

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

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- Electricity Association
- Energy Industries Council
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- Health and Safety Executive [560200]
- Imperial College of Science and Technology
- Institution of Mechanical Engineers
- Lloyd's Register of Shipping
- Power Generation Contractors Association — PGCA (BEAMA)
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Foreword

This British Standard has been prepared by Technical Committee WEE/37. PD 6493 was first published in 1980 and was revised in 1991. A further revision has now been carried out. It was decided that sufficient experience had been obtained in the use of the methods described, since the first publication in 1980, for the document to be produced now as a British Standard, rather than a Published Document. This standard, BS 7910, now therefore supersedes PD 6493:1991 which is withdrawn.

As the number of application standards specifying requirements for weld flaw acceptance levels based on fitness for purpose increases, so it is necessary to update and extend the guidance to be used in co-ordinating and rationalizing those requirements. This revision incorporates recent developments in fracture mechanics assessment methods, details of which are given in the appropriate clauses of this Guide. While arbitrary acceptance levels will continue to be used for quality control purposes, the complementary use of the methods described in this Guide permits the acceptability of known or postulated flaws in particular situations to be evaluated in a rational manner. Applications standards that formerly referred to PD 6493 should, in future, refer to this guide.

The guidance given in PD 6493:1991 concerning creep was restricted to the derivation of “creep exemption” temperature limits, below which this mode of failure could be ignored. No guidance was given on the treatment of flaws in structures or components operating at temperatures above the exemption limit. Subsequent to the publication of PD 6493:1991, the BSI published PD 6539:1994 giving guidance on methods for assessing crack growth in components operating at high temperatures. The decision has been taken to merge the approaches described in PD 6539 into the present guide, which is now comprehensive, covering all failure modes that could be influenced by the presence of flaws. However, it should be noted that, whilst fracture, fatigue and creep are treated thoroughly, the treatment of other failure modes is less detailed.

Improvements in the methods outlined are continuing and users of this document should obtain an appreciation of the status of the various methods before applying them. For the purpose of this document, the treatment of the methods has necessarily been simplified, but appropriate references have been included to assist those willing to obtain further guidance. However, the information will seldom be found in the reference in identical form to that used in this document.

It has been assumed in drafting BS 7910 that the execution of its provisions is entrusted to appropriately qualified and experienced people, having appropriate knowledge of inspection technology, NDT, materials behaviour and fracture mechanics.

Annexes A, D, E, G, H, K, M, N, P, R and S are normative.

Annexes B, C, F, I, J, L, O, Q, T and U are informative.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to viii, pages 1 to 261 and a back cover.

Sideline in this document indicates the most recent changes by amendment.

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Introduction

In circumstances where it is necessary to examine critically the integrity of new or existing constructions by the use of non-destructive testing methods, it is also necessary to establish acceptance levels for the flaws revealed. The derivation of acceptance levels for flaws is based on the concept of fitness for purpose. By this principle, a particular fabrication 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 purpose.

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 application standards, are acceptable without further consideration. If flaws more severe than the quality control levels are revealed, rejection is not necessarily automatic. Decisions on whether rejection and/or repairs are justified may be based on fitness for purpose, 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). 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 can in no circumstances 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 philosophy that the methods covered by this standard are complementary to, and not a replacement for, good quality workmanship is inherently assumed in this standard.

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

It is impossible to provide a single list of flaws, which are known not to cause premature failure, since a large number of variables are involved, as enumerated in this document. It is possible, where relevant experience and data already exist, 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. It needs to be appreciated that the unsatisfactory repair of innocuous flaws could result in the substitution of more harmful and/or less readily detectable flaws.

The implication of flaw assessment on a fitness for purpose basis is the need for thorough examination

by non-destructive testing using techniques capable of locating and sizing flaws in critical areas. This document 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 which need to be determined. Such non-destructive testing needs to be carried out after any post-weld heat treatment (PWHT) and/or proof test. However, since a major objective of this document is to reduce costs by eliminating unnecessary repair, careful consideration needs to be given to the level of inspection required to implement this document.

The limitations of non-destructive testing methods have to be taken into account. The following are the stages in the assessment of flaws revealed by such tests.

- a) If the flaws do not exceed the quality control levels in the appropriate application standard, no further action is required.
- b) 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.
- c) If no relevant documented experience exists, then an ECA based on the guidance given in this document needs to be carried out.

ECA will help to identify the limiting conditions for failure or the limiting design conditions. It is emphasized that some aspects of ECA are based on new concepts that could be subject to review. The application of these principles will mean that "safe" results will be obtained. The option of using appropriate safety factors has been incorporated or is inherent in each of the relevant clauses. 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 will not necessarily be unacceptable when it is found initially to exceed the acceptance levels that are derived from this document. A further assessment can be made following the principles given in this document, but incorporating more precise input data or analysis methods, or by testing structurally relevant components.

This document 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 may pose an unjustifiable or intolerable risk to the surrounding environment or population, then a full risk analysis may be needed, with due recognition of both individual and societal risk [1].

1 Scope

This guide outlines methods 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 developed can be used for analysing flaws in structures made from other metallic materials and in non-welded components or structures. The methods described can be applied at the design, fabrication and operational phases of a structure's life.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this British Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 806, *Specification for design and construction of ferrous piping installations for and in connection with land boilers.*

BS 3688-1, *Methods for mechanical testing of metals at elevated temperatures — Part 1: Tensile testing.*

BS 5400 (all parts), *Steel, concrete and composite bridges.*

BS 5500:1997, *Specification for unfired fusion welded pressure vessels.*

BS 5950-1:1990, *Structural use of steelwork in building — Part 1: Code of practice for design in simple and continuous construction: hot rolled sections.*

BS 6835-1, *Method for the determination of the rate of fatigue crack growth in metallic materials — Part 1: Fatigue crack growth rates of above 10^{-8} m per cycle.*

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

BS 7608, *Code of practice for fatigue design and assessment of steel structures.*

BS 8118 (all parts), *Structural use of aluminium.*

BS EN 10002-1, *Tensile testing of metallic materials — Part 1: Method of test at ambient temperature.*

BS EN 12517, *Non-destructive examination of welds — Radiographic examination of welded joints — Acceptance levels.*

BS EN 1289, *Non-destructive examination of welds — Penetrant testing of welds — Acceptance levels.*

BS EN 1290, *Non-destructive examination of welds — Magnetic particle examination of welds.*

BS EN 1291, *Non-destructive examination of welds — Magnetic particle testing of welds — Acceptance levels.*

BS EN 1435, *Non-destructive examination of welds — Radiographic examination of welded joints.*

BS EN 1712, *Non-destructive examination of welds — Ultrasonic examination of welded joints — Acceptance levels.*

BS EN 1714, *Non-destructive examination of welded joints — Ultrasonic examination of welded joints.*

BS EN 571-1, *Non-destructive testing. Penetrant testing — Part 1: General principles.*

BS EN ISO 7539 (all parts), *Corrosion of metals and alloys.*

BS EN ISO 6520-1, *Welding and allied processes. Classification of geometric imperfections in metallic materials — Part 1: Fusion welding.*

DD 186, *Method for determination of threshold stress intensity factors and fatigue crack growth rates in metallic materials.*

PD 6525, *Elevated temperature properties for steels for pressure purposes — Stress rupture properties.*

3 Symbols and definitions

For the purposes of BS 7910 the following symbols and definitions apply.

NOTE 1 Where units are given for the variations of the symbol K the following note 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 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 parenthesis.

Symbol	Definition	Units
A	constant in fatigue crack growth relationship	See footnote ¹⁾
A_c	crack area	mm^2
A_1	area of rectangle which demarcates flaw (annex M)	mm^2
A_2	full load bearing area containing flaw (annex M)	mm^2
a	half flaw length for through-thickness flaw, flaw height for surface flaw or half height for embedded flaw (see Figure 8)	mm
$\frac{da}{dN}$	flaw growth rate with cycles (clause 8)	mm/cycle
$\left(\frac{da}{dN}\right)_f$	rate of crack propagation per cycle in height direction due to fatigue (clause 9, annex T)	mm/cycle
$\left(\frac{da}{dN}\right)_c$	rate of crack propagation per cycle in height direction due to creep (clause 9, annex T)	mm/cycle
$\frac{da}{dt}$	flaw growth rate with time (clause 10)	mm/h
Δa	increment in a	mm
$\bar{a}$	effective flaw parameter for Level 1 fracture assessment(annex N)	mm
$\dot{a}_c$	rate of crack propagation in height direction due to creep (annex T)	mm/h
a_{eff}	effective crack size based on elastic analysis (annex R)	mm
a_{eff}^σ	effective crack size based on elastic-plastic stress field (annex R)	mm
a_{eff}^ϵ	effective crack size based on elastic-plastic strain field (annex R)	mm
a_f	final flaw size	mm
a_i	initial flaw size	mm
$\bar{a}_i$	initial value of effective flaw parameter for fatigue analysis	mm
$\bar{a}_{\text{max}}$	maximum value of effective flaw parameter for fatigue analysis	mm
$\bar{a}_m$	tolerable flaw parameter for Level 1 fracture assessment (annex N)	mm
a_o	initial flaw size (7.4.7.2)	mm
Δa_g	limit of tearing flaw extension (7.4.7.1)	mm
Δa_j	intermediate value of tearing flaw extension (7.4.7.2)	mm
Δa_o	notional extension of flaw defining tearing initiation (7.4.7.2)	mm
B	section thickness in plane of flaw	mm
B'	effective section thickness ($2a + 2p$) (annex M)	mm
B_{min}	minimum remaining thickness of a corroded spherical shell (annex G)	mm

¹⁾ 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:

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

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.

Symbol	Definition	Units
B_o	original, measured, pipe or vessel wall thickness, or wall thickness as defined in the original design code (annex G)	mm
b	exponent of time in creep strain equations (annex T)	
C	constant in creep crack propagation equation (clause 9)	
C^*	parameter defining creep crack propagation rate (clause 9)	N/mm·h
C_1	constant in the stress corrosion crack growth relationship (clause 10)	See footnote ²⁾
C_D	discharge coefficient (annex F)	
c	half flaw length for surface or embedded flaws (see Figure 8)	mm
$2c_b$	surface length of crack at breakthrough (annex F)	mm
$\dot{c}_c$	crack growth rate in length direction due to creep (annex T)	mm/h
Δc	increment in c	mm
D	diameter	mm
D'	constant in creep strain equation (annex T)	
D_c	accumulated creep damage (annex T)	
ΔD_c	increment of creep damage (annex T)	
D_{SM}	mean shell diameter	mm
d	deviation from true circle due to angular misalignment (annex D)	mm
d_c	depth of corroded region (annex G)	mm
d_i	depth of an individual corrosion flaw (annex G)	mm
d_{nm}	effective depth of combined flaws from n to m (annex G)	mm
$d_{1,2, \text{ etc.}}$	depth of 1st, 2nd, etc. corrosion flaws (annex G)	mm
E	elastic modulus	N/mm ² (MPa)
E'	elastic modulus corrected for constraint conditions $E' = E$ for plane stress. $E' = E/(1 - \nu^2)$ for plane strain (7.3.6.1 and T.4.1)	N/mm ² (MPa)
E_{RT}	elastic modulus at room temperature (say 20 °C) (8.2.3.4)	
E_{ET}	elastic modulus at the elevated temperature (8.2.3.4)	
E_1	electrical energy per unit length of weld (annex Q)	J/mm
e	axial misalignment (eccentricity or centre line mismatch) (annex D)	mm
F_{AR}	reduction factor to allow for loss of load-bearing area due to presence of a flaw in a tubular joint (annex B)	
F^a, F^K, F^Y	reserve factors on flaw size, toughness and yield strength (annex K)	
F^L	load factor (annex K)	
f	frequency of fatigue loading cycle (clause 9)	Hz
f_c	total factor of safety in analysis of corrosion flaw = $f_{c1} \times f_{c2}$ (annex G)	
f_{c1}	modelling factor in analysis of corrosion flaw (annex G)	

²⁾ 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.

Symbol	Definition	Units
f_{c2}	original design factor in analysis of corrosion flaw (annex G)	
f_t	friction factor for flow through crack (annex F)	
f_{imax}	effective maximum friction factor for flow through crack (annex F)	
f_{scc}	factor of safety with respect to stress corrosion cracking ($f_{scc} > 1.0$) (clause 10)	
f_ϕ, f_w, g	correction terms in stress intensity factor for elliptical flaws (annex M)	
G	constant in tubular joint stress intensity factor solutions (annex B)	
H	crack-opening area (COA) (annex F)	mm ²
H_c	creep component of crack-opening area (COA) (annex F)	mm ²
H_e	elastic component of crack-opening area (COA) (annex F)	mm ²
H'	constant in tubular joint stress intensity factor solutions (annex B)	
h	weld leg length (annexes D and K)	mm
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
$J_{0.2BL}$	resistance to crack extension expressed in terms of J at 0.2 mm crack extension offset to the blunting line (clause 7)	N/mm
J_c	value of J at either: unstable fracture; or onset of arrested brittle crack or pop-in. This term only applies 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 maximum force plateau	N/mm
J_{mat}	material toughness measured by J -methods (7.1.4.2, 7.1.5.3)	N/mm
J^s	value of J for secondary stresses alone (annex R)	N/mm
J_u	value of J at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in. This term only applies where $\Delta a_0 > 0.2$ mm offset to the blunting line.	N/mm
K	stress intensity factor	N/mm ^{3/2}
K_I	applied tensile (mode I) stress intensity factor (7.2.5, 7.3.5.1)	See note 1 N/mm ^{3/2}
ΔK_I	cyclic range in K_I	See note 1 N/mm ^{3/2}
K_{Ip}	stress intensity factor due to pre-load (annex O)	See note 1 N/mm ^{3/2}
K_I^s	stress intensity factor due to secondary stresses [= $(Y\sigma)_s\sqrt{(\pi a)}$] (annex R)	See note 1 N/mm ^{3/2}
K_I^p	stress intensity factor due to primary stresses [= $(Y\sigma)_p\sqrt{(\pi a)}$] (annex R)	See note 1 N/mm ^{3/2}
K_{ISCC}	critical stress intensity factor for stress corrosion cracking (clause 10)	See note 1 N/mm ^{3/2}
K_2	stress intensity factor following unload (annex O)	See note 1 N/mm ^{3/2}
K_{II}	mode II linear elastic stress intensity factor (annex A)	See note 1 N/mm ^{3/2}

See note 1



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Symbol	Definition	Units
K_{IIc}	critical value of K_{II} at onset of brittle fracture in mode II (annex A)	N/mm ^{3/2} See note 1
K_{II}^p, K_{II}^s	values of K_{II} due to primary and secondary stresses, respectively (annex A)	N/mm ^{3/2} See note 1
K_{III}	mode III linear elastic stress intensity factor (annex A)	N/mm ^{3/2} See note 1
K_{III}^p, K_{III}^s	values of K_{III} due to primary and secondary stresses, respectively (annex A)	N/mm ^{3/2}
K_{eff}	effective linear elastic stress intensity factor in mixed mode loading (annex A)	N/mm ^{3/2} See note 1
K_f	stress intensity factor at failure (annex O)	N/mm ^{3/2} See note 1
K_g	notional K value after flaw extension Δa_g (7.4.7.1)	N/mm ^{3/2} See note 1
K_{Ic}	plane strain fracture toughness (7.1.5.1)	N/mm ^{3/2} See note 1
K_{mat}	material toughness measured by stress intensity factor (7.1.4.2)	N/mm ^{3/2} See note 1
K_p^s	effective stress intensity factor used to define K_f^s (annex R)	N/mm ^{3/2} See note 1
K_r	fracture ratio of applied elastic K value to K_{mat}	
K_e^s	effective stress intensity factor defined from elastic-plastic strain field (annex R)	N/mm ^{3/2} See note 1
K_σ^s	effective stress intensity factor defined from elastic-plastic stress field (annex R)	N/mm ^{3/2} See note 1
ΔK	stress intensity factor range (clause 8)	N/mm ^{3/2} See note 1
ΔK_{eff}	effective stress intensity factor range (clause 8)	N/mm ^{3/2} See note 1
ΔK_o	threshold stress intensity factor range below which fatigue crack growth (or corrosion fatigue crack growth) does not occur (clause 8)	N/mm ^{3/2} See note 1
k_m	stress magnification factor due to misalignment (6.4.4, 8.8.1 and annex D)	
k_t	stress concentration factor (6.4.4)	
k_{tb}	bending stress concentration factor (6.4.4, 7.3.3, annex M)	
k_{tm}	membrane stress concentration factor (6.4.4, 7.3.3, annex M)	
$k_{t,HS}$	hot spot stress concentration factor in tubular joint (annex B)	
$k_{t,IPB}, k_{t,OPB}$	in and out of plane stress concentration factors in tubular joints (annex B)	
L	attachment length	mm
L_r	ratio of applied load to yield load (7.1.8, annex M)	
$L_{r,max}$	permitted limit of L_r (7.3.1)	
l	distance from axially misaligned joint to load or extremities of region of angular misalignment (shortest distance = l_1) (annex D)	mm

