

# Guidance on methods for assessing the acceptability of flaws in fusion welded structures

# Committees responsible for this Published Document

The preparation of this Published Document was entrusted by the Welding Standards Policy Committee (WEE/-) to Technical Committee WEE/37, upon which the following bodies were represented:

- Associated Offices Technical Committee
- Association of Consulting Engineers
- British Constructional Steelwork Association Ltd.
- British Gas plc
- British Steel Industry
- Electricity Supply Industry in United Kingdom
- Health and Safety Executive
- Institution of Mechanical Engineers
- Lloyds Register of Shipping
- Power Generation Contractors' Association (BEAMA Ltd.)
- Process Plant Association
- Railway Industry Association of Great Britain
- The Welding Institute
- Welding Manufacturers' Association (BEAMA Ltd.)

This Published Document, having been prepared under the direction of the Welding Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 30 August 1991

© BSI 11-1998

First published March 1980  
Second edition August 1991

The following BSI reference relates to the work on this Published Document:  
Committee reference WEE/37  
Draft for approval 90/78131

ISBN 0 580 19634 8

## Amendments issued since publication

| Amd. No. | Date | Comments |
|----------|------|----------|
|          |      |          |
|          |      |          |
|          |      |          |
|          |      |          |
|          |      |          |

# Contents

|                                                                                                               | Page               |
|---------------------------------------------------------------------------------------------------------------|--------------------|
| Committees responsible                                                                                        | Inside front cover |
| Foreword                                                                                                      | iv                 |
| <hr/>                                                                                                         |                    |
| Section 1. General                                                                                            |                    |
| 0 Introduction                                                                                                | 1                  |
| 1 Scope                                                                                                       | 2                  |
| 2 References                                                                                                  | 2                  |
| 3 Notation                                                                                                    | 2                  |
| 4 Types of flaw                                                                                               | 5                  |
| 5 Modes of failure                                                                                            | 5                  |
| 6 Information required for assessment                                                                         | 6                  |
| <hr/>                                                                                                         |                    |
| Section 2. Assessment for fracture                                                                            |                    |
| 7 General                                                                                                     | 11                 |
| 8 Data required for assessment                                                                                | 11                 |
| 9 Parameters required for different assessment levels (and methods)                                           | 16                 |
| 10 Level 1, preliminary assessment                                                                            | 18                 |
| 11 Level 2, normal assessment                                                                                 | 20                 |
| 12 Level 3, advanced assessment                                                                               | 20                 |
| 13 Fracture assessment for non-planar flaws, imperfect shape and fillet welds                                 | 22                 |
| <hr/>                                                                                                         |                    |
| Section 3. Assessment for fatigue                                                                             |                    |
| 14 Assessment procedures                                                                                      | 42                 |
| 15 Data required for assessment                                                                               | 43                 |
| 16 Probability of survival                                                                                    | 47                 |
| 17 General procedure for fracture mechanics assessment of planar flaws                                        | 47                 |
| 18 Basis of procedure for assessing flaws using quality categories                                            | 49                 |
| 19 Assessment of planar flaws using quality categories                                                        | 51                 |
| 20 Assessment of embedded non-planar flaws using quality categories                                           | 53                 |
| 21 Assessment of shape imperfections using quality categories                                                 | 54                 |
| 22 Estimation of tolerable sizes of flaws                                                                     | 56                 |
| <hr/>                                                                                                         |                    |
| Section 4. Assessment for other modes of failure                                                              |                    |
| 23 Yielding due to overloading of remaining cross section                                                     | 78                 |
| 24 Leakage in pressure, liquid or vacuum containing equipment                                                 | 78                 |
| 25 Environmental effects                                                                                      | 78                 |
| 26 Instability (buckling)                                                                                     | 81                 |
| 27 Creep                                                                                                      | 82                 |
| <hr/>                                                                                                         |                    |
| Appendix A Safety factors, number of tests and treatment of variability in input data for fracture assessment | 86                 |
| Appendix B Use of Charpy tests to indicate fracture toughness levels                                          | 87                 |
| Appendix C Assessment of pop-in crack extensions                                                              | 89                 |
| Appendix D Stress due to misalignment                                                                         | 91                 |
| Appendix E Stress intensity factor solutions for cracks in welded joints                                      | 96                 |
| Appendix F Formulae for effective net section stress                                                          | 104                |
| Appendix G Examples of level 3 assessment diagrams                                                            | 105                |
| Appendix H Approximate numerical integration methods                                                          | 109                |
| Appendix J References                                                                                         | 111                |

|                                                                                                                                               | Page |
|-----------------------------------------------------------------------------------------------------------------------------------------------|------|
| Figure 1 — Schematic representation of stress distributions across section                                                                    | 9    |
| Figure 2 — Alternative procedure for resolving flaws normal to principal stress                                                               | 10   |
| Figure 3 — Linearization of stress distributions                                                                                              | 23   |
| Figure 4 — Typical distributions of residual stresses at welds                                                                                | 24   |
| Figure 5 — Flaw dimensions                                                                                                                    | 25   |
| Figure 6 — Planar flaw interactions                                                                                                           | 26   |
| Figure 7 — Elliptical integral $\Phi$ as a function of $a/c$ used for calculation of $K_I$ for surface and embedded flaws                     | 29   |
| Figure 8 — Stress intensity magnification factor $M_m$ for embedded flaws in tension (at point nearest material surface)                      | 30   |
| Figure 9 — Stress intensity magnification factor $M_m$ for surface flaws in tension                                                           | 31   |
| Figure 10 — Stress intensity magnification factor $M_b$ for embedded flaws in bending                                                         | 33   |
| Figure 11 — Stress intensity magnification factor $M_b$ for surface flaws in bending                                                          | 34   |
| Figure 12 — Calculation of $\rho$ , the plasticity correction factor, using above equations and $\rho_1$ from graph                           | 36   |
| Figure 13 — Failure assessment diagrams                                                                                                       | 37   |
| Figure 14 — Relationship between actual flaw dimensions and the parameter $\bar{a}$ for surface flaws                                         | 39   |
| Figure 15 — Relationship between actual flaw dimensions and the parameter $\bar{a}$ for embedded flaws                                        | 40   |
| Figure 16 — Values of constant $C$ for different loading conditions (level 1)                                                                 | 41   |
| Figure 17 — Stress/endurance relationships                                                                                                    | 58   |
| Figure 18 — Assessment of surface flaws in axially-loaded material for simplified procedure                                                   | 59   |
| Figure 19 — Assessment of surface flaws in flat material in bending for simplified procedure                                                  | 61   |
| Figure 20 — Assessment of embedded flaws in axially-loaded joints for simplified procedure                                                    | 63   |
| Figure 21 — Assessment of weld toe flaws in axially-loaded joints for simplified procedure                                                    | 65   |
| Figure 22 — Assessment of weld toe flaws in joints in bending for simplified procedure                                                        | 71   |
| Figure 23 — Interaction criteria for slag inclusions                                                                                          | 77   |
| Figure 24 — Schematic diagrams of typical relationships between crack velocity and stress intensity factor during stress corrosion cracking   | 84   |
| Figure 25 — Types of corrosion fatigue crack growth behaviour                                                                                 | 84   |
| Figure 26 — Determination of the temperature $T_0$ at which 0.2 % creep strain is accumulated at a stress level equal to the “proof strength” | 85   |
| Figure 27 — Determination of the time $t(T)$ to achieve an accumulated creep strain of 0.2 % at a stress level equal to the “proof strength”  | 85   |
| Figure 28 — Procedure for obtaining lower bound $K_{Ic}$ toughness estimates from Charpy impact energy                                        | 88   |
| Figure 29 — Load/clip gauge displacement diagram for fracture tests showing behaviour to be assessed for pop-in                               | 90   |
| Figure 30 — Crack and welded joint geometries                                                                                                 | 102  |
| Figure 31 — Transverse load-carrying cruciform joint                                                                                          | 103  |
| Figure 32 — Example of level 3 assessment diagram for carbon steel having stated stress/strain curves                                         | 106  |

|                                                                                                                      | Page              |
|----------------------------------------------------------------------------------------------------------------------|-------------------|
| Figure 33 — Example of level 3 assessment diagram for quenched and tempered steel having stated stress/strain curves | 107               |
| Figure 34 — Example of level 3 assessment diagram for austenitic stainless steel having stated stress/strain curves  | 108               |
| Table 1 — Limits for slag inclusions and porosity                                                                    | 22                |
| Table 2 — Stress ranges used in fatigue assessments                                                                  | 45                |
| Table 3 — Details of quality category <i>S-N</i> curves                                                              | 50                |
| Table 4 — Minimum values of $\Delta\rho_j$ for assessing non-planar flaws and shape imperfections                    | 54                |
| Table 5 — Limits for non-planar flaws in as-welded steel and aluminium alloy weldments                               | 54                |
| Table 6 — Limits for non-planar flaws in steel weldments stress relieved by post-weld heat treatment                 | 54                |
| Table 7 — Acceptance levels for misalignment expressed in terms of stress magnification factor, $K_m$                | 55                |
| Table 8 — Acceptance levels for weld toe undercut in material thicknesses from 10 mm to 25 mm                        | 55                |
| Table 9 — Procedure for assessment of known flaws                                                                    | 57                |
| Table 10 — Temperature below which creep is negligible in 2 00 000 h                                                 | 83                |
| Table 11 — Equivalent fracture toughness values to the minimum of three results                                      | 86                |
| Table 12 — Definitions of failure consequences                                                                       | 86                |
| Table 13 — Partial safety factors for fracture assessments at level 2                                                | 87                |
| Table 14 — Formulae for calculating the secondary bending stress due to misalignment in butt joints                  | 92                |
| Table 15 — Formulae for calculating the secondary bending stress due to misalignment in cruciform joints             | 94                |
| Table 16 — Values of $v$ and $w$ for axial and bending loading                                                       | 101               |
| Publication(s) referred to                                                                                           | Inside back cover |

## Foreword

The revision of this Published Document has been carried out under the direction of the Welding Standards Policy Committee and supersedes PD 6493:1980 which is withdrawn. Because it is “guidance” that is being provided and the reference PD 6493 is so well known, it was decided to retain the same type of publication.

As the number of application standards specifying requirements for weld flaw acceptance levels increases, so it is necessary to update and extend the guidance to be used in achieving coordination and rationalization among those requirements. This revision incorporates recent developments in fracture mechanics assessment methods, details of which are given in the relevant sections of this document. While arbitrary acceptance levels will continue to be used for quality control purposes, the complementary use of the guidance given in this document permits the acceptability of known or postulated flaws in particular situations to be evaluated in a rational manner.

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 wishing to obtain further guidance. However, the information will seldom be found in the references in an identical form to that used in this document (see appendix J).

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

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 iv, pages 1 to 114, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

## 0 Introduction

In circumstances where it is necessary to examine critically the integrity of fusion welded joints in 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 in welds is based on the concept of “fitness for purpose”. By this principle a weld in a particular fabrication is considered to be adequate for its purpose provided the conditions to cause failure are not reached, after allowing for some measure of abuse in service. A distinction has to be made between acceptance based on quality control and acceptance based on fitness for purpose.

Quality control levels are, of necessity, both arbitrary and usually conservative and are of considerable value in the monitoring of weld quality during production. Flaws at or 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 but 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 “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 ECA, should be regarded as indicating that quality is in need of improvement.

A procedure for ECA is described, the use of which should be contractually agreed by all parties, whereby the significance of weld flaws under a particular set of circumstances may be determined. It is impossible to provide a single list of flaws which it is known will not cause premature failure, since a large number of variables is 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. ECA may also be used as a basis for deferring necessary repairs of welds containing flaws to a time mutually agreeable to the contracting parties. It should 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 thorough examination after any post-weld heat treatment and/or proof test by non-destructive testing using techniques capable of locating and sizing flaws in critical areas. However, since a major objective of this document is to reduce costs by eliminating unnecessary repair, careful consideration should 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 ECA for the appropriate combination of materials, welding process, procedure, welding consumables, stress and environmental factors, flaws should be assessed on that basis.
- c) If no relevant documented experience exists, then an ECA based on the guidance given in this document should be carried out.

ECA will help to identify the limiting conditions for failure. It should be emphasized that some aspects of ECA are based on new concepts which 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 should be agreed. Equally, a flaw will not necessarily be unacceptable when initially found to exceed the acceptance levels 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.

## Section 1. General

### 1 Scope

This Published Document gives guidance on methods for assessing the acceptability of flaws in all types of fusion welded structures and components. Although specifically aimed at welded fabrications in ferritic and austenitic steels and aluminium alloys, the procedures developed can be used for analysing flaws in welds in other materials and in non-welded applications.

### 2 References

The titles of the standards publications referred to in this Published Document are listed on the inside back cover.

### 3 Notation

For the purposes of this Published Document the following notation and units are used.

|                  |                                                                                                                                |
|------------------|--------------------------------------------------------------------------------------------------------------------------------|
| $A$              | constant in fatigue crack growth relationship <sup>a</sup>                                                                     |
| $A_1$            | full load bearing area containing flaw (mm <sup>2</sup> )                                                                      |
| $a$              | half flaw length for through thickness flaw, flaw height for surface flaw or half height for embedded flaw (see Figure 5) (mm) |
| $\Delta a$       | increment in $a$                                                                                                               |
| $a_f$            | final flaw size (mm)                                                                                                           |
| $\Delta a_g$     | limits of tearing flaw extension (mm)                                                                                          |
| $\Delta a_j$     | intermediate value of tearing flaw extension (mm)                                                                              |
| $\bar{a}$        | effective flaw parameter for level 1 fracture assessment (mm)                                                                  |
| $\bar{a}_{\max}$ | maximum value of effective flaw parameter for fatigue analysis (mm)                                                            |
| $\bar{a}_i$      | initial value of effective flaw parameter for fatigue analysis (mm)                                                            |
| $a_m$            | limiting flaw size for levels 2 and 3 fracture assessments (mm)                                                                |
| $\bar{a}_m$      | tolerable flaw parameter for level 1 fracture assessment (mm)                                                                  |
| $a_o$            | initial flaw size (mm)                                                                                                         |
| $\Delta a_o$     | notional extension of flaw defining tearing initiation (mm)                                                                    |
| $B$              | section thickness in plane of flaw (mm)                                                                                        |
| $B'$             | effective section thickness ( $2a + 2p$ ) (mm)                                                                                 |
| $C'$             | constant in the stress corrosion crack growth relationship <sup>b</sup>                                                        |

|                 |                                                                                           |
|-----------------|-------------------------------------------------------------------------------------------|
| $c$             | half flaw length for surface or embedded flaws (see Figure 5) (mm)                        |
| $\Delta c$      | increment in $c$ (mm)                                                                     |
| $\frac{da}{dN}$ | flaw growth rate (mm/cycle)                                                               |
| $\frac{da}{dt}$ | flaw growth rate (mm/time) (time measured in days, weeks, months or years as appropriate) |
| $D$             | diameter (mm)                                                                             |
| $d$             | deviation from true circle due to angular misalignment (mm)                               |
| $e$             | axial misalignment (eccentricity or centre-line mismatch) (mm)                            |
| $E$             | elastic modulus (N/mm <sup>2</sup> )                                                      |
| $F$             | peak stress (N/mm <sup>2</sup> )                                                          |
| $F_L$           | load factor [see 12.3 g)] (dimensionless)                                                 |
| $f$             | factor of safety with respect to stress corrosion cracking ( $f > 1.0$ ) (dimensionless)  |
| $f\phi, f_w, g$ | correction terms in stress intensity factor for elliptical flaws (dimensionless)          |
| $h$             | weld leg length (mm)                                                                      |

<sup>a</sup> The units of  $A$  depend on those used to measure  $da/dN$  and  $\Delta K$ , and on the value of the exponent,  $m$ . If  $A$  is known in one set of units,  $A_1$ , the corresponding value for another set of units,  $A_2$  is given by:

$$A_2 = A_1 \frac{f_1}{f_2^m}$$

where

$f_1$  is the conversion factor for  $da/dN$  from the first to the second unit system; and

$f_2$  is the conversion factor for  $\Delta K$  from the first to the second unit system.

