

BS 7910:2013+A1:2015

Incorporating Corrigenda Nos. 1 and 2



BSI Standards Publication

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

bsi.

AVA Documents
Document Sharing Hub

Publishing and copyright information

The BSI copyright notice displayed in this document indicates when the document was last issued.

© The British Standards Institution 2016

Published by BSI Standards Limited 2016

ISBN 978 0 580 95198 5

ICS 25.160.40

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

Committee reference WEE/37

Draft for comment 12/30241229 DC, 15/30320309 DC

Publication history

First published December 1999

Second edition, July 2005

Third (present) edition, December 2013

Amendments issued since publication

Date	Text affected
A1: 31 July 2015	A number of untagged editorial corrections and amendments as indicated by tags
C1: 30 September 2015	The date this standard came into effect has been inserted in the Foreword. Columns relating to the internal surface flaw have been removed from Table M.5, which is applicable to external flaws only.
C2: 31 August 2016	See Foreword

Contents

Foreword *viii*

Introduction *1*

1 Scope *4*

2 Normative references *4*

3 Symbols and definitions *5*

4 Types of flaw *24*

5 General guidance on assessment *25*

6 Information required for assessment *27*

7 Assessment for fracture resistance *35*

8 Assessment for fatigue *70*

9 Assessment of flaws under creep and creep/fatigue conditions *108*

10 Assessment for other modes of failure *132*

Annexes

Annex A (normative) Evaluation under mode I, II and III loads *139*

Annex B (informative) Assessment procedures for tubular joints in offshore structures *144*

Annex C (normative) Fracture assessment procedures for pressure vessels and pipelines *151*

Annex D (normative) Stress due to misalignment *155*

Annex E (normative) Flaw recharacterization *161*

Annex F (normative) Procedures for leak-before-break (LbB) assessment *162*

Annex G (normative) The assessment of locally thinned areas (LTAs) *187*

Annex H (normative) Reporting of fracture, fatigue or creep assessments *199*

Annex I (informative) The significance of strength mis-match on the fracture behaviour of welded joints *202*

Annex J (informative) Use of Charpy V-notch impact tests to estimate fracture toughness *210*

Annex K (informative) Probabilistic assessment *215*

Annex L (informative) Fracture toughness determination for welds *230*

Annex M (normative) Stress intensity factor solutions *240*

Annex N (informative) Allowance for constraint effects *295*

Annex O (informative) Consideration of proof testing and warm prestressing *333*

Annex P (normative) Compendium of reference stress and limit load solutions for homogeneous and strength mis-matched structures *340*

Annex Q (normative) Residual stress distributions in as-welded joints *383*

Annex R (normative) Determination of plasticity interaction effects with combined primary and secondary loading *404*

Annex S (normative) Information for making high temperature crack growth assessments *409*

Annex T (informative) Guidance on the use of NDT with ECA *422*

Annex U (informative) Worked examples in fatigue assessment using the quality category approach *439*

Bibliography *446*

List of figures

Figure 1 – Example of integrity management procedure for flaws *2*

Figure 2 – Linearization of stress distributions *31*

Figure 3 – Schematic representation of stress distribution across section *34*

Figure 4 – Procedure for resolving flaws normal to principal stress *35*

Figure 5 – General flowchart for fracture assessment *36*

Figure 6 – Flowchart for Option 1 fracture assessment *37*

Figure 7 – Flowchart for Option 2 fracture assessment *38*

Figure 8 – Flowchart for Option 3 fracture assessment *39*

Figure 9 – Flowchart for flaw characterization *41*

Figure 10 – Definitions of flaw dimensions *42*

Figure 11 – Flaw alignment rules for non-coplanar flaws	43
Figure 12 – Flaw interaction rules for coplanar flaws	44
Figure 13 – De-rating values for yield/proof strength and tensile strength at temperatures above room temperature in C-Mn steels and duplex stainless steels (DSS): (not applicable to 13% Cr steels) from DNV OS F101 [6]	47
Figure 14 – Ductile tearing assessment	66
Figure 15 – Example of non-unique solutions	68
Figure 16 – Schematic crack growth relationships	77
Figure 17 – Recommended fatigue crack growth laws	77
Figure 18 – Quality category <i>S-N</i> curves	84
Figure 19 – Quality category approach: assessment of surface flaws in plates under axial loading	89
Figure 20 – Quality category approach: assessment of surface flaws in flat material (no weld toe or other stress raiser) in bending	91
Figure 21 – Quality category approach: assessment of embedded flaws in axially loaded joints	93
Figure 22 – Quality category approach: assessment of weld toe flaws in axially loaded joints	95
Figure 23 – Quality category approach: assessment of weld toe flaws in joints loaded in bending	101
Figure 24 – Determination of temperature T_c at which 0.2% creep strain is accumulated at a stress level equal to the proof strength	112
Figure 25 – Insignificant creep curves for austenitic steels	113
Figure 26 – Insignificant creep curves for ferritic steels	113
Figure 27 – Schematic behaviour of crack subjected to steady loading at elevated temperature	115
Figure 28 – Schematic representation of crack propagation and failure conditions	116
Figure 29 – Flowchart for overall creep assessment procedure	117
Figure 30 – Schematic diagrams of typical relationships between crack velocity and stress intensity factor during SCC	134
Figure 31 – Types of corrosion fatigue crack growth behaviour	136
Figure A.1 – Definitions of loading modes	139
Figure B.1 – Assessment method for fatigue crack growth in tubular joints	145
Figure E.1 – Rules for recharacterization of flaws	161
Figure F.1 – The leak-before-break diagram	162
Figure F.2 – Flow charts for LbB procedures	165
Figure F.3 – Example characterization of a complex flaw	170
Figure F.4 – Schematic flaw profiles at breakthrough	172
Figure F.5 – Development of flaw shapes for sub-critical growth of surface flaws	175
Figure F.6 – Development of flaw shapes for sub-critical growth of through-wall flaws	175
Figure F.7 – Recommended re-characterization of flaws at breakthrough subjected to ductile tearing loading	176
Figure G.1 – Flow chart of assessment procedure	189
Figure G.2 – Dimensions of an LTA	190
Figure G.3 – Dimensions of a bend	192
Figure G.4 – Dimensions of a sphere and vessel end	193
Figure G.5 – Interaction between LTAs	195
Figure I.1 – Idealized weld geometry – the parent and weld metals have yield strengths of σ_Y^W and σ_Y^P respectively	204
Figure I.2 – Idealized definition of mis-match ratio, M , and construction of the equivalent stress-strain curve (weighted average of the other two curves)	205
Figure J.1 – Flowchart for selecting an appropriate correlation for estimating fracture toughness from Charpy data	211
Figure M.1 – Through-thickness flaw geometry	243

Figure M.2 – Edge flaw geometry	243
Figure M.3 – Surface flaw	244
Figure M.4 – Elliptical integral as a function of $a/2c$ used for the calculation of K_I for surface and embedded flaws	246
Figure M.5 – Stress intensity magnification factor M_m for surface flaws in tension	246
Figure M.6 – Stress intensity magnification factor M_b for surface flaws in bending	249
Figure M.7 – Extended flaw geometry	250
Figure M.8 – Embedded flaw	251
Figure M.9 – Stress intensity magnification factor M_m for embedded flaws in tension (at point nearest material surface)	252
Figure M.10 – Stress intensity magnification factor M_b for embedded flaws in bending	253
Figure M.11 – Corner flaw geometry	254
Figure M.12 – Corner flaw at hole geometry	256
Figure M.13 – Through-thickness flaw in cylinder oriented axially	260
Figure M.14 – Internal surface flaw in cylinder oriented axially	265
Figure M.15 – Extended internal surface flaw in cylinder orientated axially	267
Figure M.16 – External surface flaw in cylinder oriented axially	268
Figure M.17 – Extended axial external surface flaw in cylinder	269
Figure M.18 – Through-thickness flaw in cylinder oriented circumferentially	271
Figure M.19 – Internal surface flaw in cylinder oriented circumferentially	276
Figure M.20 – Fully circumferential internal surface flaw in cylinder	278
Figure M.21 – Fully circumferential external surface flaw in cylinder	279
Figure M.22 – Through-thickness flaw in spherical shell	282
Figure M.23 – Flaws in bars and bolts	283
Figure M.24 – Fully circumferential flaw in a round bar	286
Figure M.25 – Welded joint geometries	288
Figure M.26 – Transverse load-carrying cruciform joint	289
Figure N.1 – Schematic showing curve fitting of low constraint test data to obtain a and k	301
Figure N.2 – Modifications to the Option 1 failure assessment curve for various values of the material parameters, a , k , and constraint levels, β (< 0), using Equation N.23 with $k = 3$. For $a = 0$ or $\beta = 0$ the curves reduce to the Option 1 curve	303
Figure N.3 – FAD analysis for (a) fracture initiation and (b) ductile tearing	304
Figure O.1 – Schematic illustration of a proof test argument (following [3])	335
Figure O.2 – Typical warm prestress cycles	337
Figure P.1 – Double edge cracked plate under tension	346
Figure P.2 – Extended embedded flaw in a plate	348
Figure P.3 – Circumferential internal and external surface flaws in thick-walled cylinders under combined tension and bending	358
Figure P.4 – T and Y joints under a) axial load, b) in-plane and out-of-plane bending	362
Figure P.5 – K-joints under a) axial load and b) in-plane and out-of-plane bending	363
Figure P.6 – X and DT joints under a) axial load and b) in-plane and out-of-plane bending	364
Figure P.7 – Classification of plasticity deformation patterns for mis-matched structures, [367]	365
Figure P.8 – Centre cracked plate under tension $\psi = (W - a)/h$	369
Figure P.9 – Double edge cracked plate under tension	373
Figure P.10 – Single edge cracked plate under pure bending	377
Figure P.11 – Fully circumferential internal flaws in thin-walled pipes/cylinders under tension	379

Figure P.12 – Centre through-thickness flaws in clad plates under tension [372], [373]	380
Figure P.13 – Through-thickness flaw in a clad plate with repair weld	382
Figure Q.1 – Components of longitudinal residual stress distribution for plate butt welds and pipe axial seam welds (austenitic steel)	385
Figure Q.2 – Components of transverse stress distribution for plate butt welds and axial seam welds (austenitic and ferritic steels)	386
Figure Q.3 – Components of longitudinal stress distribution for pipe butt welds (ferritic and austenitic steels)	387
Figure Q.4 – Components of transverse stress distribution for pipe butt welds (ferritic steels)	388
Figure Q.5 – Components of longitudinal stress distribution for plate to plate T-butt welds (ferritic steels)	392
Figure Q.6 – Components of transverse stress distribution for plate to plate T-butt welds (austenitic and ferritic steels)	394
Figure Q.7 – Components of longitudinal stress distribution for tubular T-butt welds (ferritic steels)	395
Figure Q.8 – Components of transverse stress distribution for tubular T-butt welds (ferritic steels)	396
Figure Q.9 – Residual stress profile for repair welds (transverse and longitudinal)	398
Figure Q.10 – Finite surface crack in an infinite width plate	399
Figure Q.11 – Extended surface flaw in an infinite width plate	403
Figure R.1 – Non-dimensional stress intensity factors for through-thickness flaws with through-wall self-balancing stress distributions	407
Figure S.1 – General form of a creep curve defining the average and secondary creep strain rates	411
Figure S.2 – Derivation of strain versus time curves from iso-strain curves	412
Figure T.1 – Assessment of flaw tolerance using ECA	426
Figure T.2 – Assessment of detected flaw	427
Figure U.1 – Butt weld containing embedded flaw	439
Figure U.2 – Derivation of actual quality category for a flaw	440
Figure U.3 – Fillet weld containing a surface flaw	441
Figure U.4 – Obtaining the required quality category	442
Figure U.5 – Obtaining the quality category for the flaw	443

List of tables

Table 1 – Symbols	5
Table 2 – Coefficient of variation (COV) for tensile properties for ferritic steels	46
Table 3 – Elastic modulus	46
Table 4 – Guidance for determining whether yielding is continuous or discontinuous	49
Table 5 – Minimum of three equivalent (MOTE)	56
Table 6 – Values of $k_{0.90}$ at the lower 20th percentile for the one sided tolerance limit for a normal distribution	56
Table 7 – Limits for slag inclusions and porosity	68
Table 8 – Procedure for assessment of known flaws	70
Table 9 – Stress ranges used in fatigue assessments	75
Table 10 – Recommended fatigue crack growth laws for steels in air	78
Table 11 – Recommended fatigue crack growth laws for steels in a marine environment	79
Table 12 – Recommended fatigue crack growth threshold, ΔK_0 , values for assessing welded joints	81
Table 13 – Details of quality category $S-N$ curves	83
Table 14 – Minimum values of $\Delta\sigma_j$ for assessing non-planar flaws and shape imperfections	105
Table 15 – Limits for non-planar flaws in as welded steel and aluminium alloy weldments	106

