SINTAP
PROCEDURE
FINAL VERSION : NOVEMBER 1999

FOREWORD

NOMENCLATURE

CHAPTER I : DESCRIPTION

I.1 Introduction & Scope
I.2 Description/Choices/Levels of Analysis
I.3 Significance of Results
I.4 Procedures
I.5 Reporting

CHAPTER II : INPUTS AND CALCULATIONS

II.1 Tensile Properties
II.2 Fracture Toughness Data
II.3 Flaw Characterisation
II.4 Primary & Secondary Stress Treatment

CHAPTER III : FURTHER DETAILS AND COMPENDIA

III.1 Guidance on Level Selection
III.2 Selected SIF and LL Solutions
III.3 Compendium of Residual Stress Profiles
III.4 Compendium of equations

CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

IV.1 Default Procedure
IV.2 Ductile Tearing Analysis
IV.3 Reliability Methods
IV.4 Constraint Procedure
IV.5 Leak Before Break Procedure
IV.6 Assessment of Prior Overload
FOREWORD

1. Overview

This procedure for the assessment of the integrity of structures containing flaws has been produced by a Consortium of 17 European establishments under the European Union Brite-Euram Fourth Framework Scheme. The objective of the project, SINTAP (Structural INTegrity Assessment Procedures for European Industry), was to develop an assessment procedure for European industry which offers varying levels of complexity in order to allow maximum flexibility in terms of industrial application and user requirements.

The project has drawn upon the experience gained from the application of existing procedures and has comprised activities such as collation of published information, assessments of materials behaviour, optimisation of industrial procedures and the derivation of methods for treating the many aspects associated with assessment methodologies.

The work was part funded by the European Union under the Brite-Euram Initiative.

Like all procedures, the state-of-the-art continually changes: Suggestions for improvements and changes are therefore welcomed.

2. Advantages & Necessity of Structural Integrity Assessment

Structural integrity procedures are the techniques used to demonstrate the fitness-for-purpose of engineering components transmitting loads. They are of value at the design stage to provide assurance for new constructions, particularly where these may be innovative in the choice of materials or fabrication methods, and at the operation stage to provide assurance throughout the life of the structure. They have important implications for economic development in assuring the quality of engineered goods and services. Used correctly, they can increase efficiency by preventing over design and unnecessary inspection and repair but can also provide a balance between economy and concern for individual safety and environmental protection, where this is affected by component failure.

Attention to reliability and fitness-for-purpose will pay large dividends in terms of safety, cost, quality image and hence competitiveness of the particular industry and its products. While different failure modes such as fracture, plastic collapse, fatigue, creep and corrosion can all contribute to premature failure, the present procedure is concerned with those of fracture and plastic collapse. The Industrial need for this procedure is reflected in a number of trends and current issues:-

(i) The existence of a large number (greater than 10) of fitness-for-purpose methods in use, both in Europe and world-wide,
(ii) Increased use of such procedures in a wide range of industries, in addition to those associated with offshore and nuclear engineering which have used such methodologies over many years.

(iii) The presence of unspecified factors of safety, empiricism and undefinable reliability levels associated with such approaches.

(iv) Developments in design philosophies allowing loading in the plastic regime, such as limit-state design, and the increasing demands of industry to exploit the properties of modern materials.

(v) The industrial demand for stronger materials and high productivity joining methods.

(vi) The existence of a wide range of material suppliers, material users, designers, safety assessors, research institutes and standards development bodies involved in integrity assessments.

(vii) The extensive experimental and modelling data available within organisations within the EU.

(viii) The experience of many EU organisations in the creation of existing procedures, their application to real structures and knowledge of their limitations.

(ix) The move towards European standardisation in materials supply, fabrication and construction (such as EN Standards and Eurocodes).

Key industries essential to the economics of any country (gas, oil, petrochemical, power generation, civil and structural engineering) are strongly dependent on the safe operation of plant and structures, and, in the case of damaged or flaw-containing components, the accurate determination of the significance of any structural damage or weld flaws. In particular, there is currently a strong trend towards the prolongation of a structure's life using the concept of damage tolerance based on fracture mechanics concepts because of the large economic benefits that arise from the assurance of integrity.

3. **Objectives of SINTAP Project**

As the technological knowledge for defining flaw acceptance levels based on fitness for purpose increases, it is necessary to incorporate these developments into an industrially applicable procedure to enable those industries to take advantage of such knowledge. This document incorporates recent developments in fracture mechanics assessment methods in a stand-alone procedure. While arbitrary acceptance levels will continue to be used for quality control purposes, the complementary use of the methods described in this procedure enables the acceptability of known or postulated flaws in particular situations to be evaluated in a rational manner.

SINTAP (Structural INTEGRity Assessment Procedures for European Industry) was a three year project part-funded by the European Commission under its Brite-Euram
Framework. The project, which started in April 1996, had the objective of providing a unified structural integrity evaluation method which is applicable across a wide range of European industries. The project consortium consisted of seventeen partners from nine different European countries, representing a variety of industrial, research, academic, safety assessment and software development organisations.

The project covered three types of work areas, the first of was been to bring together existing information from many different sources through collation and review exercises. Secondly, the gathered information was enhanced through experimental and modelling work to improve the scope, quality and validation of the information. The third step was the derivation of a structural integrity assessment procedure with the aim of representing a ‘best practice’ approach for use by engineers in a range of European Industries.

In order to achieve these aims the project was divided into five task areas addressing: Weld Strength Mis-match, Failure of Cracked Components, Probabilistic Methods, Residual Stresses and Procedure Development. The overall procedure draws on the consortium’s experience gained in various assessment procedures, including, but by no means limited to, BS PD 6493, R6, the Engineering Treatment Model (ETM) and large scale tests such as those of wide plate specimens. The final procedure includes a range of route options of varying complexity with selection being made on the basis of data quality, purpose of assessment, type of structure and user knowledge.

The SINTAP procedure is only concerned with the evaluation of plastic collapse and fracture. Other failure modes such as fatigue, environmental damage, high temperature creep and creep crack growth are not the subject of this procedure.

4. Structure of Project

Through the approach described in the above section, unnecessary experimental work was avoided, benefit taken from existing research, codes and procedures with a view to world-wide developments in related technical areas over recent years being incorporated into practical procedure. Such an approach was deemed essential if technical and specialised developments were to be transferred from research to industry in the available time frame. The five task areas of the project are summarised below.

In Task 1 the influence of Weld Metal Strength Mismatch on structural assessments was defined and guidelines formulated on how to account for the mismatch effect when predicting structural behaviour. Task 2 addressed the Performance of Cracked Components and covered aspects such as constraint, yield stress/ultimate tensile stress ratio in modern steels, the effects of prior overloading and the collation of stress intensity factor and limit load solutions. Task 3 covered Optimised Treatment of Data and was aimed at the provision of a statistical approach for treating input data; aspects such as quantification of scatter in fracture toughness tests, Charpy-fracture toughness correlations, NDT guidance and assessment of safety factors were covered. Secondary Stresses were addressed in Task 4 which included the collation of a library of welding residual stress profiles together with results from newly derived modelled and experimentally determined profiles. Task 5, Procedure Development, was aimed at bringing together the tasks as a coherent procedure. A variety of assessment levels is
offered ranging from a simple but conservative approach where data availability is limited, to accurate complex approaches incorporating state-of-the-art methods.

5. **The SINTAP Procedure**

This document provides a fracture assessment procedure which can be used as the basis of a structural integrity management system by European Industry. The procedure has been produced as the output of a Brite-Euram project SINTAP (Structural Integrity Assessment Procedures for European Industry). A variety of assessment levels are offered ranging from simple but conservative approaches where data availability is limited to accurate complex approaches incorporating state-of-the-art methods.

The selection of an appropriate route is made based on the quality of the available data, the aim of the assessment and the knowledge of the user: Guidance on this aspect is provided within the procedure.

This procedure is divided into the following areas:

(I) Description and Methodology  
(II) Inputs and Calculations  
(III) Further details and compendia  
(IV) Alternatives and additions to standard methods.

In this document, the results of a fracture assessment may be represented either in terms of a crack driving force or a failure assessment diagram. In the former, the crack driving force (for example, the applied J-integral) can be plotted as a function of flaw size for different applied loads, or as a function of load for different flaw sizes and compared to the material’s resistance to fracture. In the latter, an assessment is represented by a point or a curve on a diagram and fracture judged by the position of the point or curve relative to a failure assessment line. Wherever possible, these two approaches have been made consistent so that the results of an assessment are not dependent on the representation chosen.

Support document: Background information leading to the development of the procedure described here has been collated in a supporting document published in the form of the Final Report of the project. The results of literature reviews, experimental data, modelling and validation activities are covered along with informative guidance on test procedures and aspects associated with, but no directly covered in, this procedure.

CD-ROMs of background reports and this procedure are available from British Steel. Software to automate the main procedure was also developed during the project and is available as a demonstration disk from MCS International (www.mcs-international.com)

6. **Future Development of Procedure**

It is the intention that the results of the SINTAP project will contribute to the further development of a CEN Fitness-for-Purpose standard currently under consideration of CEN TC 121. In particular contributions will be made to address those issues which are
currently unresolved, promote the further understanding of other complex areas and to provide information from the consortium's experience of other fitness-for-purpose standards and that gained during the life of the project. In this context, it should be understood that the approaches described in this procedure are not intended to supersede existing methods, particularly those based on workmanship: They should be seen as complementary, the use of which should be aimed at ensuring safe and efficient materials’ selection, structural design, operation and life extension.

Definitions and Symbols: General

Plastic Collapse Parameter

\[ L_r \]  
ratio of applied load to yield or proof load (Section 4.2.1)

\[ f(L_r) \]  
function of \( L_r \) defining FAD or CDF

\[ L_{r\text{max}} \]  
maximum permitted value of \( L_r \)

\[ L_r(L) \]  
value of \( L_r \) when structure is loaded to its limiting load.

Brittle Fracture Parameter

\[ K_I \]  
linear elastic stress intensity factor, crack tip loading calculated elastically

\[ K_{I}^P \]  
value of \( K_I \) for primary stresses

\[ K_{I}^S \]  
value of \( K_I \) for secondary stresses

\[ K_{P}^S \]  
effective stress intensity factor for secondary stresses

\[ K_{mat} \]  
characteristic fracture toughness in units of \( K \) for initiation analysis

\[ K_{mat}(\Delta a) \]  
characteristic toughness in units of \( K \) for ductile tearing analysis

\[ K_r \]  
ratio of \( K_I /K_{mat} \) (section 4.2.1)

Limit Loads

\[ F_e \]  
generic term for yield limit load

\[ F_p \]  
limit load defined by proof strength

\[ F_{eH} \]  
limit load defined at upper yield strength

\[ F_M \]  
yield limit load for mismatched weldments

\[ F_B \]  
yield limit load for base material

\[ P_e \]  
yield limit pressure

Reserve Factors

\[ F^L \]  
reserve factor on load, pressure etc

\[ F^a \]  
reserve factor on flaw size

\[ F^K \]  
reserve factor on characteristic fracture toughness

\[ F^R \]  
reserve factor on yield strength

J-Integral

\[ J \]  
integral denoting crack tip loading calculated elastic-plastically (strain energy release rate)

\[ J_e \]  
elastically calculated value of \( J \)

\[ J_{mat} \]  
characteristic fracture toughness in units of \( J \) for initiation analysis

\[ J_{mat}(\Delta a) \]  
characteristic toughness in units of \( J \) for ductile tearing analysis

CTOD

\[ \delta \]  
 crack tip opening displacement (CTOD)

\[ \delta_e \]  
elastically calculated value of CTOD

\[ \delta_{mat} \]  
characteristic fracture toughness in units of \( \delta \) for initiation analysis

\[ \delta_{mat}(\Delta a) \]  
characteristic toughness in units of \( \delta \) for ductile tearing analysis

Plasticity Interaction

\[ \rho \]  
allowance for plasticity interaction effects from combination of primary and secondary loadings
alternative form for $\theta$ (see II.4 and II.2)

**Tensile Properties**

$R_e$ general term for yield or proof strength  
$R_{el}$ lower yield strength  
$R_p$ proof strength  
$R_f$ flow stress  
$R_f^M$ mismatch flow stress of weldment  
$R_{eH}$ Upper yield strength or limit of proportionality  
$R_m$ ultimate tensile strength  
$R_e^W$ yield or proof strength of weld metal  
$R_e^B$ yield or proof strength of base metal

**Stress Components**

$\sigma$ general term for stress  
$\sigma^P$ primary stress  
$\sigma^S$ secondary stress  
$\sigma_r$ reference value of stress at value of strain, $\varepsilon_r$, on stress strain curve  
$\varepsilon$ general term for strain  
$\varepsilon_p$ plastic strain  
$N$ strain hardening exponent  
$\Delta \varepsilon$ lower yield or Luder’s strain  
$\lambda = (1+E\Delta \varepsilon/R_{eH})$  
$M$ mismatch ratio across weldment given by $R_e^W/R_e^B$

**Moduli of Materials**

$E$ Young’s modulus  
$\nu$ Poisson’s ratio  
$E' = E$ for plain stress, and $E/(1-\nu^2)$ for plain strain

**Component and Defect Geometry**

$a$ flaw size in characteristic dimension (semi length of shortest side of rectangle characterising buried flaw)  
$c$ flaw size in second dimension (semi length of longest side of rectangle characterising buried flaw)  
$a_0$ initial (original) flaw size  
$a_{eff}$ effective flaw size  
$\Delta a$ amount of crack growth  
$l$ flaw length (sometimes defined as $2c$)  
$t$ thickness of structural section  
$B$ thickness of fracture toughness specimen  
$W$ width (in a-dimensional) of fracture toughness specimen  
$b_0$ $(W-a_0)$ in fracture toughness specimen

The user is advised to use consistent units throughout. However, where the expressions or values of any constants are applicable only to certain units this is noted at the appropriate position in the main text.
CHAPTER I : DESCRIPTION

I.1 : INTRODUCTION & SCOPE

I.1.1 Applicability

The procedure described is based on fracture mechanics principles and is applicable to the assessment of metallic structures containing actual or postulated flaws. The purpose of the procedure is to determine the significance, in terms of fracture and plastic collapse, of flaws present in metallic structures and components.

The procedure is based on the principle that failure is deemed to occur when the applied driving force acting to extend a crack (the crack driving force) exceeds the material's ability to resist the extension of that crack. This material 'property' is called the material's fracture toughness or fracture resistance.

The procedure can be applied during the design, fabrication or operational stages of the lifetime of a structure.

   a) Design Phase

       The method can be used for assessing hypothetical planar discontinuities at the design phase in order to specify the material properties, design stresses, inspection procedures, acceptance criteria and inspection intervals.

   b) Fabrication Phase

       The method can be used for fitness-for-purpose assessment during the fabrication phase. However, this procedure shall not be used to justify shoddy workmanship and any flaws occurring should be considered on a case by case basis with respect to fabrication standards. If non-conforming discontinuities are detected, which cannot be shown to be acceptable to the present procedure, the normal response shall be: (i) correcting the fault in the fabrication process causing the discontinuities and (ii) repairing or replacing the faulty product.

   c) Operational Phase

       The method can be used to decide whether continued use of a structure or component is possible and safe despite detected discontinuities or modified operational conditions. If during in-service inspection discontinuities are found which have been induced by load fluctuations and/or environmental effects, these effects must be considered using suitable methods which may not be described in the present procedure. The current procedure may be used to show that it is safe to continue operation until a repair can be carried out in a controlled manner.

       Further applications of the method described are the provision of a rationale for modifying potentially harmful practices and the justification of prolonged service life (life extension).
CHAPTER I : DESCRIPTION

I.1.2 Workmanship Considerations

In circumstances where it is necessary to critically examine the integrity of new or existing constructions by the use of non-destructive testing methods, it is also necessary to establish acceptance levels for the flaws revealed. In the present procedure, the derivation of acceptance levels for flaws is based on the concept of 'fitness-for-purpose'. By this principle a particular fabrication is considered to be adequate for its purpose, provided the conditions to cause failure are not reached, after allowing for some measure of abnormal use or degradation 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 quality during production. Flaws which are less severe than such quality control levels as given, for example, in current application standards, are acceptable without further consideration. If flaws more severe than the quality control levels are revealed, rejection is not necessarily automatic. In such situations 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 emphasised, 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.

I.1.3 Philosophy of Approach

The approach described in this document is suitable for the assessment of structures and components containing, or postulated to contain, flaws. The failure mechanisms considered are fracture and plastic collapse, together with combinations of these failure modes. The philosophy of the approach is that the quality of all input data is reflected in the sophistication and accuracy of the resulting analysis. A series of levels is available, each of increasing complexity and each being less conservative than the next lower level; consequently 'penalties' and 'rewards' accrue from the use of poor and high quality data respectively. This procedural structure means that an unacceptable result at any level can become acceptable at a higher one. The user need only perform the work necessary to reach an acceptable level and need not invest in unnecessarily complicated tests or analysis.

Due to the hierarchical structure of data and assessment levels, path selection through the procedure is made based on the relative levels of contribution of brittle fracture and plastic collapse towards the overall failure. Qualitative and quantitative guidance is provided for guiding the user in the direction that will yield most benefit in terms of data improvement. The basis for this is the location of the initial analysis point in terms of brittle fracture and plastic collapse. This can be assessed by either the Failure Assessment Diagram (FAD) or the Cracking Driving Force curve (CDF). The methods can be applied to determine the acceptability of a given set of conditions, determine the value of a critical parameter, assess the safety margins against failure or determine the probability of failure. Fig. I.1.1 shows the general decision steps and possible outcome.

In order to facilitate the route through the document, information is grouped according to four chapters:

(I) Description
(II) Inputs and Calculations
(III) Further Details and Compendia
CHAPTER I: DESCRIPTION

(IV) Alternatives and Additions to Standard Methods

Each chapter is numbered with Roman numerals and each section is numbered conventionally within each chapter. These are referred to throughout the Procedure as, e.g. II.5, being Chapter II, Section 5.

I.1.4 Limits of Validity

The methods described in this procedure were derived by collating existing information, and by the undertaking of experimental and analytical modelling work. The materials to which the procedure can be applied cover the full range of metallic materials although emphasis throughout has been on welded steels since more data are available for this class of materials and these account for the majority of cases to which the methods would be applied.

The procedure is applicable to combinations of brittle fracture and plastic collapse. Other failure modes such as:

- Fatigue
- Environmentally assisted cracking
- Corrosion
- Creep and other high temperature failure modes
- Time dependent failure (such as materials' degradation)
- Buckling
- Crack arrest
- Mixed-mode loading

are not covered by this procedure but current advice/best practice can be found in R6 (I.1.1), R5 (I.1.2), BS7910 (I.1.3), API 579 (I.1.4), BS7608 (I.1.5). Two reviews of existing procedures are also available (I.1.6, I.1.7).

Extension of the procedure to incorporate sub-critical cracking processes which can lead to a failure condition but are time-dependent would be a logical step for further development of the procedure.

I.1.5 Relevant Standards

Where materials' properties are to be generated for use in an assessment, they should be done so in accordance with recognised standards. Preference should be given to ISO, EU or National Standards in this order respectively. Testing of materials, except for specific guidance on tensile and fracture toughness testing, is not covered by this procedure; a list of applicable standards which may be applied is given in Table I.1.1.
CHAPTER I : DESCRIPTION

CHAPTER I, SECTION 1 : REFERENCES


I.1.4 American Petroleum Institute, API579, “Recommended Practice for Fitness for Service”.

I.1.5 British Standard BS7608, “Code of Practice for Fatigue Design and Assessment of Steel Structures”, British Standards Institution.


## Table I.1.1: List of Applicable Test Standards

<table>
<thead>
<tr>
<th>Property Required</th>
<th>ISO</th>
<th>EU</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Temp</td>
<td>ISO 6892</td>
<td>EN 10002</td>
<td>BS EN 10002</td>
</tr>
<tr>
<td>Elevated Temp</td>
<td>ISO 783</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charpy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V - Notch</td>
<td>ISO 148</td>
<td>EN 10045</td>
<td>BS EN 10045</td>
</tr>
<tr>
<td>U - Notch</td>
<td>ISO 83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K, J, CTOD</td>
<td>ISO/CD/12135</td>
<td>BSENISO 12737 (K_{IC} only)</td>
<td>BS7448: Part 1: 1991</td>
</tr>
<tr>
<td>Dynamic Fracture Toughness</td>
<td>ISO 83</td>
<td>-</td>
<td>BS7448 : Part 3 : Draft</td>
</tr>
</tbody>
</table>

(1) No recognised standard but IIW draft standard under preparation

**Table I.1.1: List of Applicable Test Standards**
CHAPTER I : DESCRIPTION

Fig. I.1.1 Generalised Flowchart of Decision Steps and Types of Outcome
CHAPTER I: DESCRIPTION

I.2: GENERAL DESCRIPTION. CHOICES AND LEVELS OF ANALYSIS

I.2.1 Introduction

This section gives a brief introduction to the concepts used in the SINTAP procedure and describes how it is structured to provide an easy and self-consistent set of rules to guide the user through the document. Different approaches and levels of complexity are available, depending upon the quality and detail of the input data available. There are 2 basic choices which the analyst must make; the choice of approach and the choice of analysis level and these are explained in this section. The procedure is described in detail in section 1.4, a list of general definitions and symbols is given at the beginning of this procedure while nomenclature specific to individual areas is given at the relevant point in the procedure.

