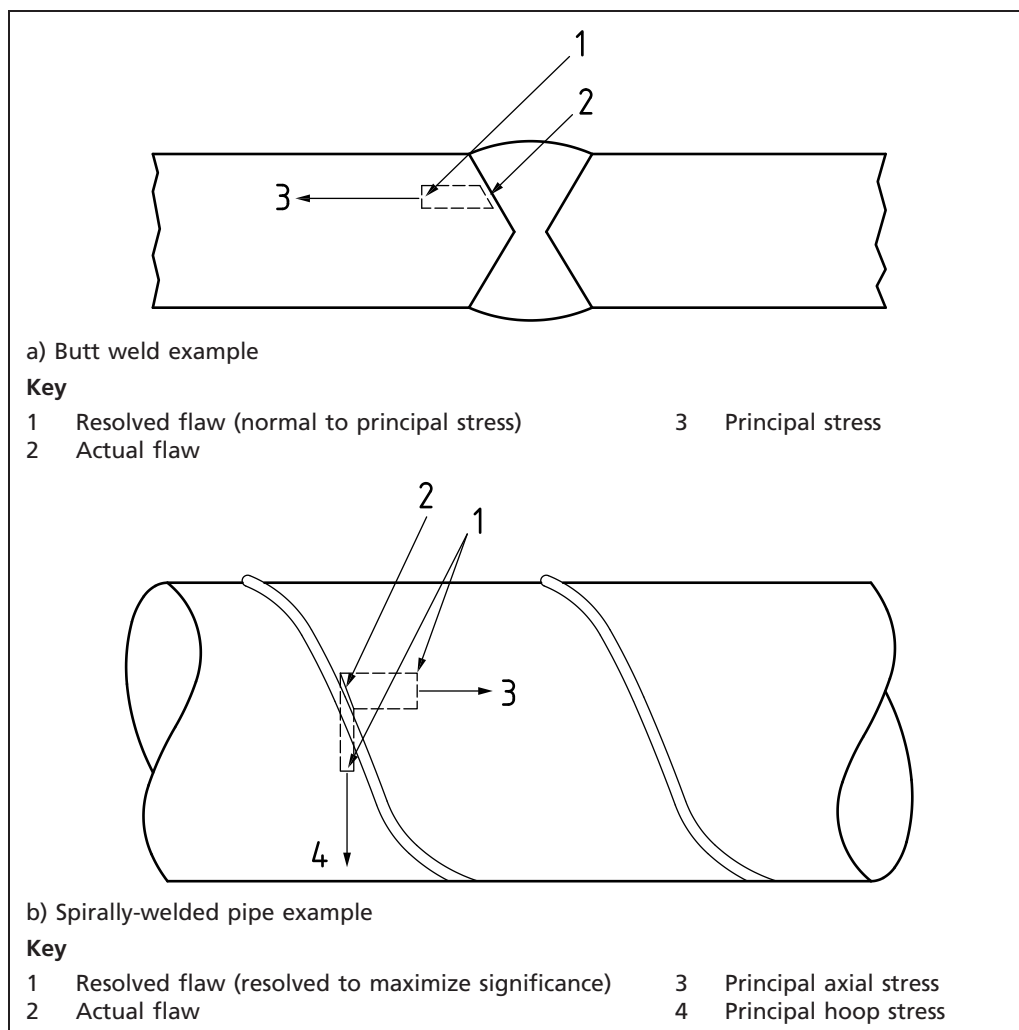
6.4.5 Treatment of flaws not aligned with a plane of principal stress

Where the plane of the flaw is not aligned with a plane of principal stress, further consideration is needed. The first step is to project the flaw on to each of the three planes normal to the principal stresses and to evaluate each of the three projected flaws. One of these projections often leads to a stress intensity factor and a reference stress that are both significantly higher than those for the other two projections. In this case, the assessment should be carried out, taking a and $2c$ as the projected dimensions on that plane. This method is often applicable to near circumferential flaws in the wall of a pipe, where the flaw is projected on to the circumferential plane (see Figure 6.2). There are however restrictions on proceeding in this way. Specialist advice (for example, alternative detailed advice is given in R6, 11.3 [6.1]) should be sought in the following situations.

- There is a large angle (greater than about 20°) between the plane of the actual flaw and the principal plane on which the stress intensity factor and reference stress are greatest.
- There is only a small difference between the stress intensity factors on two or more planes of projection.
- The maximum stress intensity factor occurs for the flaw projected onto one plane and the maximum reference stress occurs for the flaw projected onto another plane.
- One of the principal stresses is significantly compressive, i.e. of a similar magnitude to the maximum principal tensile stress.

In these circumstances significant mode II and/or III loading could be present. Annex A provides guidance on the treatment of these modes of loading.

Figure 6.2 Procedure for resolving flaws normal to principal stress



Bibliography for Clause 6

Standards publications

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ASME Boiler and Pressure Vessel Code, Section III: *Rules for construction of nuclear power plant components*

BS 7448, *Fracture mechanics toughness tests*

BS 8571, *Method of test for determination of fracture toughness in metallic materials using single edge notched tension (SENT) specimens*

BS EN 1370, *Founding – Examination of surface condition*

BS EN 17640, *Non-destructive testing of welds – Ultrasonic testing – Techniques, testing levels, and assessment*

BS EN ISO 3452, *Non-destructive testing*

BS EN ISO 7539, *Corrosion of metals and alloys*

BS EN ISO 10675, *Non-destructive testing of weld – Acceptance levels for radiographic testing*

BS EN ISO 10863, *Non-destructive testing of welds – Time-of-flight diffraction technique (TOFD) – Acceptance levels*

- BS EN ISO 11666, *Non-destructive testing of welds – Ultrasonic testing – Acceptance levels*
- BS EN ISO 13588, *Non-destructive testing of welds – Ultrasonic testing – Use of automated phased array technology*
- BS EN ISO 15548, *Non-destructive testing of welds – Eddy current examination of welds by complex plane analysis*
- BS EN ISO 15549, *Non-destructive testing – Eddy current testing – General principles*
- BS EN ISO 15626, *Non-destructive testing of welds – Time-of-flight diffraction technique (TOFD) – Acceptance levels*
- BS EN ISO 15653, *Metallic materials – Method of test for the determination of quasistatic fracture toughness of welds*
- BS EN ISO 17636-1, *Non-destructive testing of welds – Radiographic testing – X- and gamma-ray techniques with film*
- BS EN ISO 17636-2, *Non-destructive testing of welds – Radiographic testing – X- and gamma-ray techniques with digital detectors*
- BS EN ISO 17637, *Non-destructive testing of welds – Visual testing of fusion-welded joints*
- BS EN ISO 17638, *Non-destructive testing of welds – Magnetic particle testing*
- BS EN ISO 17643, *Non-destructive testing of welds – Eddy current examination of welds by complex plane analysis*
- BS EN ISO 19285, *Non-destructive testing of welds – Phased array ultrasonic testing (PAUT) – Acceptance levels*
- BS EN ISO 23277, *Non-destructive testing of welds – Penetrant testing – Acceptance levels*
- BS EN ISO 23278, *Non-destructive testing of welds – Magnetic particle testing – Acceptance levels*
- BS EN ISO 22825, *Non-destructive testing of welds – Ultrasonic testing – Testing of welds in austenitic steels and nickel-based alloys*
- BS ISO 12108, *Metallic materials – Fatigue testing – Fatigue crack growth method*
- ISO 12135, *Metallic materials – Unified method of test for the determination of quasistatic fracture toughness*
- PD 5500, *Specification for unfired fusion welded pressure vessels*