Table 16 – Limits for non-planar flaws in steel weldments stress relieved by PWHT	106
Table 17 – Acceptance levels for misalignment expressed in terms of stress magnification factor, k_m	107
Table 18 – Acceptance levels for weld toe undercut in material thicknesses from 10 mm to 40 mm	107
Table 19 – Temperature below which creep is negligible in 200,000 h	112
Table D.1 – Formulae for calculating the bending stress due to misalignment in butt joints	156
Table D.2 – Formulae for calculating the bending stress due to misalignment in cruciform joints	159
Table F.1 – Guidance on selection of assessment sites around a pipe system	164
Table F.2 – Advice on growth of surface flaws [160]	173
Table F.3 – Advice on growth of through-wall defects [160]	174
Table F.4 – Crack opening area methods for simple geometries and loading	177
Table F.5 – Summary of short wave length surface roughness values [208]	181
Table F.6 – Particulates in primary system water	186
Table K.1 – Uncertainties in Paris parameter A	219
Table K.2 – Uncertainties in Paris parameter A for the two stage model	220
Table K.3 – Target failure probability (events/year)	221
Table K.4 – Recommended partial factors for different combinations of target reliability and variability of input data based on failure on the FAD	222
Table M.1 a) – M_1 for axial through-thickness in cylinders: membrane loading	261
Table M.1 b) – M_2 for axial through-thickness flaws in cylinders: membrane loading	262
Table M.1 c) – M_3 for axial through-thickness flaws in cylinders: bending loading	263
Table M.1 d) – M_4 for axial through-thickness flaws in cylinders: bending loading	264
Table M.2 – M_m and M_b for axial internal surface flaw in cylinder	266
Table M.3 – M_m and M_b for extended axial internal surface flaw in cylinder	267
Table M.4 – M_m and M_b for axial external surface flaw in cylinder	268
Table M.5 – M_m and M_b for extended axial external surface flaw in cylinder	269
Table M.6a) – M_1 for circumferential through-thickness flaws in cylinders: membrane loading	272
Table M.6b) – M_2 for circumferential through-thickness flaws in cylinders: membrane loading	273
Table M.6c) – M_3 for circumferential through-thickness flaws in cylinders: bending loading	274
Table M.6d) – M_4 for circumferential through-thickness flaws in cylinders: bending loading	275
Table M.7 – M_m and M_b for circumferential internal surface flaw in cylinder	277
Table M.8 – M_m and M_b for extended circumferential internal surface flaw in cylindrical shell	278
Table M.9 – Influence coefficients at points A and B for an equatorial through-thickness flaw in a sphere	280
Table M.10 – M_m for semi-elliptical flaw in a round bar under tension loading	284
Table M.11 – M_b for semi-elliptical flaw in a round bar under bending loading	284
Table M.12 – Values of v and w for axial and bending loading	289
Table N.1 – Polynomial coefficients defining β_T for CCT [326 to 328]	306
Table N.2 – Polynomial coefficients defining β_T for CCBT	306
Table N.3 – Polynomial coefficients defining β_T for DECT [311], [326], [328]	307
Table N.4 – Polynomial coefficients defining β_T for SECT	307
Table N.5 – Polynomial coefficients defining β_T for SEB [311, 326, 328]	308
Table N.6 – Polynomial coefficients defining β_T for 3PB	308
Table N.7 – Polynomial coefficients defining β_T for SCT [329]	309
Table N.8 – Polynomial coefficients defining β_T for SCB [329]	310

Table N.9 – Polynomial coefficients defining β_T for CISLCCT [326], [330]	311
Table N.10 – Polynomial coefficients defining β_T for CISSCCBT [331]	312
Table N.11 – Polynomial coefficients defining β_T for CISSCCT [331]	313
Table N.12 – a and k defined with respect to T/σ_Y for $n = 5$	315
Table N.13 – a and k defined with respect to T/σ_Y for $n = 6$	316
Table N.14 – a and k defined with respect to T/σ_Y for $n = 7$	316
Table N.15 – a and k defined with respect to T/σ_Y for $n = 8$	317
Table N.16 – a and k defined with respect to T/σ_Y for $n = 9$	317
Table N.17 – a and k defined with respect to T/σ_Y for $n = 10$	318
Table N.18 – a and k defined with respect to T/σ_Y for $n = 11$	318
Table N.19 – a and k defined with respect to T/σ_Y for $n = 12$	319
Table N.20 – a and k defined with respect to T/σ_Y for $n = 13$	319
Table N.21 – a and k defined with respect to T/σ_Y for $n = 14$	320
Table N.22 – a and k defined with respect to T/σ_Y for $n = 15$	320
Table N.23 – a and k defined with respect to T/σ_Y for $n = 16$	321
Table N.24 – a and k defined with respect to T/σ_Y for $n = 17$	321
Table N.25 – a and k defined with respect to T/σ_Y for $n = 18$	322
Table N.26 – a and k defined with respect to T/σ_Y for $n = 19$	322
Table N.27 – a and k defined with respect to T/σ_Y for $n = 20$	323
Table N.28 – a and k defined with respect to Q for $n = 5$	324
Table N.29 – a and k defined with respect to Q for $n = 6$	325
Table N.30 – a and k defined with respect to Q for $n = 7$	325
Table N.31 – a and k defined with respect to Q for $n = 8$	326
Table N.32 – a and k defined with respect to Q for $n = 9$	326
Table N.33 – a and k defined with respect to Q for $n = 10$	327
Table N.34 – a and k defined with respect to Q for $n = 11$	327
Table N.35 – a and k defined with respect to Q for $n = 12$	328
Table N.36 – a and k defined with respect to Q for $n = 13$	328
Table N.37 – a and k defined with respect to Q for $n = 14$	329
Table N.38 – a and k defined with respect to Q for $n = 15$	329
Table N.39 – a and k defined with respect to Q for $n = 16$	330
Table N.40 – a and k defined with respect to Q for $n = 17$	330
Table N.41 – a and k defined with respect to Q for $n = 18$	331
Table N.42 – a and k defined with respect to Q for $n = 19$	331
Table N.43 – a and k defined with respect to Q for $n = 20$	332
Table P.1 – Calculation of bending stresses as functions of moments	342
Table P.2 – Values of χ for bending loading	359
Table P.3 – Coefficient Q_u for various joint design classifications	361
Table Q.0 – Validity ranges for as-welded residual stress distributions in ferritic steels	383
Table Q.1 – Components of longitudinal stress and K_{sb}^{max} for plate butt welds and pipe axial seam welds (austenitic steel)	385
Table Q.2 – Components of transverse stress and K_{sb}^{max} for plate butt welds and axial seam welds (austenitic and ferritic steels)	386
Table Q.3 – Components of longitudinal stress and K_{sb}^{max} for pipe butt welds (ferritic and austenitic steels)	387
Table Q.4 – Components of transverse stress and K_{sb}^{max} for pipe butt welds (ferritic steel)	391
Table Q.5 – Components of transverse stresses and K_{sb}^{max} for pipe butt welds (austenitic steel)	391
Table Q.6 – Components of longitudinal stress and K_{sb}^{max} for plate to plate T-butt welds (ferritic steels)	393
Table Q.7 – 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)	394
Table Q.8 – Components of longitudinal stress and K_{sb}^{max} for tubular T-butt welds (ferritic steels)	395

Table Q.9 – Components of transverse stress and K_{sb}^{max} for tubular T-butt welds (ferritic steels)	397
Table Q.10 – Components of transverse and longitudinal stress distribution for repair welds (ferritic and austenitic steels)	398
Table Q.11 – Geometry functions for a finite surface flaw in an infinite width plate – deepest point of the flaw	400
Table Q.12 – Geometry functions for a finite surface flaw in an infinite width plate – intersection of flaw with free surface	401
Table Q.13 – Geometry functions for an extended surface flaw in an infinite width plate	403
Table S.1 – Mean uniaxial creep properties for different steels for short (<10 000 h) and long term tests	413
Table S.2 – Constants used to derive creep crack growth rates in mm/h and C^* in MPamh ⁻¹	415
Table T.1 – Examples of inspection capabilities for sub-surface flaws	429
Table T.2 – Examples of inspection capabilities for back surface flaws	429
Table T.3 – Examples of inspection capabilities for flaws at the accessible surface	430
Table T.4 – Capabilities for detection and length measurement of surface-breaking flaws by MPI ([416])	435
Table T.5 – Flaw detection capability for liquid penetrant testing [444, 445]	436

Summary of pages

This document comprises a front cover, an inside front cover, pages i to x, pages 1 to 478, an inside back cover and a back cover.



Documents

Document Sharing Hub

© The British Standards Institution 2016 • vii

Foreword

This British Standard is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 December 2013. 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

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

Information about this document

The start and finish of text introduced or altered by Amendment No. 1 is indicated in the text by tags $\boxed{A_1}$ and $\boxed{A_1}$. Minor editorial changes are not tagged.

Text introduced or altered by Corrigenda Nos. 1 and 2, respectively is indicated in the text by tags $\boxed{C_1}$ $\boxed{C_1}$ and $\boxed{C_2}$ $\boxed{C_2}$. Minor editorial changes are not tagged.

This is a full revision of the standard, and introduces the following principal changes that reflect advances in structural integrity technology, in particular elements of the European FITNET procedure [1] and [2] and the UK nuclear industry's R6 procedure [3].

- In Clause 7 the fracture assessment "Levels" 1-3 have been replaced by "Options" 1-3 and the definitions changed substantially so that the new hierarchy of Options is in line with that used in the R6 procedure. The Level I fracture assessment procedure and the simplified implementation thereof (given in Annex N of BS 7910:2005) have been deleted.
- Annex S of BS 7910:2005 on appropriate numerical integration techniques for fatigue life estimation has been deleted.
- Annex U of BS 7910:2005, which gave worked examples to demonstrate high temperature assessment, has been deleted.
- Crack driving force is expressed in terms of K_I only. The materials toughness, K_{mat} , can be derived from K_{Ic} , CTOD or J -integral or Charpy test data.
- A procedure for incorporating weld strength mis-match has been included in Annex I for selected geometries.
- A procedure for incorporating crack tip constraint effects has been included in Annex N.
- New rules for flaw interaction criteria have been introduced in Clause 7.
- Clause 8, Clause 9 and Clause 10 have been rewritten to take into account new sources of information on environmental fatigue crack growth, creep crack growth and environmentally assisted cracking (EAC).
- Annex P now includes reference stress solutions and limit load solutions for both homogeneous and strength mis-matched structures.
- A new informative annex on the reliability of various non-destructive testing (NDT) techniques has been added as Annex T.
- Annex Q has been rewritten to facilitate the use of non-linear stress distributions for residual stress fields.
- The corrosion assessment annex (Annex G) has been renamed *Assessment of locally thinned areas (LTAs)* and substantially expanded to cover geometries other than straight pipes, e.g. elbows and spheres.

Use of this document

It has been assumed in the preparation of this British Standard that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

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

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".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

Introduction

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.