I.2.2 The Approach

Two approaches for determining the integrity of cracked structures and components have been selected for the SINTAP procedures. The first uses the concept of a Failure Assessment Diagram (FAD) and the second a diagram which uses a crack driving force curve (CDF). Both approaches are based on the same scientific principles, and give identical results when the input data are treated identically.

The basis of both approaches is that failure is avoided so long as the structure is not loaded beyond its maximum load bearing capacity defined using both fracture mechanics criteria and plastic limit analysis. The fracture mechanics analysis involves comparison of the loading on the crack tip (often called the crack tip driving force) with the ability of the material to resist cracking (defined by the material's fracture toughness or fracture resistance). The crack tip loading must be, in most cases, evaluated using elastic-plastic concepts and is dependent on the structure, the crack size and shape, the material's tensile properties and the loading. In the FAD approach, both the comparison of the crack tip driving force with the material's fracture toughness and the applied load with the plastic load limit are performed at the same time. In the CDF approach the crack driving force is plotted and compared directly with the material's fracture toughness. Separate analysis is carried out for the plastic limit analysis. While both the FAD and CDF approaches are based on elastic-plastic concepts, their application is simplified by the use of elastic parameters.

The choice of approach is left to the user, and will depend upon user familiarity with the two different approaches and the analytical tools available. There is no technical advantage in using one approach over the other.

The input to each of the approaches is limited by a variety of factors which ensure that the analysis is conservative, in the sense that it underestimates failure loads for given crack sizes and critical crack sizes for given applied load conditions. Also, restrictions are applied to ensure that the data collected from small simple specimens are valid for larger more complex engineering structures. For these reasons, the assessment is not judged against a failure condition, but against a limiting or tolerable condition (limiting load or crack size). This means that there may be scope for a further more realistic assessment which may provide a less conservative result.
Both the FAD and the CDF are expressed in terms of the parameter $L_r$. Formally, $L_r$ is the ratio of the applied load to the load to cause plastic yielding of the cracked structure. However, in the calculation of the FADs and CDFs, $L_r$ reduces to the ratio of equivalent applied stress to the material's yield or proof strength. The function $f(L_r)$ depends on the choice of analysis level, Section 1.2.3, and other details of the material's stress strain curve.

A brief description of the alternative approaches follows.

### 1.2.2.1 The FAD Approach

The failure assessment diagram, FAD, is a plot of the failure envelope of the cracked structure, defined in terms of two parameters, $K_r$, and $L_r$. These parameters can be defined in several ways, as follows:

- $K_r$: The ratio of the applied linear elastic stress intensity factor, $K_i$, to the material's fracture toughness, $K_{mat}$.
- $L_r$: The ratio of the applied stress to the stress to cause plastic yielding of the cracked structure.

The failure envelope is called the Failure Assessment Line and for the default and standard levels of the SINTAP procedure is dependent only on the material's tensile properties, through the equation:

$$K_r = f(L_r) \quad (1.2.1)$$

It incorporates a cut-off at $L_r = L_{r\text{max}}$, which defines the plastic collapse limit of the structure.

To use the FAD approach, it is necessary to plot an assessment point, or a set of assessment points, of co-ordinates $(L_r, K_r)$, calculated under the loading conditions applicable (given by the loads, crack size, material properties), and these are then compared with the Failure Assessment Line. Fig 1.2.1 (a) gives an example for a structure analysed using fracture initiation levels of analysis, and Fig 1.2.1 (b) an example for a structure which may fail by ductile tearing. Used this way, the Failure Assessment Line defines the envelope for achievement of a limiting condition for the loading of the cracked structure, and assessment points lying on or within this envelope indicate that the structure, as assessed, is acceptable against this limiting condition. A point which lies outside this envelope indicates that the structure as assessed has failed to meet this limiting condition.

Margins and factors can be determined by comparing the assessed condition with the limiting condition.

### 1.2.2.2 The CDF Approach

The CDF approach requires calculation of the crack driving force on the cracked structure as a function of $L_r$. The crack driving force may be calculated in units of $J$, equation 1.2.2, or in units of crack opening displacement, equation 1.2.3. Both are derived from the same basic parameters used in the FAD approach, the linear elastic stress intensity factor, $K_i$, and $L_r$. In their simplest forms $J$ is given by:
CHAPTER I: DESCRIPTION

\[ J = J_e[f(L_r)]^{-2} \]  \hspace{1cm} (I.2.2)

where \( J_e = K_i^2/E_i^\prime \) and \( \delta \) is given by:

\[ \delta = \delta_e[f(L_r)]^{-2} \]  \hspace{1cm} (I.2.3)

where \( \delta_e = K_i^2/E_i^\prime R_e \) where \( R_e \) is the material's yield or proof strength and \( E_i^\prime \) is Young's modulus, \( E \) for plain stress, and \( E/(1-\nu^2) \) for plain strain.

To use the CDF approach, for the basic level of analysis, the CDF is plotted as a function of \( L_r \) to values of \( L_r \leq L_r^\text{max} \), and a horizontal line is drawn at the value of CDF equivalent to the material's fracture toughness. The point where this line intersects the CDF curve defines the limiting condition \( L_r(L) \). A vertical line is then drawn at a value of \( L_r \) given by the loading condition being assessed. The point where this line intersects the CDF curve defines the assessed condition for comparison with the limiting condition. Fig I.2.1 (c) gives an example of such a plot.

To use the CDF approach for the higher level of analysis required for ductile tearing, it is necessary to plot a CDF curve as a function of crack size at the load to be assessed. The material's resistance curve is then plotted, as a function of crack size originating from the crack size being assessed. The limiting condition is defined when these two curves meet at one point only (if the resistance curve is extensive enough this will be at a tangent). Figure I.2.1 (d) gives an example of this type of plot.

As for the FAD approach, margins and factors can be assessed by comparing the assessed condition with the limiting condition.

1.2.2.3 Treatment of Secondary Stresses

The definitions \( K_r, J \) and \( \delta \) given in I.2.2.1 and I.2.2.2 are strictly valid for primary stresses only. This is because the plasticity effects are incorporated by means of the function \( f(L_r) \), which can be defined only in terms of primary loading. In the presence of secondary stresses, such as welding residual stresses, or thermal stresses, plasticity effects due to these alone, and due to their interaction with the primary stresses, are incorporated by means of an additional parameter \( \rho \). The use of this parameter is explained in II.4, and methods for its evaluation are also given.

I.2.3 The Analysis Level

There are a number of different levels of analysis available to the user, each being dependent on the quality and detail of the material's property data available. As for the choice of route, these may be chosen by the user at the outset, or they may be self selected. Self selection occurs when an unsatisfactory result at one level is re-analysed at a higher level. Simple rules determine when this can be achieved, Section III.1, and the optimum route minimises unnecessary work and complexity.

The user should be aware that the higher the level of analysis, the higher is the quality required of the input data, and the more complex are the analysis routines. Conversely, the lower the level of analysis the more conservative the result, but the lowest level which gives an acceptable result implies satisfactory results at higher levels.

The level of analysis is characterised mainly by the detail of the material's tensile data used. There are three standardised levels and three advanced levels, including
the special case of a leak before break analysis for pressurised systems. The different standardised levels produce different expressions for $f(L_r)$ which define the FAD or CDF to be used in the analysis.

A subdivision of the level arises from the details of fracture toughness data used. There are two options for this, one characterising the initiation of fracture (whether by ductile or brittle mechanisms), the other characterising crack growth by ductile tearing. The value of fracture toughness to be used in the SINTAP procedure is termed the characteristic value.

The basic level of analysis, level 1, is the minimum recommended level. This requires measures of the material's yield or proof strengths and its tensile strength, and a value of fracture toughness, $K_{mat}$, obtained from at least three fracture toughness test results which characterise the initiation of brittle fracture or the initiation of ductile tearing. For situations where data of this quality can not be obtained, there is a default level of analysis, which can be based on only the material's yield or proof strength and its Charpy data. The default level uses correlations, and as such is very conservative. It should only be used where there is no alternative. This level is described in IV.1.

In weldments where the difference in yield or proof strength between weld and parent material is smaller than 10%, the homogeneous procedure can be used for both undermatching and overmatching; in these cases the lower of the base or weld metal tensile properties shall be used. For higher levels of mismatch, and for $L_r > 0.75$, the option of using a level 2 analysis, mismatch level, can reduce conservatism. This method requires knowledge of the yield or proof strengths and tensile strengths of both the base and weld metals, and also an estimate of the mismatch yield limit load. It is however, possible to use the procedures for homogeneous materials even when mismatch is greater than 10%; and provided that the lower of the yield or proof stress of the parent material or weld metal is used, the analysis will be conservative.

The equations used to generate $f(L_r)$ for levels 1 and 2 are based upon conservative estimates of the effects of the materials tensile properties for situations when complete stress strain curves are not known. More accurate and less conservative results can be obtained by using the complete stress strain curve, and this option is given in level 3 as the SS (Stress-Strain) level. In this case every detail of the stress strain curve can be properly represented and where weldment mismatch effects are important these can also be allowed for.

Table I.2.1 gives guidance on the selection of analysis level from tensile data, and Table I.2.2 gives guidance on the selection of options for toughness data. Determination of these parameters is described in II.1 and II.2 respectively.

Stepwise procedures for the basic level are given in Section II.4, and these develop to the higher standardised levels as required. Procedures for the advanced levels are in Chapter IV, Sections 4 and 5, and for the default level in Chapter IV, Section I.
### Table I.2.1: Selection of Analysis Levels from Tensile Data

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DATA NEEDED</th>
<th>WHEN TO USE</th>
<th>GUIDANCE AND EQUATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEFAULT LEVEL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield or proof strength</td>
<td>When no other tensile data available</td>
<td>Section IV.1</td>
</tr>
<tr>
<td><strong>STANDARD LEVELS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Basic</td>
<td>Yield or Proof Strength: Ultimate Tensile Strength</td>
<td>For quickest result. Mismatch in properties less than 10%</td>
<td>Section II.1.2</td>
</tr>
<tr>
<td>2. Mismatch</td>
<td>Yield or Proof Strength: Ultimate Tensile Strength. Mismatch limit loads</td>
<td>Allows for mismatch in yield strengths of weld and base material. Use when mismatch is greater than 10% of yield or proof strength (optional).</td>
<td>Section II.1.3</td>
</tr>
<tr>
<td>3. SS (Stress-strain defined)</td>
<td>Full Stress-Strain Curves.</td>
<td>More accurate and less conservative than levels 1 and 2. Weld mismatch option included.</td>
<td>Section II.1.4</td>
</tr>
<tr>
<td><strong>ADVANCED LEVELS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Constraint Allowance</td>
<td>Estimates of fracture toughness for crack tip constraint conditions relevant to those of cracked structure.</td>
<td>Allows for loss of constraint in thin sections or predominantly tensile loadings</td>
<td>Section IV.4</td>
</tr>
<tr>
<td>5. J-Integral Analysis</td>
<td>Needs numerical cracked body analysis</td>
<td></td>
<td>Section IV.4</td>
</tr>
<tr>
<td>6. Special Case: Leak before Break Analysis</td>
<td>As per level 1 but with additional information on crack growth mechanism and estimation methods for determining crack length at breakthrough.</td>
<td>Pressurised components when a conventional approach does not indicate sufficient safety margin.</td>
<td>Section IV.5</td>
</tr>
<tr>
<td>Parameters required</td>
<td>Fracture mode Characterised</td>
<td>Reference in Procedure</td>
<td>Input obtained</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------</td>
<td>------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Default Level</td>
<td>Charpy energies</td>
<td>All modes</td>
<td>IV.1</td>
</tr>
<tr>
<td>Initiation Option</td>
<td>Fracture toughness at initiation of cracking.</td>
<td>Onset of brittle fracture: or Onset of ductile fracture</td>
<td>II.2.3</td>
</tr>
<tr>
<td>Tearing Option</td>
<td>Fracture toughness as a function of ductile tearing</td>
<td>Resistance curve</td>
<td>II.2.4</td>
</tr>
</tbody>
</table>
Fig I.2.1  FAD and CDF Analysis for Fracture Initiation and Ductile Tearing

a) FAD Analysis: Fracture Initiation

b) FAD Analysis: Tearing Resistance

c) CDF Analysis: Fracture Initiation

d) CDF Analysis: Tearing Resistance
SECTION I.3: SIGNIFICANCE OF RESULTS

I.3.1 Introduction

The procedures outlined in I.2 are deterministic. In this sense, for any level of analysis chosen, the input data is treated as a set of fixed quantities, and the result obtained is unique. Depending upon the objectives of the analysis, different forms of the result can be obtained, but in each case a comparison with a perceived critical state has to be performed. Because this perceived critical state is dependent on the choice of analysis level it will change from level to level and for this reason it should be regarded as a limiting condition rather than a critical or failure condition for the structure.

The proximity of this limiting condition to the structural failure condition not only varies from level to level but it does so even within a given level of analysis. This is because it is dependent on the quality of the data: the numbers of specimens tested, how the value of the input used in the analysis is obtained from test results, how closely these values represent the data in the location of the crack in the real structure, how accurately the loads and stresses on the structure can be determined. The treatments recommended for all these data are conservative, in the sense that when applied singly or in a combined way, an underestimate of the defect tolerance of the structure is obtained. However, the amount of the underestimation is indeterminate because of the uncertainties in the input data. The analyst must establish the necessary reserve factors with this in mind.

When assessing the acceptability of a result (step 7, I.4.2.2) confidence is established in two ways: by means of the values chosen for the input data, and by assessing the significance of the result. The first of these determines the level of confidence which can be placed in the analysis from the viewpoint of each of the variables put into the analysis, each variable being treated separately. In each case the confidence level is dependent mainly upon the quantity and type of input data. Although this may be high for any one of the data sets of concern, it says little about the overall confidence level of the final result. For this, the whole result must be assessed to establish how all the different confidence levels of the input data interact with each other to provide the final result. At this stage the necessary reserve factors can be established taking proper account of the influence of the different variables on the reliability of the result.

I.3.2 Input Data

I.3.2.1 Loads and Stresses

In most cases the values chosen for these will be simple bounds. In some cases they can be calculated accurately so that they closely represent the actual loads or stresses experienced. In non stress relieved structures, residual stresses are particularly difficult to predict, and these must be evaluated pessimistically (i.e., overestimated). It is not normal to add additional factors to loads and stresses, at this stage in the analysis.

I.3.2.2 Tensile Properties

For tensile properties, minimum measured values are normally recommended, and in the case of normal amounts of scatter these would generally be satisfactory. In cases, where there is mismatch in yield strengths between weld and base metals, the value chosen must take account of this mismatch. Thus, either a minimum value of both base and weld metal must be taken, or explicit account must be taken of the mismatch, using for example the mismatch methods given in Level 2 or 3. In both cases, measurements are needed of tensile properties in both the weld and parent material. If this cannot be done, additional
factors should be imposed to take account of any uncertainty. It is unusual to add further factors to tensile properties at this stage.

I.3.2.3 Fracture Toughness

The characteristic value of the fracture toughness must take into account the different amounts of uncertainty inherent in the fracture toughness which are dependent upon the metallurgical failure mechanism and how they are represented in the analysis. (See II.2)

(a) Brittle behaviour (Initiation Option, II.2.3.1)

Where the fracture mechanism is brittle, the fracture toughness is often highly scattered, especially where the material is inhomogeneous, as for example in weldments. For this reason, the reliability of the result is dependent on the number of specimens tested. The recommended method for treating such fracture toughness data is given in II.2.3.1, and this provides a statistical distribution of fracture toughness, from which the characteristic value may be derived. The distribution obtained following this method is biased to produce a conservative estimate of the median, where the level of conservatism is dependent on the number of specimens tested, and the incidence of low results which do not conform to the general distribution.

The characteristic value may be chosen as a fractile or percentile of the statistical distribution obtained following the II.2.3.1 procedures. A fractile suitable for a situation where reliability is a key factor (e.g., where loss of life may be a consequence of failure) is 0.05 (the 5\textsuperscript{th} percentile), while for a less critical situation a fractile of 0.2 or even 0.5 may be more appropriate. Other fractiles may be chosen for intermediate situations, but a specific recommendation on appropriate fractile cannot be more as each case must be assessed individually. Where a 'minimum of these' values is taken, the use of a partial safety factor may also be appropriate, Table IV.3.1. It should be noted that the 0.2 fractile is approximately equal to the value of toughness corresponding to the mean minus 1 standard deviation.

In deciding upon a characteristic value of toughness, other factors should also be taken into account. These are:

(i) The incidence of inhomogeneity.

II.2.3.1 contains three stages of analysis. For between 3 and 9 test results in the data set, all three stages should be performed, and the statistical distribution based on the result of these includes an allowance for small numbers of specimens. For 10 or more tests, stage 3 may be ignored, although it may be applied for indicative purposes where inhomogeneous behaviour is suspected. This is particularly important for cracks at weld centre lines, fusion lines or coarse grained regions of heat affected zones. In such cases, metallographic sectioning of the fracture toughness specimen should also be undertaken to ensure that the pre-fatigue crack tip is situated in the appropriate microstructure. This would determine whether or not there is a case for basing the characteristic value on the stage 3 distribution. If the case can be upheld for basing the characteristic value on the stage 2 distribution, the significance of the stage 3 result should be evaluated when performing a sensitivity analysis. (see I.3.3.2)

(ii) Adjustment for length of crack front.

The method given in II.2.3.1 assumes that brittle fracture occurs via a weakest link model. This implies that the length of the crack front is important in determining the fracture toughness: the longer the crack front, the more the chance of sampling a weak link. The
distribution obtained following the procedures in II.2.3.1 is normalised to a specimen 25 mm thick. If the length of the crack front in the structure is greater than 25 mm, the characteristic value for the toughness can be adjusted, using equation 6 in Table II.2.1.

It is recommended that this adjustment is performed in all cases, and especially where the material is inhomogeneous, and where there is doubt about the way the cracks in the test specimens sample the inhomogeneous regions. For crack front lengths exceeding the section thickness, \( t \), a correction equivalent to a maximum crack front length of \( 2t \) is normally sufficient, except where inhomogeneity is excessive. The significance of making the adjustment may be evaluated when performing a sensitivity analysis (I.3.3.2).

(b) Ductile behaviour (Initiation Option. II.2.3.2)

The scatter in ductile fracture toughness is generally much less than in brittle fracture toughness, and for this reason the result may be based upon the minimum value obtained in a set of three specimens tests. It is however important in ferritic and bainitic steels, to ensure that there is no risk of brittle fracture occurring because of proximity to the transition region. This can be done explicitly by testing at temperatures just below the temperature of interest and also by ensuring that the appropriate material is tested by means of metallographic sectioning. Other indications can be obtained from Charpy data. Where there is no risk of brittle fracture the characteristic value can be set at the minimum value obtained in the data set.

Where more than three specimens have been analysed, the characteristic value can be based on a statistical fractile, or standard deviation. The choice should be compatible with the minimum value of three tests, such as a mean minus 1 standard deviation or the 0.2 fractile. Again, the possibility of brittle fracture in ferritic and bainitic materials should be evaluated. In this case, however, this possibility may be excluded if a large number of tests have been performed.

(c) Ductile behaviour (Tearing Option II.2.3.3)

For ductile tearing, characteristic values of the resistance curve are needed as a function of crack extension. As with the onset of ductile tearing, the scatter in the resistance curve is generally much less than that obtained in the transition regime. Also, II.2.3.3 permits results to be obtained from the minimum curve of only three specimen tests. Often the curves will be parallel, but occasionally there may be a small difference in slope which causes them to intersect. In such cases, a lower bound curve should be drawn to the minimum of all such curves. This lower bound curve should be used to determine characteristic values.

Where more than three test results are available, the characteristic values can be based on a statistical fractile or standard deviation as described for the initiation value given in (b) (ii) above, but evaluated at the different amounts of \( \Delta a \).

As for the Initiation option, it is important to ensure that there is no risk of brittle fracture in ferritic or bainitic steels.

(d) Ductile behaviour (Maximum Load Values II.2.5)

Where only maximum load data are available, the choice of characteristic value will depend on the number of specimens and the proximity of the test temperature to the ductile brittle transition temperature where known.
It should be noted that the use of maximum load values of toughness originated in the semi-empirical method for flaw assessment, known as the crack tip opening displacement (CTOD) design curve method, incorporated in early versions of BS.PD 6493. The justification for this was based upon the fact that the CTOD values were obtained on full section thickness tests, and the design curve included 'factors of safety' of between 2 and 10.

In some cases, historic maximum load data on full-thickness specimens may only be available. It is not recommended that maximum load data are collected specially for use in the SINTAP procedure, as more modern methods of tests are more appropriate. The SINTAP procedure does not contain the 'safety factors' required of the CTOD design curve and use of maximum load data should correspondingly take full account of this. Guidance on the use of such data is given in II.2.5.