Symbol	Definition	Units
l'	generalized crack length (length of surface, buried or through-thickness crack) or equivalent length of through-thickness crack after re-characterization [annex F ³⁾]	mm
l_c	length of corroded region measured parallel to the axis of a cylindrical vessel or pipe (annex G)	mm
l'_c	limiting generalized crack length (annex F)	mm
l'_L	length of crack which leaks at the minimum detectable rate (annex F)	mm
l'_L^*	enhanced length of crack which leaks at the minimum detectable rate (annex F)	mm
l'_r	length of crack at rupture (annex F)	mm
l_i	length of an individual corrosion flaw forming part of a colony of interacting flaws (annex G)	mm
l_{nm}	effective longitudinal length of a flaw combined from adjacent flaws n to m in a colony of interacting flaws (annex G)	mm
l_{total}	total longitudinal length of a colony of interacting flaws and the spacing between them (annex G)	mm
l_w	length of weld	mm
M	bulging correction factor (annex M)	
M_{ai}, M_{ao}	applied in and out of plane moments for tubular joints (annex B)	N-mm
M_{ci}, M_{co}	fully plastic moments for cracked tubular joints calculated for in and out of plane loads (annex B)	N-mm
M_m, M_b, M_{km}, M_{kb}	stress intensity magnification factors (7.2.5, annexes M and B)	
M_m^*, M_b^*	factors used in calculating M_m and M_b (annex M)	
M_s, M_T	stress magnification factor (annexes M and P)	
m	exponent in flaw growth law (clause 8)	
m_q	exponent in the calculation of F_{AR} (annex B)	
N	fatigue life (clause 8)	cycles
N_c	number of corrosion flaws in a colony of interacting flaws (annex G)	
ΔN	increment in N (clause 8)	cycles
n	exponent of stress in creep strain equation (annex T)	
n, m	refer to the n^{th} and m^{th} flaw in a series of corrosion flaws 1.. N_c ; (annex G)	
$n(scc)$	exponent in the stress corrosion crack growth relationship (clause 10)	
n_j	number of cycles in stress spectrum at stress range $\Delta\sigma_j$ (clause 8)	cycles
P	primary stress (6.4.1)	N/mm ² (MPa)
P_a	applied axial load on tubular joint (annex B)	N
P_c	collapse load for cracked tubular joint (annex B)	N
P_b	primary bending stress (6.4.1)	N/mm ² (MPa)
$P_{b,l}$	primary bending stress due to locally applied bending loads (annex P)	N/mm ² (MPa)
P_m	primary membrane stress (6.4.1)	N/mm ² (MPa)
$P_{m,a}$	primary membrane stress due to global axial loads (annex P)	N/mm ² (MPa)
$P_{m,p}$	primary membrane stress due to pressure loading (annex P)	N/mm ² (MPa)
$P_{m,b}$	primary membrane stress due to global bending moments (annex P)	N/mm ² (MPa)

³⁾ 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.

Symbol	Definition	Units
P_f	fluid pressure (annex F)	N/mm ² (MPa)
P_f	failure pressure of a corroded pipe or vessel (annex G)	N/mm ² (MPa)
P_{nm}	failure pressure of combined adjacent corrosion flaws n to m, formed from a colony of interacting flaws (annex G)	N/mm ² (MPa)
P_o	failure pressure of plain unflawed pipe or pressure vessel (annex G)	N/mm ² (MPa)
P_{sw}	safe working pressure of the corroded pipe or pressure vessel (annex G)	N/mm ² (MPa)
$P_{1,2,...,N}$	failure pressures of individual corrosion flaws forming a colony of interacting flaws (annex G)	N/mm ² (MPa)
p	shortest distance from material surface to embedded flaw	mm
p'	internal pressure (annex P)	N/mm ² (MPa)
$p(F)$	probability of failure (annex K)	
Q	secondary stress	N/mm ² (MPa)
Q_b	secondary bending stress	N/mm ² (MPa)
Q_m	secondary membrane stress	N/mm ² (MPa)
Q_{mf}	mass flow through an equivalent rectangular crack (annex F)	kg/s or g/s ⁴)
Q_β	factor to allow for increased strength observed in tubular joints at $\beta > 0.6$ (annex B)	
Q_c	length correction factor for corrosion flaws (annex G)	
Q_i	length correction factor of an individual flaw forming part of a colony of interacting corrosion flaws (annex G)	
Q_{nm}	length correction factor for a flaw combined from adjacent flaws n to m in a colony of interacting corrosion flaws (annex G)	
q	exponent in creep crack propagation equation (annex T)	
q_o	fraction of load cycle when crack is open (annex T)	
R	stress ratio [ratio of minimum (σ_{min}) to maximum (σ_{max}) algebraic value of the absolute stress level ($k_{tm} \cdot P_m + k_{tb} \cdot P_b + Q$)] (clause 8)	
R'	parameter used in creep crack propagation equation (annex T)	mm
R_a	surface roughness of crack (annex F)	μm
R_p	cyclic plastic zone size	mm
R_s	reserve strength factor = $\frac{P_f}{P_o}$	
r	mean shell radius or radius of round bar or bolt (annexes M and P)	mm
r_h	radius of hole	mm
r_i	internal shell radius	mm
r_o	external shell radius	mm
S	stress range or, for variable amplitude loading, the equivalent constant amplitude stress range (clause 8)	N/mm ² (MPa)
S_{nom}	nominal membrane stress for level 1 analysis (7.2.3)	
S_r	ratio of applied load to flow strength load (7.1.8, annex P)	
s	distance between embedded flaws (7.1.2.2, Figure 9) or longitudinal spacing between adjacent corrosion flaws (annex G)	mm
s_i	longitudinal spacing between adjacent flaws forming part of a colony of interacting corrosion flaws (annex G)	mm

⁴ The units for Q_{mf} may be kg/s or g/s, but it is essential that they are consistent with those used for ρ_f .

Symbol	Definition	Units
T	temperature (clause 9)	°C
T_c	creep exclusion temperature (clause 9)	°C
T_1	temperature at pre-load (annex O)	°C
T_2	temperature at re-load (annex O)	°C
t	time (days, weeks, months or years as appropriate)	
t_a	time accumulated from initial start-up of plant (clause 9)	h
t_{cd}	time to failure of plant by bulk creep rupture, measured from initial start-up (clause 9 and annex F)	h
t_d	required life of plant, measured from initial start-up (clause 9)	h
t_{ff}	time to failure by unstable fracture, measured from initial start-up (clause 9)	h
t_i	crack incubation time, prior to commencement of creep crack growth (annex F)	h
t_{ix}	incubation period corresponding to crack growth x (clause 9)	h
t_R	creep rupture life (annex T)	h
$t_{R(ref)}$	time to creep rupture at reference stress (annex T)	h
$t(2c_b)$	time to breakthrough of a part wall flaw (annex F)	h
$t(l'_c)$	time to grow crack to limiting length (annex F)	h
$t(T)$	time to achieve specific creep strain at proof stress at temperature T (clause 9)	h
$t_r(\sigma)$	time to rupture at the appropriate temperature and at a stress, σ (annex F)	h
t_w	weld throat thickness (annex M)	mm
Δt	time span (annex B)	h
Δt_d	time to detect a leak (annex F)	h
W	plate width in plane of flaw (see for example Figure M.1, M.2, M.6 and M.7)	mm
W_c	crack opening width (annex F)	mm
X	factor relating δ_I and K_I to account for constraint and work hardening capability variation	
x	parameter used in Figure R.1 (annex R)	
Y	stress intensity factor correction (7.2.5, clause 9 and annex M)	
Y_m, Y_b	stress intensity correction factors for membrane and bending stress (annex B)	
Y_{wm}, Y_{wb}	stress intensity correction factors for the weld location for membrane and bending stress (annex P)	
$(Y\sigma)_p$	primary stress intensity factor correction function (7.3.5.1, annex M)	N/mm ² (MPa)
$(Y\sigma)_s$	secondary stress intensity factor correction function (7.3.5.1, annex M)	N/mm ² (MPa)
y	height of peaking due to angular misalignment (annex D)	mm
Z	circumferential angular spacing between projection lines in the analysis of corrosion flaws (annex G)	degrees
z	measure of position through the thickness (annex M and Q)	mm
z_0	through-thickness depth of tensile residual stress zone (annex Q)	mm
z_r	through-thickness depth of repair (annex Q)	mm
α	angular change at misaligned joint (annex D)	radians
α''	function of α , c , B and W used in calculation of collapse stresses (annex P)	
$\alpha(\lambda')$	bulging factor (annex F)	
β	ratio of brace diameter to chord diameter in a tubular joint (annex B)	
β'	plasticity correction factor, $\beta' = 1$ for plane stress, $\beta' = 1$ for plane strain	
β''	factor determining state of stress (clause 9)	

Symbol	Definition	Units
β_{sx}	factor used in collapse analysis of cylinders (annex P)	
β_{sy}	factor used in collapse analysis of cylinders (annex P)	
β_r	reliability (annex K)	
γ	ratio of chord radius to chord wall thickness in a tubular joint (annex B)	
γ'	estimate of K_I^s for through-wall self-balancing stress (annex R)	
$\gamma_\sigma, \gamma_a, \gamma_K, \gamma_\delta, \gamma_Y$	partial coefficients on stress, flaw size, fracture toughness in terms of K , fracture toughness in terms of CTOD and yield strength, for safety factor treatment (annex K)	
γ_c	safety factor for use with creep data (clause 9)	
δ	crack tip opening displacement (CTOD)	mm
δ_c	CTOD at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in. This term only applies where $\Delta a_0 < 0.2$ mm offset to the blunting line.	mm
δ_g	CTOD at limit of permitted tearing (7.4.7.2)	mm
δ_I	applied CTOD (7.2.6)	mm
δ_{ix}	crack opening displacement corresponding to initiation of creep crack growth of extent x (clause 9)	mm
δ_m	CTOD at first attainment of maximum force plateau	mm
δ_{mat}	material toughness measured by CTOD method	mm
$\delta_{0.2BL}$	resistance to crack extension expressed in terms of CTOD at 0.2 mm crack extension offset to the blunting line (clause 7)	mm
δ_r	fracture ratio using CTOD parameters (7.2.6)	
δ_u	CTOD at either: a) unstable fracture; or b) onset of arrested brittle crack or pop-in. This term only applies where $\Delta a_0 > 0.2$ mm offset to the blunting line.	mm
ε	strain	
ε_c	accumulated creep strain (annex T)	
ε_e	elastic strain at the reference stress (σ_{ref}/E) (annex F)	
ε_f	strain to failure of material, as measured in uniaxial creep test (annex T)	
ε_{ij}	elastic-plastic mechanical strains; $ij = x, y, z$ (annex R)	
ε_{max}	maximum tensile strain (7.2.8)	
ε_{ref}	reference strain (7.3.2.2)	
ε_Y	yield strain, i.e. strain at σ_Y (7.2.8)	
$\Delta\varepsilon_c$	increment of creep strain (annex T)	
ζ	dimensionless geometrical parameter used in collapse analysis of flawed cylinders (annex P)	
θ	parametric angle to identify position along an elliptic flaw front	radians
κ	constant depending on boundary conditions (annex D)	
$\lambda, \lambda_1, \lambda_2, \text{etc.}$	constants used in calculating stress intensity factors (annex M)	
λ_r	ratio to give the structural cut-off (annex P)	
λ_s	factor used in collapse analysis of cylinders (annex P)	
λ''	scaling factor on stress intensity factor, used to define γ' (annex R)	

Symbol	Definition	Units
μ	constant in calculating the failure pressure of a corroded sphere (annex G)	
ν	Poisson's ratio	
ξ	constant in calculating the failure pressure of a corroded sphere (annex G)	
ρ	plasticity correction factor (annex R)	
ρ_1	a parameter used in determining ρ (annex R)	
ρ_f	fluid density (annex F)	kg/mm ³ or g/mm ³ [see footnote ⁵]
Σ	ratio of flow strengths at re-load and pre-load conditions (annex O)	
σ_a	applied stress (annex O)	N/mm ² (MPa)
σ_b	linearized bending stress (clause 9)	N/mm ² (MPa)
σ_{bc}	hot spot bending stress for a cracked tubular joint (annex B)	N/mm ² (MPa)
σ_f	flow strength (assumed to be the average of the yield and the tensile strengths, limited to 1.2 σ_y for level 1 analyses) (7.2.7)	N/mm ² (MPa)
σ_f'	flow strength of the material in the vicinity of the flaw (7.3.4.2 and annex O)	
σ_m	linearized membrane stress (clause 9)	N/mm ² (MPa)
σ_{max}	maximum tensile stress for level 1 analyses (7.2.3)	N/mm ² (MPa)
$\sigma_{n,b}$	bending component of collapse stress (annex P)	N/mm ² (MPa)
$\sigma_{n,m}$	membrane component of collapse stress (annex P)	N/mm ² (MPa)
σ^p	stress arising from loads which contribute to plastic collapse (clause 9)	N/mm ² (MPa)
σ_R	residual stress	N/mm ² (MPa)
σ_{max}^r	surface value of self-balancing residual stress for through-wall crack (annex R)	N/mm ² (MPa)
σ_R^L	longitudinal residual stress (annex Q)	N/mm ² (MPa)
σ_R^T	transverse residual stress (annex Q)	N/mm ² (MPa)
$\sigma_R^{L,B}$	longitudinal residual stress at bore (annex Q)	N/mm ² (MPa)
$\sigma_R^{T,B}$	transverse residual stress at bore (annex Q)	N/mm ² (MPa)
$\sigma_R^{T,O}$	transverse residual stress on the outer surface (annex Q)	N/mm ² (MPa)
σ_{ref}	reference stress used for creep and plastic collapse considerations	N/mm ² (MPa)
$\sigma_{ref,b}$	reference stress for pure bending (annex P)	N/mm ² (MPa)
$\sigma_{ref,m}$	reference stress for pure membrane loading (annex P)	N/mm ² (MPa)
σ^s	stress arising from loads which do not contribute to plastic collapse (clause 9)	N/mm ² (MPa)
σ_s	bending stress due to misalignment (annex D)	N/mm ² (MPa)
σ_u	tensile strength	N/mm ² (MPa)
σ_Y	lower yield strength or 0.2 % proof strength	N/mm ² (MPa)
σ_Y'	yield strength of the material in the vicinity of the flaw, as defined in 7.2.4 (7.2.4, 7.3.4, annex O)	N/mm ² (MPa)
σ_{Y1}	yield strength at pre-load conditions (annex O)	N/mm ² (MPa)
σ_{Y2}	yield strength at re-load conditions (annex O)	N/mm ² (MPa)
σ_{yy}	stress distribution normal to crack plane (annex R)	N/mm ² (MPa)
$\tilde{\sigma}_{yy}$	pseudo-stress distribution normal to crack plane (annex R)	N/mm ² (MPa)
σ_w	applied stress on weld throat	N/mm ² (MPa)
$\sigma_{0.2}$	0.2 % proof strength	N/mm ² (MPa)
$\Delta\sigma$	applied stress range (clause 8)	N/mm ² (MPa)

⁵ 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_{ref} .