Other documents

- [6.1] R6 PANEL. *R6: Assessment of the integrity of structures containing defects*. Revision 4, as amended. Gloucester: EDF Energy, 2001.

7 Assessment for fracture resistance

7.0 Symbols and definitions

For the purposes of this clause, the following symbols, definitions and units apply, unless otherwise indicated at the point of use.

Symbol	Definition	Units
A_r	Coefficient used in deriving stress-strain curve for ferritic steels from yield/proof strength, tensile strength and uniform elongation [see Equation (7.4) and Equation (7.5)]	—
a	Half flaw length for through-thickness flaw, flaw height for surface flaw or half height for embedded flaw (original or recharacterized)	mm
a_j	Flaw size after ductile crack growth Δa_j	mm
a_{pl}	Measure of the extent of Irwin's plastic zone	mm
a_0	Initial flaw size	mm
a_1, a_2	Heights of non-planar or coplanar surface flaws in close proximity when considering flaw interaction	mm
$2a_1, 2a_2$	Heights of non-planar or coplanar embedded flaws in close proximity when considering flaw interaction	mm
B	Section thickness in plane of flaw	mm
b	Thickness of sub-sized fracture toughness specimen	mm
b_0	Size of the un-notched ligament, equal to $(W - a_0)$	m
C_V	Lower bound Charpy V-notch impact energy at the service temperature (for which fracture toughness is required)	J
c	Half flaw length for surface or embedded flaw	mm
$2c$	Recharacterized flaw length when considering flaw interaction	mm
$2c_1, 2c_2$	Heights of non-planar or coplanar flaws in close proximity when considering flaw interaction	mm
E	Elastic modulus	N/mm ²
E'	Elastic modulus corrected for constraint conditions $E' = E$ for plane stress, $E' = E/(1 - \nu^2)$ for plane strain	N/mm ²
HV_{10}	Vicker's hardness, determined using a 10 kg load	—
J	Line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack tip	N/mm
J_c	Value of J at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in <i>NOTE This term applies only where $\Delta a < 0.2$ mm.</i>	N/mm
J_e	Value of J determined using an elastic analysis	N/mm
J_m	Value of J at first attainment of a maximum force plateau	N/mm
J_{mat}	Material fracture toughness measured by J -methods	N/mm
J_u	Value of J at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in <i>NOTE This term applies only where $\Delta a > 0.2$ mm offset to the blunting line.</i>	N/mm

(continued)

Symbol	Definition	Units
$J_{0.2BL}$	Size insensitive fracture resistance J at 0.2 mm stable crack extension offset from the construction (blunting) line	N/mm
K	Stress intensity factor (SIF)	N/mm ^{3/2}
K_B	Fracture toughness for the equivalent full thickness of the component (determined from K_b)	MPa√m
K_b	Fracture toughness determined from sub-sized specimen of thickness b	MPa√m
K_c	Value of K at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in <i>NOTE This term applies only where $\Delta a < 0.2$ mm.</i>	N/mm ^{3/2}
K_I	Applied tensile (mode I) stress intensity factor	N/mm ^{3/2}
K_I^P	Stress intensity factor due to primary stress	N/mm ^{3/2}
K_I^S	Stress intensity factor due to secondary stress	N/mm ^{3/2}
K_i	Individual data points in statistical treatment of fracture toughness data	N/mm ^{3/2}
$\bar{K}_i$	Mean value of fracture toughness (see 7.1.7)	N/mm ^{3/2}
K_J	Value of fracture toughness derived from J-integral	N/mm ^{3/2}
$K_{Jc(limit)}$	Limiting value of K_b	N/mm ^{3/2}
K_{Jm}	Fracture toughness derived from J_m	N/mm ^{3/2}
K_m	Fracture toughness at maximum load	N/mm ^{3/2}
K_{mat}	Characteristic material fracture toughness determined in terms of stress intensity factor	N/mm ^{3/2}
K_r	Fracture ratio	—
K_u	Value of K at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in <i>NOTE This term applies only where $\Delta a > 0.2$ mm.</i>	N/mm ^{3/2}
$K_{0.2mm}$	Initiation of tearing fracture toughness	N/mm ^{3/2}
K_δ	Fracture toughness estimated from CTOD	N/mm ^{3/2}
K_{1mm}, K_{2mm}	K_{mat} corresponding to the postulated amount of tearing, typically up to 1 mm or 2 mm	N/mm ^{3/2}
k_{tb}	Bending stress concentration factor	—
$k_{0.90}$	Value of the one-sided tolerance limit for a normal distribution	—
L	Attachment length	mm
L_r	Ratio of reference stress to yield strength (or applied load to limit load)	—
$L_{r,max}$	Maximum permitted limit of L_r	—
M_{kr}, M_{km}, M_{kb}	Stress intensity magnification factors for a flaw at the weld toe	—
M_{mr}, M_b	Stress intensity magnification factors for flaw shape	—
m	Parameter as a function of yield strength and tensile strength, used in converting K_{mat} to δ_{mat} and vice versa; see Equation (7.16) and Equation (7.17)	—

(continued)