<sup>b</sup> The units of  $C'$  depend on those used to measure  $da/dN$  and  $\Delta K$ , and on the value of the exponent,  $n$ . If  $C'$  is known in one set of units,  $C'_1$ , the corresponding value for another set of units,  $C'_2$ , is given by:

$$C'_2 = C'_1 \frac{f_1}{f_2^n}$$

where

$f_1$  is the conversion factor for  $da/dN$  from the first to the second unit system; and

$f_2$  is the conversion factor for  $\Delta K$  from the first to the second unit system.

|                            |                                                                                                                                                                  |                                |                                                                                                                                                                         |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $J_{\text{mat}}$           | material toughness measured by $J$ -methods (N/mm)                                                                                                               | $n_j$                          | number of cycles in stress spectrum at stress range $\Delta\sigma_j$ (cycles)                                                                                           |
| $K$                        | stress intensity factor (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                                                     | $P$                            | primary stress (N/mm <sup>2</sup> )                                                                                                                                     |
| $\Delta K$                 | stress intensity factor range (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                                               | $P_m$                          | membrane stress (N/mm <sup>2</sup> )                                                                                                                                    |
| $\Delta K_0$               | threshold stress intensity factor range below which fatigue crack growth (or corrosion fatigue crack growth) does not occur (N mm <sup>-3/2</sup> ) <sup>a</sup> | $P_b$                          | bending stress (N/mm <sup>2</sup> )                                                                                                                                     |
| $K_I$                      | applied tensile (mode I) stress intensity factor (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                            | $P_c, P_u$                     | load related to pop-in behaviour (see appendix C) (N or kN)                                                                                                             |
| $K_{Ic}$                   | plane strain fracture toughness (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                                             | $p$                            | shortest distance from material surface to embedded flaw (mm)                                                                                                           |
| $K_{Isc}$                  | critical stress intensity factor for stress corrosion cracking (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                              | $Q$                            | secondary stress (N/mm <sup>2</sup> )                                                                                                                                   |
| $K_g$                      | notional $K$ value after flaw extension $\Delta a_g$ (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                        | $Q_b$                          | secondary bending stress (N/mm <sup>2</sup> )                                                                                                                           |
| $K_{\text{mat}}$           | material toughness measured by stress intensity factor (N mm <sup>-3/2</sup> ) <sup>a</sup>                                                                      | $Q_m$                          | secondary membrane stress (N/mm <sup>2</sup> )                                                                                                                          |
| $K_m$                      | stress magnification factor due to misalignment (dimensionless)                                                                                                  | $R$                            | stress ratio (ratio of minimum ( $\sigma_{\min}$ ) to maximum ( $\sigma_{\max}$ ) algebraic value of the absolute stress level [ $P_m + P_b + Q + F$ ] (dimensionless)) |
| $K_r$                      | fracture ratio of applied elastic $K$ value to $K_{\text{mat}}$ (dimensionless)                                                                                  | $r$                            | radius of hole (mm)                                                                                                                                                     |
| $K_t$                      | stress concentration factor (dimensionless)                                                                                                                      | $S$                            | stress range or, for variable amplitude loading, the equivalent constant amplitude stress range (N/mm <sup>2</sup> )                                                    |
| $L$                        | attachment length (mm)                                                                                                                                           | $S_r$                          | load ratio of applied load to flow strength load (dimensionless)                                                                                                        |
| $L_r$                      | load ratio of applied to yield load (dimensionless)                                                                                                              | $s$                            | distance between embedded flaws (mm)                                                                                                                                    |
| $L_{r\text{max.}}$         | permitted limit of $L_r$ (dimensionless)                                                                                                                         | $t$                            | time (days, weeks, months or years as appropriate)                                                                                                                      |
| $l$                        | distance from axially misaligned joint to load point or extremities of region of angular misalignment (mm) (shortest distance = $l_1$ )                          | $T$                            | temperature (°C)                                                                                                                                                        |
| $M, M_S, M_T$              | stress magnification factors (see 9.1) (dimensionless)                                                                                                           | $T_0$                          | temperature below which creep is negligible for a given endurance (°C)                                                                                                  |
| $M_m, M_b, M_{km}, M_{kb}$ | stress intensity factor magnification factors (dimensionless)                                                                                                    | $V_c, V_u$                     | clip gauge displacement related to pop-in behaviour (see appendix C) (mm)                                                                                               |
| $m$                        | exponent in flaw growth law (dimensionless)                                                                                                                      | $W$                            | plate width in plane of flaw (mm)                                                                                                                                       |
| $N$                        | fatigue life (cycles)                                                                                                                                            | $Y$                            | stress intensity factor correction (dimensionless)                                                                                                                      |
| $\Delta N$                 | increment in $N$ (cycles)                                                                                                                                        | $y$                            | height of peaking due to angular misalignment (mm)                                                                                                                      |
| $n$                        | exponent in the stress corrosion crack growth relationship (dimensionless)                                                                                       | $\sigma$                       | angular change at misaligned joint (radians)                                                                                                                            |
|                            |                                                                                                                                                                  | $\gamma_s, \gamma_t, \gamma_a$ | partial coefficients for safety factor treatment, appendix A (dimensionless)                                                                                            |
|                            |                                                                                                                                                                  | $\delta$                       | crack tip opening displacement (CTOD) (mm)                                                                                                                              |

|                              |                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                     |                                                                                                       |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| $\delta_c$                   | CTOD (mm) at either:<br>a) unstable fracture; or<br>b) onset of arrested brittle crack or pop-in.<br><br>This term only applies where there is no evidence in either (a) or (b) to suggest that slow crack growth has occurred | $\sigma_Y$                                                                                                                                                                                                                                                                          | lower yield strength or 0.2 % proof strength (N/mm <sup>2</sup> )                                     |
|                              |                                                                                                                                                                                                                                | $\sigma_Y$                                                                                                                                                                                                                                                                          | appropriate material yield strength (N/mm <sup>2</sup> )                                              |
|                              |                                                                                                                                                                                                                                | $\sigma_w$                                                                                                                                                                                                                                                                          | applied stress on weld throat (N/mm <sup>2</sup> )                                                    |
|                              |                                                                                                                                                                                                                                | $\sigma_{\varepsilon 0.2}$                                                                                                                                                                                                                                                          | stress to give 0.2 % creep strain (N/mm <sup>2</sup> )                                                |
| $\delta_g$                   | CTOD at limit of permitted tearing (mm)                                                                                                                                                                                        | $\Delta\sigma_m$                                                                                                                                                                                                                                                                    | membrane component of stress range (N/mm <sup>2</sup> )                                               |
| $\delta_I$                   | applied CTOD (mm)                                                                                                                                                                                                              | $\Delta\sigma_b$                                                                                                                                                                                                                                                                    | bending component of stress range (N/mm <sup>2</sup> )                                                |
| $\delta_m$                   | CTOD at first attainment of maximum force plateau (mm)                                                                                                                                                                         | $\Delta\sigma'_b$                                                                                                                                                                                                                                                                   | range in bending stress <b>excluding</b> the effects of misalignment (N/mm <sup>2</sup> )             |
| $\delta_{mat}$               | material toughness measured by CTOD method (mm)                                                                                                                                                                                | $\Delta\sigma_j$                                                                                                                                                                                                                                                                    | stress range in variable amplitude fatigue spectrum which is applied $n_j$ times (N/mm <sup>2</sup> ) |
| $\delta_r$                   | fracture ratio using CTOD parameters (dimensionless)                                                                                                                                                                           | $\Phi$                                                                                                                                                                                                                                                                              | complete elliptic integral of the second kind (dimensionless)                                         |
| $\delta_u$                   | CTOD (mm) at either:<br>a) unstable fracture; or<br>b) onset of arrested brittle crack or pop-in.<br><br>This term only applies where there is no evidence in either (a) or (b) to suggest that slow crack growth has occurred | $\phi$                                                                                                                                                                                                                                                                              | parametric angle to identify position along an elliptic flaw front (radians)                          |
| $\varepsilon$                | strain (dimensionless)                                                                                                                                                                                                         | <sup>a</sup> The two internationally recognized alternative units for stress intensity factor are N mm <sup>-3/2</sup> and MPa√m (which is identical to MN m <sup>-3/2</sup> ). The unit adopted in this document is N mm <sup>-3/2</sup> .<br>1 N mm <sup>-3/2</sup> = 0.032 MPa√m |                                                                                                       |
| $\lambda$                    | constant depending on boundary conditions (dimensionless)                                                                                                                                                                      |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\nu$                        | Poisson's ratio (dimensionless)                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma$                     | plasticity correction factor (dimensionless)                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma$                     | applied stress (N/mm <sup>2</sup> )                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\Delta\sigma$               | applied stress range (N/mm <sup>2</sup> )                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_{0.2}$               | 0.2 % proof strength (N/mm <sup>2</sup> )                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_{min}, \sigma_{max}$ | minimum and maximum algebraic values of the absolute stress level ( $P_m + P_o + Q + F$ ) (N/mm <sup>2</sup> )                                                                                                                 |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_1$                   | maximum applied tensile stress (N/mm <sup>2</sup> )                                                                                                                                                                            |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_f$                   | flow strength (N/mm <sup>2</sup> )                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_n$                   | net section stress (N/mm <sup>2</sup> )                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_R$                   | residual stress (N/mm <sup>2</sup> )                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_s$                   | bending stress due to misalignment (N/mm <sup>2</sup> )                                                                                                                                                                        |                                                                                                                                                                                                                                                                                     |                                                                                                       |
| $\sigma_u$                   | tensile strength (N/mm <sup>2</sup> )                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                     |                                                                                                       |

## 4 Types of flaw<sup>1)</sup>

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<sup>2)</sup>, root undercut<sup>2)</sup>, concavity and overlap.
- b) Non-planar flaws:
  - 1) cavities<sup>3)</sup>;
  - 2) solid inclusions<sup>3)</sup>.
- 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.

## 5 Modes of failure

**5.1** The influence of the flaws listed in clause 4 may be assessed, using this document, for the modes of failure listed in (a) to (g). For the flaw or flaw type, consideration should be given to the environment. Reference should be made to sections 2, 3 and 4 dealing with the detailed assessment of the various modes of failure and possible interactions between them. For a particular application, some of these will not be relevant.

The modes of failure are as follows:

- a) fracture;
- b) fatigue;
- c) yielding due to overloading of the remaining cross section;
- d) leakage in containment vessels;
- e) corrosion, erosion, corrosion fatigue, stress corrosion;
- f) instability (buckling);
- g) creep or creep and fatigue interaction.

There are varying degrees of confidence and accuracy with which the risk of failure from the operation of these modes can be predicted quantitatively. The behaviour of weldments subject to fatigue loading and the risk of brittle fracture is well understood largely through research efforts arising out of structural failures from these causes. Where failure by shear fracture is controlled by net section, this is also well understood, but shear failure dominated by crack tip conditions is not covered in this document. The other mechanisms listed require to be considered in an ECA, since failure can arise through their operation, but it would be misleading at this time to attempt to describe detailed methods for predicting failure from these mechanisms in the same depth and generality as can be applied to the fatigue and brittle fracture modes. Brief guidelines are offered in section 4 for the assessment of the possible risk of operation of these mechanisms. Where a risk of failure from these modes is established, before flaws can be accepted, a specific assessment should be undertaken. Justification for the assumptions and approaches used in these circumstances should be fully documented and agreed by all interested parties.

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

- a) Identify the flaw type, i.e. planar, non-planar or shape (see clause 4).
- b) Establish such of the essential data as are relevant to the particular structure (see **6.2**).
- c) Determine the size of flaw.
- d) Assess acceptability as follows.
  - 1) Determine the limiting size as appropriate for the following final failure modes:
    - i) fracture (see section 2);
    - ii) yielding due to overload of remaining cross section (see clause **23**);
    - iii) leakage (see clause **24**);
    - iv) corrosion/erosion (see **25.2**);
    - v) stress corrosion (see **25.3.2**);
    - vi) buckling (see clause **26**);
    - vii) creep (see clause **27**) if material not susceptible to macroscopic creep crack growth.
  - 2) Assess whether the flaw would grow to this final size by the following mechanisms of subcritical crack growth within the design life of the structure:

<sup>1)</sup> A comprehensive classification of the various types of flaw which may be encountered in fusion welds is given in ISO 6520.

<sup>2)</sup> On some occasions undercut and root undercut are treated as shape imperfections.

<sup>3)</sup> On some occasions cavities and solid inclusions are treated as planar flaws.

- i) fatigue (see section 3);
- ii) crevice corrosion (see 25.2);
- iii) corrosion fatigue (see 25.3.3);
- iv) creep crack growth (see clause 27);
- v) creep and fatigue interactions (see clause 27).

3) If the flaw would not grow to the limiting size including appropriate factors of safety, it is acceptable.

Estimation of tolerable planar flaw sizes may be made by starting from a series of limiting flaw shapes as determined in (d)(1) and determining the initial flaw sizes which would grow to these within the design life as in (d)(2). Procedures for calculating such tolerable initial flaw sizes with regard to fracture are given in clauses 10, 11 and 12 and with regard to fatigue in clause 22.

Tolerable sizes of embedded non-planar flaws may be determined by the procedures laid down in clause 13 and clause 20 for fracture and fatigue respectively. Such flaws should also be checked for the other failure modes listed in section 4.