Symbol	Definition	Units
$\Delta\sigma_b$	bending component of stress range (clause 8)	N/mm ² (MPa)
$\Delta\sigma_m$	membrane component of stress range (clause 8)	N/mm ² (MPa)
$\Delta\sigma_{Ax}$	axial stress range in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma_{IPB},$ $\Delta\sigma_{OPB}$	in and out of plane bending stress ranges in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma_{nom}$	nominal stress range in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma_{Hs.Tot}$	total hot spot stress range in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma_{Hs.Ax},$ $\Delta\sigma_{Hs.IPB},$ $\Delta\sigma_{Hs.OPB}$	axial, in and out of plane hot spot stress ranges in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma_{n.Ax},$ $\Delta\sigma_{n.IPB},$ $\Delta\sigma_{n.OPB}$	nominal axial, in and out of plane stress ranges in tubular joint (annex B)	N/mm ² (MPa)
$\Delta\sigma'_b$	bending stress range excluding the effects of misalignment (clause 8)	N/mm ² (MPa)
$\Delta\sigma_j$	stress range in variable amplitude fatigue spectrum which is applied n_j times (clause 8)	N/mm ² (MPa)
τ	ratio of brace wall thickness to chord wall thickness in tubular joints (annex B)	
τ'	factor used in collapse analysis of cylinders (annex P)	
Φ	complete elliptic integral of the second kind (annex M)	
φ	parameter used in defining ρ (annex R)	
ϕ_s	factor used in the collapse analysis of spheres (annex P)	radians
ϕ	circumferential angular spacing between adjacent corrosion flaws (annex G)	degrees
χ	factor used in collapse analysis of bolts (annex P)	
ψ	parameter used in defining ρ (annex R)	
Ω	degree of bending in tubular joints (annex B)	
$\Omega_{Tot}, \Omega_{Ax},$ $\Omega_{IPB}, \Omega_{OPB}$	total, axial, in plane and out of plane degrees of bending in tubular joints (annex B)	

4 Types of flaw

The effects of the following flaws may be assessed by use of this document.

- 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 known as “imperfect shape” include some which may be treated as planar flaws which are listed as such in a) and others which give rise to stress concentration effects. A comprehensive classification of the various types of weld flaw which may be encountered is given in BS EN ISO 6520-1.

5 Modes of failure and material damage mechanisms

5.1 The influence of the flaws listed in clause 4 may be assessed, using this document, for the modes of failure and damage mechanisms listed below:

- failure by fracture and plastic collapse (see clause 7);
- damage by fatigue (see clause 8);
- damage by creep and creep fatigue (see clause 9);
- failure by leakage of containment vessels (see 10.2);
- damage by corrosion and/or erosion (see 10.3.2);
- damage by environmentally assisted cracking (see 10.3.3);
- failure by instability (buckling) (see 10.4).

For each flaw or flaw type consideration should be given to the following points:



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

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.

- 1) *Embrittlement*. This type of damage can be caused in some materials by irradiation, temper-embrittlement, or by caustic, hydrogen or hydrogen sulfide rich environments.
- 2) *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.
- 3) *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.
- 4) *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.
- 5) *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 possible impurities.
- 6) *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).

7) *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 which 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.

8) *Hydrogen and hydrogen sulfide related cracking*. The damage rate is a function of material, pressure, temperature, concentration of H_2 or H_2S , etc.

9) *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.

10) *Cavitation*. The most common areas affected are pump impellers and components where high flow rates occur with significant pressure drop, such as may occur across control valves in process fluid piping or pipelines.

For a particular application, some of these failure modes and damage mechanisms will not be relevant. However, it is necessary, at the outset, to consider all operating conditions including start-up, shut-down, process upset, and external environment to establish which are relevant to the particular component under consideration. It is also necessary to take account of possible interaction between the various damage mechanisms. Reference should be made to clauses 7, 8, 9 and 10 dealing with the detailed assessment of the various modes of failure and material damage mechanisms.

The risk 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 and brittle fracture is well understood. It is not practical, at this time, to attempt to provide treatments for the other mechanisms listed in the same depth and generality as can be provided for failure by fracture, fatigue or creep. However, they all need to be considered in an ECA, since failure can arise through their operation. Brief guidelines are offered in clause 10 for the assessment of the possible risk of operation of these mechanisms. A specific assessment should be undertaken, if it is established that a risk of failure from these modes exists. This should incorporate the assumptions and approaches used in these circumstances, which should be fully documented and agreed by all parties.

5.2 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 essential data, relevant to the particular structure (see 6.2).
- c) Determine the size of the flaw.
- d) Assess possible material damage mechanisms and damage rates.
- e) Determine the limiting size for the final modes of failure.
- f) 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.
- g) Assess the consequences of failure.
- h) Carry out sensitivity analysis.
- i) If the flaw would not grow to the limiting size, including appropriate factors of safety, it is acceptable. Ideally, the safety factors should take account of both the confidence in the assessment and 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 e) and determining the initial flaw sizes which would grow to these within the remaining life as in f). Procedures for calculating such tolerable initial flaw sizes are given in clauses 7, 8, 9 and 10.

5.3 Several levels of treatment of flaws are possible, depending on the application and materials data available. Three levels of dealing with fracture are included in clause 7. Level 1 is a conservative preliminary procedure which is simple to employ. Level 2 is the normal procedure and comprises a number of options. Level 3 is an advanced procedure which allows for ductile tearing, permitting greater accuracy when sufficient materials data are obtainable. Level 3 also includes a number of options. Procedures are given in clauses 8 and 9, respectively, for estimating fatigue and creep crack growth when specific materials data are provided. Guidance is also given in these clauses for making assessments when specific information is not available. Where appropriate, comments are included on the probability of survival and on the desirability of conducting a sensitivity analysis.

6 Information required for assessment

6.1 General

It is inevitable that the ECA will require 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, it is advisable to generate relevant material properties at the construction stage, or to retain appropriate materials for later testing. In particular, the desirability of having accurate fracture toughness data cannot be

emphasized too strongly and tests on weld procedure test samples are advisable. Similarly, fatigue crack growth, creep and stress corrosion cracking 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.

Fatigue crack growth	BS 6835.
Fatigue crack growth threshold	BS DD 186.
Fracture toughness	BS 7448.
Stress corrosion cracking	ISO 7539.

The information required 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, erection and testing. In some cases, it is necessary to 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 will be required:

- 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 *J* values 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;
- h) bulk corrosion and stress corrosion cracking (K_{ISCC}) data.

6.3 Non-destructive testing

6.3.1 Non-destructive testing (NDT) is an essential aspect of a fitness for purpose 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;
- e) whether the flaw cross-section is planar or non-planar.

6.3.2 For the detection of surface-breaking flaws the following methods (in no order of preference) are suitable:

- a) visual;
- b) liquid penetrant;
- c) magnetic particle (for ferromagnetic materials);
- d) eddy current (including a.c. field measurement [ACFM]). Note that there are difficulties in applying these methods to ferromagnetic materials because of variations in magnetic permeability. Only systems developed to overcome these problems can be used with any measure of success for such materials;
- e) electrical potential drop (a.c. or d.c.);
- f) radiography;
- g) ultrasonics.

All the above 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.

6.3.3 For the detection of embedded flaws the following methods (in no order of preference) are suitable:

- a) radiography;
- b) ultrasonics;
- c) eddy current (including ACFM). Note that the comments in **6.3.2d**) concerning the application of these techniques to ferromagnetic materials apply;
- d) electrical potential drop (d.c. only).

Of these, both radiography and ultrasonics are capable of providing a measurement of flaw length, but only ultrasonics can provide a measurement of flaw height. Eddy current, ACFM and potential drop methods will tend to provide a measurement of the cross-sectional area of the flaw. However, these latter techniques are only capable of detecting flaws that lie close to the scanned surface.

6.3.4 Non-destructive testing to an agreed extent (not necessarily 100 %) should be carried out in accordance with the appropriate standards from the following list.

- Ultrasonics BS EN 1712 and BS EN 1714.
- Radiography BS EN 1435 and BS EN 12517.
- Magnetic particle BS EN 1290 and BS EN 1291.
- Liquid penetrant BS EN 571-1 and BS EN 1289.

Any inspection procedure, adopted by agreement, 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.

Standard inspection techniques, which are suitable and economically viable for examining long lengths of weld, will not necessarily be 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 Where a region of a structure cannot be inspected, appropriate judgement should be made, based on flaw distributions in areas of the structure which could be inspected, to estimate the size of flaw that could potentially exist in the uninspectable region. 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

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 may be linearized, as shown in Figure 1. The latter method will normally provide overestimates but has the advantage that linearization does not need to be repeated with crack growth. It is essential that account is 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, since 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 (e.g. 8.2.1.4), steady state primary stresses and secondary stresses also need to be considered, in order to determine the actual values of the maximum and minimum applied stresses. It should be noted that the stress categories described below do not necessarily coincide with those used in other standards (e.g. BS 5500). In the fracture assessment routes described in clause 7, shear stresses are not included. If shear stresses are significant, reference should be made to annex A.

6.4.2 Primary stress (P)

These are stresses that could (if sufficiently high) contribute to plastic collapse, as distinct from secondary stresses, which do not (see 6.4.3). They can also contribute to failure by fracture, fatigue, creep or stress corrosion cracking. They include all stresses arising from internal pressure and external loads. Some stresses classified as secondary by ASME Section III [2] and BS 5500, annex A are regarded as primary in this guide, e.g. certain thermal and residual stresses (see 7.3.3). The primary stresses are divided into membrane, P_m , and bending, P_b , components as follows.

- a) *Membrane stress*, (P_m) is the mean stress through the section thickness that is necessary to ensure the equilibrium of the component or structure.
- b) *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 (but note that fluctuating thermal stresses are treated as primary in a fatigue assessment). A significant feature of secondary stresses is that they do not, of themselves, cause plastic collapse, since they arise from strain/displacement limited phenomena. They contribute to the severity of local conditions at a crack tip, however, and, when it is necessary to include them in an assessment, they have to be included in calculations of K_I , δ_I and ΔK_I . Note that the 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 7.3.3).

6.4.4 Stresses at structural discontinuities

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 secondary (see 7.3.3), are affected by structural discontinuities. There are three basic categories of such discontinuities:

- gross discontinuities;
- misalignment and deviation from intended shape;
- local discontinuities such as welds, holes, notches, etc.

These are described further in a), b) and c). Their effects are quantified by calculating peak stresses⁶⁾ at the discontinuities, as shown in a), b) and c). The bending component may be obtained by subtracting the membrane component from the peak stress.

- a) *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 peak stress at the discontinuity is calculated by multiplying the applied stress by the appropriate stress concentration factor. For nominal stress, membrane stress and bending stress, these are k_t , k_{tm} and k_{tb} , respectively.

⁶⁾ In PD 6493:1991 the concept of Peak Stress (F) was used, where the peak stress was the elevation in stress caused by the discontinuity. This followed the practice in the ASME pressure vessel codes. However, the terminology is misleading, since "peak stress" would normally be taken to imply the highest stress at the discontinuity. This is the meaning here.

Further guidance for tubular joints and for pressure vessel nozzles is given in annexes B and C respectively.

This type of stress concentration usually decays over distances greater than the section thickness, and may lead to a plastic hinge across the full section thickness over local regions.

b) *Discontinuities due to misalignment or deviation from intended shape.* These cause bending stresses. The additional bending stress is calculated by multiplying the applied membrane stress by a stress magnification factor k_m (see for example annex D).

This type of stress magnification also decays over distances greater than the section thickness and may 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 have to be considered and this is included in the relevant formulae (7.2.3 and 7.3.5.1).

c) *Local structural discontinuities, such as holes, notches or sharp corners.* The stress concentration due to this type of discontinuity usually decays 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 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 (see M.5).

For sharp corners, the theoretical stress concentration factor is infinite, and it is preferable that cracks at such regions be treated by a stress intensity magnification factor (see 7.2.5 and 7.3.5.1). Local structural discontinuities may 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.

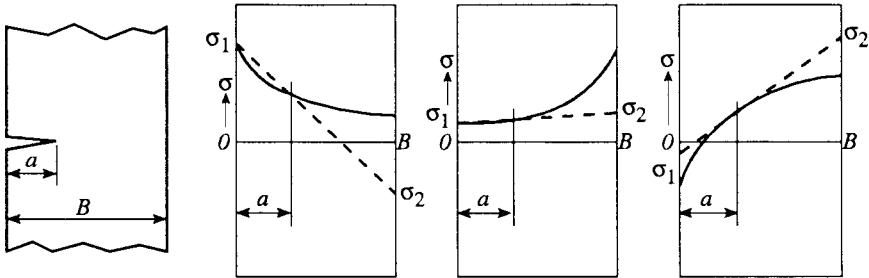
Different methods of incorporating peak stresses are used in various different assessment methods within this document, as detailed in 7.1.6, 7.2.3 and clauses 8 and 9.

6.4.5 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 be included in the assessment.

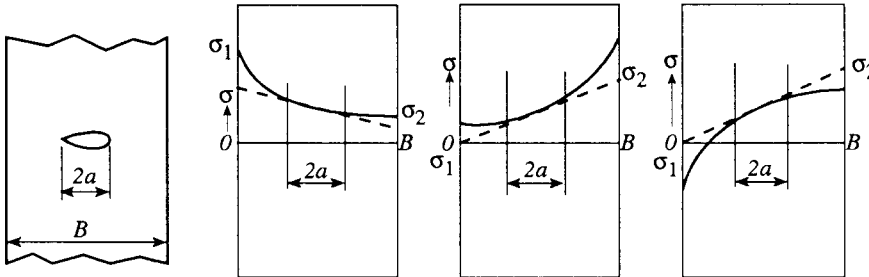
Where the plane of the flaw is not aligned with a plane of principal stress, further consideration is needed. The first step is to project the flaw on to each of the three planes normal to the principal stresses and to evaluate each of the three projected flaws. Often, one of these projections will lead to a stress intensity factor and a reference stress that are both significantly higher than those for the other two projections. The assessment is then carried out, taking a and $2c$ as the projected dimensions on that plane. This for example is the method often applicable to near circumferential flaws in the wall of a pipe, where the flaw is projected on to the circumferential plane (see Figure 3). There are however, restrictions on proceeding in this way. Specialist advice should be sought when the following situations arise.

- a) 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.
- b) There is only a small difference between the stress intensity factors on two or more planes of projection.
- c) 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.
- d) 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 may be present. Annex A provides guidance on the treatment of these modes of loading.



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

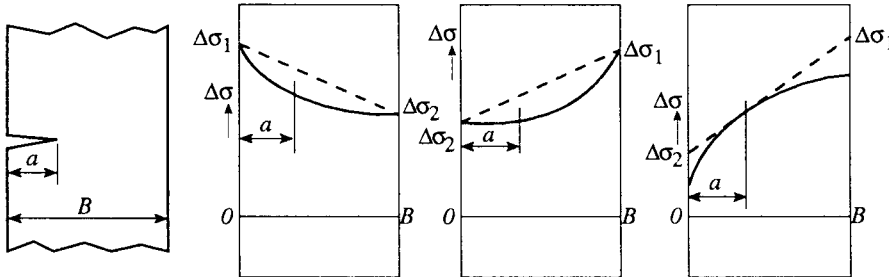


Examples of linearization of primary or secondary stress distributions for embedded flaws

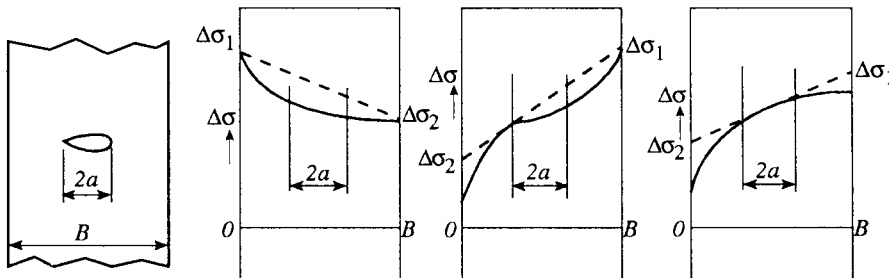
$$P_m, Q_m = \frac{\sigma_1 + \sigma_2}{2} \quad P_b, Q_b = \frac{\sigma_1 - \sigma_2}{2}$$