Symbol	Definition	Units
n	Strain-hardening exponent, see Equations (7.4), (7.6) and (7.7)	—
P	Applied load	N
P_b	Primary bending stress	N/mm ²
P_L	Limit load	N
P_m	Primary membrane stress	N/mm ²
p	Shortest distance from surface to embedded flaw	mm
Q	Secondary stress	N/mm ²
Q_b	Secondary bending stress	N/mm ²
Q_m	Secondary membrane stress	N/mm ²
R	Ratio of minimum to maximum load in fatigue	—
R_{eH}	Upper yield strength of material	N/mm ²
R_{eL}	Lower yield strength of discontinuously yielding material	N/mm ²
R_m	Ultimate tensile strength of material	N/mm ²
$R_{p0.2}$	0.2% proof strength	N/mm ²
$R_{p1.0}$	1% proof strength	N/mm ²
$R_{t0.5}$	Yield strength associated with a total elongation (strain) of 0.5%	N/mm ²
S^2	Variance	—
s, s_1, s_2	Distance between potentially interacting flaws	mm
T	Assessment temperature	°C
T_0	Temperature for a median toughness of 100 MPa√m in 25 mm thick specimens	°C
V	Plasticity correction factor	—
W	Specimen or structural width	mm
Y	Stress intensity correction factor	—
z	Number of samples in a set of fracture toughness data	—
Δa	Increment in a or ductile tearing	mm
Δa_f	Crack growth due to fatigue loading	mm
Δa_j	Intermediate value of tearing flaw extension	mm
Δa_t	Crack growth due to tearing	mm
Δa_{tot}	Total crack growth	mm
$\Delta \varepsilon$	Extent of Lüders strain as in Equation (7.8)	—
$\Delta \varepsilon$	Increase in strain as in Equation (7.33)	—
δ	Crack tip opening displacement (CTOD) or crack opening displacement (COD)	mm
δ_c	CTOD for test specimens that fail by cleavage fracture after <0.2 mm of ductile tearing	mm
δ_{mat}	Material toughness determined by CTOD method	mm
δ_u	CTOD for tests that fail by cleavage fracture after ductile tearing of at least 0.2 mm	mm
$\delta_{0.2BL}$	Resistance to crack extension expressed in terms of CTOD at 0.2 mm crack extension offset to the blunting line	mm
ε	Strain	—
ε_{ref}	Reference strain; the true strain at the true stress $\sigma_{ref} = L_r \sigma_Y$	—
ε_t	True strain	—

(continued)

Symbol	Definition	Units
ε_u	Uniform elongation strain at ultimate tensile strength	—
ε_Y	Yield strain, i.e. strain at σ_Y	—
λ	Parameter used in constructing Option 1 FAD	—
μ	Parameter used in constructing FAD line, taken as the minimum value of either $0.001(E/\sigma_Y)$ or 0.6	—
ν	Poisson's ratio	—
ρ	Plasticity interaction factor	—
σ	Stress	N/mm ²
σ_f	Flow strength (assumed to be the average of the yield and the tensile strengths)	N/mm ²
σ'_f	Value of flow strength (assumed to be the average of yield and tensile strengths) of the "appropriate" material at the assessment temperature	N/mm ²
σ^P	Stress arising from primary loads	N/mm ²
σ_{ref}	Reference stress used for creep and plastic consideration; it is sometimes calculated from plane strain von Mises limit load as in Annex N	N/mm ²
σ^S	Stress arising from secondary loads	N/mm ²
σ_t	True stress	N/mm ²
σ_U	Tensile strength	N/mm ²
σ_Y	Lower yield strength or 0.2% proof strength	N/mm ²
σ'_Y	Yield strength of "appropriate" material at the assessment temperature	N/mm ²
σ'_{YRT}	Yield strength of the "appropriate" material at room temperature in Equation (7.24a)	N/mm ²

7.1 Background

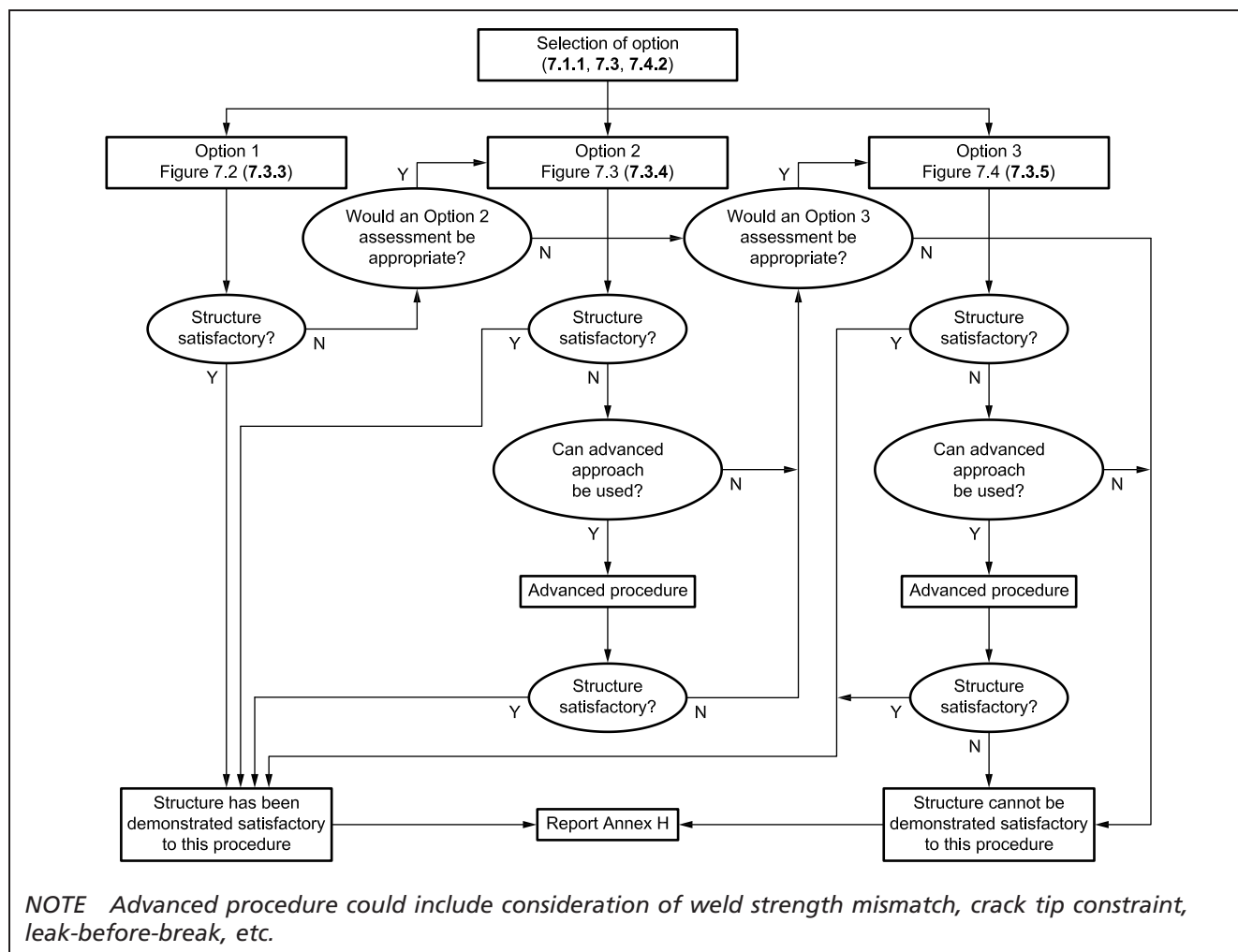
7.1.1 General

The background to this clause is given in references [7.1], [7.2], [7.3] and [7.4].