Surface breaking non-planar flaws are also treated as planar flaws.

## 6 Information required for assessment

### 6.1 General

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 will be required:

- a) position and orientation of flaw;
- b) structural and weld geometry, welding procedure;
- c) stresses (however arising) and temperatures including transients;
- d) yield or 0.2 % proof strength, tensile strength and Young's 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 CTOD) data (in certain cases fracture toughness may be estimated from relevant Charpy V-notch data or from *J*-contour integral testing);
- g) creep rupture, creep crack propagation and creep fatigue data;
- h) bulk corrosion and stress corrosion cracking ( $K_{Isc}$ ) data.

### 6.3 Non-destructive testing

6.3.1 Non-destructive testing (NDT) is an essential aspect of a fitness for purpose assessment where quantitative information about a flaw's size and shape are required. The NDT technique(s) used for flaw evaluation should be chosen so as to provide the type of information required to an acceptable degree of accuracy. Such information should include some or all of the following:

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

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

- a) visual;
- b) liquid penetrant;
- c) magnetic particle (for ferromagnetic materials);
- d) eddy current;
- 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 and potential drop methods are capable of providing a measurement of their height.

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

- a) radiography;
- b) ultrasonics;
- c) eddy current (in non-ferromagnetic materials);
- d) electrical potential drop (d.c. only).

Of these, both radiography and ultrasonics are capable of providing a measurement of flaw length, but ultrasonics only can provide a measurement of flaw height. Eddy current and potential drop methods will tend to provide a measurement of the cross-sectional area of the flaw.

**6.3.4** Non-destructive testing to an agreed extent, not necessarily 100 %, should be carried out in accordance with the appropriate standards, for example the following:

|                   |                                                         |
|-------------------|---------------------------------------------------------|
| ultrasonics       | BS 3923-1 or<br>BS 3923-2, as<br>appropriate            |
| radiography       | BS 2600-1 or BS 2600-2<br>or BS 2910, as<br>appropriate |
| magnetic particle | BS 6072                                                 |
| liquid penetrant  | BS 6443                                                 |

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 suited to examination of large amounts of welds and which are economically viable, will not necessarily be appropriate for highly accurate measurements of particular flaws for inclusion in a fitness for purpose assessment. In such cases, supplementary techniques or additional test methods should be employed.

#### 6.4 Stresses to be considered

**6.4.1** The stresses to be considered in the assessment may be treated directly, or after resolution into the four components described below in (a), (b), (c) and (d). Typical schematic representations of these are given in Figure 1. For the level 1 fracture assessment (see **9.2.1**) only the maximum value of the combined stress field can be used. For levels 2 and 3, the stress gradient can be taken into account.

a) **Membrane stress** ( $P_m$ ). The component of uniformly distributed stress which is equal to the average value of stress across the section thickness and is necessary to satisfy the simple laws of equilibrium of internal and external forces and moments.

b) **Bending stress** ( $P_b$ ). The component of stress due to imposed loading which varies across the section thickness. For the purpose of this document  $P_b$  is regarded as a stress superimposed upon  $P_m$ .

c) **Secondary stress** ( $Q$ ). The secondary stresses  $Q$  are self equilibrating stresses necessary to satisfy compatibility in the structure. Thermal and residual stresses are usually secondary. 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 may contribute to severity of local conditions at a crack tip, however, and have to be included in calculations of  $K$  or  $\delta$  in fracture assessments in clause 9.

For fracture assessment at levels 2 and 3, the secondary stresses may be divided into membrane ( $Q_m$ ) and bending ( $Q_b$ ) components as for primary stresses (see **8.2.1**).

d) **Peak stress** ( $F$ ). The peak stress is the increment of stress that is added to the primary plus secondary stresses due to concentrations at local discontinuities for use in level 1 fracture treatments (see **8.1.1** and **9.2.1**) and some parts of fatigue treatments (see **15.1.2**). The peak stress represents the highest value, usually at the surface. For level 2 and level 3 fracture treatments, more accurate representation of the effects of the stress distribution and gradients away from the peak surface value on crack tip severity is required (see **8.2.1** and **9.2.2**).

Peak stresses fall into three basic categories.

1) *Additional stresses due to gross structural discontinuities*. For nozzles, the peak stress  $F_1$  is given by

$$F_1 = (K_t - 1) \times \text{applied membrane stress,}$$
 where  $K_t$  is the stress concentration factor for membrane stress.

For tubular joints, it is common to use a hot spot stress concentration factor where the local stress on the chord or the brace is obtained as a multiple of the remote stress in the brace.

For the chord, this hot spot stress should be regarded as the peak stress and is given by

$$F_1 = K_t \times \text{remote stress in the brace.}$$

In the brace, the hot spot stress includes the primary stress and the peak stress is given by

$$F_1 = (K_t - 1) \times \text{remote stress in the brace.}$$

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

2) *Additional stresses due to misalignment or deviation from intended shape.* These stresses are usually predominantly bending stresses and the peak surface stress  $F_2$  is given by

$$F_2 = (K_m - 1) \times \text{applied stress},$$

where  $K_m$  is the stress magnification factor (see for example appendix D). This type of peak stress also decays over distances greater than the section thickness and may lead to a plastic hinge across the full thickness over local regions. If a type  $F_2$  peak stress region lies within a type  $F_1$  peak stress region, only the membrane stress part of  $F_1$  should be used to calculate  $F_2$ .

3) *Stress concentrations at local structural discontinuities, such as holes, notches, sharp corners or weld toes.* This type of peak stress usually decays over distances less than about 20 % of the hole or notch radius, or 20 % of the thickness. The peak stress  $F_3$  may be given by

$$F_3 = (K_t - 1) \times \text{applied stress},$$

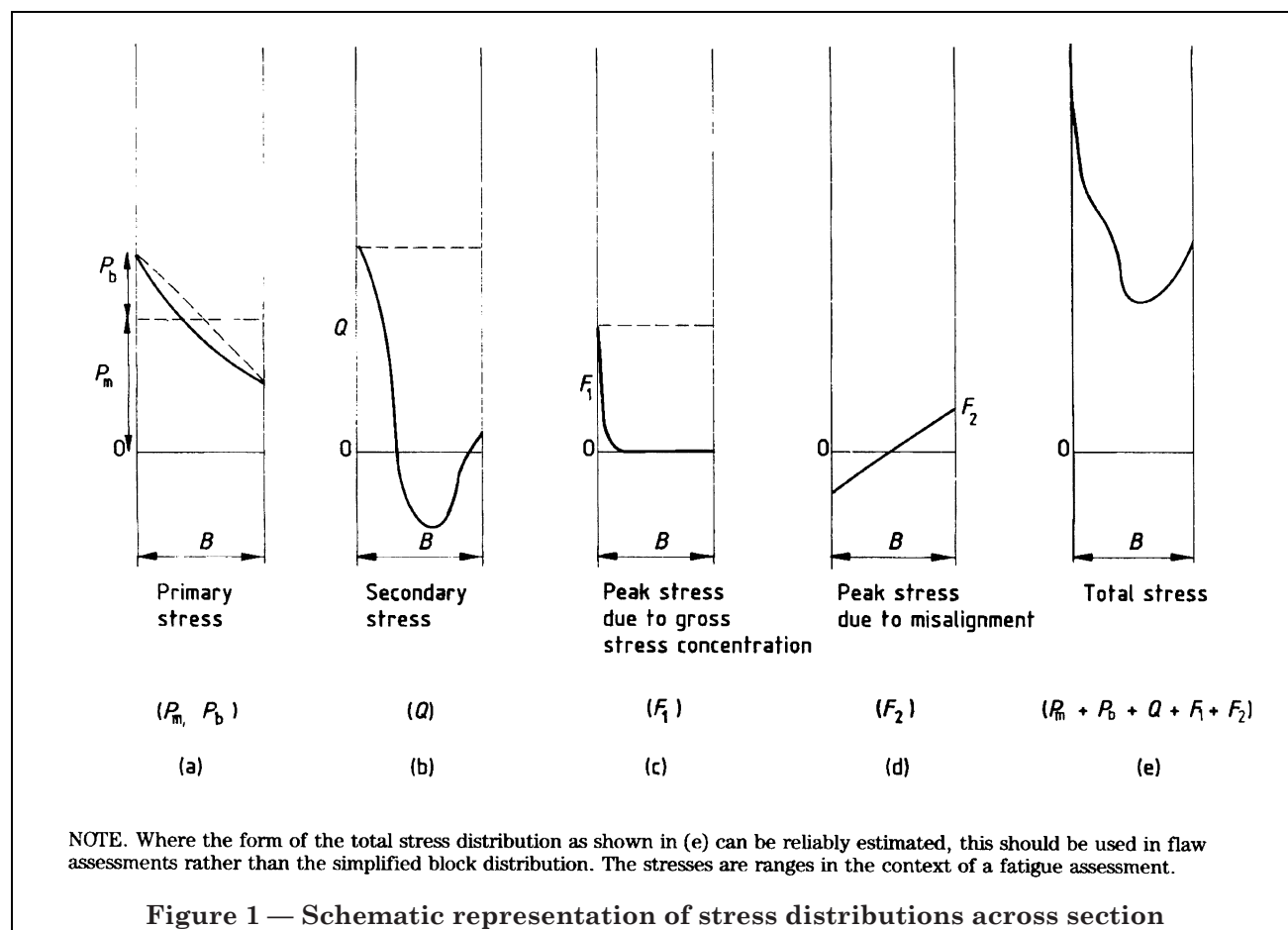
where  $K_t$  is the surface stress concentration factor. This type of peak stress will not of itself cause plastic collapse, other than net area effects. For perfectly sharp corners, the theoretical stress concentration factor is infinite, and it is preferable that cracks at such regions should be treated by a stress intensity magnification factor at level 2 or 3. Type  $F_3$  peak stress effects may be located within either type  $F_1$  or  $F_2$  zones, and at level 1 the overall effects should be multiplied together. This will inevitably give very conservative results.

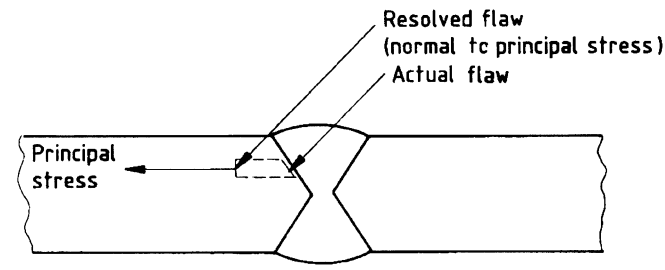
Different methods of incorporating peak stresses are used in various different assessment methods within this document, as detailed in 8.1.1, 9.2.1 and 15.1.

**6.4.2** The relevant stresses in the assessment should be the values of  $(P + Q + F)$  in the neighbourhood of the flaw and should not take into account stress concentration effects due to the flaw itself. Effects of shear stresses acting upon flaws need not be considered, provided the remaining cross-sectional area is adequate (see 6.4.3).

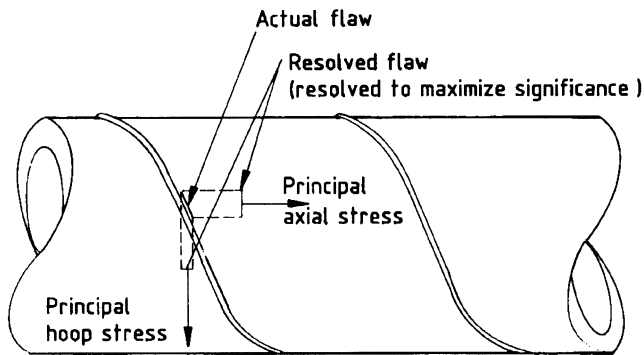
**6.4.3** For planar flaws, there are two alternatives. Either the stress components perpendicular to the plane of the flaw should be used or the flaw should be resolved onto planes perpendicular to the principal stresses and assessed for the case which maximizes its significance. Examples are shown in Figure 2 and 6 b), where this procedure is demonstrated. A check should also be made that the shear stress on net area does not exceed 48 % of the specified minimum yield strength when the flaw is resolved onto the plane of maximum shear stress.

**6.4.4** 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.





(a) Buttweld example



(b) Spiral weld pipe example

Figure 2 — Alternative procedure for resolving flaws normal to principal stress

## Section 2. Assessment for fracture

### 7 General

There are continuing developments and improvements in fracture mechanics assessment methods. In particular the Central Electricity Generating Board (CEGB) R6 procedure (see reference 1) has now been developed to revision 3, and further developments have taken place in CTOD procedures put forward by The Welding Institute (TWI) (see reference 2). Research work on  $J$ -contour integral methods has provided improved understanding and confidence in all of these approaches (see references 3 to 6). The revised treatments in this document have been prepared to be consistent with these developments. All cover tensile (mode I) failure only. Shear failure is dealt with in 13.3 and clause 23. Some increase in complexity is involved in the new treatments and it has therefore been decided to give guidance on three levels of assessment.

Level 1 is an initial screening level broadly compatible with the 1980 edition of PD 6493 (see clause 10).

Level 2 is the main new full treatment level (see clause 11). It makes use of an assessment diagram, which combines consideration of fracture and local plastic collapse. This treatment gives improved accuracy over the 1980 edition of PD 6493 in respect of flaws in stress gradients and of residual stress effects, and gives the user the opportunity to assess the safety margins required rather than use the variable safety factor inherent in the previous version.

The level 3 approach given in clause 12 will permit greater accuracy but involves greater complexity and more materials data. It is particularly appropriate for materials of high strain hardening capacity, or where analysis for stable tearing fracture is required. This level should not normally be necessary for general structural steel applications.

In the treatments at each level, the user has the alternative of methods based on the stress intensity factor  $K$ , or the CTOD  $\delta$ . It is intended that self-consistent methods should be used throughout an assessment. The choice of route will usually be determined by the form of available toughness data. While it is permissible for  $K$ -based fracture toughness data to be derived from  $J$ -methods, it is not intended that CTOD toughness data should be transformed to equivalent  $K$  data.

Because of uncertainties in effects of crack tip constraint, some differences will occur in results of assessments using  $K$ -based or CTOD based data from the same source. Self-consistent methods using one route throughout will give satisfactory safe assessments when used with appropriate safety factors.

Guidance on other than planar flaws is given in clause 13, based on derivations from fracture mechanics and on experimental evidence.

An important development in assessment of the significance of flaws is the use of reliability methods to provide guidance on partial safety factors to be applied to each of the input data. This guidance is given in appendix A as an alternative to using worst case estimates. The partial safety factor approach (if used) involves applying factors to the input data, namely stresses, flaw sizes and fracture toughness.