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

(a) Linearization of stress distributions in fracture assessment



Examples of linearization of stress range distributions for surface flaws

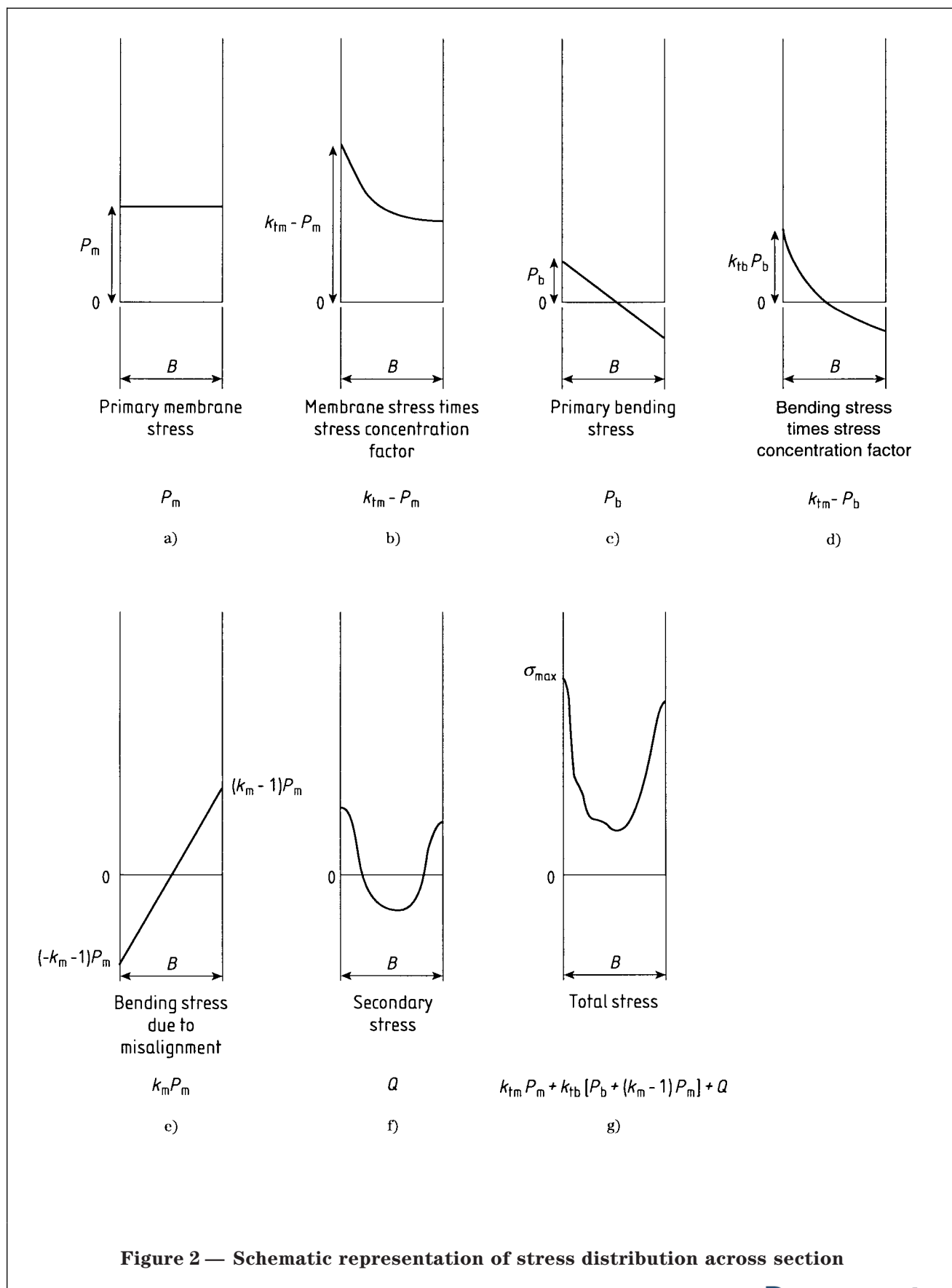


Examples of linearization of stress range distributions for embedded flaws

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

(b) Linearization of stress range distributions in fatigue assessments

Figure 1 — Linearization of stress distributions



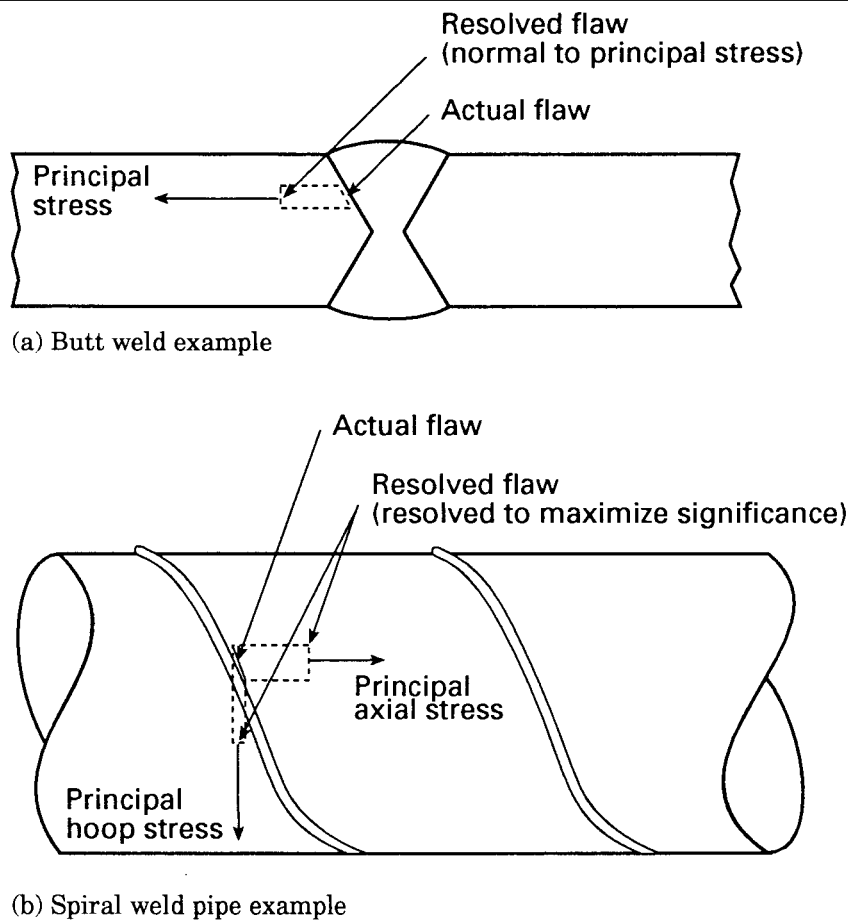


Figure 3 — Procedure for resolving flaws normal to principal stress

7 Assessment for fracture resistance

7.1 Background

7.1.1 General

There are three levels of fracture assessment in this guide, but similar methods are used in each. The choice of level depends on the materials involved, the input data available and the conservatism required. The three levels are as follows.

- Level 1 is a simplified assessment method applicable when the information on materials properties is limited.
- Level 2 is the normal assessment route.
- Level 3 is appropriate for ductile materials and enables a tearing resistance analysis to be performed.

Levels 1, 2 and 3 are described in 7.2, 7.3 and 7.4 respectively.

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 is a ratio of the applied conditions, in fracture mechanics terms, to the conditions required to cause fracture, measured in the same terms. The horizontal axis is the ratio of the applied load to that required to cause plastic collapse. An assessment line is plotted on the diagram. Calculations for a flaw provide either the co-ordinates of an assessment point or 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 procedures is shown in Figure 4 and detailed flow diagrams of each level are given in Figures 5 to 7.

It is possible that acceptability can still be demonstrated, even if an initial assessment shows a flaw to be unacceptable. This may require improving the quality of the input data and/or applying a higher assessment level, if appropriate. This is discussed in 7.5.1 and 7.5.2.

In some cases surface-breaking or embedded flaws may initially be found to be unacceptable because of plastic instability of the remaining ligament [$S_r > 0.8$ (Level 1) or $L_r > L_{r\max}$ (Levels 2 or 3)].

However, in some circumstances this prediction of ligament failure may not be critical. The flaw may be re-characterized as a through-thickness or surface-breaking flaw, and reassessed. The procedure for flaw re-characterization is given in annex E.

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

At each level, either the acceptability of a flaw may be assessed directly or the calculation may be iterated in order to determine the limiting value of a parameter such as flaw size, applied stress or fracture toughness. The limiting value may be obtained analytically or alternatively, by plotting on the FAD the results from the iterations in order to determine the point at which first contact is made with the assessment line.

The material properties required for an assessment are those for the region in which the flaw is present, i.e. parent metal, weld metal or heat affected zone (HAZ).

All FAD assessments relate to planar flaws. Guidance on the assessment of other flaw types is given in 7.5.3. Locally thinned areas may be assessed solely against plastic collapse. Methods of assessing such areas are given in annex G.

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

Annex B provides guidance on specific aspects of the assessment of offshore structures. Annex C applies similarly to pressure vessels and pipelines. Annex H gives requirements when reporting an assessment.

7.1.2 Flaw dimensions and interaction

7.1.2.1 Planar flaws should be characterized by the height and length of their containment rectangles. These dimensions [see Figure 8a), b) and c)] are as follows: $2a$ for through-thickness flaws; a and $2c$ for surface flaws; and $2a$ and $2c$ for embedded flaws.

7.1.2.2 Multiple flaws on the same cross-section may lead to an interaction and to more severe effects than single flaws alone. Simple criteria for interaction are given in Figure 9, together with the dimensions of the effective flaws after interaction. If multiple flaws exist, each flaw should be checked for interaction with each of its neighbours using the original flaw dimensions in each case. It is not normally necessary to consider further interaction of effective flaws.

7.1.3 Tensile test properties

7.1.3.1 The material yield strength, σ_Y , tensile strength, σ_u , and modulus of elasticity, E , are required from tests in accordance with BS EN 10002-1 or BS 3688-1 at the appropriate temperature. The yield strength should be taken as either the lower yield or the 0.2 % proof strength depending on the material type. HAZs should be assumed to have tensile properties that are the lower of adjacent parent metal or weld metal properties.

7.1.3.2 Where parent and weld yield strengths are subject to mismatch (see annex I) of more than 25 %, special consideration should be given to the fracture toughness data being used. Annex I gives additional requirements for HAZs and discusses the effect of mismatch on flaw assessment.

7.1.4 Stress intensity factor (K) and CTOD (δ) assessment routes

7.1.4.1 Two routes are given in each method to determine the tendency to fracture. They appear as the ordinate on the FAD and are based either on the stress intensity factor, K , or on the crack tip opening displacement (CTOD), δ . (They appear as K_r , the fracture ratio based on K , and as $\sqrt{\delta_r}$, the square root of the fracture ratio based on CTOD.) The use of the square root of δ_r enables both K_r and δ_r to be plotted on the same axis.

In any assessment, it is essential that one route is used consistently throughout.

7.1.4.2 The K route should be followed if K_{mat} is determined from one of the following:

- measured linear-elastic plane strain fracture toughness K_{Ic} ; or
- correlations from Charpy V-notch impact test data (see annex J); or
- conversion from J (see 7.1.5.3) using the following equation:

$$K_{\text{mat}}^2 = \frac{EJ_{\text{mat}}}{1 - \nu^2} \quad (1)$$

7.1.4.3 If valid K_{Ic} data are not obtained, CTOD test data and the CTOD assessment route should be used, or equivalent K_{mat} values should be derived from J -based tests.

It is not intended that CTOD toughness data should be transformed to equivalent K data.

Because of the uncertainties in the effects of crack tip constraint, differences may occur in results of assessments using K -based or CTOD-based data from the same source. However, identical results will be achieved if equation (21) is used (see 7.3.6.1).