There are three options for fracture assessment in this clause, Options 1, 2 and 3, which use similar methods (7.3). Which one is used depends on the available materials properties and the level of conservatism required. A flowchart describing the various options is given in Figure 7.1.

NOTE The methods presented in this clause are based on the assumption that the primary stresses acting on the uncracked body are predominantly in the elastic range, i.e. below the yield strength of the material (so-called stress-based assessment). A method for strain-based assessment is given in Annex V.

Figure 7.1 General flowchart for fracture assessment



Assessment is generally made by means of a failure assessment diagram (FAD) based on the principles of fracture mechanics. The vertical axis of the FAD compares the applied loading, in terms of the corresponding stress intensity factors, to the fracture toughness of the material. The horizontal axis is the ratio of the applied primary load to that required for plastic collapse. A failure assessment line (FAL) is plotted on the diagram. Calculations for a flaw provide either the co-ordinates of an assessment point or, in the case of crack growth, a locus of points. The positions of these are compared with the FAL to determine the acceptability of the flaw. Options 1 to 3 are shown in Figure 7.2 to Figure 7.4.

Figure 7.2 Flowchart for Option 1 fracture assessment

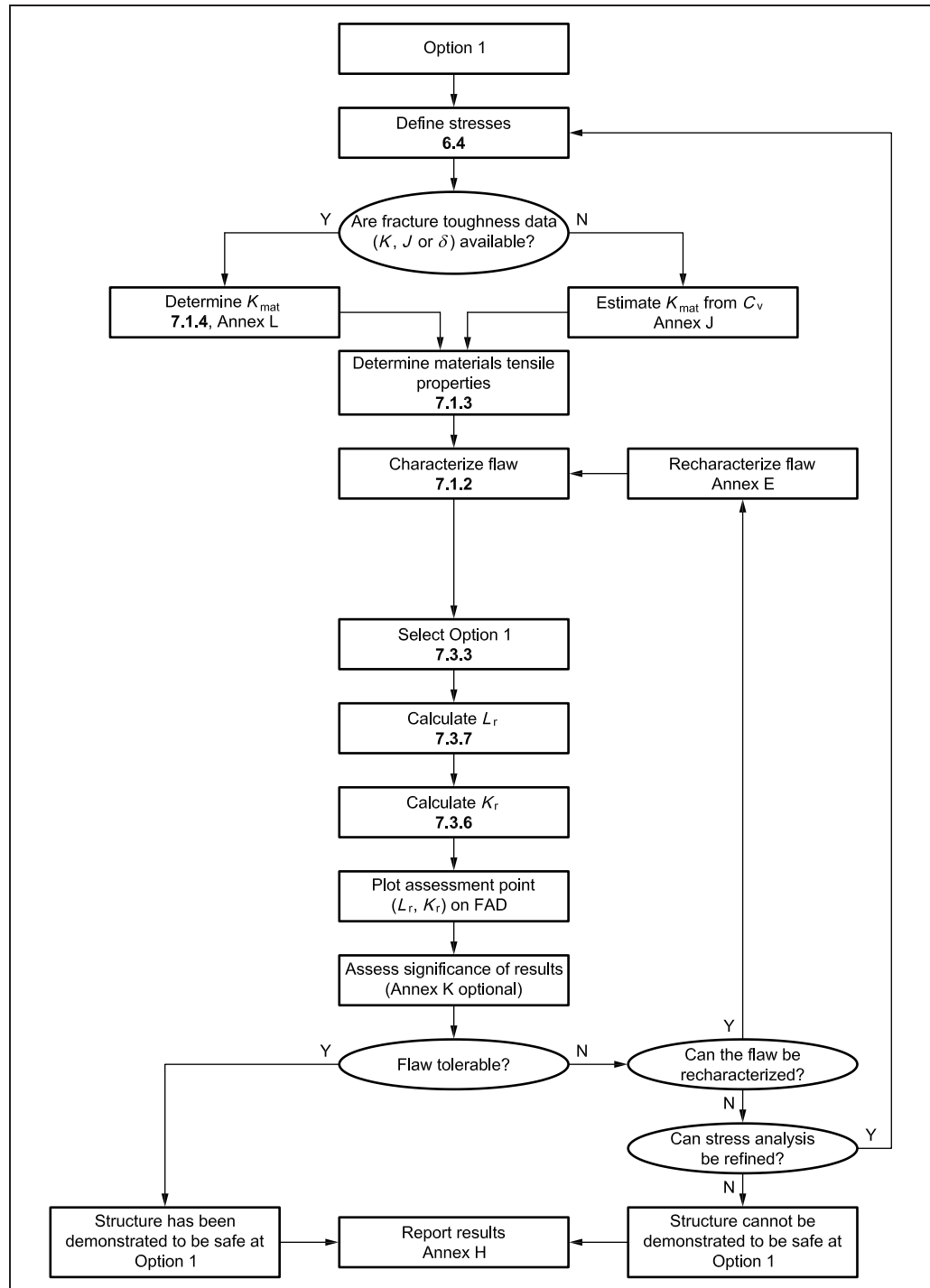


Figure 7.3 Flowchart for Option 2 fracture assessment

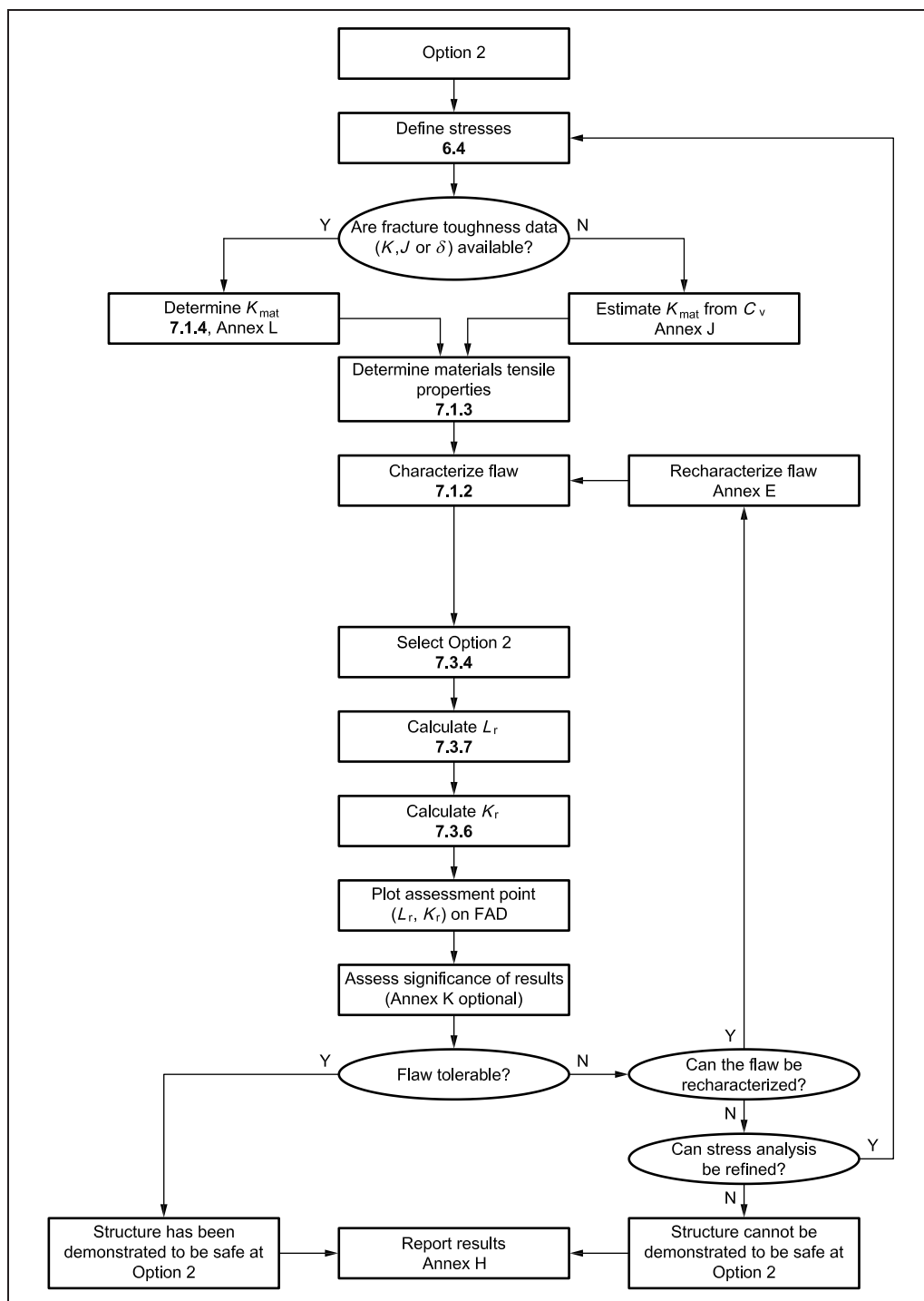
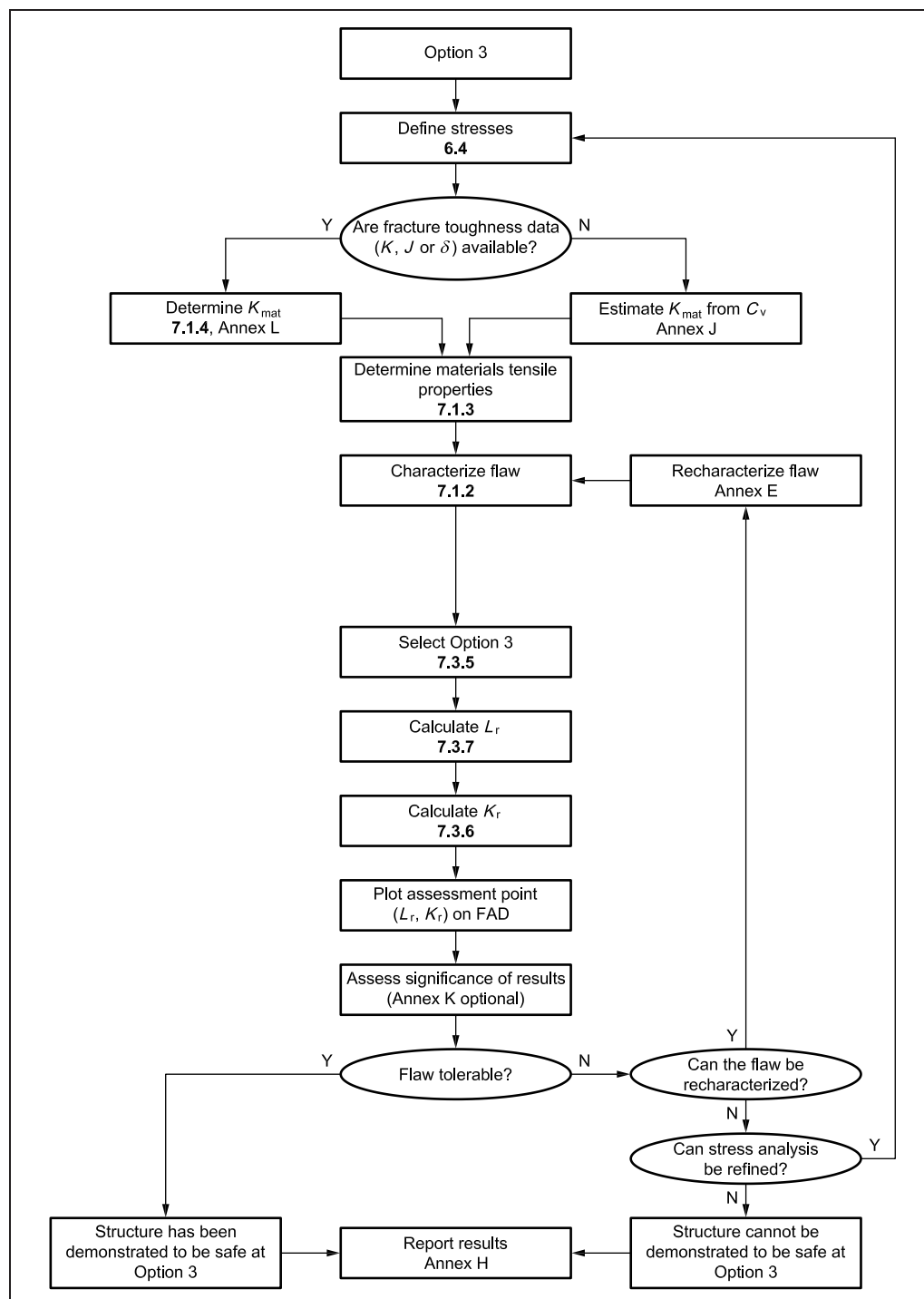


Figure 7.4 Flowchart for Option 3 fracture assessment



The acceptability of a flaw may be assessed directly or the calculation may be iterated in order to determine the limiting value of a parameter such as flaw size, applied load or fracture toughness.