### 8 Data required for assessment

#### 8.1 Stresses to be used in assessments at level 1

**8.1.1** The stress used in 9.2.1 is the maximum tensile stress  $\sigma_1$ , which is taken to be uniform and equal to the maximum sum of the values of the stress components ( $P_m + P_b + Q_m + Q_b + F$ ) as defined in 6.4 (see Figure 1). The stress components  $Q$  and  $F$  are not necessarily uniform across the section and the values appropriate to the position of the flaw are relevant. Either the direct stress components perpendicular to the plane of the flaw should be used or the alternative procedure of resolving the flaw dimensions onto planes perpendicular to the principal stresses, as shown in Figure 2, should be adopted.

**8.1.2** In structures in the as-welded condition, the tensile residual stress (part or whole of  $Q$ ) should be assumed to be equal to the room temperature yield strength of the material in which the flaw is located for flaws lying in a plane transverse to the welding direction (i.e. stresses parallel to the weld) and to the lesser of the yield strengths of the weld or parent metal for flaws lying in a plane parallel to the welding direction (i.e. stresses perpendicular to the weld).

**8.1.3** In structures subject to post-weld heat treatment (PWHT), the residual stresses will not in general be reduced to zero. The level of residual stresses remaining after PWHT in welds 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 lower alloy steels that the stresses after heat treatment in an enclosed furnace in accordance with procedures such as those of BS 5500 are 30 % of the room temperature weld metal yield strength for stresses parallel to the weld, and 15 % of the room temperature weld metal yield strength for stresses transverse to the weld. Local heat treatment may leave significantly higher residual stresses and specific assessments should be made for each case (see references 7 and 8).

**8.1.4** Advantage may be taken of the reduction in peak residual stresses due to the application of a preliminary pressure test or other form of mechanical preloading for structures of satisfactory design and construction. No advantage can be taken if the stress distribution can reverse in sign compared to the preload.

When a proof test has been performed for subsequent fracture analyses at lower temperatures, the residual stress level after the proof test can be assumed to be the lower of

$$\sigma_{Y'} \text{ or } \left(1.4 - \frac{\sigma_n}{\sigma_f}\right) \sigma_{Y'}$$

where

- $\sigma_n$  is the net section stress under the proof load conditions (see 9.4.1 and appendix F);
- $\sigma_{Y'}$  is the appropriate material yield strength at the proof test temperature; and
- $\sigma_f$  is the flow strength (assumed to be the average of the yield and tensile strengths) at the proof test temperature (see reference 9).

A large fabrication flaw may survive a proof test and result in the assumed residual stress derived from the above formula being negative. In this case a value of zero should be assumed.

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

If an assessment is carried out on a case when a proof test is applied after a period in service, the effects of the proof test have to allow for any growth of flaws which may have occurred in service.

**8.1.5** 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, so these flaws should be assessed at level 2 or 3.

## 8.2 Stresses to be used in assessments at levels 2 and 3

**8.2.1** Assessments at levels 2 and 3 are based on the actual distribution of stresses in the vicinity of the flaw, where these are known. If the partial safety factor approach is being used the stresses should be multiplied by the appropriate factor (see appendix A). The stresses may be used directly as in 9.2.2 a) or may be split into membrane and bending components as in 9.2.2 b). For 9.2.2 b) the membrane and bending components of the primary stresses,  $P_m$  and  $P_b$ , and the membrane and bending components  $Q_m$  and  $Q_b$  of the secondary stresses, can be obtained by “linearization” as illustrated in Figure 3. If the resultant total stress intensity factor calculated is negative, the value used in assessments should be taken as zero. The peak stress  $F$ , is not required at levels 2 and 3 because peak stresses are included in the stress intensity magnification factors  $M_{km}$  and  $M_{kb}$  or the stress concentration factors  $K_m$  and  $K_t$  (see 9.2.2).

In certain situations thermal and residual stresses, often self-balancing throughout the structure, may act as primary stresses on a component. In these circumstances such thermal and residual stresses should be treated as primary stresses and be incorporated in the  $(Y\sigma)_p$  and  $S_r$  or  $L_r$  calculations of clause 9.

**8.2.2** If the actual distribution of residual stresses is known, it can be taken into account in levels 2 and 3, by the general principles of 6.4 and 8.1.

Where the distribution of residual stresses in an as-welded structure is unknown, then the residual stress component ( $\sigma_R$ ) of  $Q$  may be assumed to be uniform and equal to the appropriate material yield strength,  $\sigma_{Y'}$ , as for level 1 (see 8.1.2). The residual stress  $\sigma_R$  assumed in the analysis can be reduced to the lower of

$$\sigma_{Y'} \text{ or } \left(1.4 - \frac{\sigma_n}{\sigma_f}\right) \sigma_{Y'} \text{ for level 2}$$

or to the lower of

$$\sigma_{Y'} \text{ or } \left(1.4 - \frac{\sigma_n}{1.2\sigma_{Y'}}\right) \sigma_{Y'} \text{ for level 3}$$

where  $\sigma_n$  is defined in 9.4.1 and appendix F. (See references 7 and 10.)

In these formulae,  $\sigma_n$  can be taken as being the higher of the net section stress derived for the service condition or for any prior higher loading condition.

**8.2.3** A reasonable estimate of the residual stress distribution can be made for the stresses perpendicular to a plane through the toe of a fillet or T-butt weld on a thick base plate, as illustrated in Figure 4 a) (see reference 7). The extent of the tensile stress zone is a function of the heat input of the adjacent weld run. The idealized distribution as shown in Figure 4 b) permits the residual stresses to be represented as membrane and bending components  $Q_m$  and  $Q_b$  as shown. For flaw assessment purposes, the distribution in Figure 19 b) is relevant only to flaws at the weld toe in a plane perpendicular to the plate surface.

The distribution of residual stresses transverse to the weld at a butt weld is dependent on the restraint at the joint, as illustrated in Figure 4 (c), Figure 4 (d) and Figure 4 (e). High levels of restraint occur at joints such as girth welds in pipes, closure welds and patch-in-plate welds. The restraint is also sensitive to factors which may not be subject to rigorous procedural control, such as fabrication sequence, distortion control techniques, and weld repairs (see reference 7).

A typical distribution of stresses parallel to the weld at a butt weld is illustrated in Figure 4 (f) (see reference 7). Transverse weld flaws will normally be located within the zone of tensile stresses, whose width is greater than that of the weld itself. Even for flaws whose tips are located in the initially compressive zone, the net effect of the stress distribution is to produce a positive stress intensity factor. Hence it will normally be appropriate to assume that the flaw is subject to weld metal yield magnitude tensile residual stresses. Alternatively the stress intensity factor due to residual stresses may be calculated from the stress distribution over the flaw area using integrated weight function techniques.

**8.2.4** The comments on thermal and mechanical stress relief (proof test) given in 8.1.3 and 8.1.4 are also applicable at levels 2 and 3.

### 8.3 Flaw dimensions and interaction

**8.3.1** Planar flaws should be idealized by the height and length of their containment rectangles. These dimensions,  $2a$  for through flaws,  $a$  and  $2c$  for surface flaws, and  $2a$  and  $2c$  for embedded flaws, are shown in Figure 5 (a), Figure 5 (b) and Figure 5 (c). If the partial safety factor approach is being used for levels 2 and 3, the flaw dimensions after taking account of interactions (see 8.3.2) should be multiplied by the appropriate factor (see appendix A).

**8.3.2** 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 6, together with dimensions of effective flaws after interaction. If interaction between two adjacent flaws does occur, the revised flaw dimensions should be checked again for further interaction with adjacent flaws. The dimensions of the resulting containment rectangle should be used in the assessment.

More specific calculations of the increased severity attributable to the interaction of pairs or groups of flaws may be performed provided the methods are agreed by the parties concerned and account is taken of the implications of non-destructive testing resolution capability.

**8.3.3** Where regions of a structure are uninspectable due to the design, materials used, or obscuration by other flaws, the possibility should be considered that flaws of a size up to the size of the uninspectable region may be present. Such an assumption will normally be extremely pessimistic. When assessing the likelihood of the presence of such flaws, account may be taken of knowledge of the preparations and welding process and procedures used, and the general quality of welding attained.

### 8.4 Fracture toughness

**8.4.1** The fracture toughness of the material in which the flaw lies should preferably be established by a standardized testing technique appropriate to the particular assessment route followed. Fracture toughness data may be based on  $K$ -methods (including conversion from  $J$ -methods), or on CTOD methods, but a self-consistent assessment method has to be used throughout. The representative toughness values for use in the assessment are termed  $K_{mat}$  for  $K$ -methods, and  $\sigma_{mat}$  for CTOD methods in this document. If the partial safety factor approach is being used (see appendix A) the toughness values for levels 2 and 3 should be divided by the appropriate factor. No such factors should be applied for level 1. It is not permissible to convert between CTOD and  $J$ - or  $K$ -methods.

The desirability of having appropriate accurate toughness data cannot be emphasized too strongly, and it is vital that toughness data be obtained from weld procedure test samples at the time of construction and recorded if there is any likelihood of flaw assessment being required at any later stage.

If directly measured fracture toughness data are not available, guidance on possible methods of estimating toughness from Charpy V-notch energy results is given in appendix B. In view of the uncertainties of such correlations, they should be validated for specific applications if used at level 2, by reference to published results or databases for the appropriate type of material.

Fracture toughness tests should take account of orientation of flaws in the structure relative to welded joints, and of constraint, temperature and rate of loading in service. The tests should be carried out on samples welded with consumables and procedures as used for the service application and should take account of restraint during welding and of PWHT if applicable.

It is important that when statistical analyses of sets of fracture toughness data are carried out, the results should be divided into groups for the same fracture mechanism and material. Thus values taken at maximum load should be treated as a separate group from other cases, and different regions of welded joints should be tested and analysed separately.

With fracture toughness tests on heat-affected zone (HAZ) regions, considerable variability can occur due to location of the crack tip in different microstructural regions. It is 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 the same type and grain size.

**8.4.2** The material toughness measured in terms of the stress intensity factor is termed  $K_{\text{mat}}$  in this document. If linear elastic plane strain fracture toughness  $K_{\text{Ic}}$  values are used,  $K_{\text{mat}}$  should be taken as  $K_{\text{Ic}}$  and should be established using the methods of BS 5447. If valid  $K_{\text{Ic}}$  data cannot be obtained, it is preferable to use CTOD tests (see 8.4.3) and the CTOD assessment routes (see 8.4.3) or to derive equivalent  $K_{\text{mat}}$  values from  $J$ -based tests (see 8.4.4). Maximum load  $K_{\text{mat}}$  values may be used in certain circumstances for levels 1 and 2 by agreement of all parties concerned using equivalent energy or other agreed documented methods.

**8.4.3** If CTOD values are used these should be established using the methods of BS 5762. Tests should be carried out on the full thickness, rectangular geometry wherever possible, but where assessments involve certain types of flaw and flaw orientation (i.e. shallow surface flaws, or HAZ regions), the square specimen geometry may be appropriate.

The critical CTOD value in any test is termed  $\delta_{\text{mat}}$  in this document, and should be taken as  $\delta_{\text{c}}$ ,  $\delta_{\text{u}}$ , or  $\delta_{\text{m}}$ , whichever is the lowest.

For level 1 and level 2 assessment procedures, stable tearing may be accepted up to values at maximum load in three point bend tests ( $\delta_{\text{m}}$ ). However, if the ligament in the structural situation is less than that in the test specimen, the value obtained in the toughness tests should be reduced by the ratio of the uncracked ligaments, to give the ( $\delta_{\text{mat}}$  value for application to the structure. For level assessment procedures, a full tearing resistance curve is required for tearing analyses, as described in 8.4.5.

**8.4.4** Where agreed by the parties concerned,  $J$ -contour integral based methods of fracture toughness testing may be used. The value of  $J$  at 0.2 mm total crack extension should be regarded as the initiation toughness for ferritic steels (see references 11, 12 and 13). For other materials the value should be determined by agreement. For treatment of further tearing resistance see 8.4.5. Where specimen thicknesses less than the full application thickness are used, the specimen geometry should satisfy the following unless agreed otherwise:

$$B \text{ or } (W - a) \text{ or } a > 25 \left( \frac{J_{\text{mat}}}{\sigma_Y} \right)$$

The  $J_{\text{mat}}$  value so obtained may be converted to an equivalent  $K_{\text{mat}}$  value using:

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

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 which actually occurs.

**8.4.5** The fracture tearing resistance,  $K_{\text{mat}}$  or  $\delta_{\text{mat}}$ , defined as a function of the amount of ductile crack extension or tearing,  $\Delta a$ , is for use only in the level 3 analysis. Although there are currently no nationally agreed standards several standardized test methods have been published, such as those of the CEEB (see reference 11) and TWI (see reference 12) leading to a European Group on Fracture (EGF) document (see reference 13), and these may be used by agreement. The test method employed will produce a  $K_{\text{mat}}$  or  $\delta_{\text{mat}}$  curve as a function of  $\Delta a$ , from either a single specimen or a set of specimens. When the single specimen method is used data should be obtained from at least three single specimen tests and the minimum composite curve adopted. Where a set of specimens is used at least four and preferably six specimens are needed and a lower bound curve used. In both cases, where there is considerable scatter in the data, increased confidence 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 region for ferritic steels, specimens of full thickness may fail by cleavage fracture whereas specimens 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 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 for these effects may be obtained from evidence in the literature and from data banks (see reference 14).

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 which 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  $\Delta a_g$ .

The parameter involved are as follows:

- a)  $\Delta a_g$  is the limit of tearing crack extension over which the analysis may be performed, and is defined as the smallest value of:
  - 1) for specimens equal in thickness to the structures, 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  $\delta_g$ , is the value of  $K_{\text{mat}}$  or  $\delta_{\text{mat}}$  at  $\Delta a_g$ .

- c)  $K_{\text{mat}}$  or  $\delta_{\text{mat}}$  may then be defined by an equation dependent on the crack extension,  $\Delta a$ , between  $\Delta a_0$  and  $\Delta a = \Delta a_g$ , or as point to point values at discrete quantities of  $\Delta a$  between the same limits. For ferritic steels  $\Delta a_0$  may be taken as 0.2 mm.

## 8.5 Number of tests

**8.5.1** For level 1 assessment procedures the fracture toughness value  $K_{\text{mat}}$  or  $\delta_{\text{mat}}$  may be taken as the minimum value of three similar test results all showing either brittle fracture, or all showing tearing up to maximum load. Caution should be exercised when for  $\delta_{\text{mat}}$  the minimum value is less than 50 % of the average of three such CTOD tests, or the maximum value is more than twice the average of three such CTOD tests. Similarly for  $K_{\text{mat}}$  when the minimum value is less than 70 % of the average of three, or the maximum value is more than 1.4 times the average of three, as this indicates 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 made is given in appendix A; the intermediate value recommended should be at least as safe as using the lowest of three results. Appendix A 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 the same microstructure when carrying out statistical analyses (see 8.4.1).