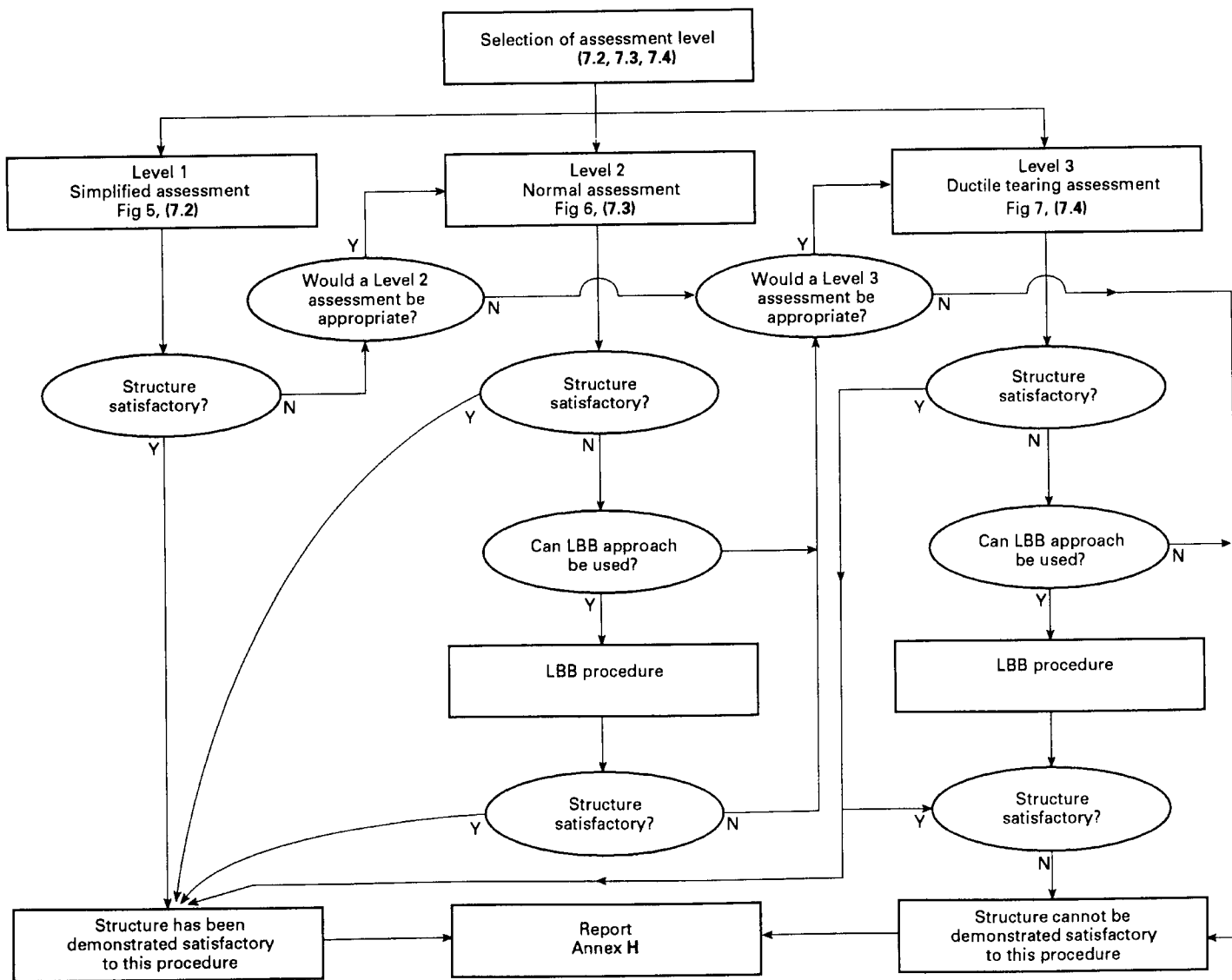


Figure 4 — Flow chart — General methods

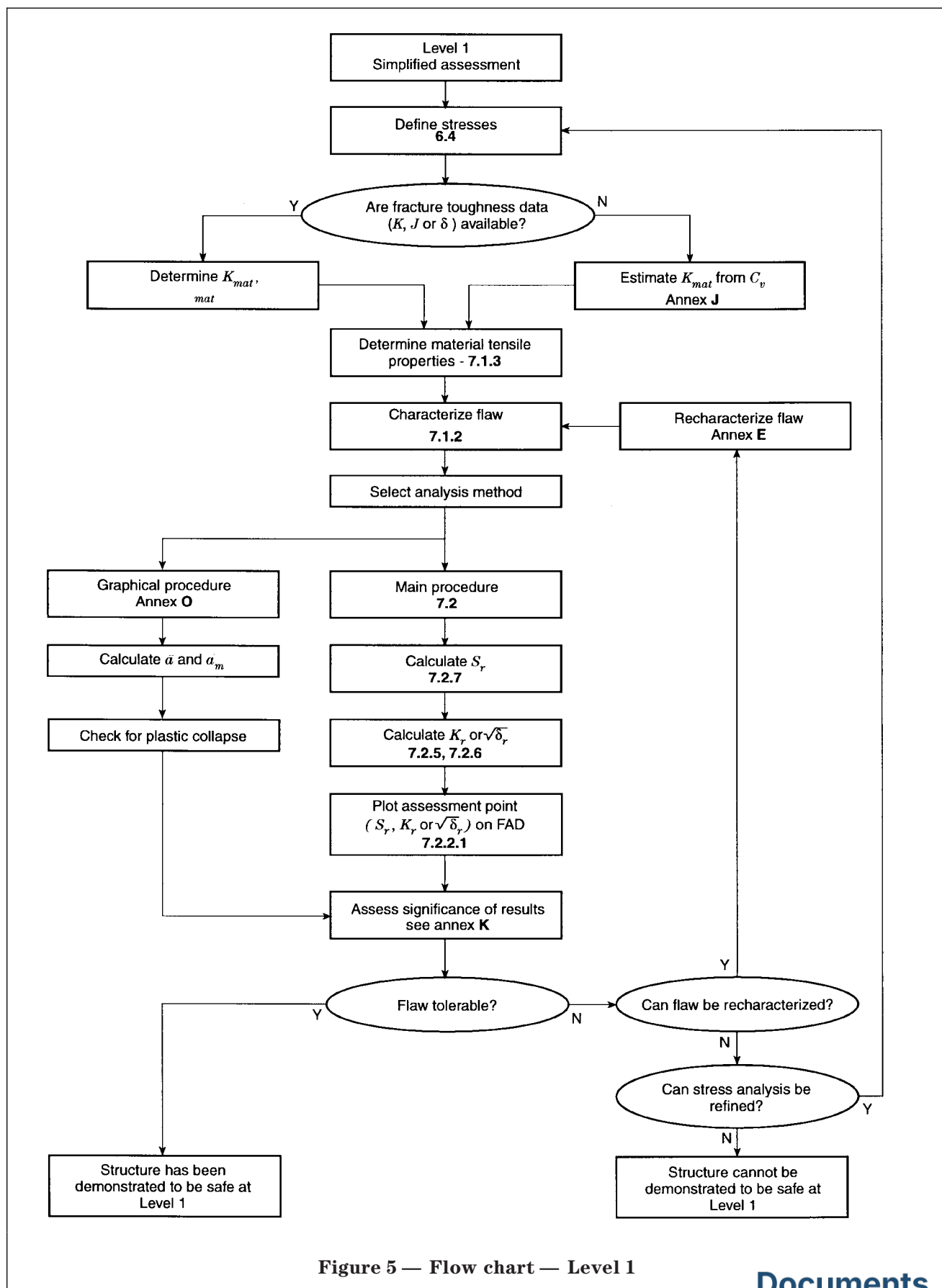


Figure 5 — Flow chart — Level 1

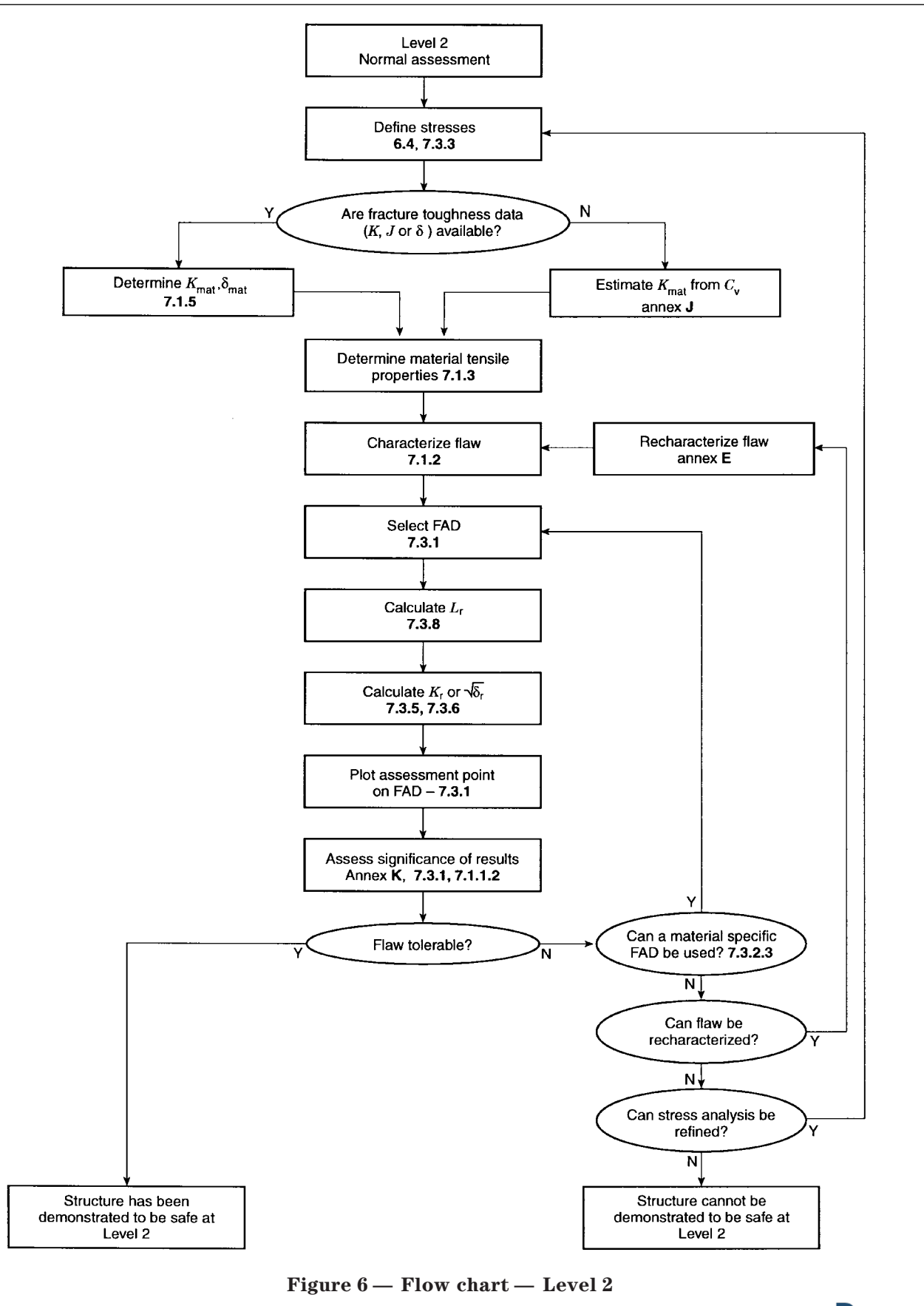


Figure 6 — Flow chart — Level 2

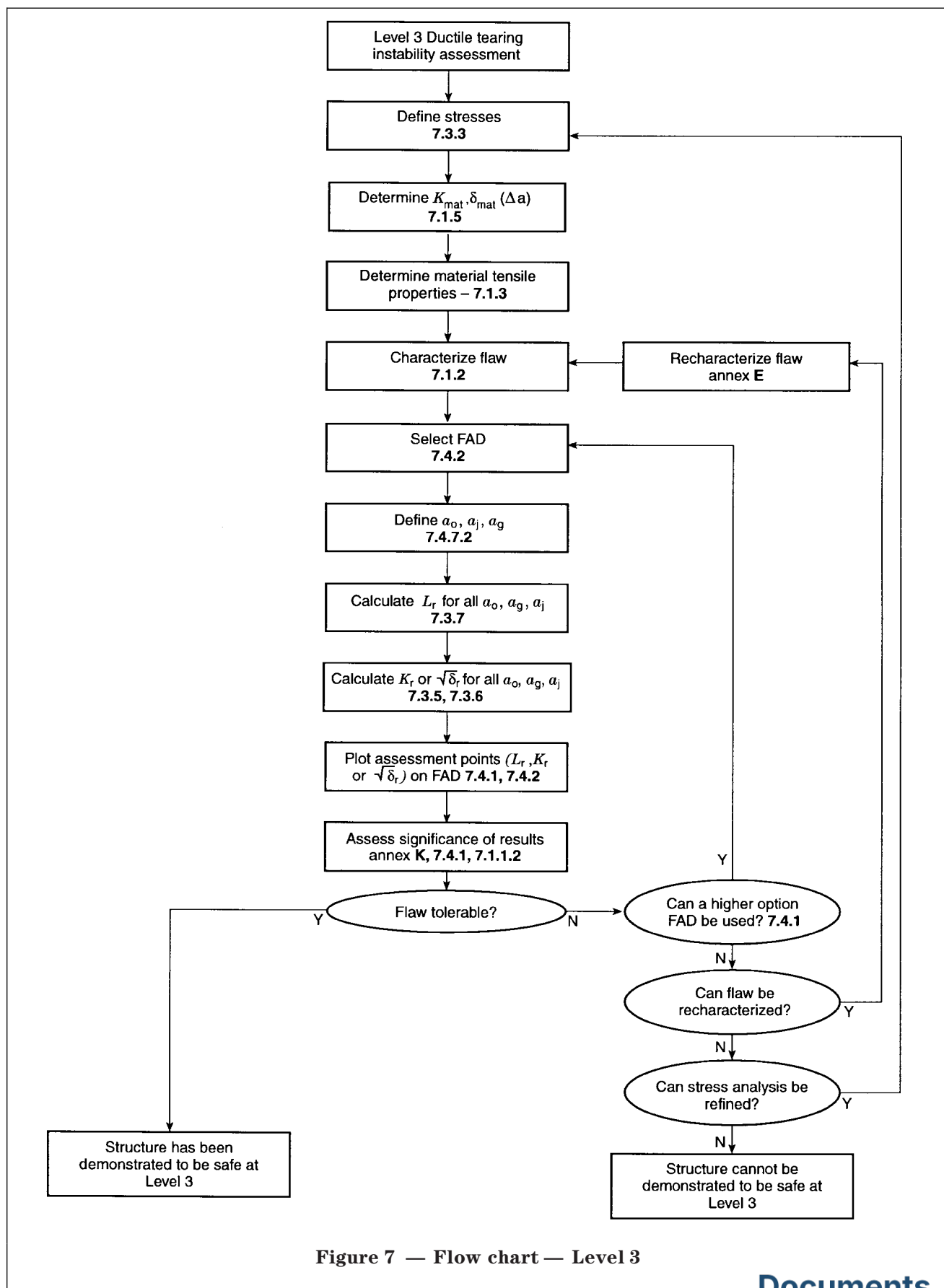
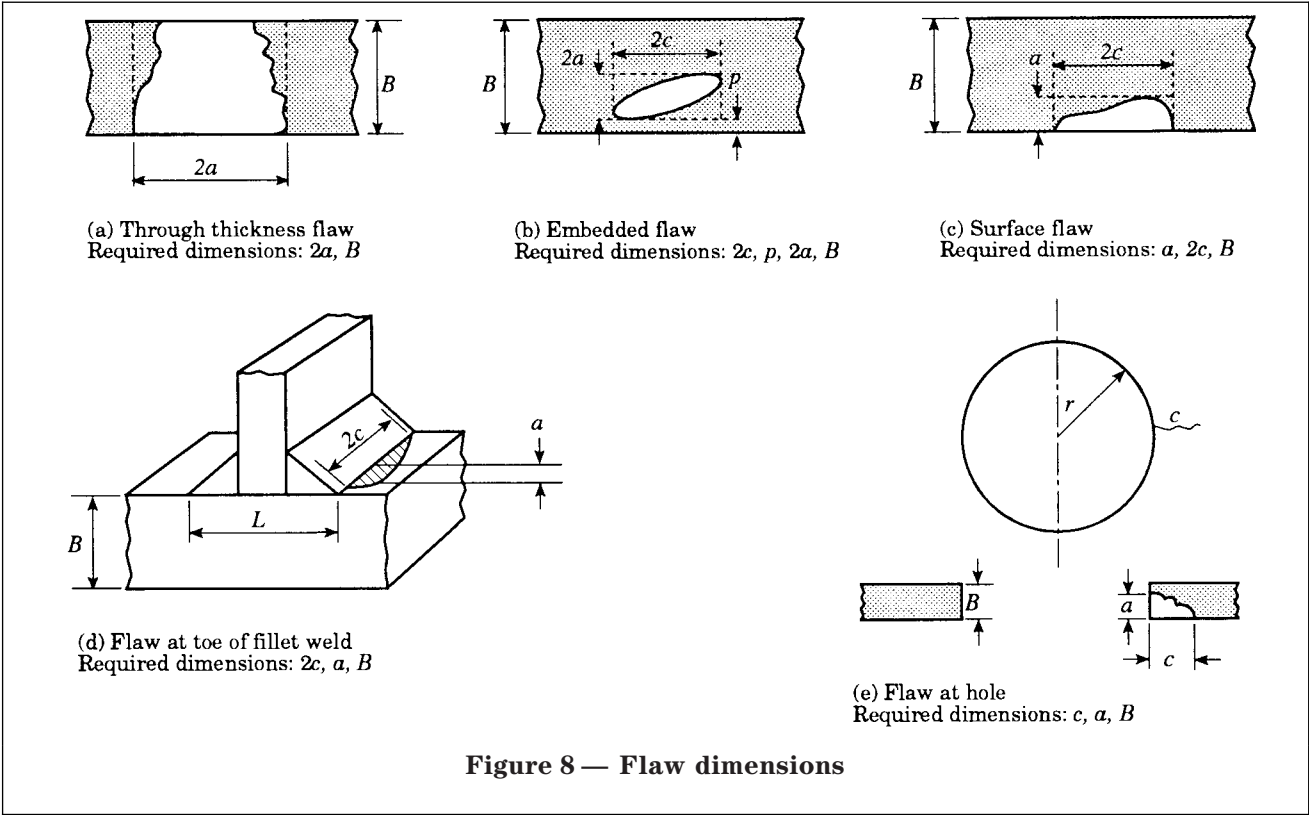
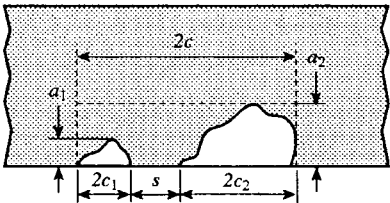
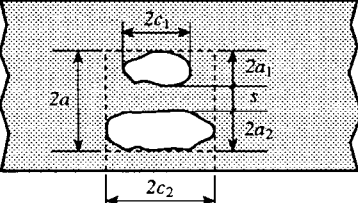
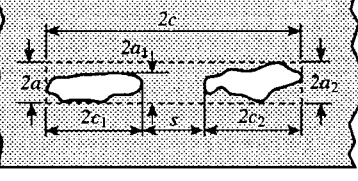
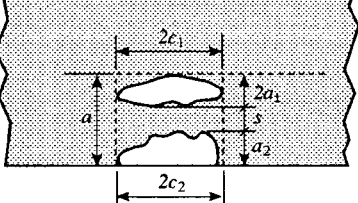
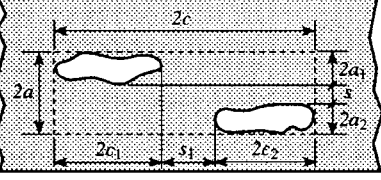
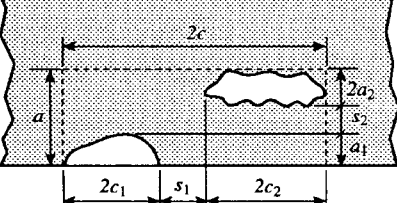


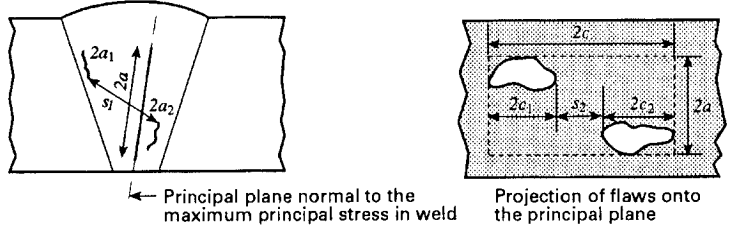
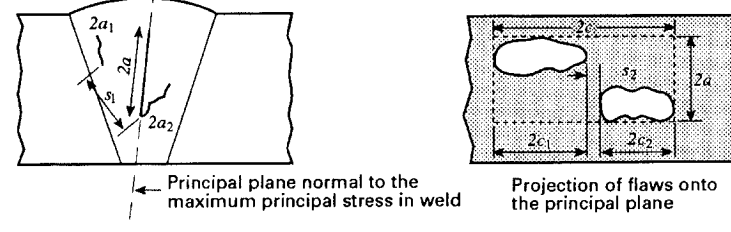
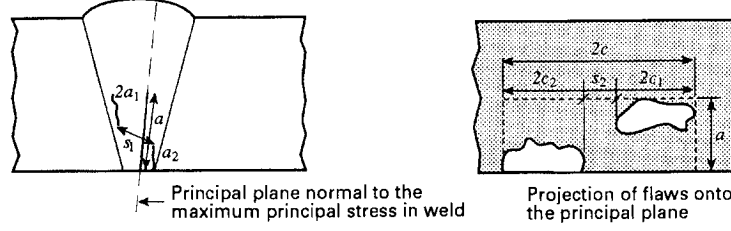
Figure 7 — Flow chart — Level 3