I.3.3 **Significance of Result**

The limiting state, evaluated using values for the input data established following the guidelines in I.3.2, in principle defines a safe operating condition. However, for some engineering purposes, for example in design calculations, confidence is traditionally gained by applying safety or reserve factors on the defect free structure. When using the SINTAP procedure, however, the application of previously specified numerical factors can be misleading because of the inherent and variable interdependence of the parameters contributing to fracture behaviour. Confidence in assessments is reinforced by investigating the sensitivity of the result to credible variations in the appropriate input parameters. Sensitivity analyses are facilitated by considering the effects that such variations have on reserve factors.

This section deals with sensitivity analysis in terms of reserve factors based upon the deterministic calculations of I.4. An alternative approach is to perform a probabilistic fracture mechanics calculation as described in IV.3.

I.3.3.1 **Reserve factors.**

Reserve factors may be expressed with respect to any parameter. Frequently the most significant one is the applied load, and the load factor, $F^L$ is defined as

$$F^L = \frac{\text{Load which would produce a Limiting Condition}}{\text{Applied Load in Assessed Condition}}$$

When using the FAD approach, for a given assessment point $\{L_o, K_f\}$ the limiting load is evaluated by changing the value of the specified load until the assessment point lies on the assessment line. When the structure is subjected to a single primary load only this may be done by scaling the assessment point along the radius from the origin, as shown in Fig I.3.1. When the structure is subjected to more than one load, only the load of interest should be changed. If both primary and secondary loads exist allowance must be made for the changes in the parameter $\rho$, with load $L_o$.

When using the CDF approach, for an initiation analysis the same scaling principle can be used. However, for a tearing analysis the limiting condition may need to be determined by an iterative process.
Similar methods may be used to calculate reserve factors on other parameters, sample definitions being:

On flaw size, \( F^a = \frac{\text{Limiting Flaw Size}}{\text{Flaw Size of Interest}} \)

On fracture toughness, \( F^K = \frac{\text{Fracture Toughness of Material being Assessed}}{\text{Fracture Toughness Which Produces a Limiting Condition}} \)

On yield stress, \( F^R = \frac{\text{Yield Stress of Material being Assessed}}{\text{Yield Stress Which Produces a Limiting Condition}} \)

I.3.3.2 Sensitivity Analysis

The reserve factors necessary to establish confidence that a specified loading condition is acceptable can be decided by assessing the sensitivity of that reserve factor to variations in an input parameter taking into account all uncertainties, including unknown, but credible, variations. The variations considered need not go outside of the bounds of credibility, other than where it is desired to demonstrate extreme robustness in the result. The parameters of interest are

- Applied Loads
- Thermal and residual stresses
- Flaw size and characterisation including possible changes in aspect ratio due to ductile tearing.
- Material properties data
- Calculational inputs (e.g., stress intensity factors, yield limit loads)

Sensitivity analyses may be performed in the way most convenient for the user but will be somewhat dependent on the level of analysis. Some guidance is given in I.3.3.2.1 and I.3.3.2.2

I.3.3.2.1 Initiation Analyses

a) Plot a graph of the reserve factor on load, \( F^L \), as a function of the variable of interest as shown in Fig I.3.2

(b) Determine the value of \( F^L \) needed by studying the sensitivity of \( F^L \) to the variable taking into account its range of uncertainty. Guidance on making this judgement is given in I.3.3.3
I.3.3.2.2. Tearing Analyses

(a) Plot the reserve factor on load, $F^L$, as a function of postulated crack growth $\Delta a$ keeping all other variables constant (Fig I.3.3a). Note that the extent of this plot will depend on the crack extension range of the resistance curve. If this is sufficiently extensive, a maximum will be obtained in the $F^L - \Delta a$ plot, Fig I.3.3b.

(b) Repeat the analysis for different values of the original flaw size, $a_0$, to establish the sensitivity of the results to $a_0$ and plot these on the same graph. Connect equivalent points on each plot to construct loci of $F^L$ as a function of initial flaw size for different values of $\Delta a$, Fig I.3.3c.

(c) Explore the effects of changing the other variables specified in I.3.3.2. In judging what reserve factors are required, account must be taken of the range of $J$-controlled crack growth and the significance of exceeding it. Further guidance is given in I.3.3.3.

I.3.3.3 Guidance on Determining Acceptable Reserve Factors.

The numerical value for a reserve factor to be acceptable depends on each individual situation and the conditions for which a component is being assessed. As a general guide, the reserve factor must be at least sufficient to prevent realistic variations in parameters or analysis methods leading to a violation of the limiting condition. In principle, a reserve factor of one is sufficient for this, but in practice, a factor greater than one is normally needed. The reserve factor cannot of course be greater than that of the defect free structure.

If an assessment is particularly sensitive to any parameter the required reserve factor should be large enough to ensure that the limiting condition is not approached. When the graphical procedures suggested in I.3.3.2.1 and I.3.3.2.2 are used this state is represented by steep gradients in the region of interest. Figs I.3.4a and b qualitatively compare the preferred and non-preferred conditions.

A common reason for requiring high values of reserve factor is uncertainty in material properties. The values used in the analysis are determined from a finite number of tests, and thus are associated with a particular statistical significance. The lower this is, the higher the required reserve factor. For toughness in particular, the incidence of inhomogeneity is important, and where a ferritic or bainitic steel is just above the ductile to brittle transition, the possibility of a mode change to brittle fracture must be considered. In such cases, a higher reserve factor may be required than for a situation where ductile behaviour can be guaranteed.

The recommended method for treating fracture toughness data of brittle steels given in II.2.3.1, can give different characteristic values depending on whether stage 2 or stage 3 is used for determining the probability distribution. The crack front length dependence arising from the weakest link model must also be considered. A sensitivity analysis which covers the variations in toughness arising from these factors is a reliable and acceptable way of judging their significance.

Sensitivity analysis is also required for the default method given in IV.1. This is particularly so where there is uncertainty in the definition of the Charpy values as these must provide a pessimistic measure of toughness from the correlation given.

In a tearing analysis there is doubt about using toughness data beyond the range of $J$-controlled crack growth and in general the reserve factor of interest is that at the limit of the valid data. However, analysis beyond this limit may give confidence in the adequacy of the
reserve factor if it can be demonstrated that the reserve factor is not sensitive to this limit, or that it would increase by allowing larger crack extensions.

There are many other circumstances which might influence the size of the reserve factors needed. Some of these are listed below.

1. The true loading system had to be over-simplified or assumptions had to be made which cannot be clearly shown to result in upper bound values.

2. The non destructive examination capabilities are doubtful

3. Flaw characterisation is difficult and uncertain.

4. The assessed loading condition is frequently applied or approached (In addition to this, the incidence of fatigue or environmentally assisted crack growth must be considered separately)

5. Little forewarning of failure is expected. Forewarning is more likely in cases of ductile failure, than brittle failure, (the consequences of ductile failure are usually less extreme than those of brittle failure). The particular case of a Leak-Before-Break condition in a pressurised system provides explicit warning, and a high intrinsic level of confidence (IV.5).

6. There is the possibility of time or rate dependent effects.

7. Changes in operational requirements (e.g. low temperatures or higher loads) are possible.

8. The consequences of failure are unacceptable.

It should be remembered that reserve factors on the different parameters are dependent on each other and therefore should not be considered in isolation. There can be no generally applicable value and each case or class of problem must be judged on its own merits.

I.3.4. Partial Safety Factors

Partial Safety Factors are factors which can be applied to the individual input variables which will give a target probabilistic reliability without the need to perform a full probability analysis. Recommended partial safety factors for given values of Co-efficient of variation and probability of failure (I.3.1) are given in Section IV.3. These can be used in place of a full probabilistic analysis where appropriate. It should be noted that the probability of failure values quoted in Table IV.3.1 are applicable to the case where partial safety factors are applied to all inputs as indicated and apply to the specific cases described in the text. The partial safety factors do not take account of any conservatism inherent in the Failure Assessment Diagram.
CHAPTER I, SECTION 3 REFERENCES

I.3.1 F. M. Burdekin, A. W. Hamour, “SINTAP, Brite-Euram BE95-1426, Contribution to Task 3.5 Safety Factors and Risk”, UMIST.
Figure I.3.1 Evaluation of $F^L$ for a Single Primary Load
a) Defect Size

b) Fracture Toughness

Figure I.3.2 Typical Load Factor Variation Graphs
a) Limited toughness
Resistance Data

b) More extensive
Resistance Data

c) Graph of Load Factor as a Function of Defect Growth for Various Initial Defect Sizes

Figure I.3.3 Load Factor Variation with Defect Size - Ductile Tearing Analysis
Note that in both cases, the load factors in the preferred and non-preferred situations are the same, but the margin against limiting flaw size in (a) or toughness in (b) is smaller in the non-preferred situation.

**Figure I.3.4 Preferred Sensitivity Curves**
SECTION I.4: PROCEDURES


I.4.1.1 Objectives:

The objectives which may be determined using these procedures are identified in I.1. Briefly these are

- to find the defect tolerance of a structure
- to find if a known defect is acceptable
- to determine or extend the life of a structure
- to determine cause of failure

Other objectives may also be determined, but in all cases these must be compatible with the data available and the reserve factors required. It is therefore important to have a clear understanding of what can be achieved.

I.4.1.2. Available Assessment Procedures

Depending on the nature of the structure being assessed, the objectives of the assessment and the type of data available, a number of alternatives are available to the user. The simplest of these is the Basic Level 1 Procedure, which is applicable for structures where the tensile properties can be considered to be homogeneous. This is appropriate for assessing defects in homogeneous materials or in weldments where the weld strength mismatch levels are less than 10% and when only the yield and ultimate tensile strengths are known. This Procedure is described in detail in I.4.2, where it deals with crack initiation only. It should be noted, however, that the homogeneous material procedure is safe to use for mismatch cases when used with the tensile properties of the lower strength constituent of the joint.

For weldments where the weld strength mismatch exceeds 10% and only yield and ultimate tensile strengths are known, the Level 1 Procedure may still be employed, but at the expense of additional conservatism. In such cases, the Level 2 Mismatch Procedure, I. 4.3, will give a more accurate result. Where full stress-strain curves are known, the Level 3 Stress-Strain Procedure may be employed, I.4.4, for either homogeneous or mismatch conditions.

The fracture mechanics approach given here, which is intended to result in a conservative outcome for the assessment, assumes that the section containing the flaw has a high level of constraint. In some instances, especially where the section is thin, or where the loading is predominantly tensile, this assumption can be over-conservative. In such cases it may be possible to reduce the conservatism by taking account of the lower constraint (see I.4.6). A method for doing this is given in IV.4.

Equations describing the FAD and CDF for Levels 1, 2 and 3 are given in detail in this section of the procedure. The advanced methods of Constraint Analysis, J-integral Analysis and Leak-Before-Break Analysis are described separately as Levels 4, 5 and 6 respectively in I.4.5, I.4.6 and I.4.7, and given in detail in IV.4 and IV.5. The Default Procedure, applicable to cases where only the yield strength and Charpy data are known, is introduced in I.4.8 and described in detail in IV.1.
The general methodology is the same for all levels, and is outlined in the flow charts in Fig I.4.1. The user may enter the procedure at any level.

I.4.2.2 gives a step-wise description of the Level 1 Procedure for fracture initiation, starting at the definition of appropriate tensile properties, and continuing to step 6 where the detailed calculations are described. Step 7 identifies the need to assess the result following the guidelines of I.3. If this result is acceptable, the analysis may be terminated and reported at this point. If the result is unacceptable, the analysis may be repeated at a higher level, provided that the materials data permit this. Step 8 gives simple rules for identifying the optimum route to follow in such cases, and more general guidance is given in III.1. If a ductile tearing analysis is required, the procedures given in IV.2 can be employed at all Levels.

The treatment of tensile data to devise the parameters necessary to construct the appropriate FAD is summarised in Fig. I.4.1.

I.4.1.3. Structural Data and Characterisation of Flaws

It is important to determine the detail and accuracy of the relevant aspects of the structural data. These include geometric details and tolerances, misalignments, details of welds, unfused lands, and details of flaws and their locations, especially when associated with weld zones. Although the procedure is aimed at establishing the integrity of a structure in the presence of planar flaws, the existence of non planar (volumetric) flaws may also be of importance. Defects treated as cracks must be characterised according to the rules of II.3, taking account of the local geometry of the structure and the proximity of any other flaw.

When determining the flaw tolerance of a structure, or determining or extending life, all possible locations of flaw should be assessed to ensure that the most critical region is covered. In the other cases, the actual location of the flaw must be assessed as realistically as possible.

I.4.1.3 Loads and Stresses on the Structure

These need to be evaluated for all conceivable loading conditions, including non-operational situations, where relevant. Residual stresses due to welding, and thermal stresses arising from temperature differences or gradients must also be considered as must fit-up stresses, and misalignment stresses. Guidance on these and other aspects is given in II.4. A compendium of weld residual stress profiles is given in III.3.

I.4.1.4 Material’s Tensile Properties

Tensile data may come in a number of forms as follows:

(a) as specified in the design, or on the test certificates supplied with the material. One or more of the yield or proof stress, (ultimate) tensile stress and elongation may be available. These are unlikely to include data at temperatures other than ambient.

(b) as measured on samples of the material of interest. These data are likely to be specially collected, and where possible should include full stress strain curves, obtained on relevant materials, including weld metal, at relevant temperatures.

The quality and type of tensile data available determines the level of the analysis to be followed. Treatment of the tensile data is described in II.1. In all cases, where scatter in the
material's tensile properties exist, the minimum value should be used to calculate $L$, consistent with the level of analysis, while best estimates should be used to calculate $f(L)$ and $L_{\text{max}}$. Similarly, for mismatched cases, realistic values should be used to calculate the Mismatch Ratio, $M$ and minimum values used for calculating $L_r$.

I.4.1.5 Material's Fracture Properties

All standard and advanced levels of analysis require the material’s fracture properties to be in the form of fracture toughness data. In some circumstances these may be as specified, or from test certificates supplied with the material, but in most cases they will be from specially conducted tests. The fracture data should relate to the material product form, microstructure (parent material, weld or heat affected zone) and temperatures of interest.

The fracture toughness data can come in different forms, depending on material type and temperature, and the test procedure adopted. Depending upon the extent and form of these data, they can be treated in different ways.

Characteristic values of the fracture toughness, $K_{\text{mat}}$, $J_{\text{mat}}$, or $\delta_{\text{mat}}$, must be chosen by the user for the analysis. For assessing against the initiation of cracking a single value of fracture toughness is required, while for assessing in terms of ductile tearing, characteristic values will be a function of crack growth (I.2.3, Table I.2.2). The value chosen depends upon the confidence level or reliability required of the result. Appropriate procedures for determining characteristic values of toughness are given in II.2.

Where it is not possible to obtain fracture toughness data, the analyst may use the default option for initiation where the characteristic value is based upon correlations with the material’s Charpy impact data. Because this is a correlation, it is designed to provide a conservative estimate of fracture toughness. The determination of fracture toughness from Charpy impact data is given in the Default Procedure in VI.1.

I.4.2 The Basic Procedure:

Level 1, Homogeneous Material, Initiation of Cracking.

I.4.2.1 Applicability

Only the simplest form of material properties data are required for this level of analysis. The tensile properties needed are yield or proof strength and ultimate tensile strength, and the characteristic value of the fracture toughness must be based upon data from at least three fracture toughness test results.

I.4.2.2 Procedure

1 Establish Yield or Proof Strength and Tensile Strength (II.1)

Mean values of these define the equation for $f(L)$ for both the FAD and CDF approaches and minimum values define $L$, for the loading on the structure. It is important to determine whether or not the material displays, or can be expected to display, a lower yield plateau or Luder’s strain. Guidance for this is given in II.1.
2. **Determine \( f(L_r) \)**

The function \( f(L_r) \) must be calculated for all values of \( L_r \leq L_r^{\text{max}} \). Equations for \( f(L_r) \) are given in Table I.4.1.

(a) For materials which have a continuous stress strain curve, \( f(L_r) \) is given by equations, I.4.2, with \( f(1) \) defined by equation I.4.1 to values of \( L_r \leq L_r^{\text{max}} \).

For \( L_r > L_r^{\text{max}} \), use equation I.4.3

(b) For materials which display or may be expected to display a lower yield plateau, \( f(L_r) \) is given by the four equations I.4.4, I.4.5, I.4.2 and I.4.3.

For \( L_r < 1 \), use equation I.4.4

At \( L_r = 1.0 \), use equation I.4.5

For \( 1 < L_r < L_r^{\text{max}} \), use equation I.4.2

For \( L_r > L_r^{\text{max}} \), use equation I.4.3

3. **Determine the Characteristic Value of the Material’s Fracture Toughness (II.2)**

It is recommended that the characteristic value for fracture toughness is obtained from an analysis of as many test results as possible, taking appropriate account of the scatter in the data, and the reliability required on the result (See I.3.2.3).

Where there is a large scatter in the data, the most representative values will be obtained for large data sets, but values can be obtained from as little as three results.

Recommended methods for analysing the data are given in II.2.3.

Where the fracture mechanism is brittle the method, II.2.3.1, uses maximum likelihood (MML) statistics. For between 3 and 9 test results there are three stages in the statistical analysis, plus a correction for the number of specimens in the data set. This imposes a penalty on the use of small data sets, to make allowance for possible poor representation of the sample. For 10 or more test results, only two stages need be performed. However, if it is known that the material is inhomogeneous, e.g., if it is taken from a weld or heat affected zone, it is advisable to perform stage 3 for indicative purposes. The choice of characteristic value can then be made with more confidence.

Use of the MML method implies acceptance of the weakest link model for brittle fracture. This also implies a crack size dependence. The characteristic value should be chosen with this in mind. Guidance is given in I.3.2.3 (a) (ii), and the equation for crack size adjustment is given in Table II.2.1.

Where the fracture mechanism is by ductile tearing, II.2.3.2, the data must relate to the onset of ductile tearing as described in the testing standards. The characteristic values may be obtained from the minimum of three test results or from a statistical analysis where more than three test results are available. As for brittle fracture the choice of characteristic value must take account of the factors outlined in I.3.2.3(b).
4. Characterise The Crack (II.3)

This is determined by the shape and size of the defect, or defects, and the geometry of the structure, see II.3.

5. Determine Loads and Stresses (II.4)

All potential forms of loading must be considered, including thermal loading and residual stresses due to welding, and test, fault and accidental loads. These must be classified into primary and secondary stresses. For the purposes of this procedure, secondary stresses cannot affect the failure of the structure under plastic collapse conditions, and all other stresses must be classed as primary.

Plasticity effects due to primary stresses are evaluated automatically by means of the expression \( f(L_r) \). However, further allowance has to be made for plasticity effects due to secondary stresses, and due to the combination of primary and secondary stresses. These are incorporated by means of a parameter defined as \( q \), and which is dependent on both \( L_r \), and the stress intensity factor due to the secondary stress.

Guidance for stress characterisation and the calculation of \( \rho \) is given in II.4.

6. Analysis

For an FAD analysis see I.4.2.2.1(a)

For a CDF analysis see I.4.2.2.1(b) when using \( J \) or section I.4.2.2.1(c) when using \( \delta \).

7. Assess Result

The result must be assessed in terms of the reliability required taking into account the uncertainties in the input data (see I.3).

If the result is acceptable the analysis can be concluded and reported as appropriate (I.5)

8. Unacceptable result

If the result is unacceptable, it may be possible to proceed to a higher level of analysis, following the flow chart in Fig I.4.1(b). This gives guidelines to determine how best to proceed. For an FAD analysis, the guidelines are based upon the ratio \( K_r/L_r \) defined under the loading conditions of the analysis. For a CDF analysis, the guidelines are based upon the value of \( L_r \) obtained when defining a limiting load for the structure, \( L_r(L) \), see I.2.2.2, Fig I.2.1. More complete guidance is given in III.1.

(a) If \( K_r/L_r > 1.1 \) or \( L_r(L) < 0.8 \), the result will be relatively insensitive to refinements in the tensile data. In this case, the result can be made acceptable only if \( K_r \) can be reduced. This may be done either by reducing the value of \( K_i \) by using a more accurate method of calculation, or by increasing the value of \( K_{mat} \). For materials failing by a brittle fracture mechanism \( K_{mat} \) may be raised by increasing the number of test results used in the MML analysis, which may necessitate the testing of more specimens. For materials failing by ductile tearing, \( K_{mat} \) may be increased by performing a ductile tearing analysis which takes account of the increase in fracture toughness due to
ductile tearing. II.2.4 gives guidelines on the treatment of fracture toughness data for ductile tearing, and I.4.3 gives step-wise procedures for the analysis.

(b) If $K_r/L_r < 0.4$ or $L_r(L) > 1.2$, the result will be relatively insensitive to refinements in the fracture toughness data. In this case, the result can only be made acceptable by refining the tensile data, thus changing the form of $f(L_r)$ and reducing the values of $L_r$ calculated for the loading on the structure. For situations of weld mismatch, where only yield and ultimate tensile data are known, employment of Level 2 may give more acceptable results. For situations where the full stress strain curve is known, employment of the more accurate Level 3 analysis may provide the necessary improvements. I.4.3 and I.4.4 give the appropriate equations for $f(L_r)$. The analysis should be repeated, modifying steps 1 and 2 and details of step 6, as required.