## 8.6 Pop-in behaviour

Test results in which pop-in behaviour is observed should be examined by the procedures detailed in appendix C.

## 8.7 Tensile test properties

For level 1 and level 2 assessment methods, the material yield strength ( $\sigma_Y$ ), tensile strength ( $\sigma_u$ ), and modulus of elasticity ( $E$ ) are required from tests in accordance with BS EN 10 002-1 or BS 3688-1 at the appropriate temperature. The weld metal strength should be taken as the lower yield or 0.2 % proof strength as appropriate. The flow stress,  $\sigma_f$ , is defined as the average of  $\sigma_Y$  and  $\sigma_u$ . In welded joints the properties required are those for the region in which a flaw assessment is to be carried out. Heat-affected zone regions should be assumed to have properties which are the higher of adjacent weld metal or parent metal in deriving CTOD toughness values from fracture toughness tests, but should be assumed to have the lower of adjacent weld metal or parent metal for application to assessment of flaws in structures.

For level 3 assessment methods an engineering stress/strain curve is required describing the material behaviour at the appropriate temperature for parent material and for weld metal (but not HAZ). The lower yield or 0.2 % proof strength, tensile strength, and modulus of elasticity should be determined together with sufficient coordinate stress/strain points to define the full curve. Particular attention should be paid to defining the shape of the stress/strain curve for strains below 1 %.

It is recommended that the stress/strain curve should be accurately defined at the following ratios of  $\sigma/\sigma_Y$ ;

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

For HAZ regions and in other circumstances where the determination of a stress/strain curve is not practicable, the yield strength data adopted for the level 1 and 2 treatments can be used to derive a conservative assessment diagram as described in 12.2

## 9 Parameters required for different assessment levels (and methods)

### 9.1 Net area, misalignment stress concentration and bulging effects

The estimation methods for stress intensity factor  $K_I$  and CTOD  $\delta_I$  in 9.2 and 9.3 respectively do not allow for situations where the flaw area is significant compared to the loadbearing cross-sectional area, where misalignment or angular distortion occurs, or for long flaws in curved shells subject to internal pressure where bulging effects may occur.

Where the actual flaw area is greater than 10 % of the loadbearing cross-sectional area, and no finite width correction has already been included, the values of  $(Y\sigma)$  used in the estimation of  $K_I$  or  $\delta_I$  should be multiplied by the factor  $f(ac/A_1)$ , where:

for embedded flaws

$$f(ac/A_1) = \{\sec(2\pi ac/A_1)\}^{0.5} \quad (2)$$

for surface flaws

$$f(ac/A_1) = \{\sec(\pi ac/A_1)\}^{0.5} \quad (3)$$

where

$a$  and  $c$  are flaw dimensions as defined in 8.3.1; and

$A_1$  is the full loadbearing cross-sectional area containing the flaw (see reference 15).

For through thickness flaws the finite width correction reduces to  $\{\sec(\pi a/W)\}^{0.5}$ .

Geometric stress concentrations in the region containing a flaw should be taken into account (see 6.4.1). Effects of misalignment or angular distortion should be taken into account by calculating the additional bending stresses as described in appendix D. These effects can be very significant in fracture assessments.

For flaws in curved shells subject to internal pressure, the values of  $P_m$  and  $P_b$  used for primary stresses in the estimation of  $K_I$  or  $\delta_I$  should be multiplied by the factor  $M$ , defined as follows unless justified otherwise (see references 16 and 17).

a) For through thickness flaws in spheres, and for axial through thickness flaws in pipes and cylinders:

$$M = M_T = \{1 + 3.2(a^2/DB)\}^{0.5} \quad (4)$$

b) For surface flaws in spheres, and for axial surface flaws in pipes:

$$M = M_S = \frac{1 - \{a/(BM_T)\}}{1 - (a/B)} \quad (5)$$

where:

$$M_T = \{1 + 3.2(c^2/DB)\}^{0.5}$$

c) For other cases, e.g. embedded flaws, circumferential flaws in pipes:

$$M = 1$$

where  $D$  and  $B$ , are the shell diameter and thickness respectively.

## 9.2 Estimation of applied stress intensity factor $K_I$

### 9.2.1 Level 1 approach

The applied stress intensity factor should be estimated as follows.

- a) For through thickness flaws the stress intensity factor  $K$  due to the idealized flaw defined in 8.3 should be calculated from:

$$K_I = \sigma_1 \sqrt{(\pi a)} \quad (6)$$

where

$\sigma_1$  is the maximum tensile stress ( $P_m + P_b + Q + F$ ), which is assumed to be uniform across the section; and

$2a$  is the flaw length (see 8.1 and 8.3).

Partial safety factors on stress and flaw size are not required for level 1.

- b) For partial thickness flaws, the maximum tensile stress is again assumed to be uniform (over the flaw length) whence:

$$K_I = \frac{M_m}{\Phi} \sigma_1 \sqrt{(\pi a)} \quad (7)$$

where

$\Phi$  is the elliptic integral shown graphically in Figure 7; and

$M_m$  is the flaw shape factor given in Figure 8 and Figure 9 for embedded and surface flaws in tension.

### 9.2.2 Level 2 and 3 approaches

Stress intensity factors should be estimated using a method which takes full account of the stress profile, and includes the partial safety factors on stress and flaw size from appendix A where appropriate.

- a) Values of stress intensity factor may be obtained using handbook solutions (see references 18 and 19), numerical analysis methods or weight function techniques (see reference 20), but the basis of the method and the results should be fully documented. Stresses and flaw dimensions should be multiplied by the relevant partial safety factor from appendix A where appropriate.
- b) Stress intensity factors may be obtained from the linearized stress distribution using the general equation:

$$K_I = (Y\sigma) \sqrt{(\pi a)} \quad (8)$$

where

for through thickness flaws  $a$  is the half flaw length;

for surface flaws  $a$  is the full flaw height; and

for embedded flaws  $a$  is half the flaw height; and

$$Y\sigma = (Y\sigma)_p + (Y\sigma)_s \quad (9)$$

where

for primary stresses

$$(Y\sigma)_p = \frac{1}{\Phi} (M_{km} M_m P_m + M_{kb} M_b P_b) \quad (10)$$

for secondary stresses

$$(Y\sigma)_s = \frac{1}{\Phi} (M_m Q_m + M_b Q_b) \quad (11)$$

In the presence of stress concentrations due to structural discontinuities, the primary and thermal stresses (but not residual stresses) should be magnified using the appropriate stress concentration factors, namely  $K_m$  for stress concentrations due to material misalignment (see appendix D) or  $K_t$  for stress concentration due to the structural configuration in the vicinity of the flaw.

Parametric formulae for  $\Phi$ ,  $M_m$ ,  $M_b$ ,  $M_{km}$  and  $M_{kb}$  are given in appendix E. In addition values of  $\Phi$  are given in Figure 7, of  $M_m$  in Figure 8 and Figure 9 for embedded and surface flaws respectively in tension, and of  $M_b$  in Figure 10 and Figure 11 for embedded and surface flaws respectively in bending.

The values of  $M_{km}$  and  $M_{kb}$  given in appendix E for the important cases of cracks at a weld toe are dependent on two non-dimensional ratios:

$L/B$ , the total surface attachment length between weld toes to main material thickness ratio [see Figure 5 d)];

$a/B$ , the crack depth to main material thickness ratio.

For embedded flaws the  $M_{km}$  and  $M_{kb}$  parameters may be taken as unity. For surface flaws these parameters may also be taken as unity for flaws with values of  $(a/B)$  greater than 0.2.

### 9.2.3 Parameter $K_r$

The parameter  $K_r$  is the ratio of the stress intensity factor  $K_I$  derived from 9.2.1 or 9.2.2 as appropriate, to the fracture toughness  $K_{mat}$ . For levels 2 and 3, if the partial safety factor approach is used, these factors have to be applied to stresses, flaw size and toughness in determining  $K_r$  (see appendix A).

Where secondary stresses are present, an additional adjustment  $\rho$  is necessary for level 2 and 3 assessments to allow for plasticity interactions of the primary and secondary stresses (see reference 21), such that:

$$K_r = \frac{K_I}{K_{mat}} + \rho \quad (12)$$

where  $\rho$  is given in Figure 12.

### 9.3 Estimation of applied crack tip opening displacement $\delta_I$

#### 9.3.1 Level 1 approach

The applied CTOD  $\delta_I$  is determined from the following equations, using  $K_I$  defined from 9.2.1.

For steels (including stainless steels) and aluminium alloys for  $\sigma_1/\sigma_Y \leq 0.5$  and for all  $\sigma_1/\sigma_Y$  ratios for other materials:

$$\delta_I = \frac{K_I^2}{\sigma_Y E} \quad (13)$$

For steels (including stainless steels) and aluminium alloys for  $\sigma_1/\sigma_Y > 0.5$ :

$$\delta_I = \frac{K_I^2}{\sigma_Y E} \left( \frac{\sigma_Y}{\sigma_1} \right)^2 \left( \frac{\sigma_1}{\sigma_Y} - 0.25 \right) \quad (14)$$

where  $\sigma_Y$  is the yield strength of the material in which the flaw lies.

#### 9.3.2 Level 2 and 3 approaches

The applied CTOD  $\delta_I$  is determined from the following equation:

$$\delta_I = \frac{(Y\sigma)^2 \pi a}{\sigma_Y E} \quad (15)$$

where  $Y\sigma$  is as given in 9.2.2, and  $\delta_I$  includes partial safety factors where appropriate from appendix A.

#### 9.3.3 Parameter $\delta_r$

For all cases of level 1, and for levels 2 and 3 without secondary stresses, the parameter  $\delta_r$  is the ratio of the applied CTOD derived from 9.3.1 or 9.3.2, as appropriate, to the fracture toughness  $\delta_{mat}$ , including partial safety factors where appropriate from appendix A.

Where secondary stresses are present for level 2 and 3 assessments, an additional adjustment  $\rho$  is necessary to allow for plasticity interactions of the primary and secondary stresses such that

$$\sqrt{\delta_r} = \sqrt{\left( \frac{\delta_I}{\delta_{mat}} \right)} + \rho \quad (16)$$

where  $\rho$  is given in Figure 12.

### 9.4 Estimation of the plastic collapse ratio $S_r$ or $L_r$

#### 9.4.1 Level 1 and 2 approaches: estimation of $S_r$

To calculate the  $S_r$  ratio, estimates are required of the collapse load of the cracked section or structure. These usually require consideration of net section stresses, but also have to take account of interactions between tension and bending on collapse behaviour. A set of simple solutions for effective net section stress on  $\rho_n$  is given in appendix F. A fuller review of solutions for more complex geometries may be obtained from references 17 and 22.

The parameter  $S_r$  is given by:

$$S_r = \frac{\sigma_n}{\sigma_f} \quad (17)$$

where  $\sigma_f$  is defined as the flow strength of the material. The flow strength should be assumed to be the average of the yield strength and the tensile strength up to a maximum of  $1.2\sigma_Y$ . For values of flow strength above  $1.2\sigma_Y$ ,  $\sigma_f$  should be taken as  $1.2\sigma_Y$  in the calculation of  $S_r$ .

For level 1 no partial safety factors on stress should be used to calculate  $\sigma_n$ , but for level 2, the partial factors on stress in appendix A should be used where appropriate.

#### 9.4.2 Level 3 approach: estimation of $L_r$

For the level 3 approach the parameter  $L_r$  is required where  $L_r = \sigma_n/\sigma_Y$ . The partial safety factors on stress from appendix A should be used where appropriate.

## 10 Level 1, preliminary assessment

### 10.1 General

This clause provides a simplified method of checking whether particular flaws present a fracture problem, or whether the flaws can be considered safe without having to use the more complex assessment procedures of clauses 11 and 12. The approach adopted in this preliminary assessment is consistent with that of PD 6493:1980 and incorporates a variable safety factor on flaw size averaging about 2. No additional partial safety factors from appendix A should be used in level 1 assessments.

## 10.2 Treatment where estimates of $K_{\text{mat}}$ are available

### 10.2.1 General

This treatment is applicable if a reliable  $K_{\text{mat}}$  can be estimated. Values of  $K_{\text{mat}}$  derived from  $J$ - or invalid  $K$ -tests may have to be adjusted to take account of the different constraint conditions present in the test piece to those of plane strain, see 8.4.

### 10.2.2 Estimation of the acceptability of known flaw

The flaw is acceptable if  $K_r$  is less than  $1/\sqrt{2}$  (i.e. less than 0.707) and  $S_r$  is less than 0.8 [see Figure 13 (a)]. As this is a level 1 procedure, no additional partial safety factors are required.

### 10.2.3 Estimation of acceptable flaw size

An equivalent flaw parameter  $\bar{a}$  is defined as the half length of a through thickness flaw in an infinite plate subject to remote tension loading. A preliminary estimate of acceptable flaw sizes can be obtained by calculating  $\bar{a}_m$  from the following relationship,

$$\bar{a}_m = \frac{1}{2\pi} \left( \frac{K_{\text{mat}}}{\sigma_1} \right)^2 \quad (18)$$

The flaw parameter  $\bar{a}_m$  may represent a variety of different flaw shapes and dimensions of equivalent severity. Equivalent part thickness flaw dimensions can be obtained from Figure 14 and Figure 15. Finite width corrections may be required, see 9.1. The resulting flaw dimension has to be checked as acceptable for no plastic collapse by calculating the associated  $S_r$  value. If  $S_r$  is less than 0.8 the flaw is acceptable. If the  $S_r$  value is greater than 0.8, the flaw dimensions have to be reduced to give an  $S_r$  value not exceeding 0.8.

## 10.3 Treatment where toughness is available as CTOD ( $\delta_{\text{mat}}$ )

### 10.3.1 General

In this case, measurements (in accordance with BS 5762 procedures) or estimates of  $\delta_{\text{mat}}$  (see 8.4) are used as input to the procedure.

### 10.3.2 Estimation of the acceptability of a known flaw

The flaw is acceptable if  $\sqrt{\delta_r}$  (see 9.3.3 for the definition of  $\delta_r$ ) is less than  $1/\sqrt{2}$  (i.e. less than 0.707) and  $S_r$  is less than 0.8 [see Figure 13 (a)]. As this is a level 1 procedure, no additional partial safety factors are required.