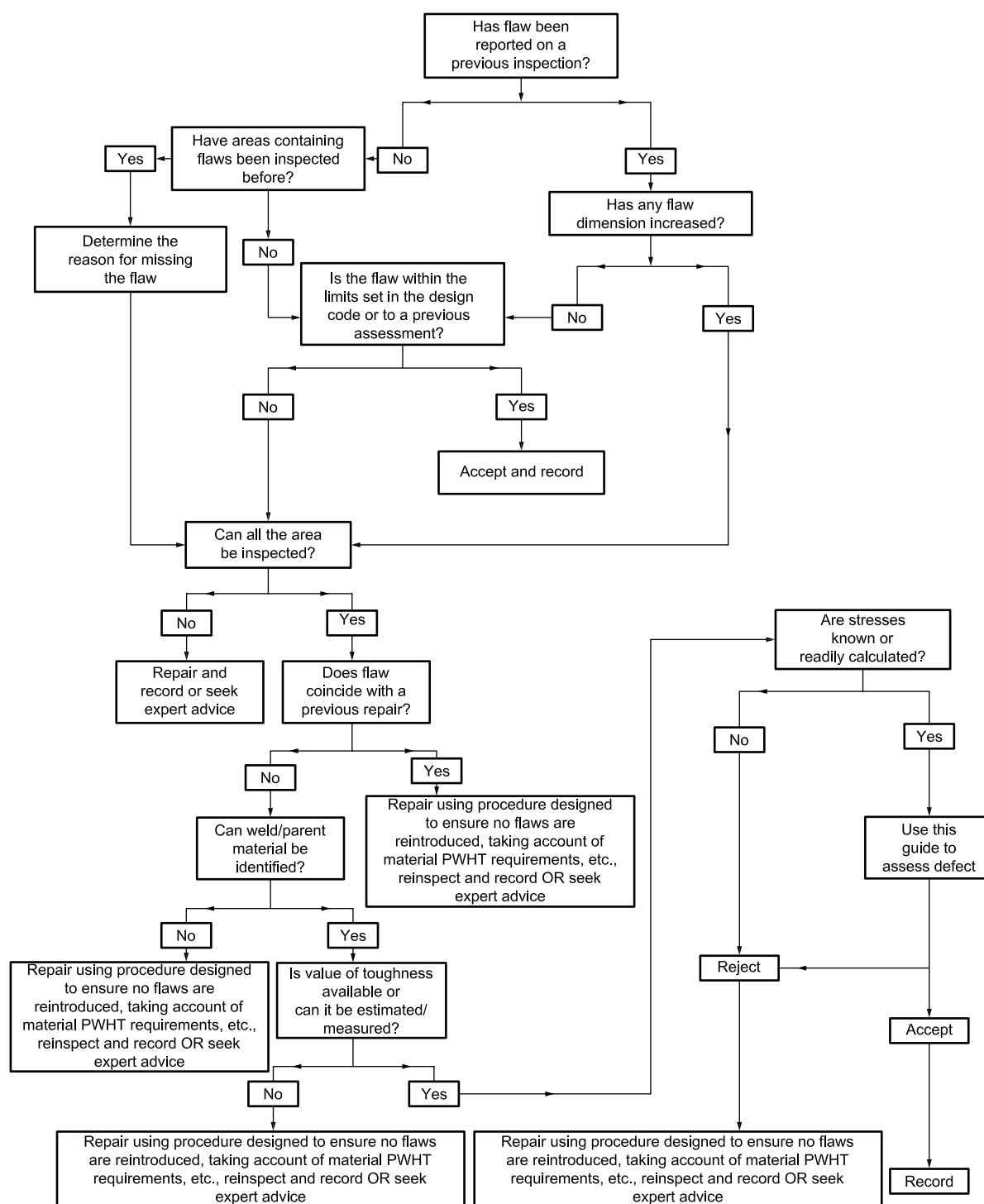
Quality control levels are usually both arbitrary and conservative, but are of considerable value in the monitoring and maintenance of quality during production. Flaws that are less severe than such quality control levels as given, for example, in current construction codes, are acceptable without further 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 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-conformance. 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 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 1 Example of integrity management procedure for flaws



NOTE If a component is rejected on the basis of a fitness-for-service analysis, downrating or retirement of the component may be considered as well as repair. Alternatively, the more advanced methods of this British Standard may be used, e.g. analyses based on leak-before-break (see Annex F) or recharacterization of flaws (see Annex E).

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 needs to 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, material 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 safety factors, reliability factors and 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 [4].

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 addresses 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 1. Alternative approaches may be developed.

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 may 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 a structure's life.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ASTM E1820, *Standard test method for measurement of fracture toughness*

ASTM E1921, *Standard test method for determination of reference temperature*

BS 7448 (all parts), *Fracture mechanics toughness tests*

BS EN 583 (all parts), *Nondestructive testing – Ultrasonic examination*

BS EN 12454, *Founding – Visual examination of surface discontinuities – Steel sand castings*

BS EN 12517 (all parts), *Non-destructive testing of welds*

BS EN ISO 6892-1, *Metallic materials – Tensile testing – Part 1: Method of test at ambient temperature*

BS EN ISO 6892-2, *Metallic materials – Tensile testing – Part 2: Method of test at elevated temperature*

BS EN ISO 7539 (all parts), *Corrosion of metals and alloys – Stress corrosion testing – Preparation and use of precracked specimens for tests under constant load or constant displacement*

BS EN ISO 11666, *Non-destructive testing of welds – Ultrasonic testing – Acceptance levels*

BS EN ISO 12737, *Metallic materials – Determination of plane-strain fracture toughness*

BS EN ISO 15548 (all parts), *Non-destructive testing – Equipment for eddy current examination*

BS EN ISO 15549, *Non-destructive testing – Eddy current testing*

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

BS EN ISO 15653, *Metallic materials – Method of test for the determination of quasistatic fracture toughness of weld*

BS EN ISO 17636-1, *Non-destructive testing of welds – Radiographic testing – Part 1: X- and gamma-ray techniques with film*

BS EN ISO 17636-2, *Non-destructive testing of welds – Radiographic testing – Part 2: 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 17640, *Non-destructive testing of welds – Ultrasonic testing – Techniques, testing levels, and assessment*

BS EN ISO 23277, *Non-destructive testing of welds – Penetrant testing of welds – Acceptance levels*

BS EN ISO 23278, *Non-destructive testing of welds – Magnetic particle testing of welds – Acceptance levels*

BS EN ISO 3452-1, *Non-destructive testing – Penetrant testing – General principles*

BS ISO 12108, *Metallic material – Fatigue testing – Fatigue crack growth method*

PD 5500, *Specification for unfired fusion welded pressure vessels*

3 Symbols and definitions

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

NOTE 1 Where units are given for the variations of the symbol K the following applies. The two internationally recognized alternative units for stress intensity factor are $\text{N/mm}^{3/2}$ and $\text{MPa}\sqrt{\text{m}}$ (which is identical to $\text{MN/m}^{3/2}$). The primary unit adopted in this document (except in Annex J, Annex L and Annex S) is $\text{N/mm}^{3/2}$. $1 \text{ N/mm}^{3/2} = 0.032 \text{ MPa}\sqrt{\text{m}}$. Equivalent values in $\text{MPa}\sqrt{\text{m}}$ are given in parentheses in most cases.

NOTE 2 Where there are variations in the units used within this British Standard, an explanation is given at the point where this occurs.

Table 1 Symbols

Symbol	Definition	Units
A	Constant in fatigue growth relation	See footnote ^{A)}
A	Temperature dependent constant in creep strain rate equation	—
A	Constant in creep crack growth equation	—
A, B	Parameters used in calculating reference stress and/or limit load solutions	—
A_A	Constant associated with the average creep rate for a given temperature	—
A^{av}	Average creep parameter	—
A_b	Parameter used in calculating bending stresses as functions of moments	—
A_C	Crack area	mm^2
A_{ex}	Exit COA	mm^2
A_i	COA corresponds to the location at which $L = 12D_i$	mm^2
A_o	Entrance COA	mm^2
A_r	A coefficient used in deriving stress-strain curve for ferritic steels from yield/proof strength, tensile strength and uniform elongation, see Equations 4 and 5	—
A_s	Secondary creep constant	—
A_1	Area of rectangle which demarcates flaw	mm^2
A_2	Full load bearing area containing flaw	mm^2
a	Half flaw length for through-thickness flaw, flaw height for surface flaw or half height for embedded flaw	mm
a	Current crack size in creep	mm
$\dot{a}$	Rate of crack propagation in unstable condition	mm/h

Table 1 Symbols (*continued*)

Symbol	Definition	Units
a'	Depth of extended surface flaw	mm
$\bar{a}/B$	Effective flaw parameter used in quality category method	—
a_{av}	Average value of crack extension based on probabilistic analysis	mm
$\dot{a}_c$	Rate of crack propagation in height direction due to creep	mm/h
a_{eff}	Effective crack size based on elastic analysis	mm
a_{eff}^{ϵ}	Effective crack size based on elastic-plastic strain field	mm
a_{eff}^{σ}	Effective crack size based on elastic-plastic stress field	mm
a_f	Final flaw size	mm
a_g	Crack size after growth	mm
a_i	Initial flaw size	mm
a_i, a_j	Height of flaw i or j to determine flaw interaction	mm
$\bar{a}_i$	Initial value of effective flaw parameter for fatigue analysis	mm
$\bar{a}_m$	Final flaw parameter	mm
$\bar{a}_{max}$	A tolerable value of flaw parameter to which fatigue crack growth is permitted (Quality category method)	mm
$\bar{a}_{max}$	Maximum value of effective flaw parameter for fatigue analysis	mm
a_{min}	Typically 0.2 mm, it is the crack depth below which the crack growth rate is assumed to be constant	mm
a_{pl}	A measure of the extent of Irwin's plastic zone	mm
a_0	Initial flaw size	mm
B	Section thickness in-plane of flaw	mm
B	Flux density	Tesla
B'	Effective section thickness ($2a + 2p$)	mm
B'	A constant, equal to 0.0523, in calculating non-equilibrium mixture quality	—
B'	A parameter used in Method II crack growth rate law	—
B^*	Biaxiality parameter of Leever and Radon	—
B_b	Parameter used in calculating bending stresses as function of moments	—
B_{ss}	Sub-size Charpy specimen thickness	mm
B_1, B_2	Thickness of plates in calculating bending stress due to misalignment in butt joints	mm
b	Plate width	mm
b	Ratio of thickness b_1/b_2 used in calculating limit load solutions for clad materials	
$b_I, b_{II}, b_{III}...$	Thickness of materials in a clad plate with repair weld	mm
b_0	Size of the uncracked ligament, equal to $(W-a_0)$	mm
C	Material constant in cyclic crack growth relationship	—
$C(t)$	Transient crack tip parameter	N/mm·h
C^*	Steady state crack tip parameter	N/mm·h
C^*	Creep fracture/crack growth parameter	MPa·h ⁻¹

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$C_D, C_D^I, C_D^{II}, C_D^{III}$	Discharge coefficients	—
C_V	Lower bound Charpy V-notch impact energy at the service temperature (for which K_{mat} is required)	J
C_{Vus}	Upper shelf energy	J
C_1	Constant in the stress corrosion crack growth equation	See footnote ^{B)}
C_1, C_2	Constants in calculating in conventional friction factor	—
c	Half flaw length for surface or embedded flaw	mm
c	Maximum half flaw length in any direction	mm
$2c_b$	Surface length of crack at breakthrough	mm
c_1	Flaw length used in defining interaction	mm
c_1	Half flaw length in the axial direction	mm
$2c_1, 2c_2$	Front surface and back surface length of flaw	mm
c_2	Half flaw length in the circumferential direction	mm
c_3	Parameter used in calculating reference stress solutions	—
D	Diameter	mm
D	Mean diameter	mm
D	Diameter of chord in a tubular joint	mm
D_c	Total accumulated creep damage	—
D_c^{surf}	Total surface creep damage accumulated up to the current time from every cycle, see Equation 72	—
D_i	Hydraulic parameter	mm
D_{max}, D_{min}	Maximum and minimum permitted diameters in a vessel or pipe	mm
d	Deviation from true circle due to angular misalignment	mm
d	Small distance ahead of a crack tip in time-dependent failure assessment	—
d	Ligament thickness $B-a$ or flaw divergence parameter	mm
d	Subscript to define deepest point	—
d	Diameter of brace in a tubular joint	mm
$\frac{da}{dN}$	Flaw growth rate with cycles	mm/cycle (except where otherwise stated, e.g. Annex K)
$\left(\frac{da}{dN}\right)_c$	Rate of crack propagation in the a direction due to creep	mm/cycle
$\left(\frac{da}{dN}\right)_f$	Rate of crack propagation in the a direction due to fatigue	mm/cycle
$\frac{da}{dt}$	Flaw growth rate with time	mm/h
d_1, d_2	Parameters used in calculating reference stress and/or limit load solutions	
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