(c) If $1.1 > K_r/L_r > 0.4$ or $1.2 > L_r(L) > 0.8$, the result can be affected by refinements in either or both fracture toughness data and tensile data (and/or refinements in $K_i$), following the guidelines given in steps 8(a) and 8(b) above.

The result may also be influenced by constraint, especially where $1.1 > K_r/L_r > 0.4$ or $1.2 > L_r(L) > 0.8$. An advanced method, giving guidelines on how to allow for constraint effects is introduced in I.4.5 and described in detail in IV.4, which also provides for a further advanced option for situations where a numerical $J$-integral is preferred (see also I.4.6).

In certain circumstances, especially where data are extensive and very well documented, it may be possible to perform a full probability analysis. Suggestions for performing a probability analysis based upon the FAD approach are given in IV.3.

If none of these avenues can be followed, the integrity of the flawed structure cannot be demonstrated and appropriate action should be taken.

I.4.2.2.1. Analysis Procedures.

The procedures given below are graphical ones. They may be adapted for computational analysis if desired.

(a) FAD Approach

1. Plot the FAD, using mean tensile properties and the appropriate expressions for $f(L_r)$ (step 2 of I.4.2.2), where the FAD is a plot of $K_r = f(L_r)$ on $L_r$ and $K_r$ axes.

2. Calculate $L_r$ for the loading on the structure at the crack size of interest, using minimum values of tensile properties, taking into account only primary loads (see II.4 and III.2).

3. Calculate $K_r$ for the loading on the structure at the crack size of interest (see II.4 and III.2). In the calculation of $K_r$, all primary and secondary loads need to be included, plus an allowance for plasticity effects due to secondary stresses by means of the parameter $q$ (II.4).

4. With co-ordinates $\{L_r,K_r\}$ plot the Assessment Point on the FAD.

5. If the assessment point lies within the assessment line the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis level pursued. Return to Step 7 (I.4.2.2). If the assessment point lies on or outside the
assessment line, the structure is not acceptable in terms of the limiting conditions imposed. Return to step 8 (I.4.2.2).

(b) CDF Analysis using $J$

1. Calculate $J_e$ as a function of the applied loads on the structure at the crack size of interest where $J_e = K^2/E \ell^4$, taking into account all primary and secondary loads (II.4 and III.2). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, $\rho$ (II.4).

2. Plot the CDF($J$) using mean tensile properties and the appropriate expression for $f(L_r)$ (step 2 in I.4.2.2) where the CDF($J$) is a plot of $J = J_e[f(L_r) - \rho]^{-2}$ on $L_r$ and $J$ axes for values of $L_r \leq L_r^{max}$ (step 2 in I.4.2.2). Draw a vertical line at $L_r = L_r^{max}$.

3. Identify the point on the CDF($J$) curve where $J = J_{mat}$.

4. Calculate $L_r$ for the loading on the structure at the crack size of interest using minimum values of tensile properties (II.4 and III.2), and draw a vertical line at this value to intersect the CDF($J$) curve at $J_{str}$.

5. If $J_{str}$ is less than $J_{mat}$ and $L_r$ for the structure is less than $L_r^{max}$, the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis level pursued. Return to step 7, I.4.2.2.

If either $J_{str}$ is greater than $J_{mat}$, or $L_r$ for the structure is greater than $L_r^{max}$, the structure is not acceptable in terms of the limiting conditions. Return to step 8 in I.4.2.2.

(c) CDF Approach using $\delta$

1. Calculate $\delta_e$ as a function of the applied loads on the structure at the crack size of interest, where $\delta_e = K^2/E \ell^4 R_e$, taking into account all primary and secondary loads (II.4 and III.2). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, $\rho$ (II.4).

2. Plot the CDF($\delta$) using mean tensile properties and the appropriate expression for $L_r$ (step 2 Section I.4.2.2) where the CDF($\delta$) is a plot of $\delta = \delta_e[f(L_r) - \rho]^{-2}$ on $L_r$ and $\delta$ axes for values of $L_r \leq L_r^{max}$ (step 2 in I.4.2.2). Draw a vertical line at $L_r = L_r^{max}$.

3. Identify the point on the CDF($\delta$) curve where $\delta = \delta_{mat}$.

4. Calculate $L_r$ for the loading on the structure at the crack size of interest using minimum values of tensile properties (II.4 and III.2), and draw a vertical line at this value to intersect the CDF($\delta$) curve at $\delta_{str}$.

5. If $\delta_{str}$ is less than $\delta_{mat}$, and $L_r$ for the structure is less than $L_r^{max}$ , the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis level pursued. Return to step 7, I.4.2.2.

If either $\delta_{str}$ is greater than $\delta_{mat}$, or $L_r$ for the structure is greater than $L_r^{max}$, the structure is not acceptable in terms of the limiting conditions. Return to step 8, I.4.2.2.
I.4.3 Mismatch Procedure (MM):
Level 2 Analysis,
Weld to Base Material Yield Strength Mismatch Greater Than 10%

I. 4.3.1 Applicability

In the case of weldments where the difference in yield strengths between the base material and the weld metal is greater than 10 %, the joint may behave as a heterogeneous bimetallic joint. In such cases, use of minimum values of yield strength in the joint to define \( L_r \) may be over-conservative. The mismatch level provides a method for reducing the conservatism by allowing for separate contributions of the base material (denoted B) and the weld material (denoted W).

This level can only be used where there is available an estimate of the yield limit load under the mismatch conditions. This is dependent on the geometry of the joint and the flaw location within the joint. Solutions for some common geometries are given in III.2.

It should be recognised that weld tensile properties may vary through the thickness of a component and may be dependent on specimen orientation. The range of weld metal microstructures sampled can often lead to a high degree of scatter. The use of the lowest tensile properties irrespective of orientation and position is necessary to provide a conservative result.

Three combinations of stress strain behaviour are possible.

- both base and weld metal exhibit continuous yielding behaviour
- both base and weld metal exhibit a lower yield plateau
- one of the materials exhibits a lower yield plateau and the other has a continuous stress strain curve.

Each of these is described briefly in II.1 and is addressed in turn below.

I.4.3.2. Both Base and Weld Metal Exhibit Continuous Yielding Behaviour

In this case the equations for \( f(L_r) \) are those given in I.4.2.2 para 2 (a): i.e., eq I.4.1.1, I.4.1.2 and I.4.1.3 in Table I.4.1, but with the values changed to those for an equivalent mismatch material defined by the mismatch ratio, \( M \), given by equation I.4.6:

\[
M = \frac{R_p^W}{R_p^B} \quad (I.4.6)
\]

where \( R_p^W \) and \( R_p^B \) are best estimates of the proof strengths. A mismatch proof strength is given by equation I.4.7.

\[
R_p^M = \frac{(F_p^M/F_p^B)R_p^B} \quad (I.4.7)
\]

where \( F_p^M \) is the yield limit load for the mismatch conditions (III.2) and \( F_p^B \) is the yield limit load given by the tensile properties of the base material assuming homogeneous behaviour.

In equations I.4.1, I.4.2.and I.4.3, the values of \( \mu \), \( N \), and \( L_r^{max} \) used are calculated for the mismatch material using equations I.4.8, I.4.9 and I.4.10 in Table I.4.2.
Note that $L_r$ for the loading on the structure should be calculated using the yield limit load for the mismatch conditions, $F_p^M$ (III.2) and the mismatch proof strength, $R_p^M$ based upon minimum properties.

I.4.3.3. **Both Base and Weld Metal Exhibit Discontinuous Yielding**

In this case, the equations for $f(L_r)$ are those given in I.4.2.1 para 2 (b), i.e., eq I.4.4, I.4.5, and I.4.2 and I.4.3, Table I.4.1, with the values changed to those for an equivalent mismatch material, as described in I.4.3.2.

The parameters are defined in terms of $R_{ehp}$, and the relevant equations are I.4.9 and I.4.10 and I.4.11, Tables I.4.2 and I.4.3.

Note that $L_r$ for the loading on the structure should be calculated using the yield limit load for the mismatch conditions, $F_p^M$ (III.2) and the mismatch proof strength, $R_p^M$ based upon minimum properties.

I.4.3.4. **When One of the Constituents has a Continuous Stress Strain Curve and the Other has a Discontinuous One.**

(a) Where only the weld metal exhibits discontinuous yielding

In this case, $f(L_r)$ is based upon equations I.4.1, I.4.5, I.4.2 and I.4.3 listed in Table I.4.1, with the input parameters changed according to equations I.4.9, I.4.10, I.4.12, and I.4.13, Tables I.4.2 and I.4.3.

(b) Where only the base metal exhibits discontinuous yielding

In this case, $f(L_r)$ is based upon equations I.4.1, I.4.5, I.4.2 and I.4.3 listed in Table I.4.1, with the input parameters changed according to equations I.4.9, I.4.10, I.4.12, and I.4.15, Tables I.4.2 and I.4.3.

Note that in both cases $L_r$ for the loading on the structure should be calculated using the yield limit load for the mismatch conditions, $F_p^M$ (III.2) and the mismatch proof strength, $R_p^M$ based upon minimum properties.

I.4.4. **Stress-Strain Level:**

**Level 3, Known Stress-Strain Curves**

I.4.4.1 **Applicability**

This level of analysis can be used where the full stress strain curves are known. Where there is scatter in the data, a composite curve should be used to describe the best estimate for the calculation of $f(L_r)$ otherwise the lowest of all available stress strain curves should be used. In situations where there is a mismatch in the weld and base material proof or yield strengths in excess of 10 % the mismatch option may be employed. This is based upon the concept of an equivalent mismatch material and requires an estimate of the yield limit load under the mismatch conditions (III.2)
I.4.4.2. Calculational Steps, Homogeneous Material.

The equation for \( f(L_r) \) is the same for all materials, at all values of \( L_r \leq L_r^{\text{max}} \), whether or not they exhibit a lower yield plateau. It is based upon the true stress true strain curve for the material, and values of \( f(L_r) \) should be calculated over small enough intervals to give a good representation of the material’s behaviour. In general, this requires calculations at values of \( L_r \) of 0.7, 0.9, 0.98, 1.00, 1.02, 1.10, 1.20, etc to \( L_r = L_r^{\text{max}} \).

For \( L_r \leq L_r^{\text{max}} \), \( f(L_r) \) is given by equation I.4.16

\[
f(L_r) = \left[ \frac{E \epsilon_r}{\sigma_r} + 0.5 \left( \frac{L_r}{E \epsilon_r/\sigma_r} \right)^2 \right]^{-1/2}
\]  

where \( \epsilon_r \) is the material’s true strain obtained from the uniaxial stress strain curve at a true stress \( \sigma_r \) of \( L_r R_e \), where \( R_e \) is the yield or proof strength of the material. Note that engineering stress strain curves can be used, but these will produce a slightly conservative result at high values of \( L_r \) compared with results obtained with true stress strain data.

For \( L_r > L_r^{\text{max}} \), \( f(L_r) = 0 \), equation I.4.3.

I.4.4.3. Calculational Steps for Mismatch Material

In this case the mismatch ratio is defined as a function of plastic strain as follows:

\[
M(\epsilon_p) = \sigma^w(\epsilon_p)/\sigma^b(\epsilon_p)
\]

where \( \epsilon^w(\epsilon_p) \) is the stress at a plastic strain, \( \epsilon_p \), in the weld metal and \( \sigma^b(\epsilon_p) \) is the stress at the same level of plastic strain in the base metal as shown in Fig II.1.2. If the stress strain curves are similar, the function \( M(\epsilon_p) \) will be only weakly dependent on \( \epsilon_p \) and a value obtained at the proof strain, \( \epsilon_p = 0.002 \), may be adequate.

For each value of \( M(\epsilon_p) \), evaluate the ratio of \( F^M/F^B \) where \( F^M \) is the mismatch limit load, see III.2, and \( F^B \) is the limit load defined for a homogeneous material with the tensile properties given by the base metal.

Define an equivalent stress-plastic strain curve, \( \sigma^m(\epsilon_p) \), for the mismatch material as follows

\[
\sigma^m(\epsilon_p) = \frac{(F^M/F^B - 1)\sigma^w(\epsilon_p) + (M - F^M/F^B)\sigma^b(\epsilon_p)}{(M - 1)}
\]

The total strain is obtained by adding the elastic strain, \( \sigma^m/\rho \), to the plastic strain, \( \epsilon_p \), from which the mismatch stress strain curve can be calculated. The function \( f(L_r) \) can then be obtained by means of equations I.4.16 and I.4.3.

\( L_r \) for the loading on the structure should be calculated using the yield limit load for the mismatch conditions, \( F^M_\sigma \) (III.2) and an estimate of the minimum value for the mismatch proof strength, \( R^M_p \) given at a value of plastic strain, \( \epsilon_p = 0.002 \).
I.4.5. **Constraint Analysis:**

**Level 4, Allowing for Reduced Amounts of Constraint**

Associated with assessment procedures for analysis levels 1 to 3, are reserve factors which indicate a proximity to a limiting condition. The limiting condition incorporates an element of conservatism so that, in general, the reserves in the structure are underestimated.

A particular conservatism implicit in the procedure arises from the value of $K_{\text{mat}}$ being derived from deeply cracked bend or compact tension specimens recommended in the testing standards. These are designed to ensure plain strain conditions and/or high hydrostatic stresses near the crack tip to provide a conservative estimate of the material's resistance to fracture which is relatively independent of geometry. However, there is considerable experience that the material's resistance to fracture increases when the loading is predominantly tensile, and when the crack depths are shallow. These situations lead to lower hydrostatic stresses at the crack tip, referred to as lower constraint.

In order to claim benefit for a situation where the constraint is reduced over that in the test specimen, it is necessary to perform additional calculations and to have more information on fracture toughness properties. Benefits are usually greatest for shallow cracks subject to tensile loads, but guidance on the cases where greatest benefit can be obtained is contained in III.1. The procedure for determining the constraint benefit is described in detail in IV.4.

I.4.6 **J-Integral Analysis**

**Level 5.**

In some situations estimates of the J-integral may be available from a numerical stress analysis of the cracked body. In these cases an analysis may be performed using this value of the J-integral directly. If such an analysis provides enough information to make plots of J as a function of load, or as a function of crack size, these values of J may be used to construct a CDF J diagram from which an initiation or a tearing analysis may be performed. As this method requires numerical methods such as finite elements, further detail of this approach is not covered in this procedure.

I.4.7 **Leak-Before-Break**

**Level 6**

For pressurised components, a situation can occur where a part penetrating flaw may propagate through the remaining ligament and result in a leaking but stable condition. This situation can be assessed by performing a Leak-Before-Break analysis. The initial analysis at levels 1, 2 or 3, must have been assessed under conditions of ductile tearing (either as an initiation analysis or as a tearing analysis, IV.2) and will have resulted in either an inability to demonstrate that the limiting condition can be satisfied, or in inadequate factors (derived following I.3). A further analysis may show that the resultant through thickness flaw is both stable and produces a detectable leak.

The Leak-Before-Break analysis requires consideration of sub-critical crack growth mechanisms and rates (stress-corrosion-cracking, fatigue, ductile tearing) and estimates of leak rates. The procedure is described in IV.5.
I.4.8. Default Procedures

Where there are insufficient data available for a Level 1 analysis, or only a simple initial analysis is required, the default procedure may be employed. The principal features of this are:-

Only the minimum yield stress is needed for tensile data.

Only Charpy impact data is needed for $K_{\text{mat}}$.

The FAD approach must be used, and the choice of FAD depends on whether the stress-strain curve is estimated to be continuous or discontinuous.

Other inputs are the same as for Level 1.

The default analysis uses pessimistic correlations to convert Charpy data into $K_{\text{mat}}$, and provides the most conservative of all the analysis routines. A component which is acceptable using the default level will therefore be acceptable using any of the higher levels of analysis.

The default level is described in IV.1.
<table>
<thead>
<tr>
<th>Equation No</th>
<th>Formula for $f(L_r)$</th>
<th>Definitions</th>
<th>Tensile Data</th>
<th>Range of $L_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq I.4.1</td>
<td>$f(L_r) = (1 + 0.5L_r^2)^{1/2} [0.3 + 0.7 \exp(-\mu L_r^6)]$</td>
<td>$\mu = \min [0.001(E/R_p); 0.6]$ $E$ is Young’s modulus $R_p$ is proof strength in MPa</td>
<td>Continuous Yielding</td>
<td>$L_r \leq 1$</td>
</tr>
<tr>
<td>Eq I.4.2</td>
<td>$f(L_r) = f(1)L_r^{(N-1)/2N}$</td>
<td>$N$ is an estimate of the strain hardening exponent given by $N = 0.3 [1 - (R_e/R_m)]$ $R_e$ is either $R_p$ or $0.95R_{el}$ depending on material, in MPa. $R_m$ is the material’s ultimate tensile strength in MPa $L_{r \text{max}} = 0.5(1 + R_m/R_e)$</td>
<td>Continuous And Discontinuous Yielding</td>
<td>$1 \leq L_r \leq L_{r \text{max}}$</td>
</tr>
<tr>
<td>Eq I.4.3</td>
<td>$f(L_r) = 0$</td>
<td></td>
<td>Continuous And Discontinuous Yielding</td>
<td>$L_r &gt; L_{r \text{max}}$</td>
</tr>
<tr>
<td>Eq I.4.4</td>
<td>$f(L_r) = \left[1 + 0.5(L_r)^2\right]^{1/2}$</td>
<td></td>
<td>Discontinuous Yielding</td>
<td>$L_r \leq 1$</td>
</tr>
<tr>
<td>Eq I.4.5</td>
<td>$f(1) = \left(\lambda + \frac{1}{2\lambda}\right)^{-1/2}$</td>
<td>$\lambda = (1 + E\Delta \varepsilon/R_{elH} )$ $\Delta \varepsilon$ is the lower yield strain given by $\Delta \varepsilon = 0.0375 (1 - R_{elH}/1000)$ $R_{elH}$ is the material’s upper yield strength or limit of proportionality.</td>
<td>Discontinuous Yielding</td>
<td>$L_r = 1$</td>
</tr>
<tr>
<td>Formulae</td>
<td>Definitions</td>
<td>Tensile Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>--------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq I.4.6 $M = R_e^W / R_e^B$</td>
<td>$R_e$ is either $R_p$, $R_{el}$ or $0.95R_{eff}$ for weld, $W$, or base metal, $B$, depending on material</td>
<td>Continuous or Discontinuous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq I.4.7 $R_e^M = (F_e^M / F_e^B) R_e^B$</td>
<td>$F_e^M$ is the mismatch yield limit load $F_e^B$ is the base metal yield limit load defined at $R_e$</td>
<td>Continuous or Discontinuous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq I.4.8 $\mu^M = \frac{(M - 1)}{(F_e^M / F_e^B - 1) / \mu^W + (M - F_e^M / F_e^B) / \mu^B}$</td>
<td>$\mu^W = 0.001E^W / R_e$ $\mu^B = 0.001E^B / R_e$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq I.4.9 $N^M = \frac{(M - 1)}{(F_e^M / F_e^B - 1) / N^W + (M - F_e^M / F_e^B) / N^B}$</td>
<td>$N^W = 0.3 (1 - R_e^W / R_m^W)$ $N^B = 0.3 (1 - R_e^B / R_m^B)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eq I.4.10 $L^\text{max} = (F_e^M / F_e^B) R_F^M$</td>
<td>$R_F^M$ is the lower of Either $0.5(1+R_m^W / R_p^W)$ Or $0.5(1+R_m^B / R_p^B)$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE I.4.3. Equations used in defining $f(L_r)$ for Mismatch Materials with Continuous and Discontinuous Yielding

<table>
<thead>
<tr>
<th>Formulae</th>
<th>Definitions</th>
<th>Tensile Data</th>
<th>Eq for $f(L_r)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq I.4.11</td>
<td>$\lambda^M = \frac{(F_{eh}^M / F_{eh}^B - 1)\lambda^W + (M - F_{eh}^M / F_{eh}^B)\lambda^B}{(M - 1)}$</td>
<td>$\lambda^W = 1 + E^W \Delta\epsilon^W / R_{eh}^W$</td>
<td>Both Base and Weld Metal Continuous</td>
</tr>
<tr>
<td></td>
<td>$\Delta\epsilon^W = 0.0375(1 - R_{eh}^W / 1000)$</td>
<td>$\lambda^B = 1 + E^B \Delta\epsilon^B / R_{eh}^B$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta\epsilon^B = 0.0375(1 - R_{eh}^B / 1000)$</td>
<td>Base metal continuous Weld metal Discontinuous</td>
<td></td>
</tr>
<tr>
<td>Eq I.4.12</td>
<td>$\mu^M = \frac{(M - 1)}{(F_p^M / F_{eh}^W - 1) / \mu^B}$</td>
<td>$\mu^B = 0.001E^B / R_p^B$</td>
<td>Base Metal Continuous Weld Metal Discontinuous</td>
</tr>
<tr>
<td>Eq I.4.13</td>
<td>$\lambda^M = \frac{(F_c^M / F_{eh}^W - 1)\lambda^W}{(M - 1)}$</td>
<td>Base Metal Continuous Weld Metal Discontinuous</td>
<td></td>
</tr>
<tr>
<td>Eq I.4.14</td>
<td>$\mu^M = \frac{(M - 1)}{(F_p^M / F_{eh}^B - 1) / \mu^W}$</td>
<td>$\mu^W = 0.001E^W / R_p^W$</td>
<td>Base Metal Discontinuous Weld Metal Continuous</td>
</tr>
<tr>
<td>Eq I.4.15</td>
<td>$\lambda^M = \frac{(M - F_c^M / F_{eh}^B)\lambda^B}{(M - 1)}$</td>
<td>Base Metal Discontinuous Weld Metal Continuous</td>
<td></td>
</tr>
</tbody>
</table>
Fig I.4.1  Treatment of Tensile Data to Devise FAD at Levels 1, 2 and 3

MM= Mismatch, B=Base Metal, W= Weld Metal, N= Strain Hardening Exponent
LYS= Lower Yield Stress.
Note (*): Cases of MM>10% can also be assessed with Level 1 provided tensile properties of weakest component are used: This will be highly conservative for OM cases.
CHAPTER I : DESCRIPTION

I.5 : REPORTING

I.5.1 Aims of Report

The aim of this section is to provide a checklist of issues that should be recorded to enable the full context of an analysis to be visible. This is necessary for several reasons:

- To record the baseline conditions used in an assessment so that refinements to the analysis can be compared with the original assumptions.
- To ease verification of an assessment.
- To provide fully documented evidence for e.g third party use.
- To provide enough detail such that the analysis can be repeated at a later stage by someone not originally connected with the work, i.e historical use.