In cases where the loading conditions are strain controlled, or where there is contained plastic deformation, the stress based plastic collapse solutions may be unnecessarily restrictive. In these cases the acceptability of a known flaw may be assessed by comparing the equivalent flaw dimension  $\bar{a}$  obtained using Figure 14 or Figure 15 for the flaw with the acceptable flaw size  $\bar{a}_m$  determined in accordance with 10.3.2 using the strain ratio  $e/e_Y$  to calculate  $C$  from fig 16.

### 10.3.3 Estimation of acceptable flaw size

The equivalent tolerable flaw parameter  $\bar{a}_m$  is given by the following relationship which includes a variable safety factor, averaging about 2. (See appendix A for general guidance on safety factors, but no additional partial safety factors are required for level 1.)

For steels (including stainless steels) and aluminium alloys, where  $\sigma_1/\sigma_Y \leq 0.5$  and for all other materials for all  $\sigma_1/\sigma_Y$  ratios,

$$\bar{a}_m = \frac{\delta_{\text{mat}} E}{2\pi \left( \frac{\sigma_1}{\sigma_Y} \right)^2 \sigma_Y} \quad (19)$$

For steels (including stainless steels) and aluminium alloys where  $\sigma_1/\sigma_Y > 0.5$ ,

$$\bar{a}_m = \frac{\delta_{\text{mat}} E}{2\pi \left( \frac{\sigma_1}{\sigma_Y} - 0.25 \right) \sigma_Y} \quad (20)$$

where  $\bar{a}_m$  is defined in 10.2.3. Equations (19) and (20) are shown in diagrammatic form in Figure 16. The resulting flaw dimensions have to be checked for plastic collapse as in 9.4, except in the specialized circumstances of strain controlled loading (see 10.3.2).

In cases where there is no risk of plastic collapse, e.g.  $S_r < 0.8$ , the applied strain ratio  $e_1/e_Y$  ( $\equiv \sigma_1/\sigma_Y$ ) can be used with equations (19) and (20) or in Figure 16 to estimate  $\bar{a}_m$  up to an applied strain ratio of 2. For strain ratios exceeding 2, 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 elastic plastic finite element analyses may be used. In applications where the component under consideration has a finite width and the calculated  $\bar{a}_m$  value exceeds one twentieth of the total width, then the calculated  $\bar{a}_m$  value should be multiplied by

$$\frac{1}{(2\bar{a}_m/W) + 1}$$

where  $W$  is the width of the component (see reference 23).

Having obtained the flaw parameter  $\bar{a}_m$ , equivalent part-thickness embedded flaw and surface flaw dimensions can be derived from Figure 14 and Figure 15 respectively.

## 11 Level 2, normal assessment

### 11.1 General

The level 2 method is based on the plane stress strip yield model approach and does not have an arbitrary safety factor incorporated. Thus due allowance has to be made for uncertainties and variability in toughness, stress levels and other data. As an alternative to worst case estimates the partial safety factor approach from appendix A can be used to obtain the required reliability. As with the level 1 approach it is possible to carry out the approach using estimates of  $K_{mat}$  or  $\delta_{mat}$ . Where  $K_{mat}$  data are available then the  $K$  route should be adopted, otherwise the  $\delta$  route using CTOD results is recommended.

### 11.2 Estimation of the acceptability of a known flaw

For the known flaw, the parameters  $K_r$  or  $\delta_r$  and  $S_r$  are calculated (as defined in clause 9) and including partial safety factors from appendix A where appropriate, and the resulting point is plotted on the failure assessment diagram given in Figure 13 (b). The equation of the assessment curve is given by:

$$\sqrt{\delta_r} \text{ or } K_r = S_r \left( \frac{8}{\pi^2} \ln \sec \left( \frac{\pi}{2} S_r \right) \right)^{-0.5} \quad (21)$$

If the point lies within the assessment curve then the flaw is acceptable; if the point lies on or outside the line then the flaw is not acceptable.

### 11.3 Estimation of limiting flaw size

The limiting flaw size  $a_m$  is defined by an assessment point which lies on the failure assessment line given in Figure 13 (b). This may be determined graphically, by plotting a series of assessment points as a function of flaw size or analytically using an iterative technique to determine the flaw size which satisfies the following equation:

$$K_I = K_{mat} \left( \left[ S_r \left( \frac{8}{\pi^2} \ln \sec \left( \frac{\pi}{2} S_r \right) \right)^{-0.5} \right] - \rho \right) \quad (22)$$

or

$$a_m = \frac{E\sigma_Y \delta_{mat} \left( \left[ S_r \left( \frac{8}{\pi^2} \ln \sec \left( \frac{\pi}{2} S_r \right) \right)^{-0.5} \right] - \rho \right)^2}{\pi(Y\sigma)^2} \quad (23)$$

In these equations,  $Y\sigma [= K_I/\sqrt{(\pi a)}]$  and  $S_r (= \sigma_n/\sigma_f)$  are functions of flaw size, thus an iterative procedure has to be adopted to determine  $a_m$ .

An initial estimate for  $a_m$  values to commence the iterative procedures may be obtained using either 10.2.3 or 10.3.3 as appropriate.

## 12 Level 3, advanced assessment

### 12.1 General

The level 3 method makes use of an assessment diagram derived from the stress/strain curve of the material, as defined in 8.7 (see reference 24). This allows advantage to be taken of any high work hardening characteristics of the material. Where failure occurs by ductile tearing the effect on fracture toughness can be allowed for. A partial safety factor approach may be adopted by agreement, but the values given in appendix A have only been calibrated for level 2.

### 12.2 Assessment diagram

**12.2.1** The assessment diagram is constructed by plotting values of  $K_r$  or  $\sqrt{\delta_r}$  against  $L_r$ , where for  $L_r \leq L_{r,max}$ .

$$K_r \text{ or } \sqrt{\delta_r} = \left\{ \frac{E \ln(1 + \epsilon)}{\sigma(1 + \epsilon)} + \frac{\sigma^3(1 + \epsilon)^3}{2\sigma_Y^2 E \ln(1 + \epsilon)} \right\}^{-0.5} \quad (24)$$

and for  $L_r > L_{r,max}$ .

$$K_r \text{ or } \sqrt{\delta_r} = 0$$

For the derivation of the assessment diagram the  $L_r$  axis is defined as the ratio of  $\sigma(1 + \epsilon)/\sigma_Y$  where  $\sigma$  is any value of stress on the materials engineering stress/strain curve at a strain of  $\epsilon$  and  $\sigma_Y$  is the lower yield or 0.2 % proof strength of the material (see clause 8).

The assessment curve should be plotted using  $K_r$  or  $\sqrt{\delta_r}$  values corresponding to  $L_r = 0, 0.7, 0.9, 0.98, 1.0, 1.02, 1.1, 1.2 \dots$  up to  $L_{r,max}$ . It is particularly important to define the curve accurately in the region  $L_r = 1.0$ .

The value of  $L_{r,max}$  is given by  $(\sigma_Y + \sigma_u)/(2 \sigma_Y)$ . In the plotting of the assessment diagram, no safety factors should be applied, and the actual experimental data should be used.

Examples of typical failure assessment diagrams are given for three different stress/strain curves in appendix G. Where no stress/strain data are available, the assessment diagram in Figure 13 (c) may be used.

**12.2.2** For circumstances where the stress/strain curve may be uncertain (e.g. HAZ regions) but a tearing instability analysis is required, then the failure analysis diagram shown in Figure 13 (c) can be adopted. This is suitable for all materials which do not exhibit a yield discontinuity in the stress/strain curve, and is described by the equations:

$$K_r = (1 - 0.14 L_r^2) \times \{0.3 + 0.7 \exp(-0.65 L_r^6)\} \quad (25)$$

for  $L_r < L_{r,max}$ .  
 $K_r = 0$  for  $L_r > L_{r,max}$ .

For materials showing a yield discontinuity,  $L_r$  should be restricted to 1.0 or a level 2 treatment should be adopted.

### 12.3 Estimation of acceptability of a known flaw

**12.3.1** In the actual assessment, if partial safety factors are used they should be applied to stress, flaw size and toughness where appropriate.

**12.3.2** When  $K_{mat}$  or  $\delta_{mat}$  represents a single value of toughness, the parameters  $K_r$  or  $\delta_r$ , and  $L_r$  are calculated as defined in clause 9. The resulting point is plotted on the failure assessment diagram derived from 12.2. If the point lies within the assessment curve then the flaw is acceptable; if the point lies on or outside the line then the flaw is not acceptable.

**12.3.3** When  $K_{mat}$  or  $\delta_{mat}$  is available in the form of a resistance curve a tearing analysis may be carried out as follows.

- Define the size of known flaw,  $a_0$ , and multiply by partial safety factor if appropriate.
- Define  $K_{mat}$  or  $\delta_{mat}$  (see 8.4), and divide by partial safety factor if appropriate.
- Define  $\Delta a_g$  (see 8.4.5).

d) If  $\Delta a_g < 1.0$  mm, calculate  $L_r = \sigma_n/\sigma_Y$  and either

$$K_r = K_I/K_g \text{ or } \delta_r = \frac{K_I}{\sigma_Y E \delta_g}$$

where  $K_I$  and  $\sigma_n$  are evaluated 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,  $\Delta a_j$ , 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,  $\Delta a_j$ , 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  $L_r = \sigma_n/\sigma_Y$  and either

$$K_r = K_I/K_{mat} \text{ or } \delta_r = \frac{K_I^2}{\sigma_Y E \delta_{mat}}$$

where  $K_I$ ,  $K_{mat}$  and  $\sigma_n$  are evaluated at flaw lengths  $a = a_0, a_0 + \Delta a_1, a_0 + \Delta a_2, \text{ etc.}$ , including partial safety factors if appropriate.

f) Plot all pairs of  $L_r$ ,  $K_r$  or  $L_r$ ,  $\sqrt{\delta_r}$  as coordinate points on the failure assessment diagram.

g) The limiting loading condition occurs when a locus drawn through the assessment points touches the failure assessment line at one point only, all other points on the locus lying outside the area bounded by the axes and the line. A factor may be specified with respect to load,  $F_L$ , as follows:

$$F_L = \frac{\text{load which would produce limiting condition}}{\text{applied load assessed}}$$

and may be evaluated by changing the value of the load of interest until the limiting condition is obtained. When the structure is subjected to one primary load only this may be found by scaling each point on the locus linearly from the origin to the failure assessment line, whence  $F_L$  is defined as the maximum value in the scaling factors. When the structure is subjected to more than one load, whether primary or secondary, only the load of interest has to be changed, and in this case the scaling factors are not generally linear.

### 12.4 Estimation of limiting initial flaw size

The limiting initial flaw size,  $a_i$ , is that flaw size which produces a locus drawn through the assessment points which touches the failure assessment line at one point only. All other points on the locus lie outside the area bounded by the axes and the assessment line.

This corresponds to the limiting load factor,  $F_L$  [see 12.3 g)] equal to unity, and is most easily obtained from a plot of  $F$  as a function of initial flaw size.

## 13 Fracture assessment for non-planar flaws, imperfect shape and fillet welds

### 13.1 Non-planar flaws

For non-planar flaws existing in ferritic materials with yield strengths not greater than  $450 \text{ N/mm}^2$  and having an average Charpy V-notch energy absorption of not less than 40 J for three tests with a minimum individual value of 28 J at the minimum service temperature, the limits of Table 1 are acceptable for porosity and solid inclusions. For other materials the limits of Table 1 are acceptable provided the fracture toughness ( $K_{Ic}$ ) of the material in which the flaw lies exceeds  $1250 \text{ N mm}^{-3/2}$ . For materials of lower toughness these flaws should be assessed on the basis of their dimensions as planar flaws.

**Table 1— Limits for slag inclusions and porosity**

| Slag inclusions              | Porosity                                   |                                     |
|------------------------------|--------------------------------------------|-------------------------------------|
|                              | Percentage of projected area on radiograph | Individual pore diameter            |
| No limit on length.          | %                                          |                                     |
| Maximum height or width 3 mm | 5                                          | $B/4$ or 6 mm, whichever is smaller |

### 13.2 Imperfect shape (including undercut)

**13.2.1** Variations in weld profile from that specified, which could give a weld throat dimension below that needed to carry the maximum allowable design stresses, are unacceptable.

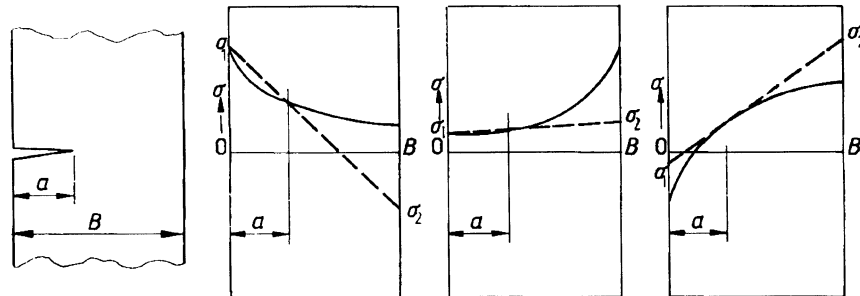
**13.2.2** Undercut may prevent detection of other flaws by non-destructive testing. If it can be shown that no planar flaws exist other than undercut, then, for steels with a yield strength up to  $450 \text{ N/mm}^2$  having a Charpy V-notch energy absorption of not less than 40 J at the minimum service temperature, undercut to a maximum depth of 1 mm or 10 % of the thickness, whichever is the lesser, is acceptable. All other cases of undercut should be assessed as planar flaws.

### 13.3 Fillet welds

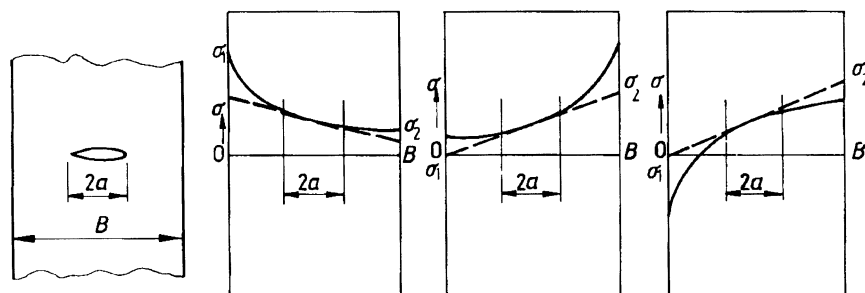
It is not normally necessary to consider the effects of flaws contained within the weld metal of fillet welds on fracture behaviour in normal structural applications except for low service temperatures or impact loading where tension loading is applied. In such cases, it is possible in principle to calculate stress intensity factors for the particular geometry, and apply the general methods of the fracture assessment clauses, although there will be considerable uncertainties about toughness, residual stresses and flaw dimensions.