Schematic flaws	Criteria for interaction	Effective dimensions after interaction
1 Coplanar surface flaws 	$s \leq 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s = 0$ for a_1/c_1 and $a_2/c_2 < 1$ $(c_1 < c_2)$	$a = a_2$ $2c = 2c_1 + 2c_2 + s$
2 Coplanar embedded flaws 	$s \leq a_1 + a_2$	$2a = 2a_1 + 2a_2 + s$ $2c = 2c_2$
3 Coplanar embedded flaws 	$s \leq 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s = 0$ for a_1/c_1 and $a_2/c_2 < 1$ $(c_1 < c_2)$	$2a = 2a_2$ $2c = 2c_1 + 2c_2 + s$
4 Coplanar surface and embedded flaws 	$s \leq a_1 + a_2$	$a = 2a_1 + a_2 + s$ $2c = 2c_1$
5 Coplanar embedded flaws 	$s \leq 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s_1 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ and $s_2 \leq a_1 + a_2$ $(c_1 < c_2)$	$2a = 2a_1 + 2a_2 + s_2$ $2c = 2c_1 + 2c_2 + s_1$
6 Coplanar surface and embedded flaws 	$s_1 < 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s_1 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ and $s_2 < a_1 + a_2$ $(c_1 < c_2)$	$a = a_1 + 2a_2 + s_2$ $2c = 2c_1 + 2c_2 + s_1$

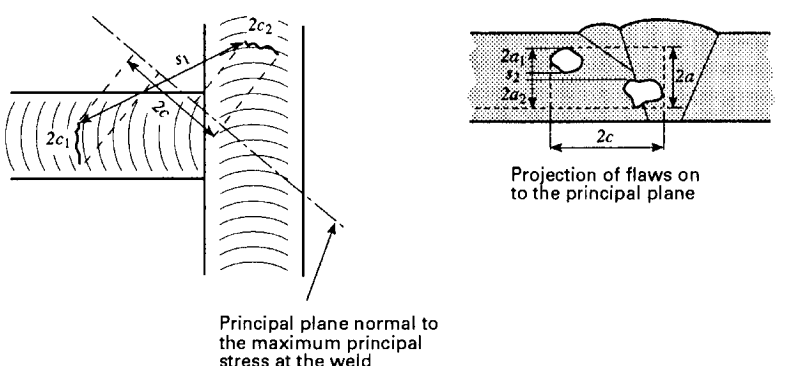
(a) Coplanar

Figure 9 — Planar flaw interactions

Schematic flaws	Criterion for interaction	Effective dimensions after interaction
1 Adjacent non-coplanar embedded flaws  Principal plane normal to the maximum principal stress in weld Projection of flaws onto the principal plane	$s_1 \leq a_1 + a_2$ and $s_2 \leq 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s_2 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ where $c_1 < c_2$ ($2c_1$ and $2c_2$ are projected lengths)	$2a$ is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld $2c = 2c_1 + 2c_2 + s_2$
2 Adjacent non-coplanar embedded flaws  Principal plane normal to the maximum principal stress in weld Projection of flaws onto the principal plane	$s_1 \leq a_1 + a_2$ and $s_2 \leq 2c$, for a_1/c_1 or $a_2/c_2 > 1$ $s_2 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ where $c_1 < c_2$ ($2c_1$ and $2c_2$ are projected lengths)	$2a$ is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld $2c = 2c_1 + 2c_2 + s_2$
3 Adjacent non-coplanar surface and embedded flaws  Principal plane normal to the maximum principal stress in weld Projection of flaws onto the principal plane	$s_1 \leq a_1 + a_2$ and $s_2 \leq 2c_1$ for a_1/c_1 or $a_2/c_2 > 1$ $s_2 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ where $c_1 < c_2$ ($2c_1$ and $2c_2$ are projected lengths)	a is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld $2c = 2c_1 + 2c_2 + s_2$

(b) Non-coplanar

Figure 9 — Planar flaw interactions (continued)

Schematic flaws	Criterion for interaction	Effective dimensions after interaction
4 Adjacent non-coplanar flaws in intersecting welds  Principal plane normal to the maximum principal stress at the weld Projection of flaws on to the principal plane	$s_1 \leq 2c_1$, for a_1/c_1 or $a_2/c_2 > 1$ $s_1 = 0$ for a_1/c_1 and $a_2/c_2 < 1$ and $s_2 \leq a_1 + a_2$ where $c_1 < c_2$ ($2a_1$ and $2a_2$ are projected heights)	$2a = 2a_1 + 2a_2 + s_2$ $2c$ is the minimum length of containment rectangle constructed on the plane normal to the maximum principal stress in the weld

(c) Non-coplanar

Figure 9 — Planar flaw interactions (*continued*)

7.1.5 Fracture toughness

7.1.5.1 K_{IC} should be established following the methods specified in BS 7448. If a valid K_{IC} is available, K_{mat} should be taken as K_{IC} . Tests should be carried out on full thickness specimens.

7.1.5.2 CTOD values, δ , should be established following the methods specified in BS 7448. Tests should be carried out on full thickness, rectangular ($W = 2B$) specimens wherever possible. However, where assessments involve certain types of flaw and flaw orientation (e.g. shallow surface flaws or HAZ regions), specimens of square section or of an alternative width to thickness ratio, as specified in BS 7448-1 and -2, may be appropriate.

7.1.5.3 J -based methods of fracture toughness testing may be used in accordance with BS 7448. Full thickness tests should be employed. For J tests on welded joints, it is essential that the measurement of J takes account of differences in properties between weld and parent material and also of the deformation pattern that actually occurs.

7.1.5.4 In this guide, the critical δ or J value from a test in accordance with BS 7448 is termed δ_{mat} or J_{mat} respectively. It should be taken as the lowest of δ_c , δ_w or δ_m , or J_c , J_u or J_m respectively; or, where no significant tearing is permitted, as $\delta_{0.2BL}$ or $J_{0.2BL}$ respectively.

For Levels 1 and 2 assessment procedures, stable tearing using full thickness laboratory test pieces in accordance with BS 7448 may be accepted up to δ_m or J_m respectively.

For a tearing analysis at Level 3, a full tearing resistance curve derived from either δ or J measurements is necessary.

At all levels, equivalence between CTOD and J or K procedures can be achieved by using a constraint factor, X , as described in 7.3.6.1.

7.1.5.5 At Levels 1 and 2, the fracture toughness value, K_{mat} or δ_{mat} , may be taken as the minimum of three similar test results, either all showing brittle fracture, or all showing tearing up to maximum load. For δ_{mat} , caution should be exercised when the minimum CTOD result is less than 50 % of the average of three, or when the maximum is more than twice the average of three. Similarly, for K_{mat} , caution should be exercised when the minimum result is less than 70 % of the average of three, or when the maximum is more than 1.4 times the average of three. Such variations of the minimum or maximum from the average indicate excessive scatter and the need for more data.

When the scatter is large, and for Levels 2 and 3 assessments, it is recommended that additional tests be made. Guidance on the value to be used in the assessment, when more than three tests are conducted, is given in K.2.3.2. Annex K also gives guidance on statistical treatments. Particular attention is drawn to the importance of ensuring that sets of HAZ specimens have the crack tip in similar microstructures when carrying out statistical analyses (see BS 7448-2).

When statistical analyses of sets of fracture toughness data are carried out (see annex K) it is important that the analyses acknowledge possible differences in fracture mechanisms and materials.

With fracture toughness tests on HAZ regions, considerable variability can occur due to location of the crack tip in different micro-structural regions. It is sometimes necessary to carry out sectioning of specimens for tests on HAZ regions after testing to determine the precise location of the crack tip. Results analysed as a set should include only data from tests in which the crack tip was located in microstructure of similar type and grain size (see annex L).

7.1.5.6 Fracture toughness tests should take account of the orientation of flaws in the structure relative to welded joints, and of the constraint, temperature, rate of loading and environment (particularly for materials exposed to hydrogen) experienced in service. The tests should be carried out on samples welded with the same consumables and procedures as were or are to be used for the service application and should take account of restraint during welding and of PWHT, if applicable.

7.1.5.7 Test results in which “pop-in” behaviour is observed should be analysed using the procedures in BS 7448. It should be noted that, although an individual “pop-in” may be ignored on the basis of the criteria described in BS 7448, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weldment, a small “pop-in” may be recorded because of fortuitous positioning of the fatigue crack tip. Thus, a slightly different fatigue crack tip position may give a larger “pop-in”, which could not be ignored. In such circumstances, the specimens should be sectioned after testing and examined to ensure that the crack tips have sampled the maximum amount of brittle micro-structure in the weld or parent metal region of interest (see BS 7448-2).

7.1.5.8 Standard testing methods (e.g. BS 7448) used to derive fracture toughness data are necessarily conservative and represent high constraint applications. In specialized circumstances, full scale or model tests (e.g. wide plate tests, pressure vessel tests and tests on specimen geometries modelling structural constraint and/or containing shallow cracks) may be adopted to give more appropriate values of the data to be used in the fracture assessments.

7.1.6 Stresses

The direct stress components perpendicular to the plane of the flaw should be used in an assessment, but, when the flaw is not aligned with the direction of the principal stress, the procedures described in 6.4.5 should be followed.

The magnitude of the stresses shall be obtained in accordance with 6.4.1.



7.1.7 Large flaws

Special provision should be made when the flaw area is greater than 10 % of the load bearing cross-sectional area and no finite width correction has already been included (see annex M).

7.1.8 S_r and L_r

The parameter for plastic collapse appears as the abscissa on the FAD. In Level 1, it is S_r and is the reference stress divided by the flow strength (see 7.2.7). In Levels 2 and 3, it is L_r and is the reference stress divided by yield strength (see 7.3.7). The reason for the difference is that the assessment line for Level 1 is based on the assumption of an elastic-perfectly plastic stress-strain curve with no strain hardening. This is conservative and to compensate for this conservatism, it is permissible to use in the denominator of S_r the flow strength rather than the yield strength. Levels 2 and 3 allow more accurately for the actual shape of the material stress-strain curve and so no such concession can be made.

7.1.9 Peak stress at weld toe

There is no simple upper bound limit for the peak stress at a shallow surface flaw ($a/B < 0.2$) located within the stress concentration zone at the toe of a weld. Thus, such flaws are most accurately assessed at Level 2 or 3. However, Level 1 assessments can be performed for surface flaws at the toes of fillet or butt welds (see Figure 8) where the stress concentration factor k_t is taken as 3 at the weld toe decreasing linearly to 1.0 as a increases from 0 to $0.15B$ ⁷⁾. If a is greater than $0.15B$ then $k_t = 1$.

Flaws at the toe of a fillet or T butt weld, which is itself in a geometric stress concentration (e.g. a nozzle/pad combination), should be considered to lie in the combined geometric and fillet weld stress concentration fields for a depth up to $0.15B$.

7.1.10 Sensitivity analysis

If the result is marginal, an analysis to determine the sensitivity of the results should be performed. This will reveal the main factors determining fracture risk. Guidance is given in annex K.

7.2 Level 1 — Simplified assessment

7.2.1 Main features

This is a simplified assessment route applicable where there is limited information on material properties or applied stresses. It contains two methods, Levels 1A and 1B. Conservative estimates of applied stress, residual stress and fracture toughness are employed. Additional partial safety factors are not used.

7.2.2 Assessment methods

7.2.2.1 Level 1A: general

The FAD is shown in Figure 10. The area bounded by the axes and by the assessment line is a rectangle. The flaw is acceptable if K_r or $\sqrt{\delta_r}$ is less than $1/\sqrt{2}$ (i.e. 0.707) and S_r is less than 0.8. The FAD contains an in-built safety factor (which approximates to a factor of 2 on flaw size).

A single FAD is used. If the assessment point lies in the area within the assessment line, the flaw is acceptable; if it lies on or outside the line, the flaw is not acceptable.

Where a measured fracture toughness (as given by K_{mat} or δ_{mat}) is not available, an estimate of K_{mat} may be used, based on Charpy V-notch energy (see annex J).

Values of K_{mat} derived from J or from “invalid” K tests may have to be adjusted to take account of the different constraint conditions in the test piece compared with those of plane strain (see 7.1.5.4 and 7.3.6.1).

Relaxation of the FAD for strain controlled loading is described in 7.2.8.

7.2.2.2 Level 1B: manual estimation

A manual estimation method, which does not involve a FAD, is given in annex N.

7.2.3 Maximum stress

The stress used is the maximum tensile stress, σ_{max} , which is taken to be equal to the sum of the values of the stress components. If only nominal membrane stresses, S_{nom} , are known, $\sigma_{max} = k_t S_{nom} + (k_m - 1) S_{nom} + Q$. If membrane and bending components are known, $\sigma_{max} = k_{tm} P_m + k_{tb} [P_b + (k_m - 1) P_m] + Q$ (see Figure 2). The variation in the stress components across the section is not taken into account and this leads to a conservative estimate of the total applied stress. Annex A should be used if shear stresses are significant.

7.2.4 Residual stress

7.2.4.1 In a structure in the as-welded condition, with a flaw lying in a plane transverse to the welding direction, (i.e. the stresses to be considered are parallel to the weld) the tensile residual stress should be assumed to be a uniform membrane stress contributing to Q_m . This stress should be assumed to be equal to the room temperature yield strength of the material in which the flaw is located.

For a flaw lying in a plane parallel to the welding direction (i.e. the stresses to be considered are perpendicular to the weld), the residual stress should be assumed to be equal to the lesser of the room temperature yield strengths of the weld or parent metal.

⁷⁾ The stress concentration factor, k_t , used at Level 1, is equivalent to the factor M_k , used at Levels 2 and 3.

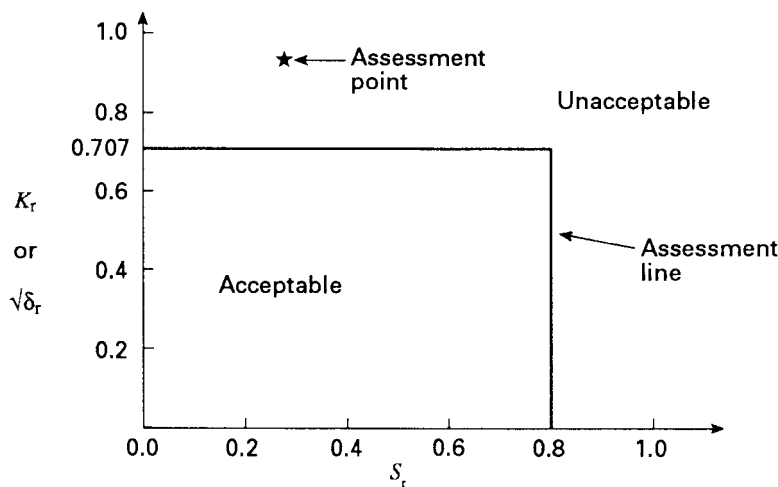


Figure 10 — Level 1A FAD

7.2.4.2 In a structure subject to PWHT, the residual stresses will not in general be reduced to zero. The level of residual stress remaining in welds after PWHT may be estimated on the basis of stress relaxation tests for all-weld or parent metal specimens, as appropriate. Where these data are not available, it may be assumed, in carbon manganese and low alloy steels, that the stresses after heat treatment in an enclosed furnace within the range 580 °C to 620 °C (in accordance with procedures such as those of BS 5500) are as follows:

- parallel to the weld, the residual stress (Q_m) should be assumed to be equal to 30 % of the room temperature yield strength of the material in which the flaw is located;
- transverse to the weld, the residual stress (Q_m) should be assumed to be 20 % of the lesser of the yield strengths of the weld or parent material.

7.2.4.3 Uncontrolled local heat treatment may leave significantly higher residual stresses and as-welded values should be assumed.

Increased levels of residual stresses may be experienced with local heat treatments to code requirements (e.g. BS 5500) and specific assessments should be made.

7.2.4.4 Advantage may be taken of the reduction in residual stresses due to the application of an initial pressure test or other forms of mechanical pre-loading, for structures of satisfactory design and construction (see annex O). No advantage can be taken if the stress distribution can reverse in sign compared to the pre-load.

It is not, in general, permissible to assume that the level of residual stresses to be used in a flaw assessment will be reduced by the application of a vibratory “stress relief” treatment.

If an assessment is carried out on a structure that received a proof test prior to entering service, but which has subsequently experienced an extensive period of operation, the potential benefits of the proof test may be reduced by the occurrence of in-service crack growth or the effects of embrittlement.

7.2.5 Fracture ratio (K_I)

The applied stress intensity factor, K_I , has the following general form:

$$K_I = (Y\sigma)\sqrt{(\pi a)} \quad (2)$$

where

$$Y\sigma = Mf_w M_m \sigma_{\max} \quad (3)^8$$

and where

M and f_w are bulging correction and finite width correction factors respectively;

$\sigma_{\max}$ is the maximum tensile stress (see 7.2.3);

M_m is a stress intensity magnification factor.

Specific solutions for various geometries are given in annex M, including flat plates, curved shells, welded joints and round bars.