Known pessimisms incorporated in the assessment route should be listed. In addition, all departures from the recommendations laid down in this procedure should be reported and separately justified. A separate statement should be made on the significance of potential failure mechanisms remote from the region containing the flaw being assessed.

Where reasonably practical, relevant information on the following aspects should be presented.

I.5.2 Loading Conditions

Structure/component Details
Design Code (Pressure vessel, bridge, offshore)
Normal operation
Fault or transient conditions
Additional loads and stresses
Stress analysis methods used (e.g design code value, linearisation, finite element, measured etc.)
Residual stress value assumed and method used to determine it
Application of PWHT
Temperature
Loading Rate

I.5.3 Material Properties

Material specification
Heat treatment
Yield stress, type (upper, lower, 0.2%) and how obtained (min spec, historical, test certificate, tested)
Ultimate Tensile Stress and how obtained (min spec, historical, test certificate, tested)
Number of tensile tests carried out and whether value used is mean or lower bound
Orientation and position of tensile specimens
Fracture toughness at relevant temperature and strain rate and how obtained (source of original data, Charpy correlation and associated P不经意，application of MML steps 1,2,3, comment on homogeneity, comment on specimen type and crack depths, test procedure used, constraint factor for CTOD-K conversion, validity of data, failure mechanism criteria, definition of characteristic value)
CHAPTER I : DESCRIPTION

Young's Modulus (assumed or measured)
Poisson's Ratio (assumed or measured)

I.5.4 Definition of Flaw

Flaw type, location (weld metal, fusion line etc.), position (centre line etc.) shape, size, orientation
Basis for flaw size assumptions, NDT method used, quality of inspection, capabilities of method, sizing errors, probability of detection/correct sizing etc.
Whether any flaw recharacterisation or interaction has been assumed

I.5.5 Welding Issues

Welding method, parameters, heat input, consumables, joint design/geometry
PWHT
Tensile data for different constituents of weld (parent plate and weld metal) as per detail given in section 2
Detailed reporting of fracture toughness determination, characteristic value and comment on inhomogeneity, metallography/fractography and site of pre-fatigue tip.
Weld misalignment

I.5.6 Failure Assessment Diagram/Crack Driving Force

Whether FAD or CDF approach used
Level of FAD/CDF (default, known YS-UTS, known stress-strain curve, J-based approach)
Comment on yield plateau
Whether any allowance is made for crack extension by prior sub-critical crack growth (fatigue, stress corrosion; crack growth laws employed) and ductile tearing
Whether Mismatch analysis applicable and invoked
Whether advanced methods are used (Constraint, LBB or prior overload analyses)

I.5.7 Limit Load

Source of limit load solution (compendium, other established solutions, finite element analysis, scale model testing)
Whether local and/or global collapse is considered.

I.5.8 Stress Intensity Factor Solution

Source of K solution (compendium, other established solutions, finite element analysis)

I.5.9 Significance of Results

Reserve factors for each combination of loading condition/material properties/flaw/category of analysis undertaken
Assessment points/reserve shown in comparison with FAD
Comment on any partial safety factors applied
Sensitivity analyses carried out
CHAPTER I : DESCRIPTION

I.5.10 **Probabilistic Analysis**

Method applied (MCS, MCS-IS, FORM, SORM)
Distribution (e.g. Normal, Log-normal, Weibull), mean and standard deviation of yield stress, tensile stress, fracture toughness and defect size.
Calculated failure probability

I.5.11 **Summary of Assessment/ Further Action**

Conclusions
Proposed further actions in analysis (e.g. generate further toughness data, repeat NDE etc.)
Proposed further actions for current structure/component (e.g. continue operation, repair, PWHT)
Implications for other similar existing plant or similar future plant.
### Chapter I: Description

**Table I.5.1: Checklist of General Issues**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>INPUT/RESULT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure/equipment identification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design code (pressure vessel, bridge, offshore etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post Weld Heat Treatment</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table I.5.1: Checklist of General Issues
<table>
<thead>
<tr>
<th>ITEM</th>
<th>INPUT/RESULT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOADING CONDITIONS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. temperature, pressure, static/dynamic loading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. temperature, pressure, static/dynamic loading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design stress analysis available</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define stresses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary stresses (tension, bending)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary thermal/residual stresses</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table I.5.2 : Checklist of Loading Conditions
### CHAPTER I : DESCRIPTION

<table>
<thead>
<tr>
<th>MATERIAL PROPERTIES</th>
<th>ITEM</th>
<th>INPUT/RESULT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material specification</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post Weld Heat Treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tensile properties (Base, weld)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum specified (yield stress, ultimate strength)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material qualification data (yield stress, ultimate strength)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full stress strain curve</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fracture toughness</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material qualification data (CTOD, K, J, R-curve)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated from Charpy data</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transition temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crack growth law (e.g. fatigue), SCC, Hydrogen Embrittlement</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ageing (Temper Embrittlement, Hydrogen Embrittlement, Irradiation Embrittlement)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weld mismatch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modulus of elasticity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table I.5.3 : Checklist of Materials Property Data**
## TABLE I.5.4: Checklist of Flaw Definition

<table>
<thead>
<tr>
<th>ITEM</th>
<th>INPUT/RESULT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEFINITION OF FLAW</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flaw type (fatigue, lack of fusion, planar, volumetric etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flaw location (weld metal, fusion line etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flaw size and orientation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basis for flaw data (NDE method, POD, accuracy etc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source of flaw (fabrication, in service)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defect interaction evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHECK LIST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITEM</td>
<td>INPUT/RESULT</td>
<td>COMMENTS</td>
</tr>
</tbody>
</table>

### ANALYSIS OPTION

- Applied assessment procedure and level of analysis
- Fracture initiation (brittle fracture, ductile fracture initiation) max. CTOD?
- Ductile tearing analysis (specify fracture resistance curve)
- Crack growth (e.g. fatigue)
- Leak before break
- Applied constraint factor (CTOD-K conversion)
- Probabilistic analysis
  - Applied method
  - Applied distributions

### LIMIT LOAD SOLUTION

- Applied limit load solution

### STRESS INTENSITY FACTOR SOLUTION

- Applied stress intensity factor solution

---

*Table I.5.5: Checklist of Analysis Option, LL and SIF Details*
## Table I.5.6: Checklist of Results Significance

<table>
<thead>
<tr>
<th>ITEM</th>
<th>INPUT/RESULT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIGNIFICANCE OF RESULTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Results sensitivity analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reserve factor as a function of e.g. defect size, fracture toughness etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability of result falling outside of FAD less than target probability values.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conclusion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SECTION II.1: TENSILE PROPERTIES

II.1.1 Introduction

The tensile properties determine both the expression \( f(L_r) \) and the value of \( L_r \) for the loading on the structure. This section describes how to use the different types of tensile data in the various standardised levels of the procedure.

The standardised levels and their requirements are as follows:

Basic level:

For the calculation of \( L_r \)

- minimum values of yield or proof strength
- minimum values of ultimate tensile strength

For the calculation of \( f(L_r) \) and \( L_r^{\text{max}} \)

- mean values of yield or proof strength
- mean values of ultimate tensile strength

Mismatch Level

For the calculation of \( L_r \)

- minimum values of yield or proof strength of both weld and base material
- minimum values of ultimate tensile strength of both weld and base material
- estimate of mismatch yield limit load

For the calculation of \( f(L_r) \) and \( L_r^{\text{max}} \)

- mean values of yield or proof strength of both weld and base material
- mean values of ultimate tensile strength of both weld and base material

SS Level

Both mean and minimum representations of the full stress-strain curve are required, as above. For the mismatch option, full stress strain curves are needed of both weld and base material, plus an estimate of the mismatch yield limit load.

The general approach for treatment of tensile data at these three levels was previously summarised in Fig. I.4.1.

Tensile properties should be determined in accordance with a recognised standard such as BS EN 10 002-1, and at the appropriate temperature.

There may be cases where the tensile data is obtainable only from test certificates, and where the ultimate tensile strength may not be known. In these cases, recourse can be made to the default level of analysis ( IV.1 ).
II.1.2. **Basic Procedure: Level 1 Analysis.**

It is first necessary to establish whether or not the material displays or may be expected to display a lower yield plateau. This is important as the value of $f(L_r)$ for materials which yield discontinuously is fundamentally different than for materials with continuous yielding characteristics. In some situations the data will be complete enough to establish the yielding characteristics, but in many situations this may not be the case. For structural steels, an indication can be obtained from the yield strength, composition, and the process route. Guidance for this decision is given in Table II.1.1 where these factors have been grouped according to standard specifications.

It should be recognised that the presence of a yield point is affected not only by the material and its test temperature but also by test method, loading rate and specimen design. Thus the guidance in Table II.1.1 is a generalisation. Also, the value of the yield strength quoted in test certificates will be a proof strength, $R_p$, for materials which exhibit continuous yielding, or the upper yield strength, $R_{uH}$, for materials which exhibit a yield point. Distinction between these two measurements is not usually made on test certificates.

Table II.1.1 applies only to the steels listed. For other materials the yielding behaviour should be determined prior to selecting the equation for the FAD. If there is some doubt, it is conservative to use the equations given in I.4.2.2, 2(b).

The values of the $R_e$ to be used for calculating $L_r$ at Level 1 are given below.

(a) For materials with a continuous stress strain curve, the value of $R_e$ should be the minimum value of $R_p$ obtained in the data set.

(b) For materials with a discontinuous stress strain curve,

Where the values are known to be either the lower yield strength or the proof strength, $R_p$, the value used should be the minimum value in the data set.

Where the values given are known to be, or are suspected to be, the upper yield strength, $R_{uH}$, the value used should be reduced by 5%, i.e., set $R_e = 0.95 R_{uH}$, where $R_{uH}$ is the minimum value in the data set.

For the calculation of $f(L_r)$ and $L_r^{max}$, the mean estimates of $R_e$ should be determined in the same way.

In Level 1, the following approximations are used:

1. For the case of a discontinuous yielding, the length of the lower yield plateau is estimated using equation I.4.1.5, Table I.4.1. This is shown in Fig. II.1.1a.

2. Knowledge of the ratio of the yield stress/tensile stress, $Y/T$, is then used to derive a generally conservative estimate of the strain hardening exponent, $N$. In this context, $N$ refers to the slope of the mean line fit in a log-log plot of the stress strain curve between $R_p$ and $R_m$ for continuous stress strain curves, or for discontinuous stress strain curves between the point defined at the end of the lower yield plateau, equivalent to $R_{el}$, and $R_{m}$. Analysis of a large data set of both ferrous and non-ferrous metals has enabled the relationship between $Y/T$ and $N$ to be defined as
\[
N = 0.3 \left[ 1 - \left( \frac{R_e}{R_m} \right) \right] \quad \text{(II.1.1)}
\]

Where \( R_e \) is either \( R_p \) or \( R_{el} \), whichever is appropriate; this relationship is shown in Fig.II 1.1b.

II.1.3. **Mismatch Level: Level 2 Analysis**

In the case of weldments where the difference in yield strengths between the base material and the weld metal is greater than 10\%, the joint may behave as a heterogeneous bi-metallic joint. In such cases, use of minimum values of yield strength may be over-conservative. The mismatch level provides a method for reducing the conservatism by allowing for separate contributions of the base material (denoted B) and the weld material (denoted W).

This level can only be used where there is available an estimate of the yield limit load under the mismatch conditions. Some solutions for standard geometries are given in III.2.

It should be recognised that weld tensile properties may vary through the thickness of a component and may be dependent on specimen orientation. The range of weld metal microstructures sampled can often lead to a high degree of scatter. The tensile properties used should be based upon the lowest properties within the weld, irrespective of orientation and position, in order to provide a conservative result.

Three combinations of stress strain behaviour are possible:

- Both base and weld metal exhibit continuous yielding behaviour
- Both base and weld metal exhibit discontinuous yielding behaviour and a lower yield plateau
- One of the materials exhibits discontinuous yielding behaviour and the other has a continuous stress strain curve.

The Level 2 analysis is performed using FADs and CDFs derived using values of \( L_r \) and \( f(L_r) \) for an equivalent material with tensile properties derived under the mismatch conditions. In general, for all combinations of yield behaviour, this requires calculation of the mismatch ratio, \( M \), a mismatch limit load, \( F_e^M \), a value for \( L_r^{max} \) under the mismatch conditions, a value for \( N \) under the mismatch conditions and similar values for \( \mu \) or \( \lambda \), all of which are defined in I.4.3. Advice for calculating the mismatch limit load is given in III.2, and this also contains solutions for some typical geometries. Note that the mismatch limit load depends not only upon the mismatch ratio but also on the location of the flaw within the weldment.

II.1.4. **Stress-Strain Level: Level 3**

This level of analysis is for situations where the complete stress-strain curves for all constituents are known. In a weldment, it may be performed as if the material is homogeneous (I.4.4.2), or where there is mismatch in yield strength in excess of 10\% it may be performed for the equivalent mismatch material (I.4.4.3). In either case, where there is scatter in the available data, the tensile data used should be based upon the lowest of the applicable stress-strain curves.

The equation for \( f(L_r) \) is the same for all materials, whether homogeneous or equivalent mismatch, (eq.I.4.16), over strain intervals small enough to give a good representation of
the material's behaviour. It is based upon true stress true strain curves, but engineering stress strain data may be used with only a small penalty at high values of $L_r$.

As for Level 2, the mismatch option involves calculation of mismatch ratio and mismatch limit loads. The mismatch ratio is now a function of strain,

\[ M(\varepsilon_p) = \frac{\sigma^W(\varepsilon_p)}{\sigma^B(\varepsilon_p)} \]  

(II.1.2)

Where $\sigma^W(\varepsilon_p)$ is the stress at a plastic strain $\varepsilon_p$ in the weld metal and $\sigma^B(\varepsilon_p)$ is the stress at a plastic strain $\varepsilon_p$ in the base material, as shown in Fig II.1.2. If the stress strain curves are similar, $M(\varepsilon_p)$ will be only weakly dependent on plastic strain, and a value at the proof strain, $\varepsilon_p = 0.002$ may be adequate.

The mismatch limit loads are also a function of strain, being dependent on $M(\varepsilon_p)$.

The equivalent stress strain curve is obtained by adding the elastic and plastic parts of the stress-strain curve. The plastic part of the stress strain curve is given by

\[ \sigma^M(\varepsilon_p) = \left[ \frac{F^M}{F^B - 1} \right] \sigma^W(\varepsilon_p) + \left[ M(\varepsilon_p) - \frac{F^M}{F^B} \right] \sigma^B(\varepsilon_p) \left[ M - 1 \right] \]  

(II.1.3)

and the total strain at any stress is given by adding the elastic strain, $\sigma^M/E$, to the plastic strain at that stress level.

**II.1.5. Temperature Compensation.**

For situations where the operating temperature is below room temperature, but room temperature yield strength is known, the yield strength may be estimated from the following equation

\[ R_y = (R_0)_{RT} + 10^5/(491 + 1.8T) - 189 \text{ MPa} \]

(II.1.4)

Where $R_y$ is $R_m$, $R_p$ or $0.95R_{off}$, as appropriate, $T$ is the temperature in °C and RT denotes room temperature.
## Table II.1.1 : Selection Procedure for Determining Whether A Yield Plateau Should be Assumed

<table>
<thead>
<tr>
<th>Yield Stress Range (MPa)</th>
<th>Process Route</th>
<th>Composition Aspects</th>
<th>Heat Treatment Aspects</th>
<th>Assume Yield Plateau</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As-Rolled</td>
<td>Conventional Steels (e.g. EN 10025 grades) without microalloy additions</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mo, Cr, V, Nb, Al or Ti present</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Normalised</td>
<td>EN 10025 type compositions without microalloy additions</td>
<td>Conventional normalising</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EN 10113 type compositions with microalloy additions</td>
<td>Conventional normalising</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Controlled Rolled</td>
<td>EN 10113 compositions</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Controlled Rolled</td>
<td>EN 10113 compositions</td>
<td>Light TMCR schedules (YS &lt;400)</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heavy TMCR schedules (YS &gt;400)</td>
<td>(Yes)</td>
</tr>
<tr>
<td></td>
<td>Quenched &amp; Tempered</td>
<td>Mo or B present with microalloy additions Cr, V, Nb or Ti</td>
<td>Heavy tempering favours plateau</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mo or B not present but microalloying additions Cr, V, Nb or Ti are (V particularly strong effect)</td>
<td>Light tempering favours no plateau</td>
<td>(Yes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heavy tempering</td>
<td>(Yes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Light tempering</td>
<td>(No)</td>
</tr>
<tr>
<td></td>
<td>Quenched &amp; Tempered</td>
<td>Mo or B present with microalloy additions Cr, V, Nb or Ti</td>
<td>Tempering to YS &lt; ~690</td>
<td>(No)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mo or B not present but microalloy additions Cr, V, Nb or Ti are</td>
<td>Tempering to YS &lt; ~690</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tempering to YS ≥ ~690</td>
<td>(No)</td>
</tr>
<tr>
<td></td>
<td>As-Quenched</td>
<td>All compositions</td>
<td>NA</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>No</td>
</tr>
</tbody>
</table>

( ) = Some Uncertainty, Sensitivity Analysis should be carried out
II.6

a) Estimation of Length of Yield Plateau

b) Estimation of Strain Hardening Exponent

Fig. II.1.1  Treatment of Tensile Data at Level 1
Fig. II.1.2  Definition of Mis-Match Ratio, M, and Construction of the Equivalent Material Stress-Strain Curve
SECTION II.2 : CHARACTERISTIC VALUES OF FRACTURE TOUGHNESS

Symbols for MML Method

\( K_{cen} \) censored value of toughness in units of \( K \)
\( \delta \) censoring parameter
\( K_i \) individual values of fracture toughness adjusted to 25 mm thickness
\( K_{min} \) minimum value of \( K_i \)

\( n \) number of specimens in data set
\( r \) number of specimens in data set which fail by brittle mechanism

\( K_0 \) 63.2\% cumulative failure probability
\( \overline{K_m} \) median value (50\% cumulative failure probability)
\( K_{0(min)} \) minimum value of \( K_0 \)
\( \overline{K_T} \) test value of \( \overline{K_m} \) for MML stage 2
\( \overline{K_K} \) constant value of \( \overline{K_m} \) derived from MML stage 2
\( K_{OK} \) value of \( K_0 \) associated with \( \overline{K_K} \)
\( K_{0R} \) reference value of \( K_0 \)
\( K_{KR} \) reference value of \( \overline{K_m} \)

\( t \) section thickness
\( T_i \) test temperature of specimen of toughness \( K_i \)
\( T_0 \) transition temperature corresponding to median at toughness of 100 MPa√m
\( T_R \) reference value of \( T_0 \)
\( T_T \) test value of \( T_0 \)
\( T_K \) constant value of \( T_0 \) obtained from MML stage 2
\( T_{0(max)} \) maximum value of \( T_0 \)

\( P\{K_{mat}\} \) probability distribution
\( P_T \) probability fractile

II.2.1. Introduction

This Section sets out the preferred methods for obtaining characteristic values for fracture toughness.

Fracture toughness is a measure of the material’s ability to resist cracking and characteristic values of toughness are needed at step 3 in the procedures of I.4. A number of different types and qualities of toughness data can be obtained, depending upon the material, the temperature of the test (the operating temperature of the structure) and the type and number of tests performed. These determine how the characteristic value can be determined, and the level of the analysis which can be performed (I.2.3).