Flaws in fillet welds which may affect the static strength of the weld do so through their effect on the cross-sectional area. The real stressing situation in fillet welds is complex, particularly under combined loading situations. It is recommended that the maximum shear stress should be calculated on the net minimum throat area, by combining the normal, parallel shear and perpendicular shear components as in the IIW method (see reference 25). This maximum shear stress should not exceed 0.48 times the minimum tensile yield strength of the weld metal used.

There will be a significant effect of flaws in fillet welds on fatigue performance for potential failure on the weld throat (see section 3).



Examples of linearization of stress distributions for surface flaws

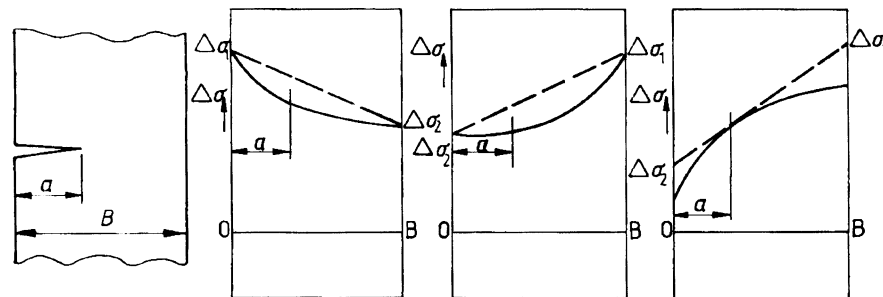


Examples of linearization of stress distributions for embedded flaws

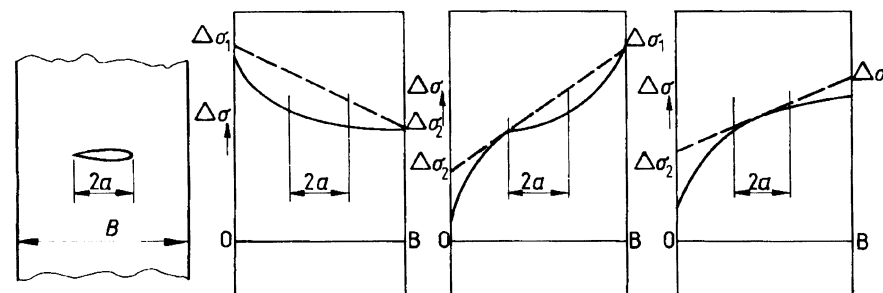
$$\sigma_m = \frac{\sigma_1 + \sigma_2}{2} \quad \sigma_b = \frac{\sigma_1 - \sigma_2}{2}$$

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

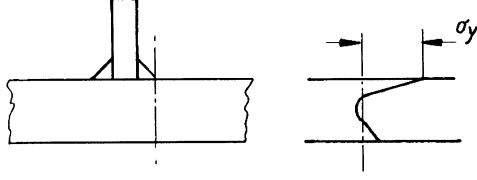
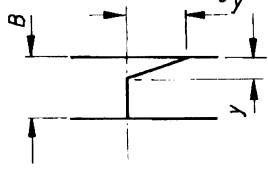
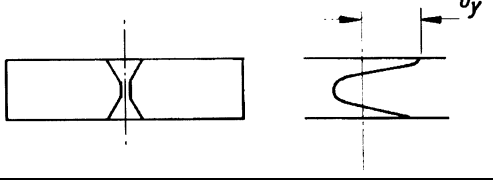
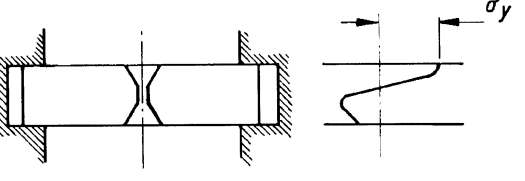
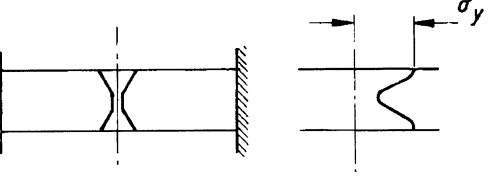
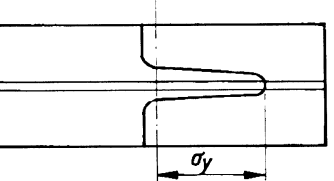


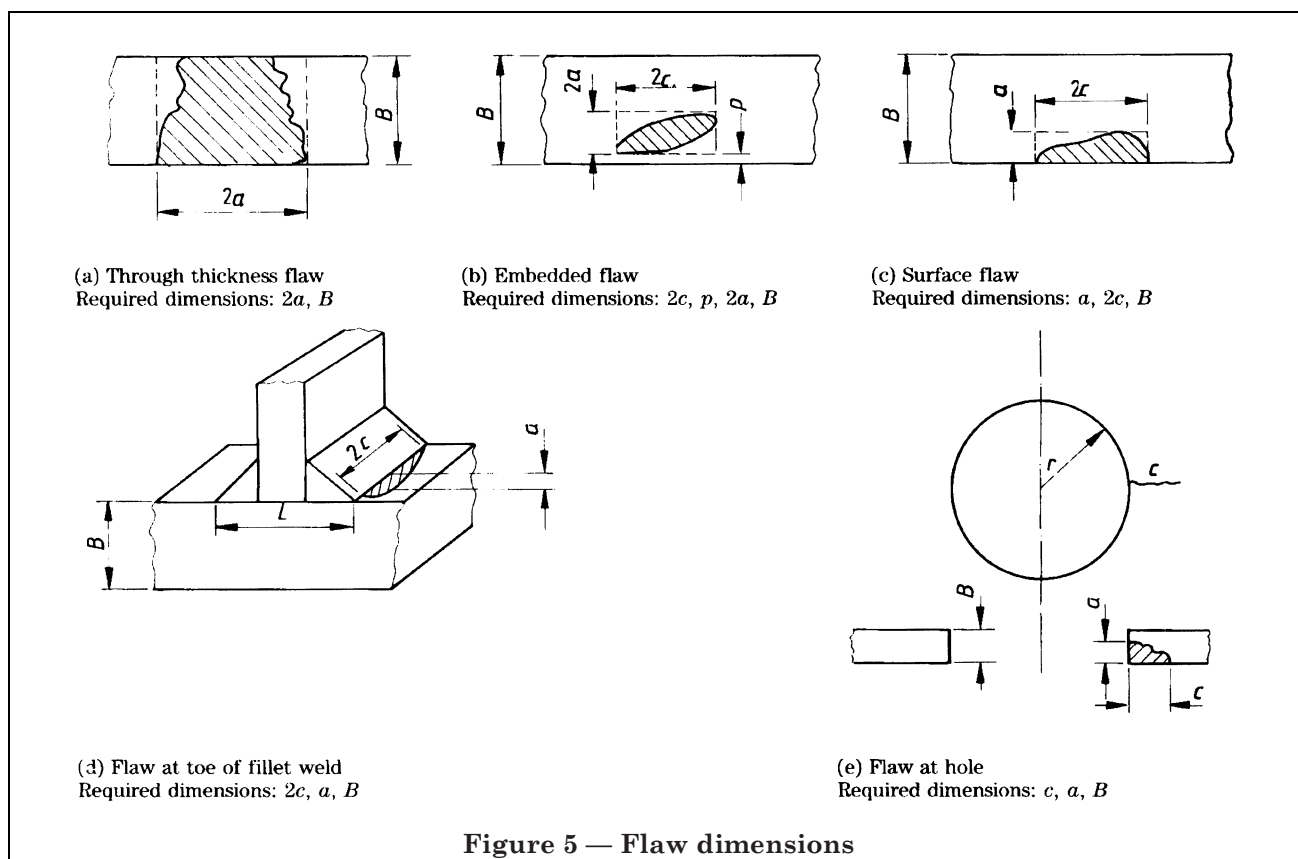
Examples of linearization of stress range distributions for embedded flaws

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

(b) Linearization of stress range distributions in fatigue assessments

Figure 3 — Linearization of stress distributions

|                                                                                                               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (a) Variation through-thickness of base plate of transverse residual stresses at toe of fillet or T-butt weld |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| (b) Idealized distribution of transverse residual stresses at toe of fillet or T-butt weld                    | <p>For carbon manganese steel</p> $y = \left( \frac{122 q}{\sigma_y v} \right)^{0.5}$ <p>where <math>q/v</math> is the heat input of the weld run adjacent to flaw (in J/mm), <math>y</math> (in mm), <math>\sigma_y</math> (in N/mm<sup>2</sup>) and <math>y &lt; B</math>. If <math>y &gt; B</math>, assume residual stress <math>\sigma_y</math> throughout thickness.</p> <p>Then for <math>a &lt; y</math></p> $Q_m = \sigma_y \{1 - (B/2y)\}$ $Q_b = \sigma_y (B/2y)$ <p>and for <math>a \geq y</math></p> $Q_m = Q_b = 0$  |
| (c) Variation through-thickness of transverse residual stresses at unrestrained butt weld                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| (d) Variation through-thickness of transverse residual stresses at butt weld with membrane restraint          | <p>Second side welded</p>  <p>First side welded</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| (e) Variation through-thickness of transverse residual stresses at butt weld with bending restraint           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| (f) Variation across panel of longitudinal residual stresses at but weld                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Figure 4 — Typical distributions of residual stresses at welds                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |



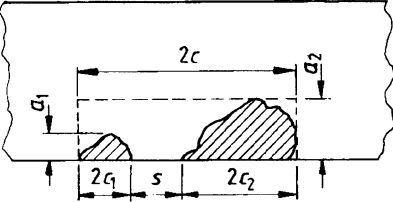
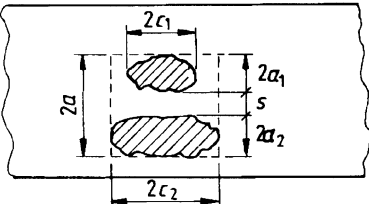
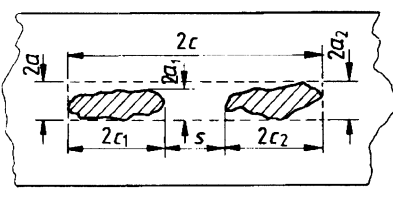
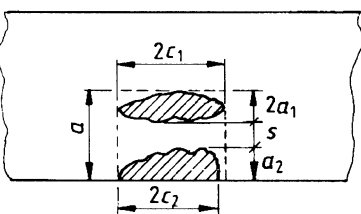
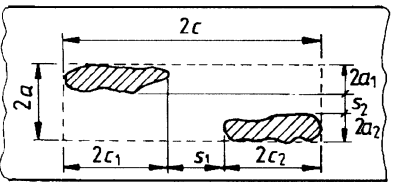
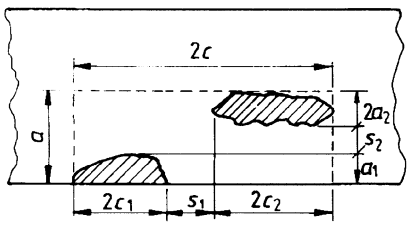
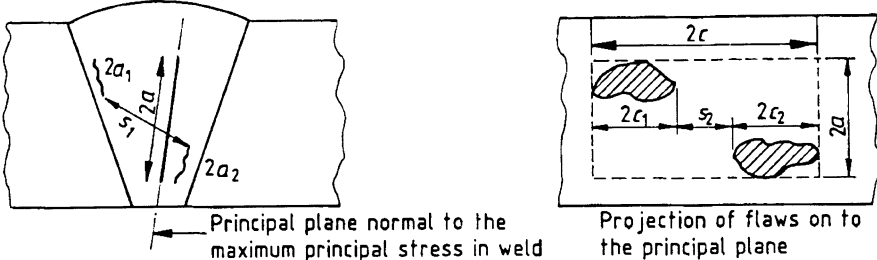
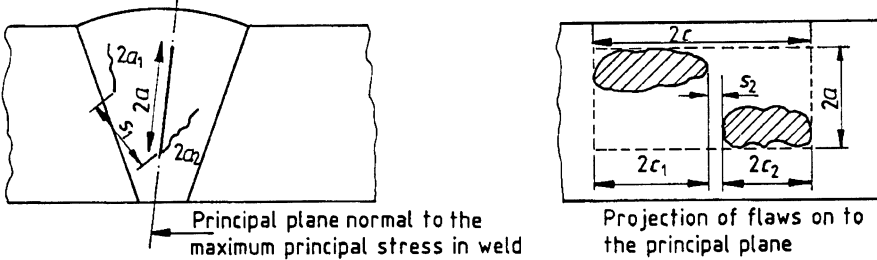
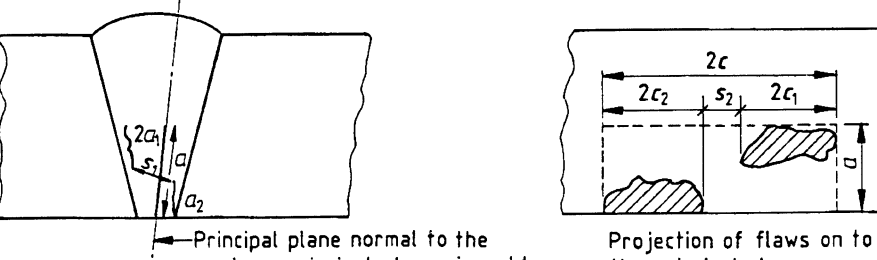
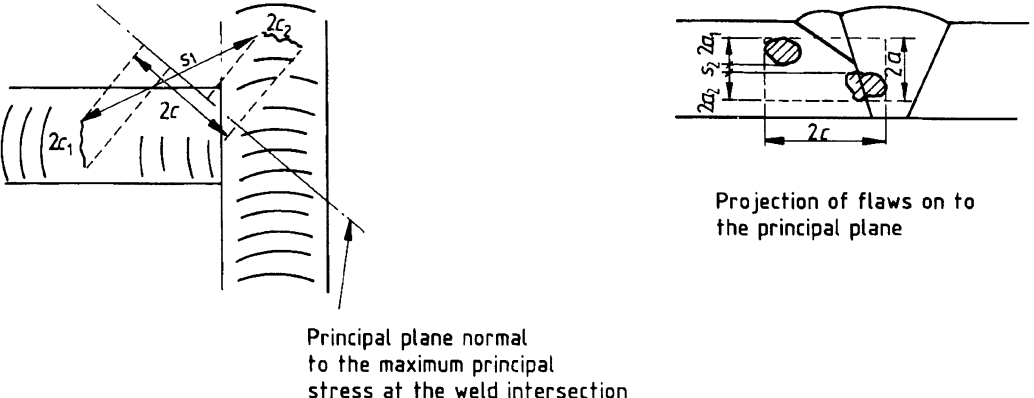
| Schematic flaws                                                                                                              | Criterion for interaction                                     | Effective dimensions after interaction               |
|-------------------------------------------------------------------------------------------------------------------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