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\pm E$	Symmetric confidence intervals for the sizing errors for UT	mm
E_{ET}	Elastic modulus at elevated temperature	N/mm ²
E^P	Parent metal elastic modulus	N/mm ²
E_{RT}	Elastic modulus at room temperature	N/mm ²
E^W	Weld metal elastic modulus	N/mm ²
E_1	Electrical energy per unit length of weld	J/mm
E_1, E_2	Asymmetric confidence intervals	mm
e	Axial misalignment (eccentricity or centre line mis-match)	mm
F	Tension	N
F_{AR}	Reduction factor to allow for loss of load-bearing area due to presence of a flaw in a tubular joint	—
$F_e(\lambda)$	Limit load as a function of load ratio	N
$F_e^{(h)}$	The tensile limit load of the homogeneous plate containing a through-thickness flaw made of the softer material (here Material 2) with yield strength $\sigma_Y^{\text{Material 2}}$ and thickness of $B = b_1 + b_2$	N
F_e^{clad}	Tensile limit load of the whole clad system	N
$F_e^M, F_e^{M(1)}, F_e^{M(2)}, F_e^{M(3)} \dots$	Limit load solution of the mis-match configuration	N
F_e^N	Limit load	N
F_e^P	Limit load solution for a homogeneous component made of material with yield strength σ_Y^P	N
F_e^1, F_e^2	Limit load of material 1, material 2	N
F^L	Reserve factor on load	—
f	Fanning friction factor	—
f	Testing frequency of manual eddy current testing	Hz
$f(K_I)$	Probability density function for fracture toughness	—
$f_a, f_b, f_c \dots f_e$	Parameters used in calculating reference stress and/or limit load solutions	—
f_c	Factor of safety in analysis of LTA	—
f_{conv}	Conventional friction factor	—
f_{max}	Maximum effective friction factor, f	—
f_{ps}	Parameter used in limit load calculation for cylinder under internal pressure	—
f_{scc}	Factor of safety with respect to stress corrosion cracking ($f_{\text{scc}} > 1.0$)	—
f_w	Finite width correction factor	—
f_{wb}	Modified finite width correction factor for bending component	—
f_{wm}	Modified finite width correction factor for membrane component	—
$f_x(X)$	A known joint probability density function of the random vector X	—
$f_z(Z)$	Multivariate probability density function of Z in Level II reliability analysis method	—
$f_0^A, f_1^A, f_2^A, f_3^A \dots$	Geometry functions used in calculating SIF	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$f_0^D, f_1^D, f_2^D, f_3^D \dots$	Geometry functions used in calculating SIF	—
f_1, f_2, f_3, f_θ	Parameters in calculating stress intensity factor solutions	—
$\bar{G}$	Average flow rate per unit area in the flaw	tonne/mm ² /s
G_0	Mass flow rate per unit area at the flaw entrance plane	tonne/mm ² /s
G_p	Influence coefficient used in calculating stress intensity factor solutions due to internal pressure, see M.8	—
$\bar{G}_T$	Average mass flux in the dispersed two-phase region of the flaw	tonne/mm ² /s
G_1	Influence coefficient used in calculating stress intensity factor solutions due to uniform loading, see M.8	—
$G_1, G_2, G_{11}, G_{12}, G_{13}, G_{21}, G_{22}, G_{23}$	Parameters in calculating stress intensity factor solutions	—
G_2	Influence coefficient used in calculating stress intensity factor solutions due to linear loading, see M.8	—
g	Gap between two braces in a K-joint	mm
$g(X)$	Limit state function for Level II reliability analysis	—
$g, g_1, g_2 \dots g_{14}$	Parameters in calculating stress intensity factor solutions	—
$2H$	Distance between the (outermost) points at which loading is applied	mm
H, H_1, H_2	Parameter in calculating stress intensity factor solutions	—
h	Weld leg length	mm
$h(L_r)$	Function of L_r used for determination of plasticity interaction	—
h_1, h_2	Parameter used in calculating reference stresses and/or limit load solutions	—
J	A 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 front	N/mm
J_c	Value of J at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in. This term applies only where $\Delta a_0 < 0.2$ mm offset to the blunting line	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^s	Value of J for secondary stresses alone	N/mm
J_u	Value of J at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in. This term applies only where $\Delta a_0 > 0.2$ mm offset to the blunting line	N/mm
K	Stress intensity factor	N/mm ^{3/2}

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\dot{K}$	Rate of increase in SIF	$\text{MPa}\sqrt{\text{ms}}^{-1}$
K_a	Parameter used in calculating reference stress and/or limit load solutions for tubular joints	—
K_B	Fracture toughness for the equivalent full thickness of the component (determined from K_b)	$\text{MPa}\sqrt{\text{m}}$
K_b	Fracture toughness determined from sub-sized specimen of thickness b	$\text{MPa}\sqrt{\text{m}}$
K_b	Stress intensity factor for the bending component of stress	$\text{N}/\text{mm}^{3/2}$
K_c	Critical stress intensity factor for failure under static load	$\text{N}/\text{mm}^{3/2}$
$K_{\text{CENS}}(T_0)$	Estimate of K when using Master Curve method	$\text{N}/\text{mm}^{3/2}$
K_{mat}^c	Constraint-corrected fracture toughness in cleavage region	$\text{N}/\text{mm}^{3/2}$
K_{mat}^c	Fracture toughness appropriate to the level of constraint	$\text{N}/\text{mm}^{3/2}$
K_{eff}	Effective linear elastic stress intensity factor in mixed mode loading	$\text{N}/\text{mm}^{3/2}$
K_f	Stress intensity factor at failure	$\text{N}/\text{mm}^{3/2}$
K_I	Applied tensile (mode I) stress intensity factor	$\text{N}/\text{mm}^{3/2}$
K_i	Adjusted value of fracture toughness, equivalent to that for a specimen size of 25 mm	$\text{N}/\text{mm}^{3/2}$
K_i	Individual fracture toughness value	$\text{N}/\text{mm}^{3/2}$
$K_{i(\text{min})}$	Minimum value of individual fracture toughness K_i	$\text{N}/\text{mm}^{3/2}$
K_I^{bending}	Contributions to K_I of through-wall bending	$\text{N}/\text{mm}^{3/2}$
K_{Ic}	Plane strain fracture toughness	$\text{N}/\text{mm}^{3/2}$
$K_{Ic, \text{median}}$	Estimate of fracture toughness when using Master Curve assuming $P[K] = 0.5$	$\text{N}/\text{mm}^{3/2}$
K_I^{membrane}	Contribution of through-wall bending (tensile on outside surface, compressive on inside surface) stresses to K_I	$\text{N}/\text{mm}^{3/2}$
K_I^p	Stress intensity factor due to primary stress	$\text{N}/\text{mm}^{3/2}$
K_I^s	Stress intensity factor due to secondary stress	$\text{N}/\text{mm}^{3/2}$
$K_I^{s, \text{res}}$	Elastic stress intensity factor due to residual stresses	$\text{N}/\text{mm}^{3/2}$
$K_I^{s, \text{sec}}$	Stress intensity factor due to other secondary stresses (e.g. thermal stresses)	$\text{N}/\text{mm}^{3/2}$
K_{II}	Mode II linear elastic stress intensity factor	$\text{N}/\text{mm}^{3/2}$
K_{IIc}	Critical value of K_{II} at onset of brittle fracture in mode II	$\text{N}/\text{mm}^{3/2}$
K_{II}^p, K_{II}^s	Values of K_{II} due to primary and secondary stresses, respectively	$\text{N}/\text{mm}^{3/2}$
K_{III}	Mode III linear elastic stress intensity factor	$\text{N}/\text{mm}^{3/2}$
K_{III}^p, K_{III}^s	Values of K_{III} due to primary and secondary stresses, respectively	$\text{N}/\text{mm}^{3/2}$
K_{ISCC}	Critical stress intensity factor for stress corrosion cracking	$\text{N}/\text{mm}^{3/2}$
K_J	SIF based on the elastic-plastic cracking force J	$\text{N}/\text{mm}^{3/2}$
$K_{Jc(\text{cen})}$	Estimate of K when using Master Curve method	$\text{N}/\text{mm}^{3/2}$
$K_{Jc(\text{limit})}$	Limiting value of K_b	$\text{N}/\text{mm}^{3/2}$
K_J^s	Linear elastic plastic SIF	$\text{N}/\text{mm}^{3/2}$
K_{Ju}	Fracture toughness derived from J_u for MML method	$\text{N}/\text{mm}^{3/2}$
$K_{J0.2}$	Fracture toughness at initiation of stable ductile tearing	$\text{N}/\text{mm}^{3/2}$

Table 1 Symbols (*continued*)

Symbol	Definition	Units
K_m	Stress intensity factor for the bending component of stress	$\text{N/mm}^{3/2}$
K_{mat}	Material fracture toughness measured by stress intensity factor	$\text{N/mm}^{3/2}$
$\bar{K}_{\text{mat}}$	Mean fracture toughness	$\text{N/mm}^{3/2}$
$K_{\text{mat}}(\Delta a_j)$	Fracture toughness after a given amount, (Δa_j) , of ductile tearing allowing for the influence of constraint	$\text{N/mm}^{3/2}$
$K_{\text{mat}(l)}$	The value of K_{mat} adjusted for length of crack front, l , in mm for $l < 2B$	$\text{N/mm}^{3/2}$
$K_{\text{mat}(25)}$	Characteristic fracture toughness for a reference thickness of 25 mm	$\text{N/mm}^{3/2}$
$K_{\text{mat}0.2}$	Fracture toughness for initiation of ductile tearing at ductile crack extension of 0.2 mm	$\text{N/mm}^{3/2}$
K_{max}	Maximum stress intensity factor	$\text{N/mm}^{3/2}$
K^{P}	Stress intensity factor due to primary load only	$\text{N/mm}^{3/2}$
K^{P}	Elastically calculated stress intensity factor at $\theta = \pi/2$ for growth in the height direction and at $\theta = 0$ for growth along the surface	$\text{N/mm}^{3/2}$
$K_{\text{eff}}^{\text{P}}$	Effective linear elastic stress intensity factor due to primary load	$\text{N/mm}^{3/2}$
K_r	Fracture ratio of applied elastic K value to K_{mat}	—
$K_r^{\text{calculated}}$	Fracture ratio evaluated from procedure given in 7.3.6	—
K_r^{P}	Fracture ratio of applied primary K value to K_{mat}	—
K_r^{S}	Contribution to K_r from secondary stresses	—
K_{rs}	SIF for residual stress profile	$\text{N/mm}^{3/2}$
$K_{\text{r}}^{\text{S, sb}}$	Self-balancing stress field	$\text{N/mm}^{3/2}$
K^{S}	Effective stress intensity factor defined from elastic-plastic strain field	$\text{N/mm}^{3/2}$
K_{sb}	SIF for self-balancing component of residual stress profile	$\text{N/mm}^{3/2}$
$K_{\text{sb}}^{\text{max}}$	Maximum SIF for self-balancing component	$\text{N/mm}^{3/2}$
$K_{\text{eff}}^{\text{S}}$	Effective linear elastic stress intensity factor due to secondary load	$\text{N/mm}^{3/2}$
$K_{\text{single crack}}$	Stress intensity factor for a single corner crack at a hole	$\text{N/mm}^{3/2}$
$K_{\text{symmetric crack}}$	Stress intensity factor for a symmetric crack	$\text{N/mm}^{3/2}$
$K_0, K_{0(\text{stage}2)}, K_{0(\text{stage}3)}, K_{0(\text{min})}$	Estimates of K when using Master Curve method	$\text{N/mm}^{3/2}$
$K_{0.2}$	Value of initiation toughness, calculated from $J_{0.2}$	$\text{N/mm}^{3/2}$
$K_{0.2\text{mm}}$	Initiation of tearing fracture toughness	$\text{N/mm}^{3/2}$
K_1	Stress intensity factor following preload	$\text{N/mm}^{3/2}$
K_2	Stress intensity factor following unload	$\text{N/mm}^{3/2}$
K_{12}	Fracture toughness at initiation of ductile tearing	$\text{N/mm}^{3/2}$
K_{σ}^{S}	Effective stress intensity factor defined from elastic-plastic stress field	$\text{N/mm}^{3/2}$
k	Parameter in calculating discharge coefficient	—
k	Shape parameter of the Weibull	—
k	Reference stress correction factor for welds	—
k	Constant depending on boundary conditions	—
k	Material and temperature constant	—
k	Normalized crack off-set equal to $[(B/2) - p - a]/B$	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
κ	A factor dependent on restraint for calculating bending stress due to misalignment in butt joints	—
k_m	Stress intensity factor due to misalignment	—
k_t	Stress concentration factor	—
k_{tb}	Bending stress concentration factor	—
k_{tm}	Membrane stress concentration factor	—
$k_{t,HS}$	Hot spot stress concentration factor in tubular joint	—
$k_{t,AX}$	Axial, in and out-of-plane stress concentration factor in tubular joints	—
$k_{t,IPB}$	In plane stress concentration factor in tubular joints	—
$k_{t,OPB}$	Out-of-plane stress concentration factor in tubular joints	—
$k_{0.90}$	Value of the one-sided tolerance limit for a normal distribution	—
k_2	Shear yield strength of material 2	N/mm ²
L	Attachment length	mm
L	Average of the front and back surface flaw lengths	mm
L	Load	—
L_r	Ratio of applied load to yield load	—
$L_{r,max}$	Permitted limit of L_r	—
L_r^b	Normalized limit moment	—
L_r^N	Normalized limit force	—
l	Distance from axially misaligned joint to load or extremities of region of angular misalignment (shortest distance = l_1)	mm
l	Length of the crack front in the Master Curve method	mm
l	Exponent in cyclic crack growth equation (Method I cyclic data in Clause 9)	—
l	Crack length in leak-before-break (LbB) assessment, see Figure F.1 and see footnote ^{c)}	mm
l'	Length of a semi-elliptical flaw in LbB assessment	mm
l_b	Flaw length at break through in a LbB assessment	mm
l_c	Limiting generalized crack length in a LbB assessment	mm
l_L	Length of through-wall defect at limit of leak detection or length of detectable through wall defect in a LbB assessment	mm
l'_L	Enhanced value of l_L in a LbB assessment	mm
l_w	Length of weld	mm
l_1	Front surface crack length of a flaw in LbB assessment	mm
l_1^*	Front surface crack length of a flaw at wall penetration in a LbB assessment	mm
l_2	Back surface crack length of a flaw in LbB assessment	mm
l_2^*	Back surface crack length of a flaw at wall penetration in a LbB assessment	mm
l_1, l_2	Plate length	mm
M	Bulging correction factor	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
M	Strength mis-match or mis-match ratio, which is the ratio of the yield strength of the weld metal to that of the parent material	—
$M(\varepsilon_{pl})$	Mismatch ratio at a number of plastic strain values, ε_{pl}	—
M_{ai}	Applied in-plane moments for tubular joints	Nmm
M_{ao}	Applied out-of-plane moment for tubular joints	Nmm
M_{ci}, M_{co}	Fully plastic moments for cracked tubular joints calculated for in and out of plane loads	Nmm
$M_e(\lambda)$	Limit moment	Nmm
M_e^b	Limit bending moment	Nmm
$M_e^M, M_e^{M(1)}, M_e^{M(2)}, M_e^{M(3)} \dots$	Limit moment of the mis-matched system	Nmm
M_e^P	Limit moment for plate made wholly of parent material	Nmm
M_{ex}	Parameter used in calculating limit load	Nmm
M_{global}	Global moment	Nmm
M_i	In-plane bending moment	Nmm
M_i	In-plane moment	Nmm
M_{in}	Parameter used in calculating limit load	Nmm
M_k	Stress intensity magnification factor	—
M_m^*, M_b^*	Factors used in calculating M_m and M_b	—
M_m, M_b, M_{km}, M_{kb}	Stress intensity magnification factors	—
M_o	Out-of-plane moment	Nmm
M_s, M_T	Stress magnification factors	—
M_1, M_2, M_3, M_4	Parameters in calculating stress intensity factor solutions	—
m	Exponent in flaw growth law	—
m	A parameter as a function of yield strength and tensile strength, used in converting K_{mat} to δ_{mat} and vice versa; see Equations 16 and 17	—
m	Applied axisymmetric through-wall bending moment per unit angle of cross section	Nmm
$(m)_L$	Limit axisymmetric through wall bending moment per unit angle of cross section	Nmm
m_q	Exponent in the calculation of F_{AR}	—
N	Fatigue life	cycles
N	Work hardening coefficient	—
N	Strain hardening coefficient as in Equation 7	—
N	As in Equation 27	—
N^m	Strain hardening exponent of a mis-matched system	—
N^P	Strain hardening exponent of parent metal	—
N^W	Strain hardening exponent of weld metal	—
n	Strain-hardening exponent, see Equation 6	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
n	Power-law creep stress exponent	—
n	Total number of data set in the set, including those censored, for Master Curve Maximum Likelihood (MML) method; or, total number of tests (specimens) in data set	—
n	Factor used in calculating stress intensity factor solutions for corner flaws at hole; $n = 1$ for a single flaw; $n = 2$ for two symmetric flaws	—
n	Total number of data set in the set	—
$n(\text{scc})$	Exponent in the stress corrosion crack growth relationship	—
n_A	A constant associated with the average creep rate for a given temperature	—
n_j	Number of cycles in stress spectrum at stress range $\Delta\sigma_j$	cycles
n_s	An exponent associated with the secondary creep rate for a given temperature	—
$O(r^{1/2})$	Higher-order terms in William's expanded crack tip stress field	—
P	Primary stress	N/mm ²
P	Applied load	N
P	Axial load	N
P	Pressure	N/mm ²
$P(D_c < 1),$ $P(D_c = 1)$	Probability of creep damage	—
$P[K]$	Probability of fracture toughness exceeding the value given	—
P_a	Applied axial load on tubular joint	N
P_b	Primary bending stress	N/mm ²
$P_{b,l}$	Primary bending stress due to locally applied bending loads	N/mm ²
P_c	Collapse load for cracked tubular joint	N
P_c	Characteristic strength for brace axial load	N/mm ²
P_F	Probability of failure	—
P_f	Probability of exceedance	—
P_f	The fractile representing the cumulative failure probability for fracture toughness distribution derived from experimental data	—
P_L	Limit load	N/mm ¹
P_m	Primary membrane stress	N/mm ²
$P_{m,a}$	Primary membrane stress due to global axial loads	N/mm ²
$P_{m,b}$	Primary membrane stress due to global bending moments	N/mm ²
$P_{m,p}$	Primary membrane stress due to pressure loading	N/mm ²
p	Shortest distance from material surface to embedded flaw	mm
p	Internal pressure	N/mm ²
p'	Internal pressure	N/mm ²
p_{aa}	Pressure loss due to acceleration arising from changes in area	N/mm ²
p_c	Critical pressure, i.e. pressure at the choking plane	N/mm ²
p_e	Entrance pressure loss	N/mm ²
p_{ex}	Pressure of fluid at the exit	N/mm ²