The assessments using the FAD relate to planar flaws. Guidance on the assessment of other anomalies is given in 7.4.4.

The assessments in this clause refer to tensile mode I loading only. Mixed mode loading is addressed in Annex A.

In some cases acceptability can be demonstrated when an initial assessment shows a flaw to be unacceptable. This can require improving the quality of the

input data, and/or applying a higher assessment option, or accounting for ductile tearing under increasing load.

In some cases, surface-breaking or embedded flaws are initially found to be unacceptable due to predicted ligament failure, but this might not be limiting. The flaw may then be re-characterized as a through-thickness or surface-breaking flaw and reassessed. The procedure for flaw re-characterization is given in Annex E.

For pressurized applications, a leak-before-break analysis might show that a stable leak would occur rather than a break (see Annex F).

The procedures in this clause assume that the region affected by the flaw consists of a single material. Advice on the appropriate materials properties in the case of a welded component is given in 7.1.3 to 7.1.7, for tensile and fracture toughness properties. A procedure for performing a strength mismatch assessment which takes benefit from materials of higher strength in the vicinity of the flaw is given in Annex I.

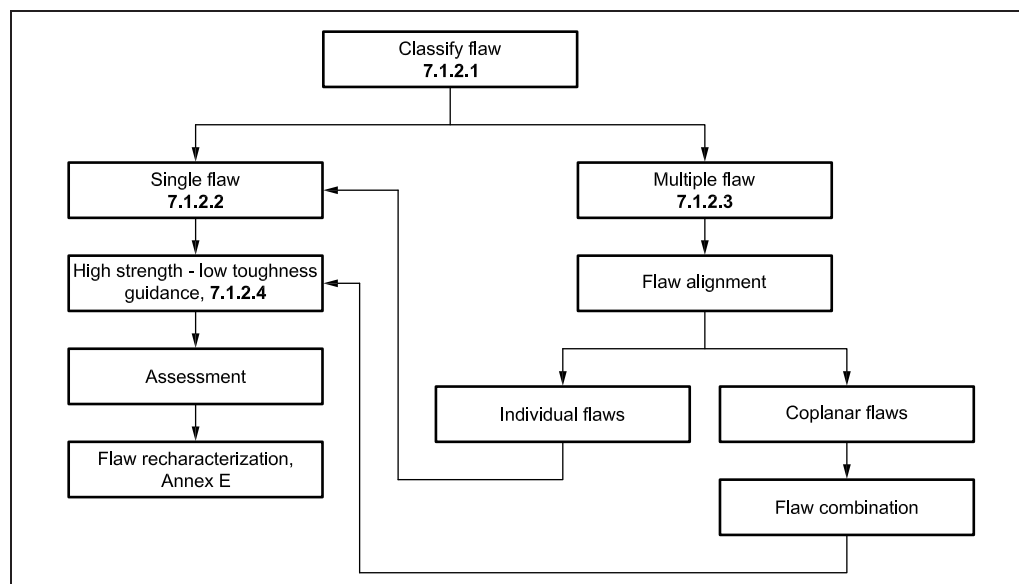
The fracture toughness used in this clause is obtained following the advice in 7.1.4 to 7.1.7 and assumes conditions of high constraint at the crack tip. Low constraint conditions, as promoted for example by shallow flaws and predominantly tensile loading (e.g. when the through-wall bending stress is much smaller than membrane stress, as in a pipe), can lead to increased fracture toughness and hence increased margins in the assessment. A procedure that allows for conditions of low in-plane structural constraint is given in Annex N. Annex N should not be used in conjunction with Annex I.

7.1.2 Flaw dimensions and interaction

- 7.1.2.1** This subclause provides guidance on determining the flaw dimensions from non-destructive or other means of flaw detection. The guidance is given for individual flaws (single flaws) in 7.1.2.2 and for multiple flaws in 7.1.2.3, where the interaction effects between neighbouring flaws in close proximity might require multiple flaws to be combined into a virtual larger flaw for the purpose of flaw assessment. Flaw interaction is normally assessed at the start and at the end of the evaluation interval incorporating any sub-critical crack growth during that interval. For cases of high strength/low toughness steels where cleavage is a concern, special consideration is required, as detailed in 7.1.2.4. In cases where ligament failure might not be critical to the overall integrity of the component, flaw recharacterization may be performed as described in Annex E. A flowchart of the overall process of flaw characterization is given in Figure 7.5.
- 7.1.2.2** Single planar flaws should be characterized by the height and length of their containment rectangles. These dimensions are defined in Figure 7.6 as follows: $2a$ for through-thickness flaws; a and $2c$ for surface flaws; and $2a$ and $2c$ for embedded flaws. One side for the case of a surface flaw, and two (parallel) sides for the case of embedded flaws, should be aligned with the free surface nearest to the flaw and denoted as $2c$. The remaining two sides should be orthogonal to the same free surface and denoted as a for surface flaws or $2a$ for embedded flaws. When it is demonstrated that it is conservative to do so and the appropriate stress intensity factor and reference stress solutions are used, it is permissible to construct a containment rectangle not aligned with the free surface.
- 7.1.2.3** Multiple planar flaws in close proximity can lead to an interaction and to more severe effects than single flaws alone. Simple criteria for interaction are given in Figure 7.7 and Figure 7.8, with the dimensions of the effective flaws after interaction. If multiple flaws exist, each flaw should be checked for interaction with each of its neighbouring flaws using the original flaw dimensions. Flaws on different cross-section planes should first be checked for alignment using the flaw alignment criteria in Figure 7.7. Aligned flaws or flaws that occur on the

same plane (coplanar flaws) should then be checked against the flaw combination criteria of Figure 7.8 and combined into a single flaw if necessary. It is not normally necessary to consider further interaction of a combined flaw with the neighbouring flaws. It is not necessary to apply flaw interaction criteria for fatigue assessment. However, if there is any uncertainty as to whether flaws are separate, they should be combined or specific calculations carried out.

Figure 7.5 Flowchart for flaw characterization



7.1.2.4 In high strength/low toughness materials the bounding flaw might not provide sufficient conservatism [7.5]. In such cases the maximum height of the flaw for surface flaws (actual or calculated tolerable flaw) or the larger of the two orthogonal flaw dimensions for embedded flaws (actual or calculated tolerable flaw) should be compared with the simplified calculation of Irwin's plastic zone size given by Equation (7.1):

$$a_{pl} = \frac{1}{\pi} \left(\frac{K_{mat}}{\sigma_Y} \right)^2 \quad (7.1)$$

where:

- K_{mat} is determined in accordance with 7.1.4;
- σ_Y is determined in accordance with 7.1.3.