K_r is the ratio of the stress intensity factor, K_I , to the fracture toughness K_{mat} i.e.:

$$K_r = \frac{K_I}{K_{mat}} \quad (4)$$

⁸⁾ The equations in this document differ in appearance from those to be found, for example, in the publications of Newman and Raju and in the original BS PD 6493. For surface, embedded and corner flaws, M_m and M_b have been modified here by dividing by the complete integral, Φ . By making this change, it has been possible to write one set of equations that apply to all geometries.

7.2.6 Fracture ratio (δ_r)

The applied CTOD, δ_I , is determined from K_I as follows:

- a) for steels (including stainless steels) and aluminium alloys where $\sigma_{\max}/\sigma_Y \leq 0.5$, and for all $\sigma_{\max}/\sigma_Y$ ratios with other materials:

$$\delta_I = \frac{K_I^2}{\sigma_Y E} \quad (5)$$

- b) for steels (including stainless steels) and aluminium alloys where $\sigma_{\max}/\sigma_Y > 0.5$:

$$\delta_I = \frac{K_I^2}{\sigma_Y E} \left(\frac{\sigma_Y}{\sigma_{\max}} \right)^2 \left(\frac{\sigma_{\max}}{\sigma_Y} - 0.25 \right) \quad (6)$$

and where

δ_r is the ratio of δ_I to the fracture toughness, δ_{mat} ; and

the square root of δ_r is calculated from the following equation:

$$\sqrt{\delta_r} = \sqrt{\delta_I / \delta_{mat}} \quad (7)$$

7.2.7 Load ratio (S_r)

The load ratio, S_r , is calculated from the following equation:

$$S_r = \frac{\sigma_{ref}}{\sigma_f} \quad (8)$$

where

σ_{ref} is obtained from an appropriate reference stress solution given in annex P.

The flow strength, σ_f , should be assumed to be the arithmetic mean of the yield strength and the tensile strength up to a maximum of $1.2\sigma_Y$.

7.2.8 Strain-controlled loading

In cases where the loading conditions are strain-controlled or where there is contained plastic deformation, the stress-based plastic collapse solutions in annex P may be unnecessarily restrictive.

Where this is judged to apply, and hence where there is no risk of structural plastic collapse, the restriction on the load ratio ($S_r \leq 0.8$) can be ignored and the FAD (see Figure 10) can be extended, provided that the following conditions apply.

$P_m + P_b \leq \sigma_Y$ or $S_{nom} \leq \sigma_Y$; and

$k_{tm}P_m + k_{tb}P_b \leq 2\sigma_Y$ or $k_t S_{nom} \leq 2\sigma_Y$.

Alternatively, if the same strain-controlled conditions apply and the strain local to the crack tip is known or can be estimated, the strain ratio ($\epsilon_{\max}/\epsilon_Y$) can be used in place of the stress ratio, ($\sigma_{\max}/\sigma_Y$), in equation (6) to determine δ_I . From δ_I , the ratio $\sqrt{\delta_r}$ can be calculated. Assessments can then be performed to Level 1A, using the strain-based $\sqrt{\delta_r}$ ratio. Once again, the S_r requirement is ignored. These calculations can also be performed to Level 1B, applying the procedures of annex N to assess a known flaw or to calculate the tolerable flaw size, $\bar{a}_m$, using the strain ratio ($\epsilon_{\max}/\epsilon_Y$) in equations (N.2) and (N.3).

For high strain ratios (i.e. $\epsilon_{\max}/\epsilon_Y > 4$) an elastic-plastic stress analysis is recommended. One method of estimating plastic strains at strain concentration regions is to use the Neuber hypothesis that the product of plastic stress and strain concentration factors is equal to the square of the elastic stress concentration factor. Alternatively, Level 2 or 3 assessment procedures for global collapse may be considered (see annex P).

7.3 Level 2 — Normal assessment

7.3.1 Main features

This is the normal assessment route for general application. It has two methods.

Each method has an assessment line given by the equation of a curve and a cut-off. If the assessment point lies within the area bounded by the axes and the assessment line, the flaw is acceptable; if it lies on or outside the line, the flaw is unacceptable.

The cut-off is to prevent localized plastic collapse and it is set at the point at which $L_r = L_{rmax}$ where:

$$L_{rmax} = (\sigma_Y + \sigma_u)/(2\sigma_Y) \quad (9)$$

For the purposes of defining the cut-off, mean rather than minimum properties may be used.

No inherent safety factors are included. To obtain the required reliability, appropriate partial safety factors (see annex K) may be applied to the flaw dimensions, stresses, yield strength and fracture toughness. For the flaw dimensions, either the size of the individual flaws (see Figure 8) or the effective dimensions after interaction (see Figure 9) should be multiplied by the partial safety factor. Stresses are similarly multiplied (by the appropriate partial safety factor), but fracture toughness and yield strength are divided.

Assessments are based on a single value of toughness. This may be a value associated with limited ductile tearing, but, for a full analysis of ductile tearing, a Level 3 approach is required.

The assessment may be carried out with estimates of either K_{mat} or δ_{mat} . Where a correlation from Charpy V-notch energy results is used (see annex J), it should be validated for specific applications by reference to published results or databases for the appropriate type of material.

Margins of safety can be assessed using reserve factors and probabilistic approaches as described in annex K.

7.3.2 FADs

7.3.2.1 Level 2A: generalized FAD, not requiring stress/strain data

The equations describing the assessment line are the following:

$$\sqrt{\delta_r} \text{ or } K_r = (1 - 0.14L_r^2)(0.3 + 0.7\exp(-0.65L_r^6)) \quad (10)$$

for $L_r \leq L_{r\max}$; and

$$\sqrt{\delta_r} \text{ or } K_r = 0 \quad (11)$$

for $L_r > L_{r\max}$.

The FAD is shown in Figure 11a) with different cut-offs for different materials.

For materials which exhibit a yield discontinuity (often referred to as a Lüders plateau) in the stress/strain curve (i.e. any curve which is not monotonically increasing), or for which it cannot be assumed with confidence that no discontinuities exist, either a cut-off value for L_r of 1.0 should be applied or Level 2B should be used. It is impractical to determine a Level 2B FAD, the FAD at and beyond $L_r = 1.0$ can be estimated [238] using:

$$\sqrt{\delta_r}(L_r=1) \text{ or } k_r(L_r=1) = \{1 + E\varepsilon_L/\sigma_Y^u + 1/[2(1 + E\varepsilon_L/\sigma_Y^u)]\}^{-0.5} \quad (10a)$$

where

$\varepsilon_L = 0.0375(1 - \sigma_Y^u/1000)$ is the estimated length of the Lüders plateau (this relation is restricted to $\sigma_Y^u < 976\text{N/mm}^2$);

σ_Y^u is the upper yield strength (if this is unavailable, it is conservative to use the yield or 0.2 % proof strength),

and

$$\sqrt{\delta_r}(L_r > 1) = \sqrt{\delta_r}(L_r = 1) L_r^{(N-1)/2N} \quad (10b)$$

$$\text{or } K_r(L_r > 1) = K_r(L_r = 1) L_r^{(N-1)/2N}$$

where

$N = 0.3(1 - \sigma_Y/\sigma_u)$ is the lower bound strain hardening exponent estimated from the yield to tensile strength ratio, σ_Y/σ_u [238].

7.3.2.2 Level 2B: material-specific curve

This method is suitable for parent material and weld metal of all types. It will generally give more accurate results than Level 2A but requires significantly more data. It requires a specific stress-strain curve; therefore, it is not suitable for HAZs, for which Level 2A is appropriate. Stress-strain data are required at the appropriate temperature for parent material and/or weld metal. The lower yield or 0.2 % proof strength, tensile strength, and modulus of elasticity should be determined together with

sufficient co-ordinate stress/strain points to define the curve. Particular attention should be paid to defining the shape of the stress/strain curve for strains below 1 %. It is recommended that the engineering stress/strain curve should be accurately defined at the following ratios of applied stress, σ , to yield strength, σ_Y :

$\sigma/\sigma_Y = 0.7, 0.9, 0.98, 1.0, 1.02, 1.1, 1.2$ and intervals of 0.1 up to σ_u .

The equations describing the assessment line are the following:

$$\sqrt{\delta_r} \text{ or } K_r = \left(\frac{E \varepsilon_{\text{ref}}}{L_r \sigma_Y} + \frac{L_r^3 \sigma_Y}{2E \varepsilon_{\text{ref}}} \right)^{-0.5} \quad (12)$$

for $L_r \leq L_{r\max}$; and

$$\sqrt{\delta_r} \text{ or } K_r = 0 \quad (13)$$

for $L_r > L_{r\max}$

where

ε_{ref} is the true strain⁹⁾ obtained from the uniaxial tensile stress-strain curve at a true stress, $L_r \sigma_Y$.

For most applications it is acceptable to use engineering stress-strain data, but it is important to concentrate calculation points around σ_Y . A typical FAD and the associated stress-strain curve are shown in Figure 11b) and c) respectively.

7.3.3 Stress components

The assessments take account of the actual distributions of stress in the vicinity of the flaws, where they are known. The stresses required are the membrane and bending components of the primary and secondary stresses, i.e. P_m , P_b , Q_m and Q_b . They can be obtained by linearization as illustrated in Figure 1 and should be multiplied by the appropriate partial safety factor, if required (see K.2). If the resultant total stress intensity factor calculated is negative, the value used in assessments should be taken as zero.

In certain situations, thermal and residual stresses, which may be self-balancing throughout a structure, may act as primary stresses on an individual component (see annex Q). This occurs when the flaw is small compared with the zone of influence of the thermal or residual stress, for example, in the case of large elastic follow-up or when the spatial extent of the stress is large compared with the flaw size. In these circumstances, such thermal and residual stresses should be treated as primary stresses and be incorporated in the $\sqrt{\delta_r}$ or K_r and L_r calculations.

⁹⁾ True stress, σ_t , and true strain ε_t , may be derived from engineering stress-strain data using $\sigma_t = (1 + \varepsilon)\sigma$ and $\varepsilon_t = \ln(1 + \varepsilon)$.

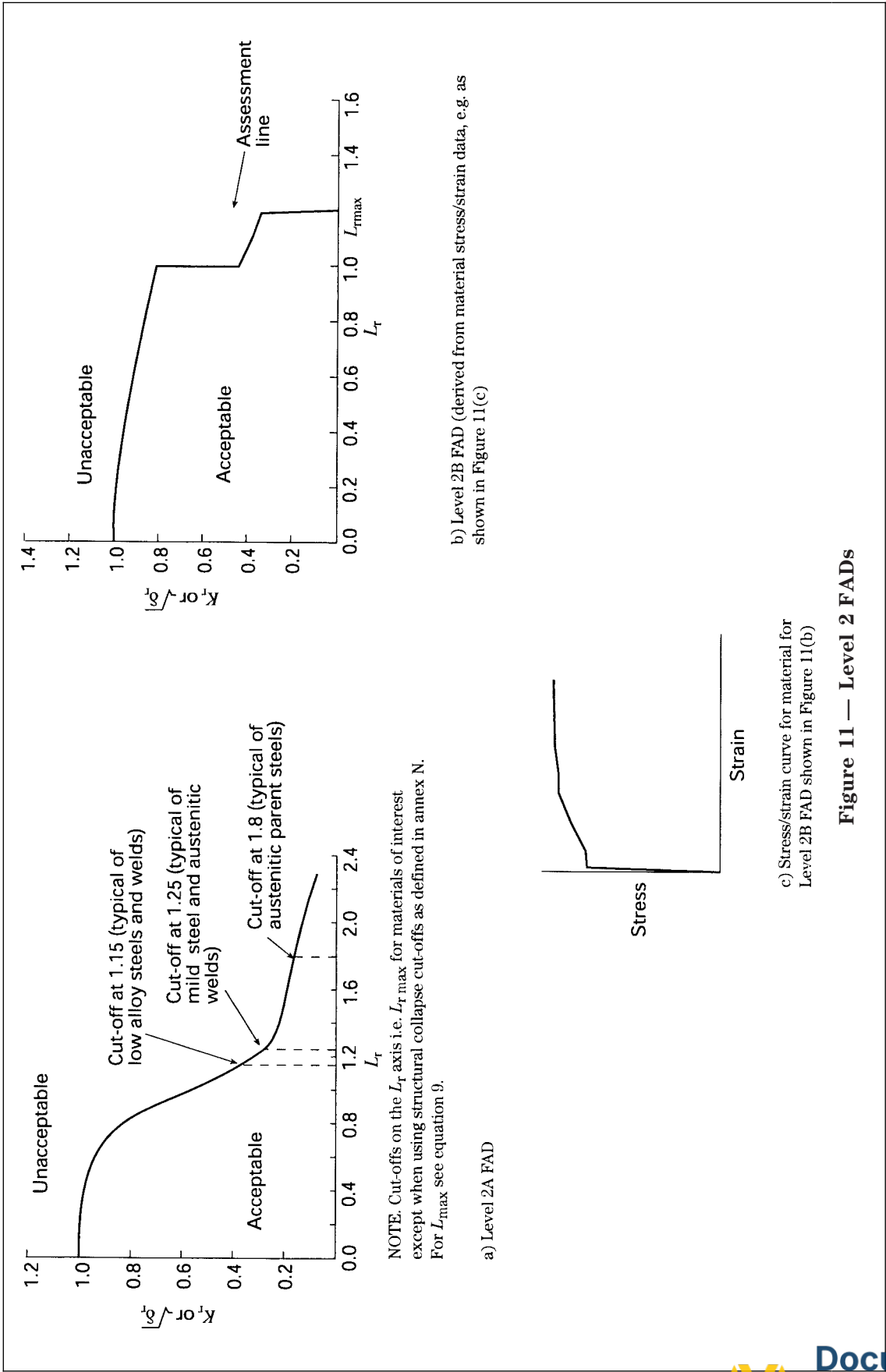


Figure 11 — Level 2 FADs

7.3.4 Residual stresses

7.3.4.1 The residual stresses may in general be assumed to be uniform, as in 7.2.4 for level 1, or non-uniform. Annex Q contains guidance on appropriate non-uniform residual stress distributions for specific weld geometries. The secondary stress components Q_m and Q_b may be obtained from non-uniform distributions using the linearization method illustrated in Figure 1.

The residual stress distributions in Annex Q are upper bound profiles to data on residual stresses in as-welded joints at room temperature. They may be used in assessments of welded joints at any temperature, but may not be modified to take account of stress relaxation caused by elevated temperature, prior overload or interaction with applied stresses.

7.3.4.2 Where the residual stresses are assumed to be uniform, the residual stress component, Q_m , may be assumed to be equal to the lower of the following values:

$$Q_m = \sigma'_Y \quad (14a)$$

or

$$Q_m = (1.4 - \sigma_{ref}/\sigma'_f)\sigma'_Y \quad (14b)$$

where

σ'_Y is the appropriate material yield strength at the assessment temperature, except that for temperatures below ambient, the room temperature value of σ'_Y is used in equation (14a);
 σ'_f is the appropriate flow strength (assumed to be the average of the yield and the tensile strengths) at the assessment temperature.¹⁰⁾

Note that, if secondary stresses are treated as primary in the above derivation of residual stresses, they should be treated as primary in the overall assessment.

7.3.4.3 Where the structure is subject to PWHT and/or pressure test, 7.2.4.2 to 7.2.4.4 and annex O apply.

7.3.4.4 Note that, in cases where the reference stress, σ_{ref} , is high, the application of 7.3.4.2 may predict lower residual stresses than values determined by actual measurements or those assumed for PWHT conditions, where appropriate. In such cases, the assumed value of 7.3.4.2 may still be used, as it has been found to provide a conservative assessment.

7.3.5 Fracture ratio (K_I)

7.3.5.1 For Level 2 and 3, K_I has the general form given in equation (2) (see 7.2.5), where $Y\sigma$ is given by:

$$Y\sigma = (Y\sigma)_p + (Y\sigma)_s \quad (15)$$

where

$(Y\sigma)_p$ and $(Y\sigma)_s$ represent contributions from primary and secondary stresses, respectively.

$$(Y\sigma)_p = Mf_w[k_{tm}M_{km}M_mP_m + k_{tb}M_{kb}M_b(P_b + (k_m - 1)P_m)] \quad (16)$$

$$(Y\sigma)_s = M_mQ_m + M_bQ_b \quad (17)^{11)}$$

In the above equations, expressions for M , f_w , M_m and M_b are given in Tables M.2 to M.4 and M.6 for different types of flaw in different configurations. M_{km} and M_{kb} apply when the flaw or crack is in a region of local stress concentration and are given in Tables M.5 and M.6. For k_{tm} , k_{tb} and k_m , reference should be made to 6.4 and annex D.