Table 1 Symbols (*continued*)

Symbol	Definition	Units
p_f	Fluid pressure	N/mm ²
p_f	Frictional pressure loss	N/mm ²
p_k	Pressure loss due to bends and protrusions	N/mm ²
p_L	Limit pressure	N/mm ²
p_m	Maximum pressure in calculation of misalignment in pressurized pipe	N/mm ²
p_o	Pressure of fluid at the flaw entrance, or, absolute pressure at the crack entrance plane	N/mm ²
Q	Secondary stress	N/mm ²
Q	Exponent in cyclic crack growth equation (Method II cyclic data in Clause 9)	—
Q	Elastic-plastic constraint parameter	—
Q	Hydrostatic parameter	—
Q	Stress scaling parameter	—
Q	Mass flow through an equivalent rectangular flaw	tonne/s See footnote ^{D)}
Q_b	Secondary bending stress	N/mm ²
Q_f	A factor to allow for the presence of axial and moment loads in the chord	—
Q_g	A factor to calculate limit load solution for tubular joint	—
Q_m	Secondary membrane stress	N/mm ²
Q^P	Stress scaling parameter for primary loading	—
Q^S	Stress scaling parameter for secondary loading	—
Q_β	Factor to allow for increased strength observed in tubular joints at $\beta > 0.6$	—
Q_β	Geometric modifier	—
q	Exponent in creep crack growth equation	—
q	Parameter in calculating stress intensity factor solutions	—
q_o	Fraction of load cycle when crack is open	—
R	Stress ratio [ratio of minimum ($\sigma_{\min}$) to maximum ($\sigma_{\max}$) algebraic value of the absolute stress level ($k_{tm}P_m + k_{tb}P_b + Q$)]	—
R	Ratio of minimum to stress intensity factor, $K_{\min}$, to maximum stress intensity factor, $K_{\max}$, in fatigue analysis	—
R	Mean radius	mm
R	Radius of centreline of the bend	mm
R	Resistance	—
R'	Characteristic length used in creep crack propagation equation	mm
R_a	Surface roughness of crack	mm
R_{eH}	Upper yield strength of material	N/mm ²
R_{eL}	Lower yield strength of discontinuously yielding material	N/mm ²
R_{eH}^P	Upper yield strength of the parent metal	N/mm ²
$R_{p0.2}$	0.2% proof strength	N/mm ²
R_T	Specified minimum target reliability	—

Table 1 Symbols (continued)

Symbol	Definition	Units
$R_{t0.5}$	Yield strength associated with a total elongation of 0.5%	N/mm ²
R_{eH}^W	Upper yield strength of the weld metal	N/mm ²
r	Radius of round bar or bolt	mm
r	Outer radius	mm
r	Number of specimens which failed by brittle fracture	—
r_c	Size of creep damage zone	µm
r_{eff}	Radius for a sphere and spherical vessel end	mm
r_h	Radius of hole	mm
r_i	Internal radius	mm
r_m	Mean radius	mm
r_o	External radius	mm
r_p	Cyclic plastic zone size	µm
r_p^{crack}	Cyclic plastic zone size at the crack tip	µm
S	Stress range or, for variable amplitude, the equivalent constant amplitude stress range	N/mm ²
S	Ratio of $(\sigma_m/\bar{\sigma})$	—
S'	Quality category reference stress range for crack growth in seawater	—
S_{gc}	Gas entropy at choking plane	Nmm/°C/tonne
S_i	S for $\bar{a}_i$	N/mm ²
S_{Lc}	Liquid entropy at choking plane	Nmm/°C/tonne
S_m	S for $\bar{a}_{max}$	—
S_o	Stagnation entropy	N/mm ²
S^2	Variance	—
s	Subscript to define free surface point	—
s, s_1	Distance between embedded flaws	mm
T	Temperature	°C
T	Assessment temperature	°C
T	Temperature at which K_{mat} is to be determined	°C
T	Chord thickness	mm
T	T-stress	N/mm ²
T'	Factor used in collapse analysis of tubular joints	—
T_c	Creep exclusion temperature	°C
T_i	Test temperature of a specimen of toughness K_i , adjusted to a 25 mm specimen size using Equation L.2	°C
T_i	Test temperature for a specimen i	°C
T_K	Temperature term describing the scatter in Charpy versus fracture toughness correlation	°C
T^P	T-stress for the σ^P (primary) stress	N/mm ²
T_{ref}	Reference temperature in creep	°C
T^S	T-stress for the σ^S (secondary) stress	N/mm ²

Table 1 Symbols (*continued*)

Symbol	Definition	Units
T_0	Temperature for a median toughness of 100 MPa√m in 25 mm thick specimens	°C
$T_{0(max)}$	Temperature term used in MML method	°C
$T_{0(stage3)}$	Temperature term used in MML method	°C
$T_{0,deep}$	Master Curve transition temperature obtained from high constant specimens in accordance with ASTM E1921	°C
T_1	Temperature at preload	°C
T_2	Temperature at reload	°C
T_{27J}	Temperature for energies of 27J measured in a standard 10 mm × 10 mm Charpy V specimen	°C
T_{40J}	Temperature for energies of 40J measured in a standard 10 mm × 10 mm Charpy V specimen	°C
t	Time	hours, days, weeks, months or years as appropriate
t	Brace thickness	mm
t_{CD}	Time to failure of plant by bulk creep rupture, measured from initial start-up (Clause 9 and Annex F)	h
t_h	Hold time at a given temperature	h
t_i	Crack initiation time, prior to commencement of creep crack growth	h
t_m	Maximum allowable time at reference temperature	h
$t_{r\ ref}$	Time to creep rupture at reference stress	h
$t_r(\sigma)$	Time to rupture at the appropriate temperature and at a stress, σ	h
t_{red}	Redistribution time	h
t_s	Future life required	h
t_w	Weld throat thickness	mm
t_0	Life to date	h
U	Parameter used in calculating reference stress and/or limit load solutions for tubular joints	—
V	Plasticity correction factor	—
ν	Poisson's ratio	—
$\bar{v}_g$	Average specific volume of the vapour in the flaw	mm ³ /tonne
v_{gc}	Specific volume of vapour at the choking plane	mm ³ /tonne
$\bar{v}_L$	Average specific volume of the liquid in the flaw	mm ³ /tonne
v_{Lc}	Specific volume of liquid at the choking plane	mm ³ /tonne
v_{Lo}	Specific volume of liquid at the flaw entrance plane	mm ³ /tonne
W	Structure width (or half-width) in-plane of flaw	mm
$\bar{W}$	Mean flaw width	mm
W	Weld width	mm
W_c	Crack opening width	mm
W_{ex}	Exit crack width	mm

Table 1 Symbols (*continued*)