If the maximum flaw height or the larger of the two orthogonal flaw dimensions is less than the value from Equation (7.1), the normal assessment route is followed. Conversely, if the maximum flaw height or the larger of the two orthogonal flaw dimensions is greater than the value from Equation (7.1), one of the following routes should be followed:

- a) actual flaws should be characterized as normal and the stress intensity factor(s) for the characterized flaw increased by 10%; or
- b) the actual flaws should be characterized so that the characterized flaw is increased by 20%, both in length and height.

The two approaches above provide a conservative characterization, but they do not necessarily produce the same assessment results. A sensitivity study should be undertaken. The acceptability of the flaws should normally be based on the more conservative assessment.

Figure 7.6 Definitions of flaw dimensions

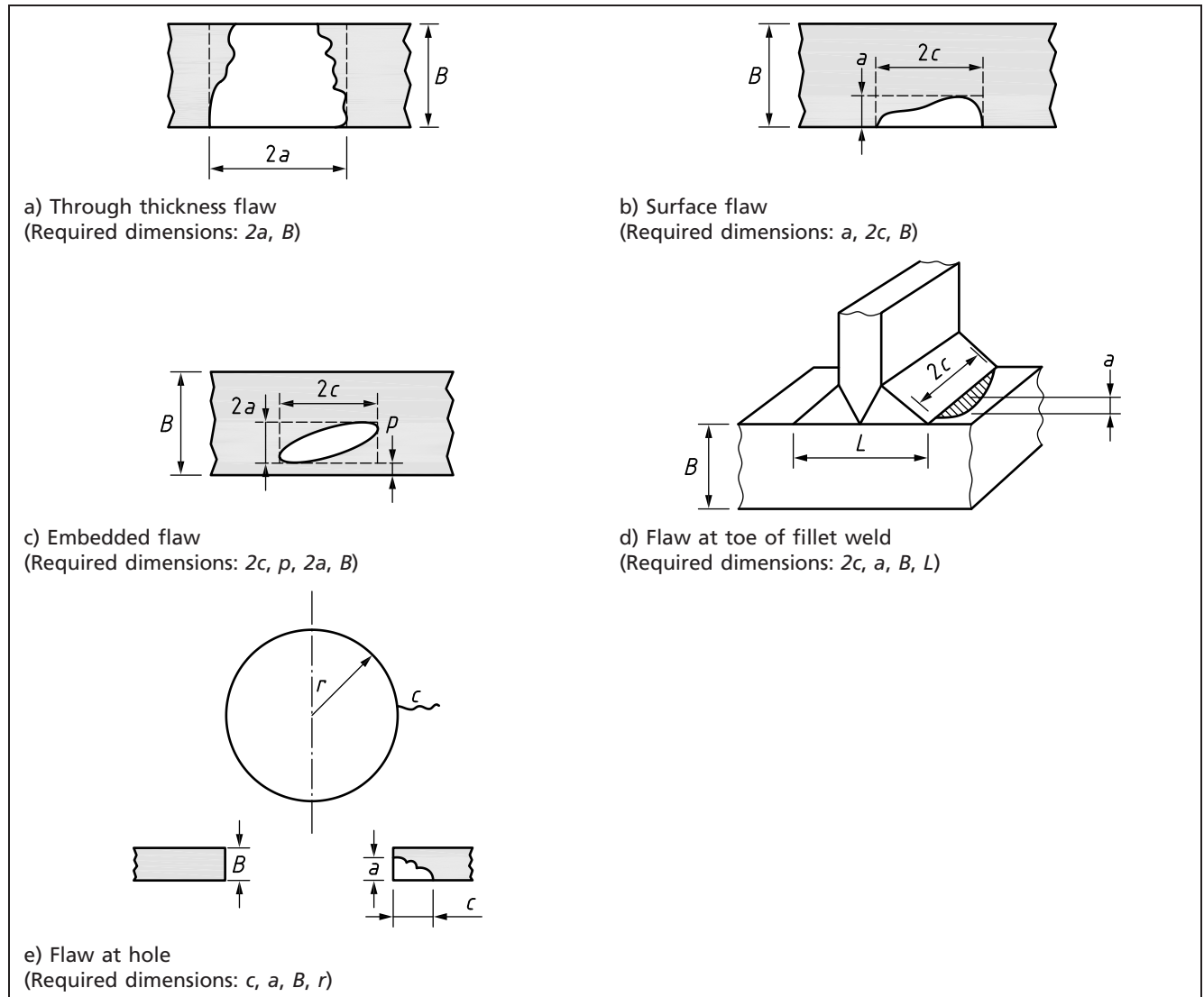


Figure 7.7 Flaw alignment rules for non-coplanar flaws

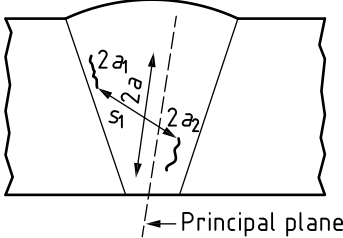
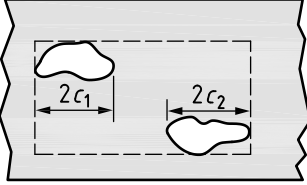
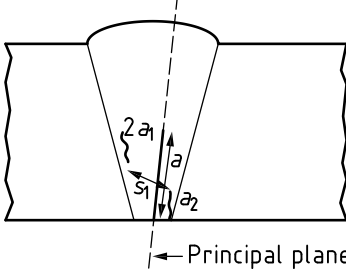
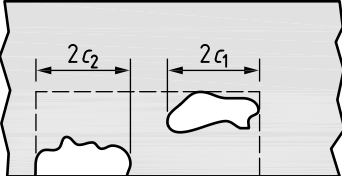
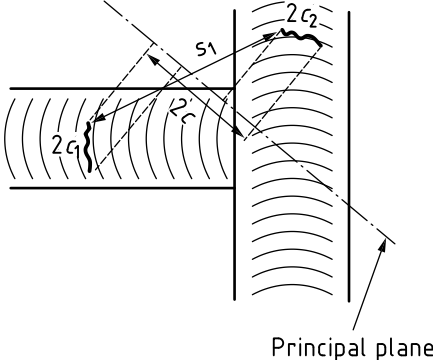
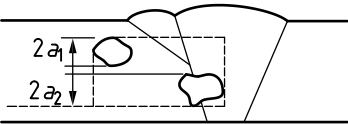
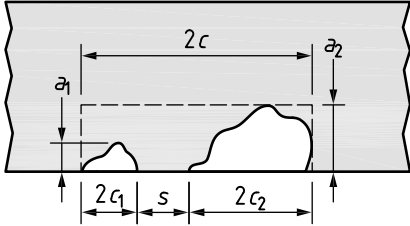
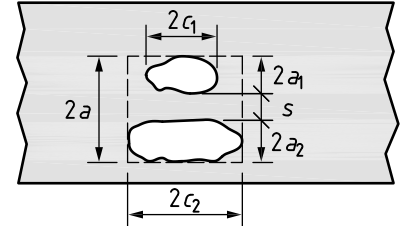
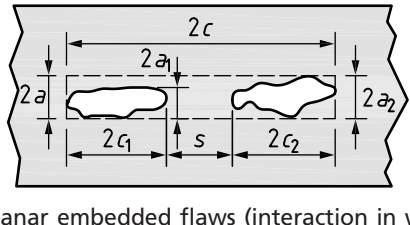
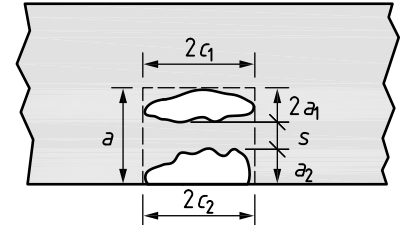
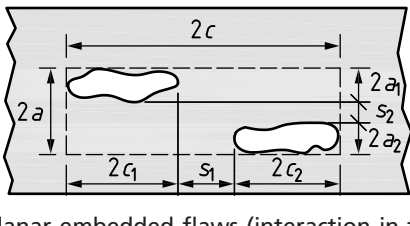
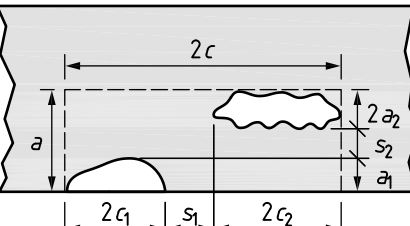
Schematic flaws	Criteria for alignment
 ← Principal plane 1) Principal plane normal to the maximum principal stress in weld a) Adjacent non-coplanar	 2) Projection of flaws onto the principal plane $s_1 \leq a_1 + a_2$
 ← Principal plane 1) Principal plane normal to the maximum principal stress in weld b) Adjacent non-coplanar surface and embedded flaws	 2) Projection of flaws onto the principal plane $s_1 \leq a_1 + a_2$
 Principal plane c) Adjacent non-coplanar embedded flaws in intersecting welds	 2) Projection of flaws onto the principal plane $s_1 \leq a_1 + a_2$

Figure 7.8 Flaw interaction rules for coplanar flaws

Schematic flaws	Criteria for interaction	Effective dimensions after interaction
 a) Coplanar surface flaws	$s \leq \max. (0.5a_1, 0.5a_2)$ for all flaws except a_1/B and $a_2/B > 0.5$ $s \leq \max. (a_1, a_2)$ for flaws with a_1/B and $a_2/B > 0.5$	$a = \max. (a_1, a_2)$ $2c = 2c_1 + 2c_2 + s$
 b) Coplanar embedded flaws (interaction in thickness direction)	$s_1 \leq a_1 + a_2$	$2a = 2a_1 + 2a_2 + s$ $2c = \max. (2c_1, 2c_2)$
 c) Coplanar embedded flaws (interaction in width direction)	$s \leq \max. (a_1, a_2)$ for all flaws	$2a = \max. (2a_1, 2a_2)$ $2c = 2c_1 + 2c_2 + s$
 d) Coplanar surface and embedded flaws (interaction in thickness direction)	$s_1 \leq a_1 + a_2$	$a = 2a_1 + a_2 + s$ $2c = \max. (2c_1, 2c_2)$
 e) Coplanar embedded flaws (interaction in thickness and width direction)	$s_1 \leq \max. (a_1, a_2)$ for all flaws and $s_2 \leq a_1 + a_2$	$2c = 2c_1 + 2c_2 + s_1$ $2a = 2a_1 + 2a_2 + s_2$