In metallurgical terms, materials can fail in one of two mechanisms: ductile and brittle. The brittle mechanism is characteristic of ferritic and bainitic steels at low temperatures, but it can occur in other materials. Unless crack arrest occurs, the initiation of brittle fracture coincides with structural failure. As the temperature of a ferritic or bainitic steel is increased, the brittle fracture toughness rises markedly, until a temperature is reached where brittle fracture is no longer the prevailing failure mechanism. This is the transition temperature, above which the fracture mechanism is by ductile tearing. This ductile fracture is also the failure mechanism of most other materials and it is characterised by a resistance curve. In
contrast to the brittle fracture toughness, which appears as a single value of toughness defining the initiation of brittle fracture, the resistance curve is a rising function of crack extension. This resistance curve property means that, in structures made of ductile materials, structural failure does not generally coincide with the onset of ductile tearing, but occurs after some amount of crack growth. The amount of crack growth leading to structural failure is dependent upon geometry, loading and the resistance curve. An initiation analysis uses a characteristic value of toughness equivalent to the onset of cracking, whether brittle or ductile, while a ductile tearing analysis needs characteristic values which allow for ductile tearing.

Fracture toughness values characteristic of brittle fracture tend to be highly scattered and are dependent on the size and constraint of the specimen (or structure). In the transition region, scatter is also high so that the transition temperature is also likely to be highly scattered. In ferritic and bainitic steels there is also a zone of temperature immediately above the first appearance of ductile fracture where brittle fracture can appear after some small amount of ductile tearing.

In all of these cases, the toughness can be characterised by the same parameter. This can be written in terms of $K$, $J$ or CTOD. Standardised methods are available for determining all fracture toughness values needed for this procedure, and the treatments for determining the characteristic values given in the following sections are designed around these standardised methods.

The material's ability to resist fracture, although most appropriately characterised by fracture toughness, can also be characterised from Charpy tests. These give a qualitative measure of the fracture toughness. For example, a ferritic steel typically produces a Charpy transition curve, the lower shelf being characteristic of fully brittle fracture, the upper shelf of fully ductile fracture and the transition zone characteristic of the change between the two fracture mechanisms. In the absence of appropriate fracture toughness data, Charpy data can be used to give a conservative estimate of fracture toughness by using appropriate correlations. These correlations are given in the default section IV.1.

### II.2.2. Toughness Data Format

The desirability of having appropriate toughness data cannot be emphasised too strongly, as this may be one of the main determinants in the accuracy of the assessment. The different mechanisms of fracture result in different forms of fracture toughness data, and these are treated in different ways in the recommended procedures. For brittle fracture, the recommended method is based on the concept of the Master Curve and maximum likelihood (MML) statistics. For ductile tearing, the minimum value of a set of three results is usually sufficient.

Any of the fracture toughness parameters can be described as $K_{\text{mat}}$, $J_{\text{mat}}$ or $\delta_{\text{mat}}$ depending on the approach adopted by the user. However, for calculating characteristic values using the MML method, all data should first be transformed into units of $K$. They may be converted back for use in the CDF approaches, where preferred. Recommended equations for conversion between fracture toughness parameters are given in Table II.2.1.
II.2.2.1. Fracture Initiation

The MML method is based upon the weakest link model for brittle fracture. The fracture toughness is obtained as a single value for each specimen tested. In principle data can be collected on any number of specimens at a single temperature representative of the temperature of interest in the structure, or at different temperatures. For practical purposes, at least three test results are required, but the credibility and accuracy of the MML representation is greatly improved with a larger number. The MML method provides a median fracture toughness and a statistical distribution from which the characteristic value can be obtained. Any choice of characteristic value can be made, such as the 5th or 20th percentile, depending on the reliability required of the analysis. Since use of the MML method implies acceptance of the weakest link model of brittle fracture, and a crack front length dependence, this must also be taken into account when determining characteristic values. (See I.3).

For fully ductile behaviour the toughness or resistance curve obtained depends upon the amount of tearing. It is usually measured in terms of $J$, and may be represented by an initiation value, $J_i$ or a function $J(\Delta a)$, which depends upon the ductile crack extension, $\Delta a$. For an initiation analysis, data characteristic of the onset of ductile tearing is used in the analysis, as a single value of toughness. Ductile tearing does not proceed by a weakest link model, and so ductile tearing data is not analysed using the MML method.

II.2.2.2. Ductile Tearing Analysis

This option is for use in situations where advantage can be taken of the increase in toughness as a function of ductile crack growth. In this case, characteristic values of toughness are determined as a function of small discrete amounts of crack growth.

II.2.2.3 Ductile Tearing and Maximum Load Values of Toughness

In some situations, only single values of fully ductile toughness are available, measured at the maximum load obtained in the test, and there is no possibility of performing further tests. Where the possibility of brittle fracture can be confidently excluded, such maximum load values may be used, subject to certain specimen size and ligament length considerations (see II.2.5).

II.2.2.4. Data Collection

Preferably, the test data should be specially collected from samples of the actual material of interest. If this is not possible, it may be obtained from replicate samples. In either case, care should be taken to ensure that the data is representative of the material product form of interest at the appropriate temperature, and any potential degradation due to manufacture or service is taken into account. In the case of welded structures, if the tests are performed on replicate samples, care should be taken to ensure that they truly represent the original weldments used in the structure. The samples should be welded with welding procedures, base materials and consumables as used for the service application and should take account of restraint during welding and of PWHT if applicable. The welding procedures should be appropriately documented (see EN 288-3 and EN 25817). In all cases care should be taken to ensure that the fracture data have been obtained from specimens whose fatigue crack tip samples the appropriate weld microstructures.

The fracture toughness tests should be carried out either on full thickness tests specimens, or on specimens complying with the specimen size criteria of eq II.2.1.2, Table II.2.1. Various procedures, such as BS7448 and ESIS-P2, 1992, give guidance on fracture
toughness testing which include, in the case of the latter, validity tests to ensure that the result is compatible with the theoretical basis underpinning the tests. The screening criteria used in the MML method to censor the data are in accordance with ASTM E 1921-97 and ensure that the result is not unduly biased by unrepresentative high values. Specimens which produce a result which fail these criteria should not be discarded, since these results are used as censored data in the analysis.

Ideally, fracture toughness tests should not be undertaken with the aim of measuring maximum load CTOD values for use in modern assessment methods, as the R-Curve is a more correct way of defining fracture toughness for these cases. However, in the case of maximum load data being the only available type, recommendations for using such values are given in II.2.5.

II.2.3. Analysis of Data for Initiation of Fracture

II.2.3.1. Brittle Fracture

The MML method given below contains three stages of analysis. Stage 1 gives an estimate of the median value of fracture toughness. Stage 2 performs a lower tail MML estimation, checking and correcting any undue influence of excessive values in the upper tail of the distribution. Stage 3 performs a minimum value estimation to check and make allowance for gross inhomogeneities in the material. In Stage 3, an additional safety factor is incorporated for cases where the number of tests is small. The MML procedure produces reference values $K_{oR}$ and $K_R$ for, respectively, the 63.2% and 50% (median) cumulative failure probabilities from which a probability distribution can be calculated. The characteristic values are then obtained following II.2.3.1.3, taking account of the factors discussed in I.3.

It is recommended that all three stages are employed when the number of tests to be analysed is between 3 and 9. With an increasing number of tests, the influence of the penalty for small data sets is gradually reduced. For 10 and more tests, only stages 1 and 2 need to be used. However, stage 3 may still be employed for indicative purposes, especially where there is evidence of gross inhomogeneity in the material (e.g. for weld or heat affected zone material). In such cases, it may be judged that the characteristic value is based upon the stage 3 result, or alternatively, such a result may be used as guidance in a sensitivity analysis (I.3.3.2).

Results obtained using the MML method described here have been compared with those of the so-called 'Minimum-of three equivalent' (MOTE). For small data sets (less than about 12 results) the MML method provides more consistent estimates of $K_{mat}$ when compared to values determined from the MOTE method. In these cases, the MML procedure minimises the risk of overestimating the true fracture toughness of the material. For large data sets (greater than about 15 results), the values determined from the two methods are similar.

A flow chart defining the major steps in this treatment is given in Fig. II.2.1. The principle for applying the method to the case of data at a single temperature and data at a different temperature is shown schematically in Fig. II.2.2.
II.2.3.1.1 Preliminary Steps

Ensure all data are in units of $K$

Equations II.2.1.1(a) and (b) in Table II.2.1 give relationships for converting $J$ or $\delta$ to $K$.

In equation II.2.1.1(b) the value of the coefficient $m$ was determined from a large data set on structural steels and represents the 25$^{th}$ percentile. This will give conservative estimates of $K_{mat}$ when converted from $\delta_{mat}$. It should be noted, however, that the value of $m$ in this equation may not be appropriate for steels with a very low work hardening exponent (i.e., where $N < 0.05$), or for materials other than steel, or for test results taken from specimens with shallow cracks. Where an alternative value of $m$ can be justified, it may be used in eq II.2.1.1(b).

Treatment of Non-valid Data

This is to ensure compliance with the fracture toughness testing standards and to ensure that all results relate to failures by brittle fracture only.

The following data should be excluded (censored) from the data set and designated by the censoring parameter $\delta_i = 0$.

(i) All results where the final failure mode was non-brittle (i.e. results from specimens which failed only by ductile tearing). Where failure was by brittle fracture, even after some ductile tearing, treat these data as uncensored subject to para (ii) below.

(ii) All results which failed the validity test for excessive plasticity given by eq II.2.1.2, Table II.2.1. For all these specimens, define the fracture toughness as the maximum value of toughness allowed by the standard ASTM E 1921-97 (see eq II.2.1.2 Table II.2.1) and designate as $K_{cen}$.

(iii) All other data should be treated as uncensored and designated $\delta_i = 1$.

Perform Specimen Size Adjustment

For results from specimens whose thickness is not 25 mm, adjust these according to equation II.2.1.3 Table II.2.1. Note that $K_B$ is the original value for the fracture toughness in a specimen of thickness $B$, and $K_i$ is the adjusted value, equivalent to that for a specimen size of 25 mm.

II.2.3.1.2 Maximum Likelihood Method

(I) For data collected at a single temperature.

MML Stage 1. Determination of MML Median Value

(a) Calculate $K_0$ according to equation II.2.2.1 Table II.2.2.

Note that $K_i$ is the individual fracture toughness of a specimen, adjusted for size according to equation II.2.1.3 Table II.2.1, and includes also each value of $K_{cen}$ and $\delta_i = 1$ or 0, as required in II.2.3.1.1 (i) (ii) and (iii). Perform the summations from $i = 1$ to $i = n$, where $n$ is the total number of data points in the set (including the specimens which were censored)
(b) Calculate a median value, $\bar{K}_m$, according to eq II.2.2.2 Table II.2.2.

**MML Stage 2. Lower Tail MML Estimation**

Establish, $\bar{K}_R$ as a reference value of $\bar{K}_m$, in the following way

a) For all data with a value above $\bar{K}_m$, set $K_i = \bar{K}_m$ and $\delta_i$ equal to 0, and for all other data retain their individual values of $K_i$ and set $\delta_i$ equal to 1.

(b) Establish a test value for $\bar{K}_m$, $\bar{K}_T$, following the procedures of paragraphs (a) and (b) in MML Stage 1 above using the remaining values of $K_i$ and the new restriction at $\bar{K}_m$.

(c) Compare the two values, $\bar{K}_m$ and $\bar{K}_T$.

If $\bar{K}_T$ is not less than $\bar{K}_m$, stop the stage 2 analysis at this point. Call $\bar{K}_m$ $\bar{K}_K$ and also call $K_0$, $K_{0K}$.

If $\bar{K}_T$ is less than $\bar{K}_m$, repeat the exercise, using $\bar{K}_T$ as the new benchmark for restricting the data. Iterate until a constant value for $\bar{K}_T$ is obtained. Call this value $\bar{K}_K$ and the associated value of $K_0$, $K_{0K}$.

(d) If the number of specimens in the data set was 10 or more (i.e., if $n > 9$) call $K_{0K}$ $K_{0R}$ and $K_{0K}$ $K_{0R}$ and determine probability distribution and characteristic values (II.2.3.1.3).

If the number of specimens in the data set was less than 10 perform MML stage 3 (minimum value) estimation, below.

**MML Stage 3. Minimum Value Estimation**

(a) Establish the lowest value of $K_i$ in the data set, and call this $K_{min}$.

(b) Determine $K_{0(min)}$ from equation II.2.2.3 Table II.2.2 noting that $n$ is the total number of data points in the set.

(c) Compare $K_{0(min)}$ and $K_{0K}$ established in Stage 2 (para (c)).

If $K_{0(min)} > 0.9K_{0K}$ this indicates that the data is homogeneous. The values $\bar{K}_K$ and $K_{0K}$ obtained in Stage 2 can therefore be taken as representative and used for determining the value for $K_{0R}$ in para (d) below.

If $K_{0(min)} < 0.9K_{0K}$ this indicates significant inhomogeneity. In this case establish a new value of $K_{0K}$ as $K_{0(min)}$, and use this for determining the value for $K_{0R}$ in para (d) below.

(d) Determine $K_{0R}$ and $\bar{K}_R$ including small data set safety correction.
Use eq II.2.2.4 and II.2.2.5 in Table II.2.2 to calculate final value of $K_{OR}$ and $\overline{K}_R$ noting that $r$ is the total number of specimens which failed by brittle fracture.

(II) For data over a range of temperatures

**Stage 1. MML estimation of $T_0$**

This must be calculated by an iterative process using the equation II.2.3.1 in Table II.2.3

Note that $T_i$ is the test temperature for a specimen $i$, with $K_i$ as its fracture toughness. For censored data whose toughness is represented by $K_{cen}$ (II.2.3.1.1), $T_i$ should be regarded as the temperature of that test. Perform the summations over values of $i$ from 1 to $n$, where $n$ is the total number of data in the set, including those censored.

**Stage 2. Lower Tail Estimation**

Establish $T_R$ as a reference value for $T_0$, in the following way.

(a) Censor all data whose toughness $K_i$ exceeds a value given by equation II.2.3.2 in Table II.2.3 setting $i$ for the censored data equal to 0 and $\delta$ for all other data equal to 1

(b) Define the fracture toughness for these data as $K_i = K_T$

(c) Establish a test value for $T_0$, $T_T$, following the procedures of stage 1 above.

(d) Compare the two values, $T_0$ and $T_T$

If $T_T$ is not greater than $T_0$, call this value $T_K$.

If $T_T$ is greater than $T_0$ repeat the exercise, using $T_T$ as a new benchmark for determining $K_T$. Continue the iteration until a constant value of $T_T$ is obtained. Call this value $T_K$.

(e) If the number of specimens in the data set was 10 or more (i.e., if $n > 9$) call $T_K$ $T_R$ and determine $K_{OR}$ and $\overline{K}_R$ from eq II.2.3.5 and II.2.3.6 in Table II.2.3. Use these values to determine the probability distribution and characteristic values (II.2.3.1.3).

If the number of specimens in the data set was less than 10 perform MML Stage 3 (minimum value) estimation, below.

**Stage 3. Minimum Value Estimation**

(a) Calculate the maximum value of $T_0$, $T_{0(max)}$ using only non-censored data, i.e. where $\delta_i = 1$, and eq II.2.3.3 in Table II.2.3

Note that $T_i$ is the test temperature of a specimen of toughness $K_i$ and $n$ is the total number of test results in the data.
(b) Compare $T_0(\text{max})$ and $T_K$

If $T_0(\text{max}) - 8 \, ^\circ C < T_K$ the data may be considered to be homogeneous, and the value $T_K$ may be taken as representative.

If $T_0(\text{max}) - 8 \, ^\circ C > T_K$, this indicates that the data is inhomogeneous, and $T_0(\text{max})$ should be taken as the representative value. Call this value $T_K$.

(c) Determine reference values including small data set safety correction.

Use equation II.2.3.4 in Table II.2.3 to calculate the final value of $T_0$, $T_R$, for determination of reference values of toughness using para (d), below. Note that $r$ is the number of specimens in the data set which failed by a brittle mechanism.

(d) Calculate both $K_R$ and $K_{0R}$ as a function of temperature, $T$, using eq II.2.3.5 and II.2.3.6 in Table II.2.3

II.2.3.1.3 Determination of Characteristic Values.

(i) Calculate the statistical distribution, $P(K_{\text{mat}})$, from eq II.2.1.4 in Table II.2.1. For data over a range of temperatures, these may be calculated at any appropriate temperature.

(ii) Determine the characteristic value $K_{\text{mat}}$

Equation II.2.1.5 in Table II.2.1 can be used to give a characteristic value for the toughness in terms of $K_{\text{mat}}$ as a function of the probability fractile, $P_r$, and the value of $K_0$ obtained.

In using eq II.2.1.5, the following factors need to be considered:

- The reliability needed of the result: this will determine the choice of $P_r$ (0.05 or 0.2).
- The importance of the stage 3 result for data sets above 10: this will determine what value of $K_0$ is used.

An additional factor may be needed in cases where crack length in the structure exceeds 25 mm. Eq II.2.1.6 in Table II.2.1 can be used for this, where $l$ is the length of the crack in the structure. It is recommended that where the crack length in the structure exceeds the section thickness, $t$, a correction equivalent to a maximum crack front length of $2t$ should be applied, except in the case of excessive inhomogeneity.

Guidance on all these considerations is given in I.3.2.3.

(iii) When using the CDF approaches, reconvert to units of $J$ or $\delta$

Use the equations II.2.1.1(a) and (b) in Table II.2.1 to reconvert.

II.2.3.2 For the Onset of Ductile Tearing

Since the scatter in data representing the onset of ductile tearing is normally small, it is sufficient to base the characteristic value on the minimum value of three valid test results.
Where results are invalid, consideration should be given to using the valid limit of toughness as the characteristic value. Alternatively, the significance of this limit could be explored by means of a sensitivity analysis. (See I.3.3.3)

If the lowest value in the data set is more than 10% below the highest value in units of $K$ (or more than 20% in units of $J$ or $\delta$), this indicates inhomogeneous behaviour. In this case, metallographic sectioning should be undertaken to ensure that the pre-fatigued crack tip is situated in the microstructure of interest, and consideration should be given to performing more tests.

For ferritic or bainitic steels, it is important to ensure that the temperature of interest is high enough to avoid any risk of brittle fracture occurring from proximity to the ductile brittle transition. Guidance is given in I.3.2.3.

II.2.4 Analysis of Data for a Ductile Tearing Analysis

In this case, characteristic values are required at amounts of ductile crack growth which are consistent with the small increments used in the ductile tearing assessment (See IV.2).

As for the onset of ductile crack growth, the scatter in the resistance curve is normally small, so the characteristic values can be derived from a curve which defines the minimum resistance curve from a set of three tests. Generally over the small amount of tearing used in the ductile tearing assessment the curves will be parallel. If not, a composite curve should be drawn below all three curves and the characteristic values derived from this.

Where results become invalid, consideration should be given to using the valid limit of toughness as the limit of the characteristic values. Alternatively, the significance of this limit could be explored by means of a sensitivity analysis. (See I.3.3.2.2 and I.3.3.3)

If at any crack extension considered, the lowest value in the data set is more than 10% below the highest value in units of $K$ (or more than 20% in units of $J$ or $\delta$) this indicates inhomogeneous behaviour. In this case, metallographic sectioning should be undertaken to ensure that the pre-fatigued crack tip is situated in the microstructure of interest, and consideration should be given to performing more tests.

For ferritic or bainitic steels, it is important to ensure that the temperature of interest is high enough to avoid any risk of brittle fracture occurring from proximity to the ductile brittle transition. Guidance is given in I.3.2.3.

II.2.5 Use of Maximum Load Fracture Toughness Data

In some circumstances the only type of fracture toughness data available may be values relating to the first attainment of a maximum load plateau (Maximum load CTOD, $J$ or $K_J$). Such toughness values represent thickness and size-dependent points on the fracture toughness resistance $R$-curve of the material. Nevertheless, they give useful estimates of toughness for many situations. Such values can be used in the SINTAP procedure, particularly for predominantly tension-loaded structures, but the following points should be considered in connection with their use.

Increasing specimen thickness while maintaining a constant ligament length leads to an increase in ductile-brittle transition temperature but also an increase in the level of upper shelf fracture toughness. The upper shelf toughness is also dependent on the ligament length, the smaller the ligament is the smaller the maximum load fracture toughness will be.
If cleavage occurs after the attainment of maximum load, the use of maximum load fracture toughness values will usually be conservative compared to the initiation value.

Maximum load fracture toughness values may be used in an analysis where historic data of this type are the only data available, provided that the ligament area of the fracture toughness specimen is equal to or smaller than the corresponding dimension in the structure.

In the case where the possibility of brittle fracture of specimens in the appropriate thickness can be excluded with confidence, the thickness of the fracture toughness specimen should be less than or equal to that of the structure. In such a case the maximum load fracture toughness value can be treated as if it was a ductile value and the size correction is not applied. The characteristic value should be determined from three or more results, following the method for the initiation of tearing in II.2.3.2. Care should be taken in the case of a high resistance to tearing since the maximum load fracture toughness may then exceed the toughness corresponding to the onset of stable crack extension. If this is so, a full tearing analysis may often be more appropriate. Where resistance to ductile tearing is low, the maximum load fracture toughness will usually be a conservative estimate of the toughness level at initiation of tearing and can be used with relative confidence. Where it is possible to establish the amount of ductile tearing occurring prior to the attainment of the maximum load, this should be taken into account by increasing the flaw size in the structure by the same or greater amount. In other situations, the maximum load toughness value should be taken to correspond to 6% crack growth relative to the ligament.