Symbol	Definition	Units
W_o or W_0	Entry crack width	mm
$\bar{X}$	Average mixture quality in the flaw	—
X_c	Non-equilibrium mixture quality	—
X_E	Equilibrium mixture quality	—
$X_0, X_1, X_2 \dots X_6$	Polynomial coefficients	—
x	Ratio of a/W	—
Y	Stress intensity correction factor	—
Y	Ratio of chord radius to chord wall thickness in a tubular joint	—
$(Y\sigma)_p$	Primary stress intensity correction function	N/mm ²
$(Y\sigma)_s$	Secondary stress intensity correction function	N/mm ²
Y'	Estimate of K_I^S for through-wall self-balancing stress	—
Y_m, Y_b	Stress intensity correction factors for membrane and bending stress	—
$Y_{w,m}, Y_{w,b}$	Stress intensity correction factors for weld location for membrane and bending stress	—
y	Equal to $1 - x$, where x is a ratio of a/W	—
y	Height of peaking due to angular misalignment	mm
Z_A	Relationship used in probabilistic creep crack growth calculation	—
z	Measure of position through the thickness	mm
z_r	Through thickness depth of repair	mm
z_0	Through thickness depth of tensile residual stress zone	mm
α	Angular change at misaligned joint	Radians
α	Parameter used in defining K_{eff}	—
α	Parameter used in defining stress intensity solutions	—
α	Material constraint parameter	—
α	Material and temperature constant	—
α	Parameter used in defining limit load solutions for thick-walled pipes/cylinders containing circumferential flaws under combined tension and global bending	—
α''	Function of a, c, B and W used in calculation of collapse stresses	—
$\alpha(\lambda)$	Bulging factor	—
β	Ratio of brace diameter to chord diameter in a tubular joint	—
β	Plasticity correction factor, $\beta = 1$ for plane stress, $\beta = 3$ for plane strain	—
β	Exponent in creep crack initiation equation	—
β	Factor determining stress state in the plastic zone	—
β	Reliability	—
β	Normalized constraint parameter	—
β	Parameter used in calculating reference stress/limit load solutions	—
β_R, β_T	Reliability index used in calculating P_F	—
β_∞	Parameter used in calculating reference stress/limit load solutions for flaw at interface of a bimaterial joint in plane strain condition	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\Gamma(z)$	Gamma function used in reliability analysis	
γ	Ratio of chord diameter to twice its thickness	—
γ	Material constant obtained from creep crack growth tests as specified in ASTM E1457	—
γ	Ratio of $D/2T$; where D is the outer diameter of tubular joints and T is thickness	—
γ, γ_i	Partial safety factors	—
$\gamma_\sigma, \gamma_a, \gamma_K, \gamma_M$	Partial coefficients on stress, flaw size, fracture toughness in terms of K , yield strength, for safety factor treatment	—
γ_0	Isentropic exponent	—
$\Delta 2a$	Through thickness sizing accuracy	mm
$\Delta 2c$	Length sizing accuracy	mm
Δa	Increment in a or ductile tearing	mm
Δa	Crack growth	mm
Δa	Through thickness sizing accuracy	mm
Δa_f	Crack growth due to fatigue loading	mm
Δa_g	Limit of tearing flaw extension	mm
Δa_j	Intermediate value of tearing flaw extension	mm
Δa_t	Crack growth due to tearing	mm
Δa_{tot}	Total crack growth	mm
Δa_0	Initial crack length	mm
Δc	Increment in c	mm
$\Delta \epsilon$	Extent of Lüders strain	—
$\Delta \bar{\epsilon}_t$	Total surface strain range	—
ΔK	Stress intensity factor range	N/mm ^{3/2}
ΔK_{eff}	Effective stress intensity range	N/mm ^{3/2}
ΔK_I	Cyclic range in K_I	N/mm ^{3/2}
ΔK_u	SIF decrement (equal to $K_f - K_2$) due to unloading during warm pre-stressing; an additional SIF at failure due to reload	N/mm ^{3/2}
ΔK_0	Threshold stress intensity factor range below which fatigue crack growth (or corrosion fatigue crack growth) does not occur (Clause 8)	N/mm ^{3/2}
ΔN	Increment in N	cycles
Δp	Ligament sizing accuracy	mm
ΔP_m	Primary membrane stress range	N/mm ²
ΔT_0	Shift in the Master Curve reference temperature T_0	°C
$\Delta T_{0,st}$	Temperature to be determined from quasi-static tests	°C
Δt_d	Time to detect a leak	h
Δt_i	Time during which the structure is subjected to stress, σ_i , and temperature, T_i	hours, days, weeks, months or years as appropriate
ΔT_{ss}	Temperature shift corresponding to a full size specimen	°C

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\Delta\sigma$	Applied stress range	N/mm ²
$\Delta\sigma_{Ax}$	Axial stress range in tubular joint	N/mm ²
$\Delta\sigma_b$	Bending component of stress range	N/mm ²
$\Delta\sigma'_b$	Bending stress range excluding the effects of misalignment	N/mm ²
$\Delta\sigma_{HS}$	Hot spot stress range	N/mm ²
$\Delta\sigma_{HS.Ax}$	Axial, in- and out-of-plane hot spot stress ranges in tubular joint	N/mm ²
$\Delta\sigma_{HS.IPB}$	Hot spot axial, in-plane stress range in tubular joint	N/mm ²
$\Delta\sigma_{HS.OPB}$	Hot spot axial, out-of-plane stress range in tubular joint	N/mm ²
$\Delta\sigma_{HS.Tot}$	Total hot spot stress range in tubular joint	N/mm ²
$\Delta\sigma_{IPB}$	In plane bending stress range in tubular joint	N/mm ²
$\Delta\sigma_j$	Stress range in variable amplitude fatigue spectrum which is applied n_i times	N/mm ²
$\Delta\sigma_m$	Membrane component of stress range	N/mm ²
$\Delta\sigma_{nom}$	Nominal stress range in tubular joint	N/mm ²
$\Delta\sigma_{nom.Ax}$	Axial, in and out of plane nominal stress ranges in tubular joint	N/mm ²
$\Delta\sigma_{nom.IPB}$	Nominal axial, in plane stress range in tubular joint	N/mm ²
$\Delta\sigma_{nom.OPB}$	Nominal axial, out of plane stress range in tubular joint	N/mm ²
$\Delta\sigma_{OPB}$	Out-of-plane bending stress range in tubular joint	N/mm ²
$\Delta\sigma_s$	Bending stress range due to misalignment	N/mm ²
δ	Crack tip opening displacement (CTOD) or crack opening displacement (COD)	mm
δ	Standard penetration depth of eddy current testing	m
δ_A	Standard deviation of the logarithm of A	—
δ_C	CTOD at either: a) unstable fracture; or b) onset of brittle crack of pop-in. This term only applies where $\Delta a_0 < 0.2$ mm offset to the blunting line	mm
δ_C	Standard deviation of the logarithm of the rupture time	hours
δ_i	Crack tip opening displacement corresponding to initiation of creep crack growth	mm
$\delta_{ij}, \delta_{1i}, \delta_{1j}$	Kronecker's delta	mm
δ_{mat}	Material toughness measured by CTOD method	mm
δ_U	CTOD for tests that fail by cleavage fracture after ductile tearing	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_c	Accumulated creep strain	—
$\dot{\varepsilon}_C$	Creep strain rate	/h
$\bar{\dot{\varepsilon}}_C$	Equivalent creep strain rate	/h
$\dot{\varepsilon}_{CA}$	Average creep rate	/h
$\dot{\varepsilon}_{CS}$	Secondary creep rate	/h
ε_e	Elastic strain at the reference stress σ_{ref}/E	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
ε_f	Strain to failure of material, as measured in uniaxial creep test	—
$\bar{\varepsilon}_f$	Creep ductility	/h
ε_{ij}	Elastic-plastic mechanical strains; $ij = x, y, z$	—
ε^P	Strain in parent metal	—
ε_{pl}	Plastic strain	—
ε_{ref}	Reference strain	—
$\dot{\varepsilon}_{ref}$	Creep strain at reference stress	/h
ε_t	True strain	—
ε_u	Uniform elongation strain at ultimate tensile strength	—
ε^W	Strain in weld metal	—
ε_Y	Yield strain, i.e. strain at σ_Y	—
ζ	Dimensionless geometrical parameter used in collapse analysis of tubular joints	—
η	Ratio of thickness to mean radius, B/r_m	—
η_i	Ratio of thickness to internal radius, B/r_i	—
θ	Parametric angle to identify position along an elliptical flaw front	Radians
θ	Angle between the weld seam and the point at which the maximum diameter is observed	—
θ	Scale parameter of the Weibull	—
θ	Term used for limit load calculation	—
θ	Angle between the centre axes of brace(s) and chord in a tubular joint	—
θ	Probability of detection (PoD) term	—
λ	Parameter used in constructing Option 1 FAD	—
λ	Parameter used in LbB assessment	—
λ	Load ratio	—
$\lambda, \lambda_0, \lambda_1, \lambda_2 \dots etc.$	Parameters used in calculating stress intensity factors	—
λ^M	Parameter used in mis-match analysis	—
λ^P	Parameter of parent metal used in mis-match analysis	—
λ_s	Factor used in collapse analysis of cylinders	—
λ^W	Parameter of weld metal used in mis-match analysis	—
μ	Parameter used in constructing FAD line, it is taken as the minimum value of either $0.001(E/\sigma_Y)$ or 0.6	—
μ, μ_0, μ_1	Parameters used in calculating stress intensity factors	—
μ_A	Mean value of the logarithm of A	—
μ_c	Mean value of the logarithm of the rupture time $\ln \tau$	—
$\mu_{K_{Ic}}$	Mean value of K_{Ic}	N/mm ²
μ_{LogNor}	Log normal distribution parameter	—
μ^M	Parameter used in mis-match analysis	—
μ^P, μ^W	Parameter of parent metal and weld metal used in mis-match analysis	—
μ_r	Relative magnetic permeability	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
μ_0	Magnetic permeability of free space	H/m
$\rho, \rho(a)$	Plasticity interaction factor	—
ρ_c	Plasticity interaction factor corrected for constraint	—
ρ_f	Fluid density	tonne/mm ³ footnote ^{E)}
ρ_l	Parameter used in replacing ρ	—
ρ_o	Density of fluid at the flaw entrance	kg/mm ³ or g/mm ³
ρ_1	Parameter used in determining ρ	—
σ	Conductivity of material	siemens/m
σ_a	Applied stress	N/mm ²
σ_b	Bending stress	N/mm ²
σ'_b	Bending stress excluding effect of misalignment	N/mm ²
σ_{bc}	Hot spot bending stress concentration for a cracked tubular joint	N/mm ²
$\sigma_b^{\max}$	Value of bending stress at $z = 0$	N/mm ²
σ_d	Stress at a small distance, d , ahead of the crack tip	N/mm ²
σ_f	Flow strength (assumed to be the average of the yield and the tensile strengths)	N/mm ²
σ'_f	Appropriate flow strength (assumed to be the average of the yield; and the tensile strengths) at the assessment temperature	N/mm ²
$\sigma_I, \sigma_{II}, \sigma_{III}, \dots$	Yield strength of materials in a clad plate with repair weld	N/mm ²
σ_{ij}^{ssy}	Stress field close to a crack tip under small-scale yielding in plane strain, for the same value of J as that used to evaluate σ_{ij} , and for a remote stress field corresponding to the $T = 0$ field	N/mm ²
$\sigma_{K_{Ic}}$	Standard deviation of K_{Ic}	—
σ_{LogNor}	Log normal distribution parameter	—
σ_m	Membrane stress	N/mm ²
$\sigma_{(\epsilon_{pl})}^M$	Equivalent stress strain curve for use in constructing an Option 2M FAD	N/mm ²
$\sigma_{\max,m}$	Membrane component of the maximum applied tensile stress	N/mm ²
$\sigma_{n,b}$	Bending component of collapse stress	N/mm ²
$\sigma_{n,m}$	Membrane component of collapse stress	N/mm ²
σ^P	Stress arising from primary loads	N/mm ²
σ_R	Residual stress	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
$\sigma_{\text{ref corner crack, no hole}}$	Reference stress of a corner crack in a plate when no hole is present	N/mm ²
$\sigma_{\text{ref,b}}$	Reference stress used for pure bending	N/mm ²
$\sigma_{\text{ref,hole}}$	Reference stress for corner flaws at hole under combined tension and bending	N/mm ²
$\sigma_{\text{ref,hom}}$	Homogenous cracked-body reference stress, obtained from Equation 61	N/mm ²

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\sigma_{\text{ref},m}$	Reference stress used for pure membrane	N/mm ²
$\sigma_{\text{ref},\text{no hole}}$	Reference stress of a corner crack when no hole is present	N/mm ²
$\sigma_{\text{ref } 1}, \sigma_{\text{ref } 2}$	Reference stress based on the axial ($\sigma_{\text{ref } 1}$) and hoop stress ($\sigma_{\text{ref } 2}$) respectively in LTAs assessment in a cylinder	N/mm ²
σ_R^L	Longitudinal residual stress	N/mm ²
σ_R^{LB}	Longitudinal residual stress at bore	N/mm ²
σ_R^{LO}	Longitudinal residual stress at the outer surface	N/mm ²
σ_{max}^r or σ_{max}	Surface value of self-balancing residual stress for through-wall crack	N/mm ²
σ_R^T	Transverse residual stress	N/mm ²
σ_R^T	Upper bound transverse residual stress	N/mm ²
σ^s	Stress arising from secondary loads	N/mm ²
σ_{sb}	Self-balancing stress component	N/mm ²
σ_t	True stress	N/mm ²
σ_U, σ_u	Tensile strength	N/mm ²
σ_W	Applied stress on weld throat	N/mm ²
σ_Y	Lower yield strength or 0.2% proof strength	N/mm ²
σ_Y'	Appropriate value of yield strength at the assessment temperature	N/mm ²
σ_Y'	Yield strength of the material in the vicinity of the flaw, as defined in 7.2.4	N/mm ²
σ_{Y1}	Yield strength at preload conditions	N/mm ²
σ_{Y2}	Yield strength at reload conditions	N/mm ²
σ_Y^M	Equivalent yield strength for a strength mis-match geometry	N/mm ²
σ_Y^P	Yield strength of the parent material	N/mm ²
σ_{Yp}	Yield strength of parent	N/mm ²
σ_Y^W	Yield strength of the weld material	N/mm ²
σ_{Yw}	Yield strength of weld	N/mm ²
σ_{YY}	Stress distribution normal to crack plane	N/mm ²
$\tilde{\sigma}_{YY}$	Pseudo-stress distribution normal to crack plane	N/mm ²
$\sigma_{0.2}$	0.2% proof strength	N/mm ²
σ_1, σ_2	Axial stress and hoop stress respectively in LTAs assessment in a cylinder	N/mm ²
τ	Random variable - rupture time	hours
Φ	Complete elliptical integral of the second kind	—
Φ	Cumulative distribution function of a normalized Gaussian distribution	—
Φ, Φ_s	Parameters used in calculating reference stress and/or limit load solutions	—
χ	Factor used in collapse analysis of bolts	—
ψ	Parameter used in defining ρ	—
ψ	Normalization parameter used in the analysis of welded joints with strength mis-match. For a plate, is defined to be equal to $(W - a)/h$, and for cylinders it is defined as $(B - a)/h$, where B is the wall thickness	—