 f) Coplanar surface and embedded flaws (interaction in both thickness and width direction)	$s_1 \leq \max. (0.5a_1, a_2)$ for all flaws and $s_2 \leq a_1 + a_2$	$a = a_1 + 2a_2 + s_2$ $2c = 2c_1 + 2c_2 + s_1$

7.1.3 Tensile properties

7.1.3.1 Tensile test properties

The material yield strength, σ_Y , tensile strength, σ_U , and modulus of elasticity, E , are required for assessment of fracture resistance. They should be determined in accordance with BS EN ISO 6892-1, BS EN ISO 6892-2 or BS EN ISO 6892-3 at the appropriate temperature and strain rate. Where possible, the longitudinal axis of the tensile specimen should be normal to the plane of the flaw being assessed. However, in the case of welds, where this is impractical (because welds are generally narrow compared to the size of a tensile specimen), it is acceptable to employ tensile specimens which are parallel to the longitudinal axis of the weld. Unless specific solutions are available to assess the effect of weld strength mismatch (see Annex I and Annex P), safe assessments can be made of flaws located in welded regions (weld metal and HAZ) if the tensile properties assumed are the lower of the parent metal, weld metal or HAZ. For assessment Options 2 and 3 the full stress-strain curve is required.

NOTE 1 Unless otherwise stated, guidance given on tensile properties refers to the engineering definitions of tensile properties determined under quasi-static loading conditions. Where assessments consider dynamic loading, tensile properties need to be established for the appropriate loading rate.

NOTE 2 Materials are generally non-isotropic. Tensile properties depend on processing history and specimen orientation. Where the flaw orientation is not known, the tensile specimen orientation needs to be representative of the lowest yield strength direction.

When an assessment is conducted according to the Option 1 FAD, yield strength, σ_Y , corresponds to $R_{p0.2}$, R_{eL} or $R_{t0.5}$ as described in BS EN ISO 6892-1 and in a number of material specification standards. Some steel product standards define yield strength in terms of the upper yield strength, R_{eH} . For the purposes of this British Standard, σ_Y is then to be considered as $0.95R_{eH}$. When an assessment is conducted to Options 2 or 3, yield strength corresponds to $R_{p0.2}$ or $R_{p1.0}$ for ferritic or austenitic steels, respectively. Tensile strength, σ_U , corresponds to R_m . These definitions are listed in Table 7.1 and illustrated in Figure 7.9.

Table 7.1 Engineering definitions of yield and tensile strengths for Options 1, 2, 3

Definition	Option 1	Option 2	Option 3
0.2% offset to elastic slope	$R_{p0.2}$	$R_{p0.2}$	$R_{p0.2}$
1% offset to elastic slope	$R_{p1.0}$	$R_{p1.0}$	$R_{p1.0}$
Lower yield strength	R_{eL}	—	—
Strength at 0.5% strain	$R_{t0.5}$	—	—
95% upper yield strength	$0.95R_{eH}$	—	—
Tensile strength	R_m	R_m	R_m