In the situation where brittle fracture of specimens in the appropriate thickness cannot be excluded, a step three analysis should be performed, treating the lowest value of maximum load fracture toughness as if it was brittle, and following the method described in II.2.3.1.2. This also requires an assessment of the validity of the data (II.2.3.1.1) subject to equation II.2.1.2 and test II.2.1.

In all cases, the user should establish that the structure is capable of withstanding any ductile tearing that may occur. Stable tearing using full thickness fracture toughness specimens up to the measured maximum load toughness value is acceptable.
Table II.2.1. GENERAL EQUATIONS FOR MML PROCEDURE

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eq. II.2.1.1(a)</strong>&lt;br&gt;Convert $J$ to $K$&lt;br&gt;$K = \sqrt{J.E / (1 - \nu^2)}$</td>
<td>$E$ is Young’s modulus&lt;br&gt;$\nu$ is Poisson’s ratio</td>
</tr>
<tr>
<td><strong>Eq II.2.1.1(b)</strong>&lt;br&gt;Convert $\delta$ to $K$&lt;br&gt;$K = \sqrt{mR_e \delta E / (1 - \nu^2)}$</td>
<td>$R_e$ is yield or proof stress&lt;br&gt;$m = 1.5$</td>
</tr>
<tr>
<td><strong>Eq. II.2.1.2</strong>&lt;br&gt;$K_{cen} = (E.b_0.R_e / 30)^{0.5}$</td>
<td>$b_0$ is the size of the uncracked ligament</td>
</tr>
<tr>
<td><strong>Eq. II.2.1.3</strong>&lt;br&gt;Adjust to 25 mm specimen size&lt;br&gt;$K_i = K_{25} = 20 + (K_B - 20)(B / 25)^{0.25}$</td>
<td>$K_B$ is the toughness of specimen of original thickness $B$</td>
</tr>
<tr>
<td><strong>Eq II.2.1.4</strong>&lt;br&gt;Statistical Distribution&lt;br&gt;$P{K_{mat}} = 1 - \exp\left{\frac{K_{mat} - 20}{K_{0R} - 20}\right}^4$</td>
<td>$K_{mat}$ is the reference toughness&lt;br&gt;$K_{0R}$ is the reference value for the 63.2% cumulative failure probability</td>
</tr>
<tr>
<td><strong>Eq II.2.1.5</strong>&lt;br&gt;Calculation of $K_{mat}$&lt;br&gt;$K_{mat} = 20 + (K_{0R} - 20){-\ln(1 - P_f)^{0.25}$</td>
<td>$P_f$ is the 0.05 or 0.2 fractile representing 5%&lt;br&gt;Or 20% cumulative failure probability of the set of specimens (See I.3.2.3)</td>
</tr>
<tr>
<td><strong>Eq II.2.1.6</strong>&lt;br&gt;Crack Length Adjustment&lt;br&gt;$K_{mat} = K_{mat(l)} = 20 + (K_{mat(25)} - 20)(25 / l)^{0.25}$</td>
<td>$K_{mat(l)}$ is the value of $K_{mat}$ adjusted for length of crack front, $l$, in mm, for $l &lt; 2t$. Where $l &gt; 2t$ this correction to a value of $K_{mat}$ given by $l = 2t$, where $t$ is the section thickness</td>
</tr>
</tbody>
</table>
Table II.2.2: For Data from Specimens Tested at One Temperature.

<p>| Eq II.2.2.1 | Calculation of $K_0$ (63.2% cumulative failure probability) | $K_0 = 20 + \left( \frac{\sum_{i=1}^{n} (K_i - 20)^4}{\sum_{i=1}^{n} \delta_i} \right)^{1/4}$ | $K_i$ is individual toughness value adjusted to 25 mm specimen size. $n$ is total number of tests in data set |
| Eq II.2.2.2 | Calculation of $\overline{K}<em>{m}$ (median value) | $\overline{K}</em>{m} = 20 + (K_0 - 20) \cdot 0.91$ |
| Eq II.2.2.3 | Calculation of $K_{0(\text{min})}$ (minimum value of $K_0$) | $K_{0(\text{min})} = 20 + (K_{\text{min}} - 20) \left( \frac{n}{\ln 2} \right)^{1/4}$ | $K_{\text{min}}$ is minimum value of $K_i$ in data set |
| Eq II.2.2.4 | Calculation of $K_{0R}$ and correction for small data set | $K_{0R} = 20 + \frac{K_{0K} - 20}{1 + \frac{0.25}{\sqrt{r}}}$ | $K_{0K}$ is value of $K_0$ from MML stage 3. $r$ is number of specimens which failed by brittle fracture. |
| Eq II.2.2.5 | Calculation of $\overline{K}_R$ | $\overline{K}<em>R = 20 + (K</em>{0R} - 20) \cdot 0.91$ |</p>
<table>
<thead>
<tr>
<th>Eq II.2.3.1</th>
<th>Calculation of $T_0$ (median temperature corresponding to 100 MPa m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sum_{i=1}^{n} \frac{\delta_i \exp{0.019(T_i - T_0)}}{11 + 77 \exp{0.019(T_i - T_0)}}$ - $\sum_{i=1}^{n} \frac{(K_i - 20)^4 \exp{0.019(T_i - T_0)}}{[11 + 77 \exp{0.019(T_i - T_0)}]^5} = 0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Eq II.2.3.2</th>
<th>Calculation of $K_T$ (censoring level corresponding to median)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_T = 30 + 70 \exp{0.019(T_i - T_0)}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Eq II.2.3.3</th>
<th>Calculation of $T_{0(max)}$ (maximum value of $T_0$ corresponding to 100 MPa m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{0(max)} = \max T_i - \frac{\ln\left[\frac{(K_i - 20)^{\frac{n}{\ln 2}}}{11}</td>
</tr>
</tbody>
</table><p>ight]}{77}$ |</p>

$n$ is total number of tests in data set.

<table>
<thead>
<tr>
<th>Eq II.2.3.4</th>
<th>Calculate $T_R$ including small data set correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_R = T_K + \frac{14}{\sqrt{r}}$</td>
</tr>
</tbody>
</table>

$T_K$ is value of $T_0$ from MML stage 3.
$r$ is the number of specimens which failed by brittle fracture.

<table>
<thead>
<tr>
<th>Eq II.2.3.5</th>
<th>Calculation of $K_{0R}$ (median value as function of temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\overline{K}_{R} = 30 + 70 \exp{0.019(T - T_R)}$</td>
</tr>
</tbody>
</table>

$T_R$ is reference value for $T_0$.

<table>
<thead>
<tr>
<th>Eq II.2.3.6</th>
<th>Calculation of $K_{0R}$ (63.2% cumulative failure probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{0R} = 31 + 77 \exp{0.019(T - T_R)}$</td>
</tr>
</tbody>
</table>

$K_{0R}$ is value of $T_0$ from MML stage 3.
Fig. II.2.1. Flowchart for Treatment of Fracture Toughness Data in Accordance with the SINTAP Procedure
a) Principles of the treatment of fracture toughness data in the case of data at a single temperature

b) Principles of the treatment of fracture toughness in the case of data at different temperatures

Fig. II.2.2 Principles of the SINTAP Procedure for Fracture Toughness Estimation for Data AT (a) Single Temperature and (b) Different Temperatures
II.3 FLAW CHARACTERISATION

II.3.1  Single Planar Flaws

Planar flaws should be characterised by the height and length of their containment rectangles. These dimensions can be summarised as 2a for through thickness flaws; a and 2c for surface flaws; and 2a and 2c for embedded flaws.

A full range of geometries and flaw dimension definitions is presented in the SINTAP compendium of stress intensity factors and limit load solutions. Examples of definitions of flaw dimensions for a range of common geometries are given in Fig. II.3.1.

II.3.2  Interaction of Multiple Flaws

II.3.2.1  General Case

Multiple flaws on differing cross-sections, need not be assessed for interaction. Multiple flaws on the same cross-section may lead to an interaction and to more severe effects than single flaws alone. If multiple flaws exist, each flaw should be checked for interaction with each of its neighbours using the original flaw dimensions in each case. It is not normally necessary to consider further interaction of effective flaws.

The interaction criteria applied to multiple flaws depend on whether the failure mode for the largest defect before interaction is plastic collapse ($K_r/L_r < 0.4$) or brittle fracture ($K_r/L_r > 1.1$). The criteria for plastic collapse are based on the concepts of net-section and gross-section yield while those for brittle fracture are based on stress intensity factors. For values of $K_r/L_r$ between 0.4 and 1.1 both approaches should be evaluated and the larger of the two calculated effective flaw sizes used in subsequent calculations.

II.3.2.2  Collapse - Dominated Cases

II.3.2.2.1  General Approach

For situations where failure by brittle fracture can be excluded, interaction of multiple flaws can be determined based on the mode of plastic collapse:

Local collapse, occurs when the ligament between flaws, or between the deepest flaw and the free surface (the ligament), become plastic. Global collapse, or Net Section Yielding (NSY), occurs when the complete cross-sectional area containing the flaws becomes plastic. In the case of Gross-Section Yield (GSY), the applied stress in the material remote from the plane containing the defects exceeds the yield strength.

The conditions for which the local, NSY and GSY collapse occur depend on the size and geometry of the flaws, the spacing between them and the strain hardening behaviour of the material. By calculating the maximum flaw length that will still enable GSY with the total length of the two coplanar flaws, the necessity or otherwise to treat the flaws as a single flaw with dimensions determined by the envelope drawn around them can be determined.

II.3.2.2  Gross-Section Yielding Criterion

If the criterion for interaction is based on gross-section yielding, the total length of two (or more) surface flaws, excluding their spacing, should be compared with the maximum flaw length for gross-section yielding, $2c_{gsy}$, which is given by:
\[ 2c_{gsy} = \frac{W \cdot B}{a_{max}} \left( 1 - R \right) \left( 1 + R \right) \]  

(II.3.1)

Where: \( W \) = plate width, \( B \) = thickness, \( a_{max} \) = height of the deepest flaw and \( R \) = Yield to Tensile strength ratio \( (R_{el}/R_m \text{ or } R_{p0.2}/R_m) \).

For the case of most structural steels, the value of \( W \) is set at a maximum of 300 mm for plate widths exceeding 300 mm. For critical applications, the exact value of \( W \) can be obtained by experiments. For smaller plate widths, the actual plate width should be used.

For welded joints in which the level of yield strength mis-match is significant, the value of 2\( c_{gsy} \) may be estimated by Eq. II.3.2. By introducing the factor, \( M (= YS_w/YS_{pp}) \), which quantifies the level of weld metal yield strength mis-match, Eq. II.3.1 can be written as:

\[ 2c_{gsy} = \frac{M(1+R) - 2R}{M(1+R)} \cdot \frac{W \cdot B}{a_{max}} \]  

(II.3.2)

For conformity, the yield-to-tensile ratio, \( R \), in Eq. II.3.2 is that of the parent metal. In case the weld metal strain hardening characteristics differ significantly from those of the parent metal, the weld metal yield to tensile ratio, \( R_w \) \( (R_{el(weld)}/R_{m(weld)} \text{ or } R_{p0.2(weld)}/R_{m(weld)}) \), should be used as input. Up to values of \( R \) of 0.90, the level of weld metal mis-match has a greater effect on the calculated defect length than the yield-to-tensile ratio has. Therefore, replacing \( R \) by \( R_w \) is not strictly necessary, unless \( R_w \) exceeds the value of 0.90.

II.3.2.2.3 Interaction Criterion and Plastic Collapse Loads

Having determined the value of 2\( c_{gsy} \), the criterion for interaction is a comparison of this flaw length with the total length of the flaws, Fig. II.3.2.

1. Where the total length of two (or more) coplanar flaws is less than the value of 2\( c_{gsy} \), interaction need not be considered. Since the applied interaction criterion is intended to cause gross-section yielding, the plastic collapse stress will be equal to or greater than the yield strength. If required, the actual collapse stress, \( \sigma_{pc} \) can be conservatively estimated from Eq II.3.3

\[ \sigma_{pc} = \sigma_{flow} \left( 1 - \frac{(2c_1 + 2c_2) a_{max}}{W \cdot B} \right) \]  

(II.3.3)

2. Where the total length of two (or more) coplanar flaws is greater than 2\( c_{gsy} \) interaction is possible and the flaw length to be used in the assessment of the plastic collapse load should be that of the individual flaw lengths plus their spacing. The interacting flaws are treated as a single flaw with dimensions determined by the envelope drawn around the flaws:

\[ \sigma_{pc} = \sigma_{flow} \left( 1 - \frac{(2c_1 + s + 2c_2) a_{max}}{W \cdot B} \right) \]  

(II.3.4)

If the spacing, \( s \), is greater than the length of the shortest flaw, the collapse load can be predicted from Eq. II.3.3.

For the conditions of net-section yielding (plastic deformation is confined to the plane of the flaws) and gross-section yielding (yielding of remote cross section), the stress at plastic
collapse is derived from the net-section area. This implies that the total length, Eq. II.3.3, or the total length plus the spacing, Eq. II.3.4, have to be used in the calculations. The use of the length of the (longest) single flaw might underestimate the actual collapse load.

The above approach does not account for the increased constraint at the inner tips of the flaws due to the presence of the ligament. Additionally, since load assessments accounting for strain hardening are not applied the actual collapse load will be greater than predicted by equations II.3.3 and II.3.4 and the approach therefore, incorporates an element of conservatism.

II.3.2.3 Fracture - Dominated Cases

Simple criteria for interaction of coplanar flaws in the case of the failure mode being fracture dominated \((K_r/L_r > 1.1)\) are presented in Fig. II.3.3, together with the dimensions of the effective flaws after interaction. These are equivalent to those presented in BS7910 and reference should be made to this standard for further guidance on non-coplanar flaws.

Where there is uncertainty as to whether the criteria for plastic collapse or fracture should be applied, the effective flaw size after interaction should be determined using both approaches and the most conservative result taken for use in subsequent analysis.

II.3.3 Flaw Re-Characterisation

When an embedded or a surface flaw cannot be assessed as tolerable, it is possible that, in some circumstances, the prediction of failure of a ligament may not be critical to the overall integrity of the structure or component. In such cases, a further assessment step may be carried out, in which the ligament concerned is assumed not to be present and the initial flaw is re-characterised as a surface or through thickness flaw, as appropriate. The resulting flaw may require an allowance to be made for dynamic conditions and for possible crack growth at the ends if ligament failure actually occurred.

(a) When ligament failure is predicted to occur by local yielding or it is known that ligament failure will be by a ductile mechanism (upper shelf operation) an allowance should be made for possible crack growth at the ends during ligament breakthrough. The size of the re-characterised flaw is calculated by increasing the total length of the original flaw, as shown in Fig. II.3.4.

It should be noted that re-characterisation of flaws is also required for leak-before-break assessments, although these are generally used to assess leak rates. The development of crack shapes by sub-critical crack growth is shown in Fig. II.3.5 for surface cracks and Fig. II.3.6 for through-wall cracks as a function of crack length and loading mode. Recommended re-characterised dimensions are described in Section IV.5 in the description of LBB procedures.

(b) When an assessment indicates that ligament failure may occur and where this failure may be by a brittle mechanism (lower shelf or transition regime) an allowance should be made for possible dynamic conditions at the moving crack tip. The dimensions of the recharacterised flaw should be made as per Fig. II.3.4 but the fracture toughness used in the assessment of the recharacterised flaw should be a dynamic or crack arrest toughness, appropriate for the material and temperature.

The recharacterised flaw may then be assessed according to the current fracture assessment procedures. This procedure will only be of benefit if local conditions in the ligament are more severe than those of the recharacterised flaw. If the recharacterised flaw also fails the assessment, the initial flaw is not applicable.
II.3.4  Flaw Detection, Sizing and NDE (Non-Destructive Evaluation) Capabilities

II.3.4.1  Scope

Inspection procedures are made up of a mix of NDE techniques, setting procedures or calibrating principles, decision steps, scanning systems, recording and illustration tools and software. They often involve a process of interpretation of indications which relies on the skill of the operator. As a result they cannot be considered simply as measurements and NDE performance for detecting, locating, classifying and sizing defects cannot be represented by simple confidence intervals.

To be able to use NDE inspection data in a structural integrity assessment it is essential to establish whether all the defects above a certain size were detected and reported and how precise the given sizes in depth and in length are.

Guideline performance values which have been derived from analysis of specific blind test results or from parametric studies conducted by independent institutions are presented in this section.

It is important to clarify the terminology used to understand the meaning of NDE evaluations and to use reliability data correctly for structural integrity assessment purposes. Reliability (R) of NDE-based inspection procedures is considered to consist of three key elements.

\[ R = f(\text{IC}) - g(\text{AP}) - h(\text{HF}) \]

where
- IC = intrinsic capability of techniques/procedures
- AP = limitations imposed by the specific application
- HF = human factors

Effectiveness of the inspection can be defined as:

\[ E = f(\text{IC}) - g(\text{AP}) \]

This section considers mainly inspection effectiveness.

II.3.4.2  Definitions and Terminology

Defect Types

Flaws can take many forms but NDE effectiveness assessments refer chiefly to planar type defects, approximately perpendicular to the surface (tilt angle ±30°). To detect and size these correctly specific NDE techniques are required or the usual (ASME type ed. I986) techniques have to be set at a high level of sensitivity or cut off: 20 or even 10% DAC. This leads to many indications and also to false calls. This class of defects, which are homogeneous only from an NDE point of view, are referred to as PPD (perpendicular planar defects) and cover lack of fusion and cracks arising due, for example, to mechanical fatigue, thermal fatigue, corrosion and reheating cracking.

The present compilation is limited to PPD defects with a through wall size larger than 5% of the wall thickness (t). Although volumetric defects can also be used for effectiveness evaluations, they are not included here since detection and sizing performance of NDE procedures is often better such defects than for PPDs.
NDE Performance Levels

Inspections can be conducted at different “quality” or performance levels. The present compilation considers two different levels:

- **Q level** fixed by Qualification according to the European Methodology which fixes the effectiveness of the inspection procedure at a level considered possible after capability evaluation.
- **B level** (Blind tests) corresponding to what was achieved by 60% of the inspection procedures applied in round-robin trials relevant to the situation considered. Effectiveness can be very good with high performance inspection procedures but also very poor with low performance procedures even if applied with care by a good team. Within this level two sub-sets are considered: ‘good practice’ and ‘low capability’.

Performance Parameters

The following parameters are used in assessing NDE performance:

- **FDP**: false detection performance of an inspection team or procedure for a given population of defects
- **CRP**: correct rejection performance of defects to be rejected by the inspection procedure, according to the ASME acceptance/rejection criteria (often around 10% of the wall thickness)
- **MESD**: mean error of sizing in depth
- **SESD**: standard deviation of sizing error in depth
- **MESL**: mean error of sizing in length
- **SESL**: standard deviation of sizing error in length
- **FCRP**: false call rate leading to erroneous rejection

II.3.4.3 Condensed NDE Effectiveness Data

To give an indication of NDE effectiveness it is necessary to condense the information previously assembled into a limited number of figures and data tables. For this reason only two groups of components are considered in detail.

**Ferritic steel piping (5 mm \( \leq t \leq 50 \) mm)**

*Figure II.3.7* provides an example of the variation in capabilities of ultrasonic inspection. a) shows results expected from procedures qualified to reasonably attainable targets for detection and sizing. b) pertains to ‘good practice’ procedures subjected to qualification, while c) shows results from low capability (but still commonly applied) procedures, or due to unconsidered environmental or human effects.

**Austenitic steel piping (5 mm \( \leq t \leq 30 \) mm)**

*Figure II.3.8* presents a similar overview for wrought austenitic components, which is also appropriate for welds in castings. As a benchmark a defect size of 40% \( t \) is used, indicating acceptable sentencing capability for ‘good practice’ procedures. However 100% success is never obtained.
II.3.4.4 **Input data for structural integrity assessment**

a) **Using inspection qualification**

Providing:
- inspection targets are clear and used to define targets or levels of qualification,
- such targets are acceptable for some procedures (as shown by exercises or previous evaluations), and
- qualification can be performed with all the necessary elements to provide the operator with a procedure known for its capability (European Methodology)

Then it is straightforward to provide the structural integrity engineer with an objective measure of inspection capability (or effectiveness, if relating it to a specific application).

It appears reasonable to declare that, if no defect that is deeper than 40% $t$ is found by these high effectiveness inspection procedures then no such defect exists in the component.

b) **Not using inspection qualification**

Probabilistic assessment of the data for defects smaller than 40% $t$ is possible but of limited realism in practice since no input data exist prior to inspection about the defect distribution in different components after fabrication and after service. If inspection is performed using non-qualified procedures (Figures II.3.7c and II.3.8c) it is not possible to exclude the presence of a defect of depth $< 75\% t$.

In contrast, using qualified procedures, probabilistic approaches can be used for defects in the range $0 \leq t \leq 40\%$.