Table 1 Symbols (*continued*)

Symbol	Definition	Units
$\psi, \psi_1, \psi_2, \psi_3, \psi_4$	Parameters used in calculating reference stress and/or limit load solutions	—
Ω	Normalized Gaussian random variable $N(0,1)$	—
Ω	Degree of bending in tubular joints	—
Ω_{Ax}	Axial degree of bending in tubular joints	—
Ω_{IPB}	In-plane degree of bending in tubular joints	—
Ω_{OPB}	Out-of-plane degree of bending in tubular joints	—
Ω_{Tot}	Total degree of bending in tubular joints	—

- A) The units and value of A depend on those used to measure da/dN and ΔK , and on the value of the exponent, m . If A is known in one set of units, A_a , the corresponding value for another set of units, A_b is given by:

$$A_b = A_a \frac{f_a}{f_b^n}$$

where:

f_a is the conversion factor for da/dN from the first to the second unit system; and
 f_b is the conversion factor for ΔK from the first to the second unit system.

- B) The units and value of C depend on those used to measure da/dt and ΔK , and on the value of the exponent, n . If C is known in one set of units, C_a , the corresponding value for another set of units, C_b , is given by:

$$C_b = C_a \frac{f_a}{f_b^n}$$

where:

f_a is the conversion factor for da/dt from the first to the second unit system; and
 f_b is the conversion factor for ΔK from the first to the second unit system.

- C) In Annex F, l' has been used for the length of a crack, irrespective of whether it is part wall or through thickness. This is in place of $2c$ and $2a$ respectively. This is because Annex F deals with flaws which start as part wall and grow to through thickness.
- D) The units for Q may be kg/s or g/s, but it is essential that they are consistent with those used for σ_f . In order for fluid parameters to be consistent with units in this section, Q should be in tonne/s and ρ_f should be tonne/m³.
- E) The units for ρ_f may be kg/mm³ or g/mm³, but it is essential that they are consistent with those used for Q , also see footnote ^{D)} above.



4 Types of flaw

The effects of the following flaws may be assessed using methods given in this 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);

- 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.

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 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 sulphide 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, 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 sulphide 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 are 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 shapes 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 initial 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.

NOTE 1 The Option 1 FAD (failure assessment diagram) is similar (but not identical) to the Level 2A/Level 3A generalized FAD of BS 7910:2005¹⁾.

- Option 2 is based on the use of a material-specific stress-strain curve.

NOTE 2 Option 2 is the equivalent of the "Level 2B" and "Level 3B" procedures of BS 7910:2005¹⁾.

- Option 3 uses numerical analysis to generate a FAD and is not confined to use with materials showing ductile tearing.

NOTE 3 Option 3 is the equivalent of Level 3C analysis in BS 7910:2005¹⁾, which was confined to use with materials showing ductile tearing.

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.

6 Information required for assessment

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 material properties should be generated at the construction stage, or appropriate materials should be retained for later testing. Accurate fracture toughness data is 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;

¹⁾ BS 7910:2005 has been withdrawn.

- BS 7448 and BS EN ISO 12737 for 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 considered. 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 a.c. field measurement (ACFM)];
- e) electrical potential drop (a.c. or d.c.);
- 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 (d.c. 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 583, and BS EN ISO 11666;
- radiography: BS EN 12517, 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 3452-1 and BS EN ISO 23277;
- eddy current: BS EN ISO 15548 and BS EN ISO 15549;
- visual: BS EN ISO 17637 and BS EN 12454.

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

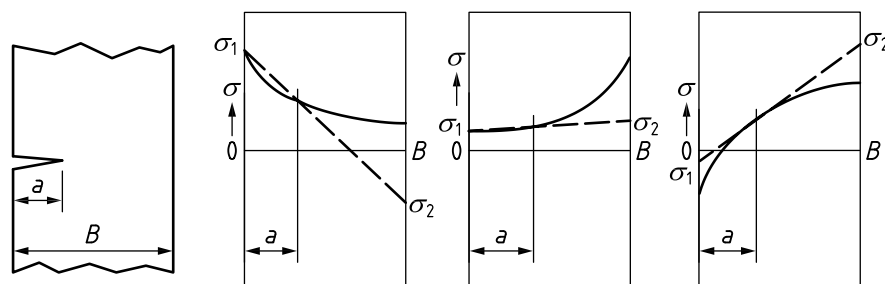
6.4.1 General

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. Elements of this British Standard may also be used in strain-based assessment.

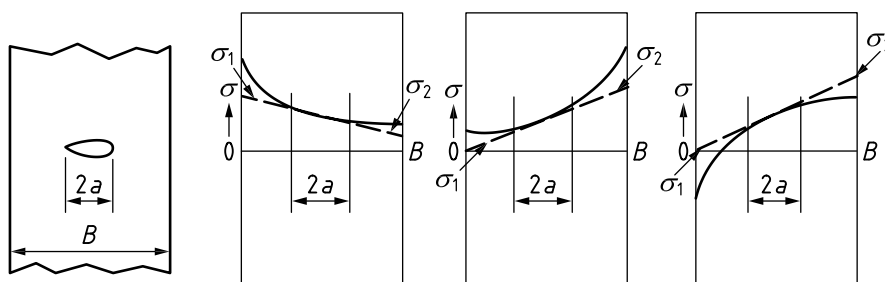
The stresses to be considered in the assessment are those which would be calculated by a stress analysis of the unflawed structure. The actual stress distributions may be used, or the stresses (or stress ranges) may be linearized, as shown in Figure 2. Linearization may be carried out across the flaw (Figure 2a) or across the section containing the flaw (Figure 2b). 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 2. 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 considered, 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. See Annex A if shear stresses are significant.

Figure 2 Linearization of stress distributions

a) Linearization of stress distributions across flaw in fracture assessments



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



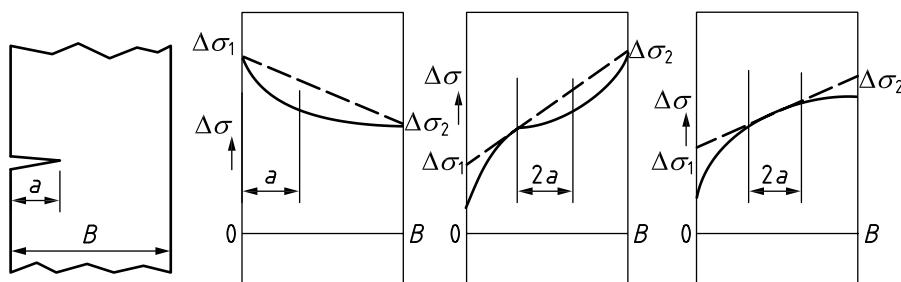
ii) Examples of linearization of primary or secondary stress distributions for embedded flaws

P_m, Q_m and P_b, Q_b can be determined from the distributions in i) and ii) using the following equations:

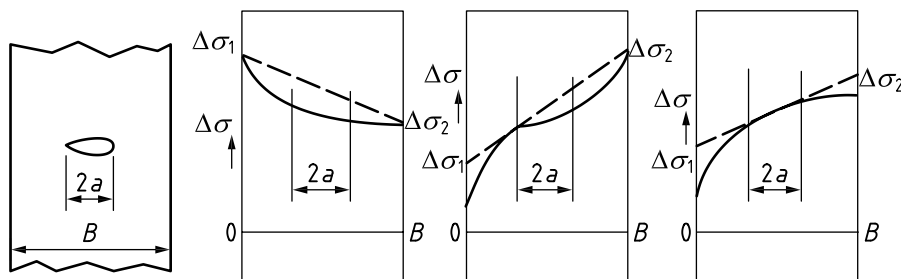
$$P_m, Q_m = \frac{\sigma_1 + \sigma_2}{2} \quad P_b, Q_b = \frac{\sigma_1 - \sigma_2}{2}$$

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 in fatigue assessment



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



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

$\Delta\sigma_m$ and $\Delta\sigma_b$ can be determined from the distributions in i) and ii) using the following equations:

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

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 ASME Boiler and Pressure Vessel Code Section III and PD 5500 are regarded as primary in this guide, 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 document, P_b is regarded as a stress superimposed upon P_m .

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 C_2 primary C_2 (see 7.1.8), are affected by structural discontinuities. Their effects are quantified by calculating peak stresses at the discontinuities, as described in 6.4.4.1 to 6.4.4.3. 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 considered.

6.4.4.4 Local structural discontinuities (e.g. holes, notches, sharp corners)

The stress concentrations due to local structural discontinuities usually decay over distances less than about 20% of the hole or notch radius, or 20% of the thickness. If the flaw lies within this region, then the effect of stress concentration on both fracture/fatigue and plastic collapse should be considered 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 document, as detailed in 7.1.6, 7.2.3 and 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 4). There are however restrictions on proceeding in this way. Specialist advice (for example, alternative detailed advice is given in R6, 11.3 [3]) 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 3 Schematic representation of stress distribution across section