Figure 6 — Planar flaw interactions

| Schematic flaws                                                                                                                                                                                                                                                           | Criterion for interaction                                                                                         | Effective dimensions after interaction                                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>1 Adjacent non-coplanar embedded flaws</p>  <p>Principal plane normal to the maximum principal stress in weld</p> <p>Projection of flaws on to the principal plane</p>               | $s_1 \leq a_1 + a_2$<br>and<br>$s_2 \leq 2c_1$<br>where $c_1 < c_2$<br>( $2c_1$ and $2c_2$ are projected lengths) | <p><math>2a</math> is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld</p> $2c = 2c_1 + 2c_2 + s_2$ |
| <p>2 Adjacent non-coplanar embedded flaws</p>  <p>Principal plane normal to the maximum principal stress in weld</p> <p>Projection of flaws on to the principal plane</p>              | $s_1 \leq a_1 + a_2$<br>and<br>$s_2 \leq 2c_1$<br>where $c_1 < c_2$<br>( $2c_1$ and $2c_2$ are projected lengths) | <p><math>2a</math> is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld</p> $2c = 2c_1 + 2c_2 + s_2$ |
| <p>3 Adjacent non-coplanar surface and embedded flaws</p>  <p>Principal plane normal to the maximum principal stress in weld</p> <p>Projection of flaws on to the principal plane</p> | $s_1 \leq a_1 + a_2$<br>and<br>$s_2 \leq 2c_1$<br>where $c_1 < c_2$<br>( $2c_1$ and $2c_2$ are projected lengths) | <p><math>a</math> is the minimum height of containment rectangle constructed on the plane normal to the maximum principal stress in the weld</p> $2c = 2c_1 + 2c_2 + s_2$  |
| <p>(b) Non-coplanar</p> <p style="text-align: center;">Figure 6 — Planar flaw interactions (continued)</p>                                                                                                                                                                |                                                                                                                   |                                                                                                                                                                            |

| Schematic flaws                                                                                                                                                                                                                      | Criterion for interaction                                                                                                                                                                      | Effective dimensions after interaction                                                                                                                                                       |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>4 Adjacent non-coplanar flaws in intersecting welds</p>  <p>Principal plane normal to the maximum principal stress at the weld intersection</p> | <p><math>s_1 \leq 2c_1</math></p> <p>and</p> <p><math>s_2 \leq a_1 + a_2</math><br/>where <math>c_1 &lt; c_2</math></p> <p>(<math>2a_1</math> and <math>2a_2</math> are projected heights)</p> | <p><math>2a = 2a_1 + 2a_2 + s_2</math></p> <p><math>2c</math> is the minimum length of containment rectangle constructed on the plane normal to the maximum principal stress in the weld</p> |
| <p>(b) Non-coplanar (concluded)</p> <p><b>Figure 6 — Planar flaw interactions (concluded)</b></p>                                                                                                                                    |                                                                                                                                                                                                |                                                                                                                                                                                              |

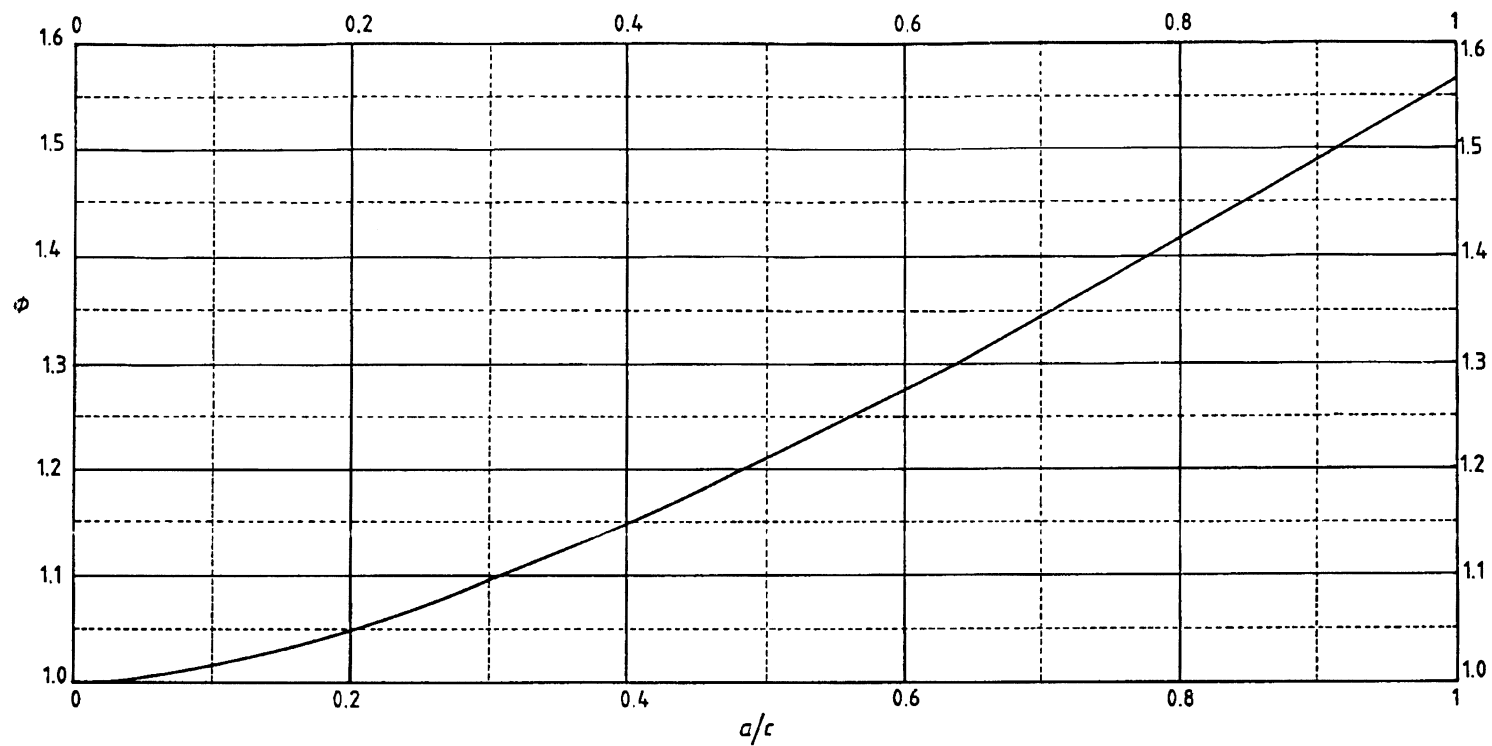


Figure 7 — Elliptical integral  $\Phi$  as a function of  $a/c$  used for the calculation of  $K_I$  for surface and embedded flaws

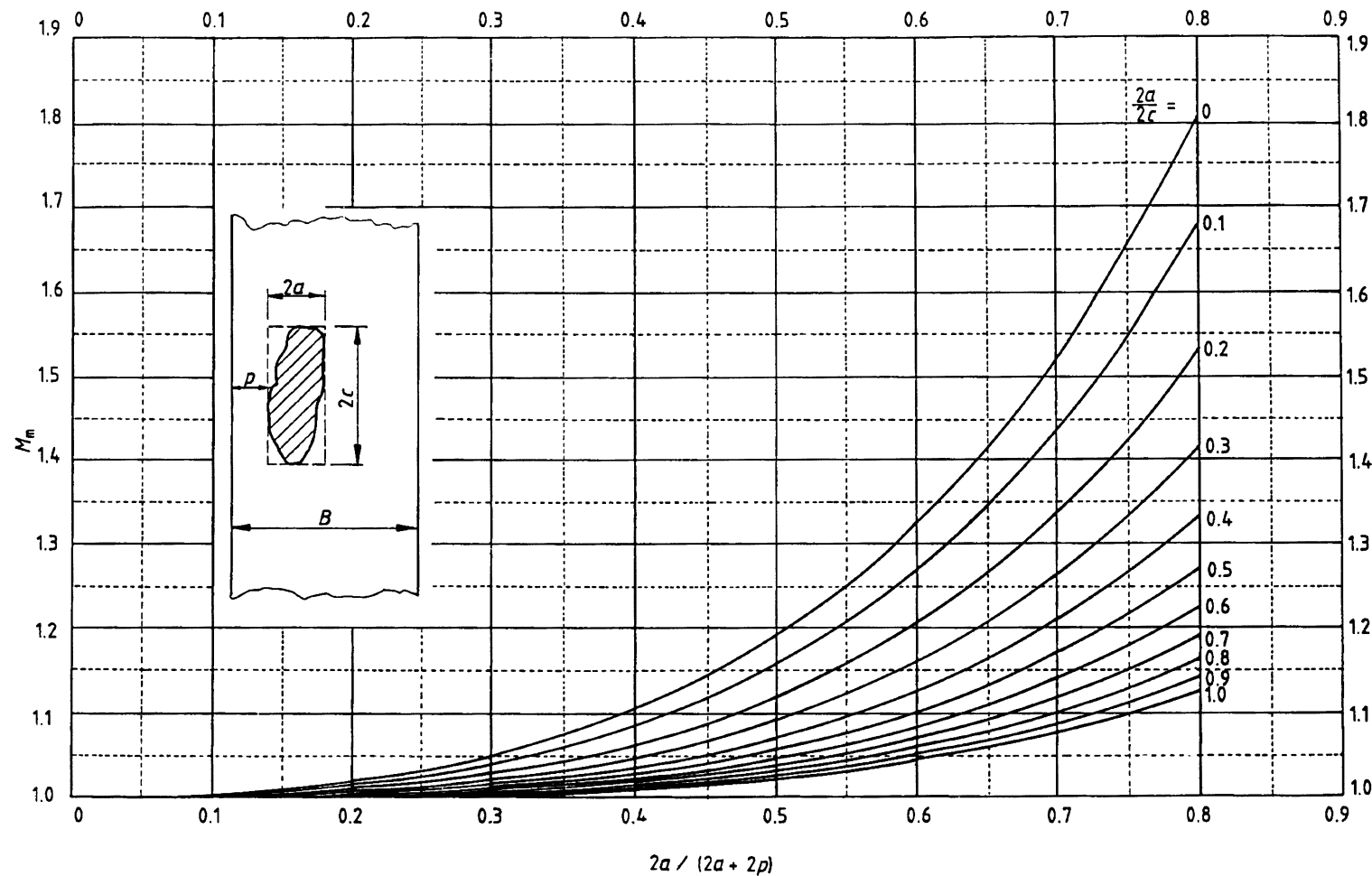
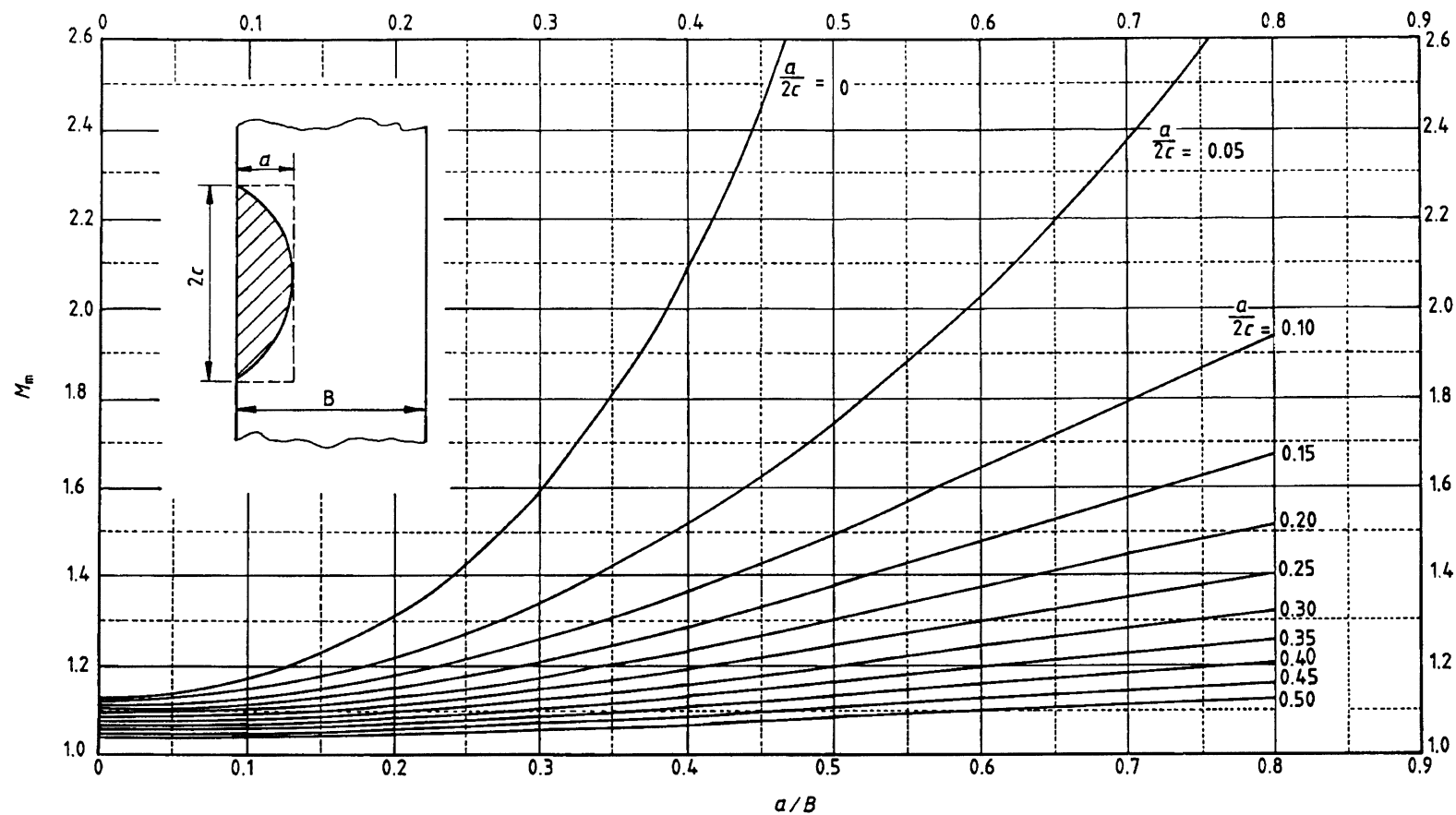


Figure 8 — Stress intensity magnification factor  $M_m$  for embedded flaws in tension (at point nearest material surface)



(a) At deepest point along flaw front, i.e.  $\phi = \pi/2$  rad

Figure 9 — Stress intensity magnification factor  $M_m$  for surface flaws in tension