Annex M contains specific solutions for various geometries, including flat plates, curved shells, welded joints and round bars. Alternatively, handbook solutions, numerical modelling or weight function methods may be used to derive stress intensity factors. The procedure adopted should be fully documented.

K_I is calculated from the following equation:

$$K_I = \frac{K_I}{K_{mat}} \quad (18)$$

Where secondary stresses are present, a plasticity correction factor, ρ , is necessary to allow for interaction of the primary $(Y\sigma)_p$ and secondary $(Y\sigma)_s$ stress contributions, such that:

$$K_I = \frac{K_I}{K_{mat}} + \rho \quad (19)$$

where

ρ is as defined in annex R.

7.3.5.2 Note that, for surface breaking and embedded flaws, the calculated value of stress intensity factor K_I will vary around the crack front. The maximum value of K_I will frequently occur at the deepest point (for surface breaking flaws) or the point closest to the surface (for embedded flaws) where, in both cases, the parametric angle, θ , equals $\pi/2$ (see Figures M.2 and M.7). However, this is not always the case. The location of the point of maximum K_I round a crack front can be influenced by a number of factors including the following:

- flaw aspect ratio ($a/2c$);
- surface stress concentrations (e.g. weld toes);
- thermal shock;
- residual stress variation.

¹⁰⁾ For the purposes of determining the residual stress, the flow stress is not restricted to a maximum of 1.2 times the yield strength, as it is elsewhere in this guide.

¹¹⁾ Equations (16) and (17) differ in appearance from those to be found, for example, in the publications of Newman and Raju and in the original BS PD 6493. For surface, embedded and corner flaws, M_m and M_b have been modified here by dividing by the complete integral, Φ . By making this change it has been possible to write one set of equations that apply to all geometries.

Therefore, in the case of surface breaking and embedded flaws, K_I should be calculated at a number of points along the crack front.

Similarly, it is possible for K_{mat} to vary with depth either due to a lack of homogeneity in the material in which the flaw is located, or due to variation in constraint (see 7.4.1).

To ensure conservatism, the fracture assessment should use the maximum value of K_r that is calculated around the crack front.

7.3.6 Fracture ratio (δ_r)

7.3.6.1 The applied CTOD, δ_I , is determined from the appropriate K_I solution using the following equation:

$$\delta_I = \frac{K_I^2}{X\sigma_Y E'} \quad (20)$$

where

X is a factor (generally of value between 1 and 2) influenced by crack tip and geometric constraint and the work hardening capability of the material.

Appropriate values of X may be determined from elastic analyses which model structural constraint. The value of X will also be affected by work hardening and this may be allowed for by appropriate elastic-plastic analyses. If values of X are not quantified by structural analyses, use $X = 1$.

When fracture assessments are performed using K_{mat} determined via J_{mat} , identical predictions will be achieved using δ_{mat} results derived from the same tests when X is determined using the following equation:

$$X = \frac{J_{mat}}{\sigma_Y \delta_{mat} (1 - \nu^2)} \quad (21)$$

7.3.6.2 For assessments without secondary stresses, the parameter δ_r is the ratio of the applied CTOD δ_I to the fracture toughness δ_{mat} , including partial safety factors from annex K. To facilitate plotting the FAD, the square root of δ_r is calculated using the following equation:

$$\sqrt{\delta_r} = \sqrt{\delta_I / \delta_{mat}} \quad (22a)$$

Where secondary stresses are present, an additional adjustment, ρ , is necessary to allow for plasticity interactions of the primary $(Y\sigma)_p$ and secondary $(Y\sigma)_s$ stress contributions. In such circumstances the following equation is applicable:

$$\sqrt{\delta_r} = \sqrt{\left(\frac{\delta_I}{\delta_{mat}}\right)} + \rho \quad (22b)$$

where

ρ is as defined in annex R.

7.3.6.3 As explained in 7.3.5.2, for surface breaking and embedded flaws, K_I varies around the crack front. The value of δ_I from equation (20) will similarly vary and its maximum will be determined by the factors listed in 7.3.5.2. Therefore, K_I should be calculated at a number of points along the crack front in the same manner.

Similarly, it is possible for δ_{mat} to vary with depth either due to a lack of homogeneity in the material in which the flaw is located, or due to variation in constraint.

To ensure conservatism, the fracture assessment should use the maximum value of $\sqrt{\delta_r}$ that is calculated around the crack front.

7.3.7 Estimate of L_r

For Levels 2 and 3, the load ratio L_r is calculated from the following equation:

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} \quad (23)$$

where

σ_{ref} is obtained from an appropriate reference stress solution as outlined in annex P, with partial safety factors applied as appropriate.

7.4 Level 3 — Ductile tearing assessment

7.4.1 Main features

This is appropriate for ductile materials that exhibit stable tearing (e.g. austenitic steels and ferritic steels on the upper shelf). However, Level 3 assessments may also be applied to materials exhibiting a brittle failure mechanism, after pure ductile tearing, provided toughness data are obtained from specimens of adequate constraint. There are three assessment methods: Levels 3A, 3B and 3C.

Each method uses a different assessment line and applies a ductile tearing analysis. The analysis results in a plot of either a single assessment point or a locus of assessment points. If either the point or any part of the locus lies within the area bounded by the axes and the assessment line, the flaw is acceptable; if it does not, the flaw is not acceptable.

The L_r cut-off is as given in 7.3.1.

No inherent safety factor is included. Partial safety factors may be applied, as described in 7.3.1.

Margins of safety can be assessed using reserve factors and probabilistic approaches as described in annex K.

The FADs presented in 7.4.2 represent high structural constraint applications. When toughness is measured using standard procedures, it is possible to modify the FAD to account for lower constraint [3]. Alternatively, it is possible to maintain the use of a high constraint FAD and account for lower structural constraints using appropriate test geometries, as described in 7.1.5.8. These two approaches have been shown to be equivalent [4]. The effect of geometry on constraint is described further by Anderson and Dodds [5], O'Dowd, et al [6] and Sumpter and Hancock [7].

For the ductile tearing analysis, the fracture toughness is required in the form of a δ or J resistance curve (see 7.4.7).

Strictly speaking, the shape of the FAD should be modified when performing a tearing instability analysis dependent on the extent of stable crack extension [8]. This effect is small, however, and it is conservative to ignore it.

The FADs have been validated for a wide range of metallic structures [9].

7.4.2 FADs

7.4.2.1 Level 3A: generalized FAD of Level 2A (not requiring stress-strain data)

The FAD is the same as that for Level 2A and as described by equations (10) and (11) (see 7.3.2.1). This FAD provides a reasonable underestimate of the flaw tolerance of a structure but the underestimate may be excessive in cases where the initial rate of hardening in the stress-strain curve is high (such as materials operating in the strain ageing régime). In those cases, Level 3B should be considered.

For materials that exhibit a discontinuous yield point, the use of Level 3A should be restricted to values of $L_T \leq 1.0$, or it may be preferable to use Level 3B.

7.4.2.2 Level 3B: material-specific curve

The material-specific FAD is derived as for Level 2B (see 7.3.2.2). Stress-strain data for the material are needed, especially at strains below 1 %.

This diagram is suitable for all metals, regardless of their stress-strain behaviour.

7.4.2.3 Level 3C: J -integral

A FAD specific to a particular material and geometry is obtained by determining the J -integral using both elastic and elastic-plastic analyses of the flawed structure under the loads of interest. Determination of the respective values, J_e and J , for a range of loads (i.e. a range of values of L_T) leads to the assessment line being described by the following equations:

$$K_R = (J_e/J)^{1/2} \text{ for } L_T \leq L_{T\max};$$

$$K_R = 0 \text{ for } L_T > L_{T\max};$$

where

J_e and J are values corresponding to the same load (same L_T) and K_R is plotted as a function of L_T .

All analyses to determine J_e or J should be performed using validated computer codes. An accurate description of the true uniaxial stress-strain curve should be used in the analysis.

7.4.3 Stress components

The procedures for determining the stress components and related factors are identical to those for Level 2 described in 7.3.3.

7.4.4 Residual stress

Calculation of residual stress is identical to that in 7.3.4 for Level 2.

7.4.5 Applied stress intensity factor (K_I)

The calculation of K_I should follow the same procedure as outlined in 7.3.5.1 for Level 2. However, because of the increased accuracy required for this level, consideration should be given to the use of specific numerical solutions.

7.4.6 Applied CTOD (δ_I)

The calculation of δ_I should follow the same procedure as given in 7.3.6.1 for Level 2. However, because of the increased accuracy required for this level, consideration should be given to the use of specific numerical solutions for the calculation of K_I .

7.4.7 Ductile tearing analysis

7.4.7.1 For a ductile tearing analysis, the fracture tearing resistance, K_{mat} , J_{mat} or δ_{mat} , is defined as a function of the amount of ductile crack extension or tearing, Δa . R-curve testing should be carried out in accordance with BS 7448-4. The test method employed will produce a resistance curve of toughness as a function of Δa , from either a single specimen or a set of specimens. The toughness may be determined as a series of values of one of two parameters, δ_{mat} or K_{mat} derived from J .

When the single specimen method is used, data should be obtained from at least three single specimen tests. A lower bound curve to these data should be adopted. Where a set of specimens is used, at least six specimens are needed and a lower bound curve should be used. In both cases, where there is considerable scatter in the data, increased confidence in the main curve can be obtained by increasing the number of tests.

The crack plane and direction of propagation in the test specimen should be consistent with those in the structure.

In the transition temperature régime for ferritic steels, specimens of full thickness may fail by cleavage fracture, whereas specimens that are less than the full thickness may fail by shear fracture, and not give representative toughness values. Therefore, where there is a risk of brittle fracture, the test specimens should preferably be equal in thickness to the structure. For thick structures this is not always possible, either because of geometry effects or because of limitations of available testing machine capacity. In such instances, data should be obtained from the thickest practicable specimens and use of the results for application to the full section thickness should be fully justified after assessment for the possible effects of increasing section size. Guidance on these effects may be obtained from evidence in the literature and from data banks e.g. [10].

Where there is no risk of brittle fracture, e.g. for non-ferritic materials, or for ferritic steels at temperatures well above the ductile/brittle transition, it is permissible to use data from test specimens that are thinner than the structure. In such cases the data should be restricted to a valid range up to a limiting value of the crack extension Δa_g .

NOTE This is the same quantity as $\Delta a_{\max}$ given in BS 7448-4.

The parameters involved are the following:

- a) Δa_g is the limit of tearing crack extension over which the analysis may be performed, and is defined as follows:
 - 1) for specimens equal in thickness to the structure, the limit of the experimental data;
 - 2) for specimens which are thinner than the structure, the limit for J -validity for the particular specimen geometry;
- b) K_g or δ_g , is the value of K_{mat} or δ_{mat} at Δa_g .
- c) K_{mat} or δ_{mat} may then be defined by an equation dependent on the crack extension, Δa , between Δa_0 and Δa_g , or as point to point values at discrete quantities of Δa between the same limits. For ferritic steels, Δa_0 may be taken as 0.2 mm.

7.4.7.2 The tearing analysis is made in accordance with the following procedure:

- a) define the size of known flaw, a_0 ;
- b) define K_{mat} or δ_{mat} [see 7.4.7.1c)];
- c) define Δa_g [see 7.4.7.1a)]; read off K_g or δ_g ;
- d) if $\Delta a_g < 1.0$ mm, calculate L_T using 7.3.7 and K_I or δ_I using the following equation:

$$K_I = \frac{K_I}{K_g} + \rho \text{ see equation (19)}$$

K_I is defined in 7.4.5.

$$\sqrt{\delta_I} = \sqrt{\frac{\delta_I}{\delta_g}} + \rho \text{ see equation (22)}$$

δ_I is defined in 7.4.6.

K_I , δ_I and σ_{ref} are determined at a flaw length of $a = a_0 + \Delta a_g$, including partial safety factors on stress and flaw size if appropriate;

- e) if $1.0 \text{ mm} < \Delta a_g < 5.0 \text{ mm}$, define intervals of flaw extension, Δa_j , as follows:

$$\Delta a_0 = 0;$$

$$\Delta a_1 = 1.0 \text{ mm};$$

$$\Delta a_2 = 2.0 \text{ mm, etc.}$$

- If $\Delta a_g > 5.0$ mm, define intervals of flaw extension, Δa_j , as follows:

$$\Delta a_0 = 0;$$

$$\Delta a_1 = 1.0 \text{ mm};$$

$$\Delta a_2 = 0.2\Delta a_g;$$

$$\Delta a_3 = 0.4\Delta a_g, \text{ etc.}$$

Calculate L_T using 7.3.7 and K_I or δ_I using equations (19) and (22) respectively.

K_I , δ_I , K_{mat} , δ_{mat} and σ_{ref} are determined at flaw lengths $a = a_0$, $a_0 + \Delta a_1$, $a_0 + \Delta a_2$, etc.;

- f) plot all pairs of L_T , K_I or L_T , $\sqrt{\delta_I}$ as co-ordinate points on the FAD to derive the locus of the assessment points (see Figure 12). If the locus lies completely outside the assessment line, the flaw is unacceptable. If it crosses the assessment line, some ductile tearing may occur. However, this is predicted to stabilize, and the flaw is deemed acceptable.

7.5 Further points

7.5.1 Comparison of the levels

Although conservatism generally reduces with increasing level of analysis, the assessment levels each provide a self-contained procedure and there are situations where this does not occur. In particular, when assessing flaws subject to high residual stresses using CTOD toughness as input to a Level 1 analysis, there may be little or no advantage in moving to a Level 2 analysis.

7.5.2 Non-unique solutions

Because of the mathematical form of solutions used in the procedures, and the interaction of the input data, it is possible that a flaw of one size is acceptable but that a flaw of a smaller size is unacceptable (see Figure 13). Such conditions [11], are most likely to occur where stress distributions decrease through the section (for example, due to bending stresses or the stress raising effect of weld toes), or where increasing primary stresses result in increased relaxation of assumed residual stresses (see 7.3.4.2). Sensitivity analyses should be employed to check for possible non-unique solutions (see annex K).

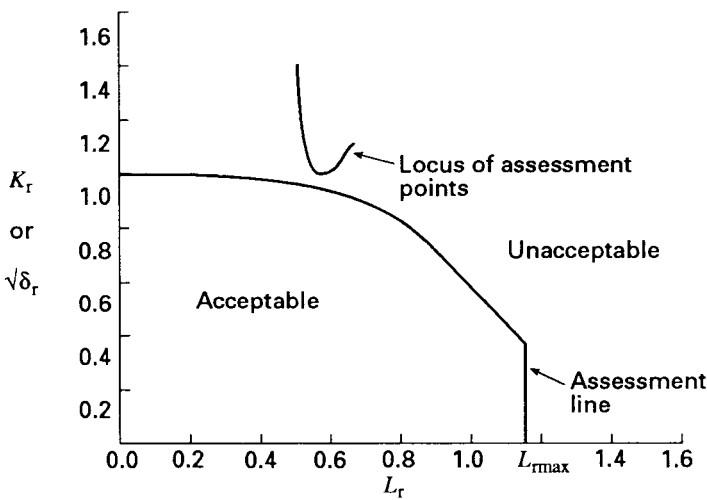


Figure 12 — Level 3A FAD with assessment locus for a known flaw

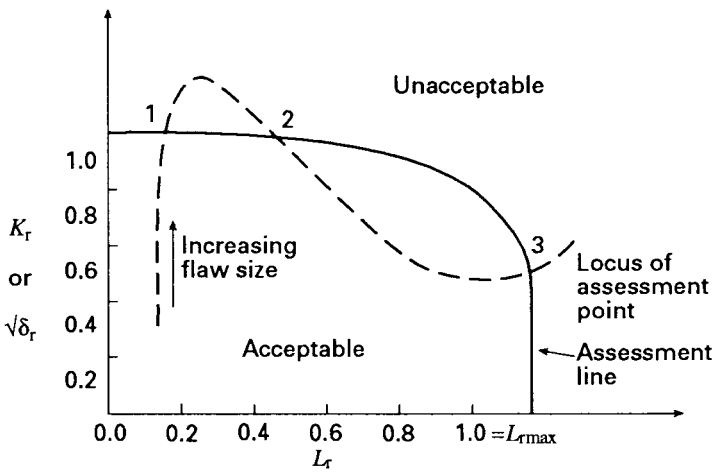


Figure 13 — Example of non-unique solutions (schematic)