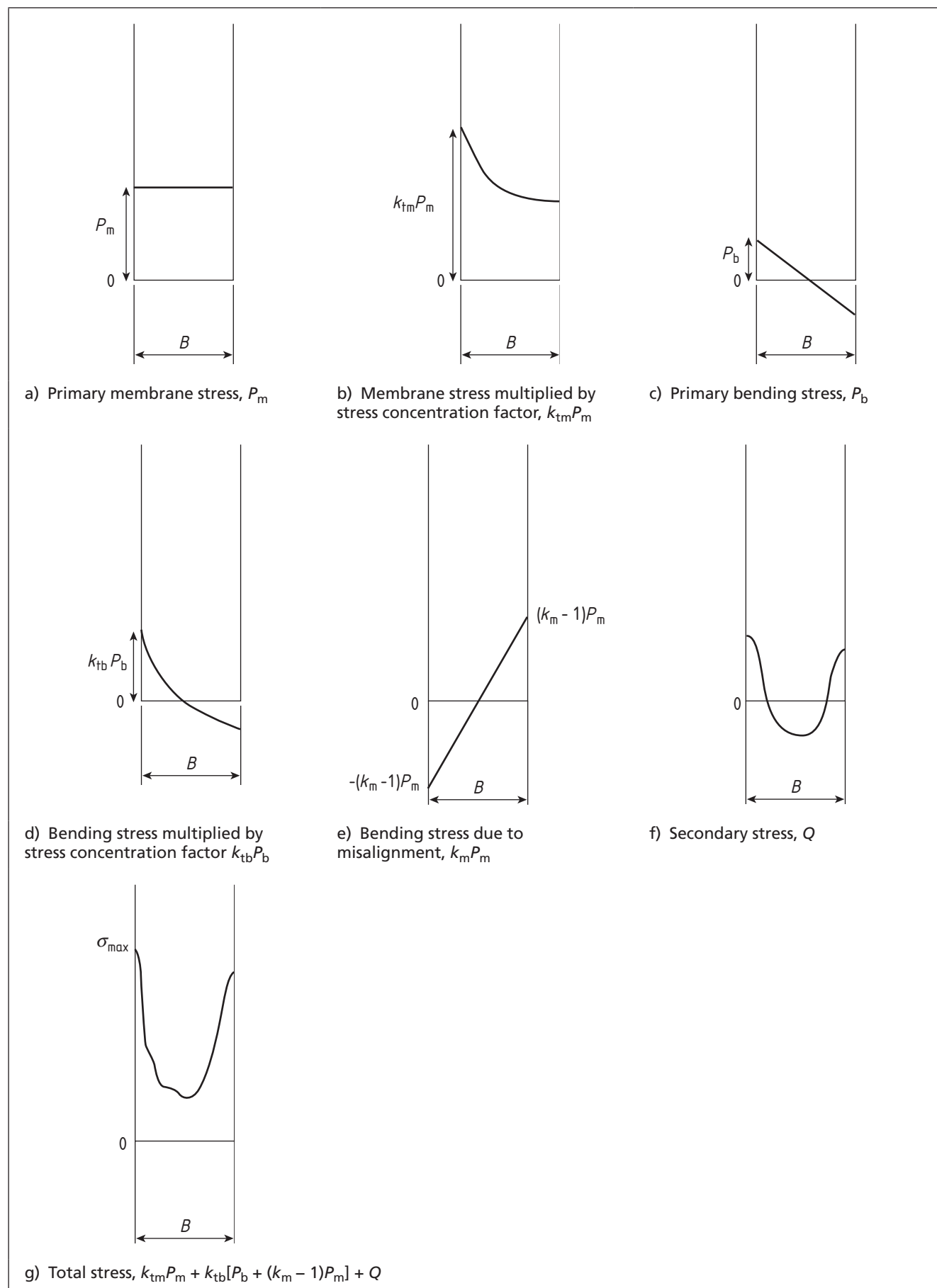
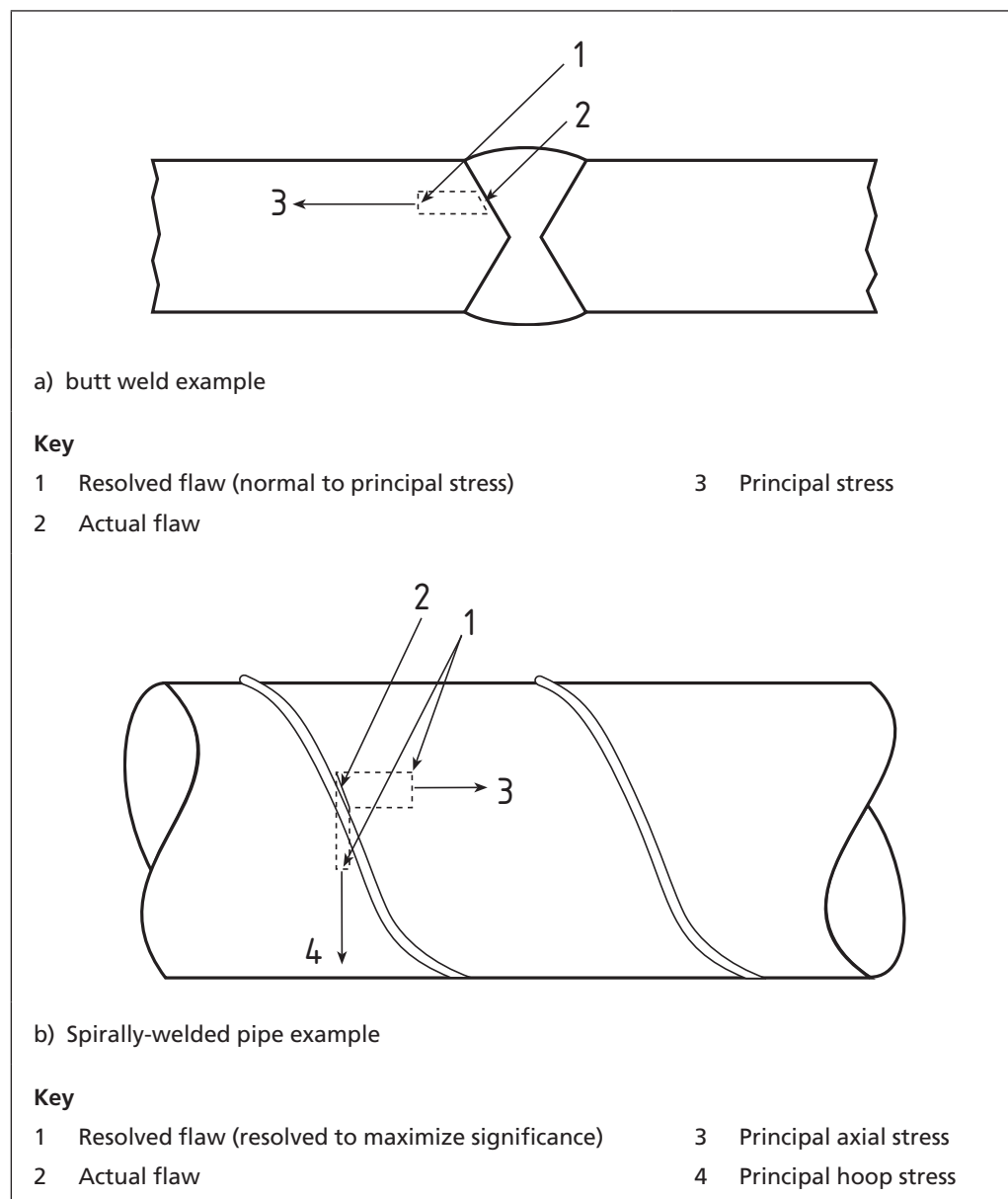


Figure 4 Procedure for resolving flaws normal to principal stress



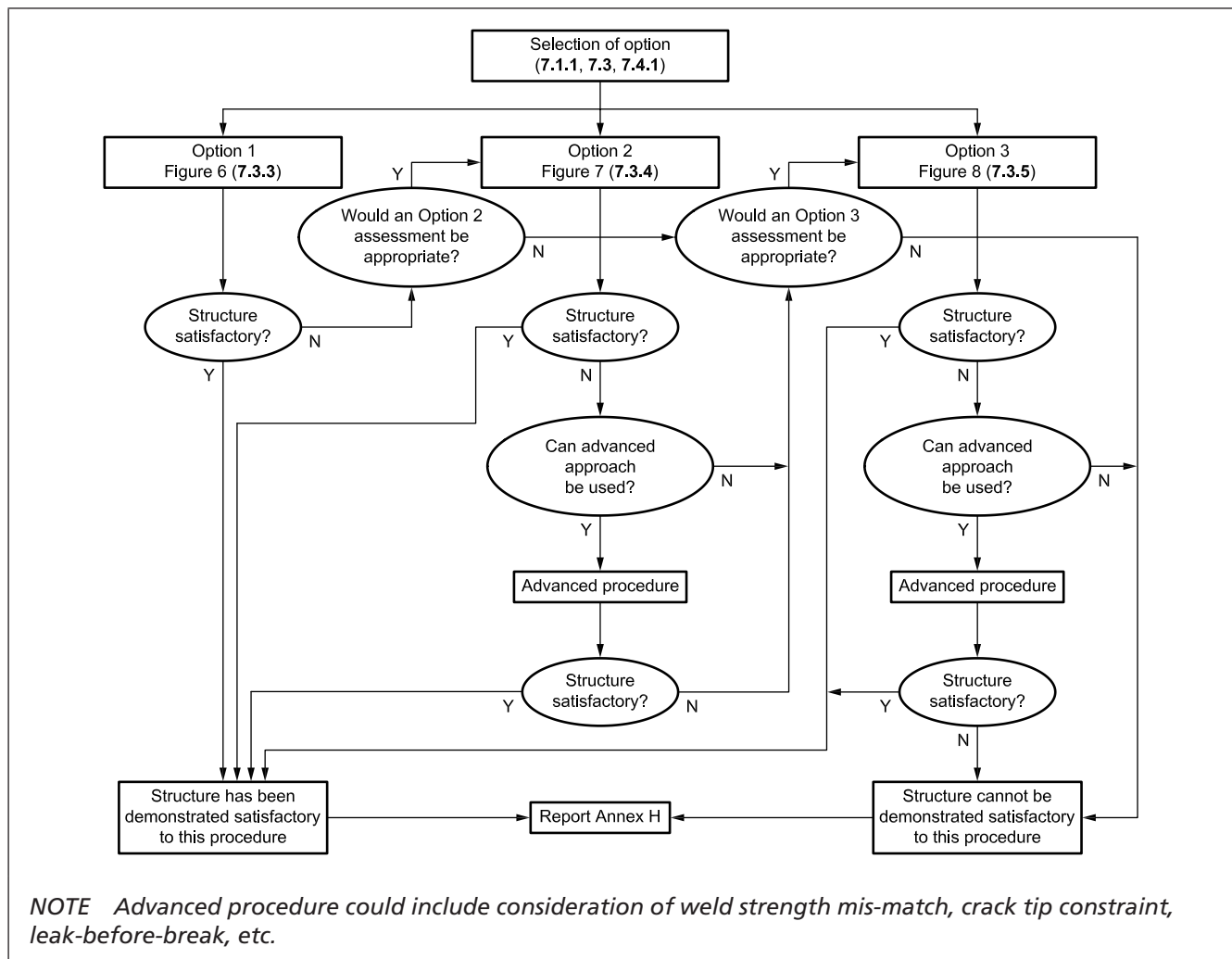
7 Assessment for fracture resistance

7.1 Background

7.1.1 General

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 5.

Figure 5 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 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 assessment line to determine the acceptability of the flaw. A general flow diagram of the procedure is shown in Figure 5. Options 1 to 3 are shown in Figure 6 to Figure 8.

Figure 6 Flowchart for Option 1 fracture assessment

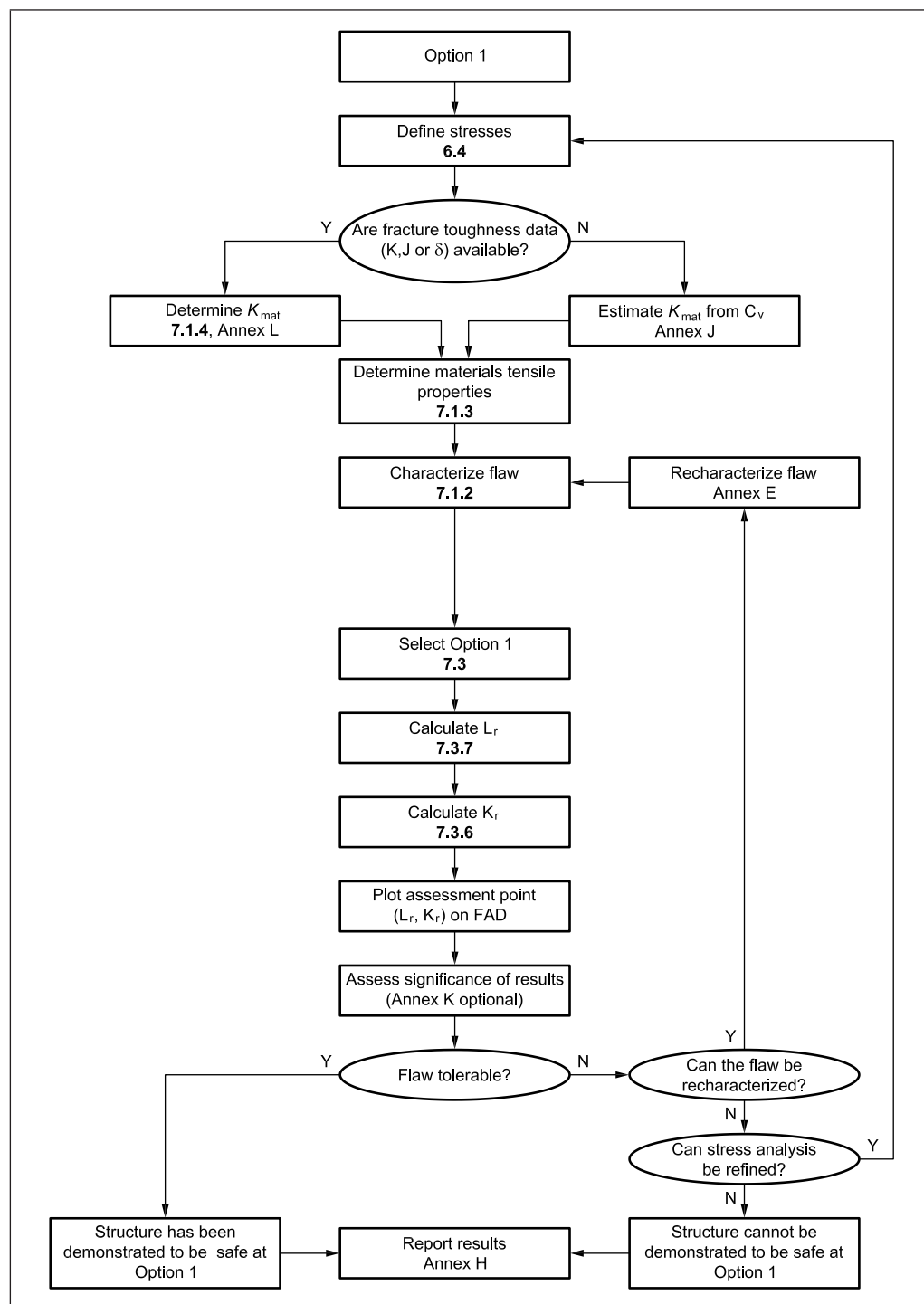


Figure 7 Flowchart for Option 2 fracture assessment