II.3.4.5 **Summary**

A point to note is that most levels of inspection often range between ‘good practice’ and ‘low capability’. Table II.3.1 summarises the types of components for which data are available. Table II.3.2 provides information on the parameters MESD, SESD, MESL and SESL for those nine component types when they contain planar flaws of depth equal to 40% of the wall thickness. In particular, the values of mean error and standard deviation of error in the depth sizing provide useful quantitative values for consideration when defining the appropriate inputs for flaw depth in an assessment.
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Material</th>
<th>( t ) (mm)</th>
<th>( D ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heavy pressure vessel (or flat plates)</td>
<td>carbon steel</td>
<td>&gt;75</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Heavy section piping (or flat plates)</td>
<td>carbon steel</td>
<td>30 - 75</td>
<td>&gt;250</td>
</tr>
<tr>
<td>3</td>
<td>Thin section piping (or flat plates)</td>
<td>carbon steel</td>
<td>10 - 30</td>
<td>&gt;250</td>
</tr>
<tr>
<td>4</td>
<td>Small diameter piping</td>
<td>carbon steel</td>
<td>5 - 30</td>
<td>50 - 250</td>
</tr>
<tr>
<td>5</td>
<td>Heavy section piping as wrought</td>
<td>as wrought</td>
<td>&gt;30</td>
<td>&gt;250</td>
</tr>
<tr>
<td>6</td>
<td>Small diameter piping as wrought</td>
<td>as wrought</td>
<td>&lt;30</td>
<td>50 - 250</td>
</tr>
<tr>
<td>7</td>
<td>Heavy section piping (or elbow)</td>
<td>as cast</td>
<td>20 - 80</td>
<td>&gt;250</td>
</tr>
<tr>
<td>8</td>
<td>Dissimilar metal zones (piping or comp.)</td>
<td>Various</td>
<td>20 - 80</td>
<td>&gt;250</td>
</tr>
<tr>
<td>9</td>
<td>Small tube (steam generators)</td>
<td>as wrought</td>
<td>1 - 5</td>
<td>20 - 50</td>
</tr>
<tr>
<td>10</td>
<td>Small tube (heat exchangers)</td>
<td>carbon steel</td>
<td>1 - 5</td>
<td>30 - 50</td>
</tr>
<tr>
<td>11</td>
<td>Thin flat plate</td>
<td>alloys</td>
<td>&lt;5</td>
<td>-</td>
</tr>
</tbody>
</table>

\( t \) : thickness  \( D \) : pipe internal diameter

**Table II.3.1 : Categorisation of Component Types.**
<table>
<thead>
<tr>
<th>Ultrasonic Inspection Class</th>
<th>Component Classification</th>
<th>MESD (mm)</th>
<th>SESD (mm)</th>
<th>MESL (mm)</th>
<th>SESL (mm)</th>
<th>t (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good practice and qualified procedure (aQ)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>10</td>
<td>&gt;75</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>30 - 75</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>10 - 30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>5 - 30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>-5</td>
<td>12</td>
<td>&gt;30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>-3</td>
<td>10</td>
<td>&lt;30</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>20</td>
<td>20 - 80</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0(^{(1)})</td>
<td>4(^{(1)})</td>
</tr>
<tr>
<td>Good practice and non-qualified procedure (aB)</td>
<td>1</td>
<td>5</td>
<td>20</td>
<td>5</td>
<td>50</td>
<td>&gt;75</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>20</td>
<td>30 - 75</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10 - 30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>5 - 30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-2</td>
<td>5</td>
<td>-10</td>
<td>25</td>
<td>&gt;30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-2</td>
<td>3</td>
<td>-10</td>
<td>25</td>
<td>&lt;30</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2</td>
<td>6</td>
<td>0</td>
<td>25</td>
<td>20 - 80</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-3(^{(2)})</td>
<td>9(^{(2)})</td>
</tr>
<tr>
<td>Low effectiveness and non-qualified procedure (bB)</td>
<td>1</td>
<td>-7</td>
<td>15</td>
<td>-30</td>
<td>50</td>
<td>&gt;75</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-5</td>
<td>15</td>
<td>-20</td>
<td>30</td>
<td>30 - 75</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-3</td>
<td>10</td>
<td>-5</td>
<td>20</td>
<td>10 - 30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-3</td>
<td>10</td>
<td>-5</td>
<td>15</td>
<td>5 - 30</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-4</td>
<td>7</td>
<td>-10</td>
<td>40</td>
<td>&gt;30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-4</td>
<td>5</td>
<td>-20</td>
<td>20</td>
<td>&lt;30</td>
</tr>
</tbody>
</table>

(1) Using qualified eddy current method (ETQ level)
(2) Using non-qualified eddy current method (ETB level)

**TABLE II.3.2 SUMMARY OF ULTRASONIC INSPECTION CAPABILITIES FOR PLANAR FLAWS OF DEPTH EQUAL TO 40% WALL THICKNESS**
Fig. II.3.1 Definition of Flaw Dimensions for Common Component Geometries
Interaction criteria under plastic collapse (Applied stress Yield Strength, YS)

Determine defect length for GSY

\[ 2c_{\text{gsy}} = \frac{M(d + R) - 2R}{M(d + R)} \cdot \frac{W \cdot B}{a_{\text{max}}} \]

Compare length \(2c_{1} + 2c_{2}\) of adjacent defects with \(2c_{\text{gsy}}\)

NO Interaction

\[ 2c_{1} + 2c_{2} < 2c_{\text{gsy}} \]

\[ \sigma_{pc} \geq \sigma_{\text{YS}} \]

\[ \sigma_{pc} = \sigma_{\text{flow}} \left(1 - \frac{2c_{1} + 2c_{2}}{W \cdot B} a_{\text{max}}\right) \]

Interaction possible

\[ 2c_{1} + 2c_{2} > 2c_{\text{gsy}} \]

\[ \sigma_{pc} \geq \sigma_{\text{YS}} \text{ or } \sigma_{pc} \leq \sigma_{\text{YS}} \]

\[ \sigma_{pc} = \sigma_{\text{flow}} \left(1 - \frac{2c_{1} + s + 2c_{2}}{W \cdot B} a_{\text{max}}\right) \]

**Fig. II.3.2** Criteria for Interaction of Flaws in Collapse – Dominated Cases
Fig. II.3.3  Coplanar Flaw Interactions For Fracture-Dominated Cases
Fig. II.3.4 Recharacterisation of flaws for ligament failure by ductile mechanisms

(i) Embedded Flaws

(ii) Surface Flaws
Fig. II.3.5 Developments of crack shapes for subcritical surface crack growth

Fig. II.3.6 Development of crack shapes for subcritical through-wall crack growth
Fig. II.3.7 Inspection effectiveness for UT of small ferritic steel piping. Qualified procedure (a), good practice (b), and low capacity (c). d) refers to the defect length (good practice)
**Fig. II.3.8** Inspection effectiveness for UT of wrought austenitic steel piping. Qualified procedure (a), good practice (b), and low capacity (c).

<table>
<thead>
<tr>
<th></th>
<th>5%</th>
<th>10%</th>
<th>40%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a6Q</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDP</td>
<td>0.3</td>
<td>0.95</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CRP</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>MESD (mm)</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESD (mm)</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MESL (mm)</td>
<td>-3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESL (mm)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCRP</td>
<td></td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5%</th>
<th>10%</th>
<th>40%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a6B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDP</td>
<td>0</td>
<td>0.7</td>
<td>0.95</td>
<td>1</td>
</tr>
<tr>
<td>CRP</td>
<td>0.4</td>
<td>0.9</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>MESD (mm)</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESD (mm)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MESL (mm)</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESL (mm)</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCRP</td>
<td></td>
<td></td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>5%</th>
<th>10%</th>
<th>40%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>b6B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDP</td>
<td>0</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>CRP</td>
<td>0.1</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>MESD (mm)</td>
<td>-4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESD (mm)</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MESL (mm)</td>
<td>-20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESL (mm)</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCRP</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>
SECTION II.4: PRIMARY AND SECONDARY STRESS TREATMENT
EVALUATION OF $L_r$, $K_r$, $J$ AND $p$.

II.4.1 General

The stresses to be considered in the assessment are those which would be calculated by a stress analysis of the unflawed structure. All forms of loading should be considered in the stress analysis, actual and potential. The stresses should include thermal stresses, residual stresses due to welding, and stresses due to test, fault and accidental loads. The stresses must be classified into primary and secondary components. In general, primary stresses are stresses which, if high enough, could cause failure by plastic collapse in the absence of any other failure mode intervening, while secondary stresses could not. Typically, all forms of mechanical loads produce primary stresses. These are generally externally induced, and include such loads as pressure, weight, wind loading and other live loads. Examples of secondary stresses are residual stresses due to welding, and thermal stresses. However, these stresses may also act as primary stresses across a part of a component or a substructure, where conditions for local plastic collapse may be created. The classification therefore depends upon how the flawed part of the structure responds to the stresses and how they influence the development of plasticity across it (see II.4.6).

Note that, for the purposes of this procedure, structural collapse is considered to be governed by failure of the ligament at the flaw. The possibility of premature collapse remote from the flawed section is not part of this procedure, and should be separately investigated if considered a possibility.

II.4.2 The Evaluation Of $L_r$ From Primary Stresses

All forms of mechanical loading and some forms of residual and thermal loading should be considered as resulting in primary stresses. These stresses contribute to failure by plastic collapse, of the component in question, are characterised as $\sigma^p$ stresses, and as such they are included in the calculation of $L_r$.

Plasticity effects due to primary stresses are included in the procedure by means of the parameter $L_r$. This is a measure of how close to plastic yielding is the structure containing the flaw, (I.2) and is defined as the ratio of the loading condition being assessed to that required to cause plastic yielding of the flawed structure, equation II.4.1

$$L_r = \frac{\text{Total applied loads giving rise to } \sigma^p\text{ stresses}}{\text{Plastic yield load to the flawed structure}}$$  \hspace{1cm} (II.4.1)

The plastic yield load depends on the material's yield or proof strength, $R_e$, and also on the nature of the flaw being assessed. For fully penetrating flaws, or for flaws which requires to be recharacterised as fully penetrating, the yield load is the so-called global yield load, defined as the rigid-plastic limit load of the structure, calculated for a rigid-plastic material with a yield stress equal to $R_e$. For part penetrating flaws, the yield load is the local limit load, i.e., the load needed to cause plasticity to spread across the remaining ligament, calculated for an elastic perfectly plastic material of yield stress $R_e$.

The effect of the flaw must be included when evaluating the plastic yield load. When ductile tearing is being considered, (I.4.3 and II.2.4) the relevant flaw size is the size of the original flaw plus the amount of crack growth postulated for that step in the analysis.
Any appropriate form of analysis may be used to perform the plastic failure analysis provided that it results in an upper bound to $L_r$. The main calculation approaches are given in III.2, as are some solutions for common geometries, and source documentation of limit loads for other geometries. This section also contains guidance for the determination of mismatch limit loads needed for a Level 2 analysis (I.4.3), and solutions for common geometries of these.

### II.4.3. Evaluation of $K_r$ From Primary And Secondary Stresses.

Where loads give rise to secondary stresses, these stresses are characterised as $\sigma^s$ stresses. These are stresses which cannot contribute to failure by plastic collapse. However they can contribute to the development of plasticity, and in this procedure this contribution is evaluated through the parameter $\rho$ contained in the definition of $K_r$ in equation II.4.2

$$K_r = K_p(a) / K_{mat} + K^s_i(a) / K_{mat} + \rho(a)$$

(II.4.2)

where at the flaw size, $a$, of interest (taking account of any postulated flaw growth for ductile tearing, I.4.2 and II.2.4), $K_p(a)$ is the linear elastic stress intensity factor calculated for all $\sigma^p$ stresses, $K^s_i(a)$ is the linear elastic stress intensity factor calculated for all $\sigma^s$ stresses, and $K_{mat}$ is the characteristic value of fracture toughness.

The parameter $\rho(a)$ takes account of plasticity corrections required to cover interactions between $\sigma^p$ and $\sigma^s$ stresses and depends not only on flaw size but also on the magnitude of the $\sigma^p$ stresses (i.e., on $L_r$). A method for calculating $\rho$ is given in III.2.

The linear elastic stress intensity factor, $K_i$, is defined as the amplitude of the crack-tip singularity in the stress field obtained using linear elastic stress analysis methods. There are a number of standardised methods for deriving $K_i$ for any imposed stress profile and geometry, and some well known standard solutions for a most common geometries. Some methods for evaluation $K_i$ are general and may be used for all categories of loading, whether $\sigma^p$ or $\sigma^s$. Others are specific to only one category of loading. Procedures, solutions and references are given in III.2, and whichever method is adopted it is important for the users to satisfy themselves as to the appropriateness and accuracy of the solutions adopted.

For semi-elliptical flaws, $K_i$ varies with location around the crack front, the maximum value being dependent on the stress gradient. Some solutions provide averaged values of $K_i$ while others provide values at specific locations, typically at the major and minor axes. Maximum values should always be used, where these are available.

As an alternative to the additive factor $q$ used for determining $K_r$ in equation II.4.2, the SINTAP project has developed a multiplying factor, $V$. If this factor is preferred, the definition of $K_r$ changes to that in equation II.4.3

$$K_r = [K_p(a) + V.K^s_i(a)] / K_{mat}$$

(II.4.3)

The calculation of $V$ is described in III.2, The two approaches are fully compatible using the recommended definitions of $\rho$ and $V$. 
II.4.4. Evaluation Of J_e And J From Primary And Secondary Stresses

J_e, the elastically calculated value for J, is defined as

\[ J_e = \frac{K_i^2}{E I} \]  \hspace{1cm} (II.4.4)

where, in plane stress \( E I \) is Young's modulus for the material, \( E \), and in plane strain it is \( E/(1 - \nu^2) \), where \( \nu \) is Poisson's ratio. J is defined as

\[ J = \frac{J_e}{[f(L_r) - q]^2} \]  \hspace{1cm} (II.4.5)

Note that now the parameter q is separated from the elastic part of the calculation, and appears in the denominator in equation II.4.5 but it is defined in the same way. This is entirely consistent with the equivalence of the CDF and FAD approaches, and provides the most tractable way of performing the calculations. \( J_e \) is calculated from the linear elastic stress intensity factors described in II.4.3, according to equation II.4.6

\[ J_e = \left[ K_i^P(a) + K_i^S(a) \right]^2 / E I \]  \hspace{1cm} (II.4.6)

and \( \rho \) is calculated following the procedures of III.2. \( f(L_r) \) is the function describing the FAD or CDF according to the Level chosen (I.2).

If the alternative to \( \rho \), \( V \), is to be used, equations II.4.5 and II.4.6 combine to become

\[ J = \frac{[K_i^P(a) + V.K_i^S(a)]^2 / E I}{F(L_r)^2} \]  \hspace{1cm} (II.4.7)

II.4.5. Evaluation of CTOD from Primary And Secondary Stresses

The calculation of \( \delta \) is a modification of the calculation of \( J \). For example, \( \delta_e \), the elastically calculated value for \( \delta \), is defined as

\[ \delta_e = \frac{K_i^2}{E I}.R_e \]  \hspace{1cm} (II.4.8)

where, \( E I \) is defined as in II.4.4, and \( R_e \) is the material's yield or proof strength. \( \delta \) is defined as

\[ \delta = \frac{\delta_e}{[f(L_r) - \rho]^2} \]  \hspace{1cm} (II.4.9)

Hence, \( \delta_e \) is calculated from the linear elastic stress intensity factors described in II.4.3, according to equation II.4.10

\[ \delta_e = \left[ K_i^P(a) + K_i^S(a) \right]^2 / E I \]  \hspace{1cm} (II.4.10)

and again \( \rho \) is calculated following the procedures of III.2, and \( f(L_r) \) is the function describing the FAD or CDF according to the Level chosen (I.2).

As for \( J \) if the alternative to q, \( V \), is to be used, equations II.4.9 and II.4.10 combine to become
\[
\delta = \frac{\left[ K_p^p(a) + VK^8(a) \right]^2}{E I} \tag{II.4.11}
\]

### II.4.6. Thermal And Residual Stresses

Although in general thermal and residual stresses are self equilibrating and therefore classed as secondary stresses, there are situations where they can act as primary ones. These situations arise when the thermal or residual stress in question act over a range or gauge length large enough that they could induce failure by plastic collapse in the sub-structure of concern. A simple example of this is where a thermal displacement acts at the ends of a long cracked beam. In this case, if the elastic follow-up in the cracked beam is large enough, the beam cannot experience the self-equilibrating nature of the thermal stress. The flawed section is therefore loaded by a primary thermal stress. It is important that thermal and residual stresses are correctly classified taking elastic follow-up in the flawed section into account.

It is particularly difficult to decide on the magnitude of residual stresses due to welding to be included in the assessment. Among other things, these are dependent on material, weld designs and procedures, structural geometry, and post weld heat treatment. As part of the SINTAP project a special study was made of residual stress profiles and a compendium of these for common geometries and materials is provided in III.3. The stress profiles given in this compendium should be used to calculate \( K_t^8 \) for equations given in II.4.3, II.4.4 and II.4.5.
CHAPTER III : FURTHER DETAILS & COMPENDIA

III.1 : GUIDANCE ON LEVEL SELECTION

III.1.1 Introduction

This document sets out a step-by-step procedure for assessing the integrity of structures containing defects. Information on carrying out the calculations required at each step is provided in those sections with further advice in the annexes. For some of the steps, a choice of routes is possible.

To assist the user, this section provides guidance on selection of the various routes in the procedure. Additionally, the potential decisions necessary at the various levels are briefly summarised and guidance on the benefits of consulting advice contained in the appropriate section is given. Note, however, that the guidance on selection of routes is not meant to be prescriptive nor to obviate the need for a sensitivity study, which may involve comparison of these alternative routes. The recommendations given below refer in many cases to specific regions of the Failure Assessment Diagram. A summary of these is given in Fig. III.1.1.

III.1.2 Selection of Failure Assessment Diagram - Level 0 to 4

In Section I.4 various discrete Levels are provided for deriving the shape of the failure assessment curve. A summary of these is given in Table III.1. The Level 0 curve is the easiest to apply and requires only the yield stress to be known; Level 1 is applicable to homogeneous materials and requires a knowledge of the ultimate strength as well as the yield strength; Level 2 is a specific mis-match assessment level and requires knowledge of yield stress and ultimate tensile stress of base metal and weld metal. Level 3 requires additional information on the material stress-strain properties and can be applied to homogeneous materials or those cases where weld strength mis-match is an issue; Level 4 invokes constraint treatment while Level 5 requires results of detailed elastic-plastic analysis of the defective component. Level 6 is applicable only to fluid-containing structures. To assist in deciding whether or not to choose one of the more complex Levels, the following information may be noted.

- At low values of load, typically $L_r \leq 0.8$, the shape of the failure assessment curve is dominated by small-scale yielding corrections and all four Levels are likely to produce similar curves. There is, therefore, likely to be little benefit in going to a higher Level for $L_r \leq 0.8$. Note, however, that the relevant range of $L_r$ values should include not only those at the load and crack size being assessed but also those at any limiting conditions used to derive margins or factors.

- For materials which exhibit significant strain hardening beyond yield, such as austenitic stainless steels, Level 3 curves are close to Level 1.

- For materials with a Lüders strain, there is conservatism in the Level 1 and 3 curves for $L_r > 1$ for geometries not loaded in simple tension, i.e. where there is significant bending in the plane of the defect. This conservatism may be reduced by going to Level 4.

- For surface defects, significant conservatism can arise from the use of a local, rather than a global, limit load. Such conservatism can be quantified by detailed analysis leading to a Level 4 curve. In principle the Level 4 curve can be based on either the local or global...
CHAPTER III : FURTHER DETAILS & COMPENDIA

limit load, but whichever is chosen must be used in the calculation of $L_r$. It is preferable to use the global limit load as otherwise the cut-off at $L_r^{\text{max}}$ may be imposed at loads which correspond to only small plastic strains.

III.1.3 Aspects of Fracture Toughness

Section II.2 provides recommendations on methods for evaluating statistical bounds to fracture toughness data. The guidance in this Annex should, therefore, be referred to where it is necessary to determine a value of $K_{\text{mat}}$, for evaluation of $K_r$. Note, however, that an assessment is insensitive to the precise value of toughness in collapse-dominated situations. Greater benefit in obtaining a more precise value of fracture toughness occurs for assessments towards the left-hand fracture-dominated part of the failure assessment diagram.

III.1.4 Selection of Analysis Methods: Initiation and Tearing

The use of initiation fracture toughness values is the usual approach. The following guidance is given for those cases where it may be appropriate to invoke ductile tearing.

- Greatest benefit arises from the use of ductile tearing for materials with a steep fracture resistance ($J-\Delta a$) curve, i.e., where toughness for small amounts of ductile tearing is significantly greater than the initiation toughness.

- Greatest benefit occurs when the component and defect dimensions, such as crack size, section thickness and remaining ligament, are much greater than the amount of ductile tearing being considered. This latter amount is usually about 1-2 mm as this is typically the limit of valid data collected on test specimens of standard size.

- When moving to a tearing analysis, care must be taken to account for any interactions between tearing and other modes of crack growth.

III.1.5 Plastic Yield Load Analysis

III.2 contains suggested procedures and solutions for the plastic yield load used to define $L_r$. Clearly, the guidance in this Annex is of most value for collapse-dominated assessments, those towards the right-hand side of the failure assessment diagram.

III.1.6 Determination of Stress Intensity Factors

III.2 also contains information and source references for determination of the stress intensity factor. Clearly, this is of most benefit for assessments towards the left-hand side of the failure assessment diagram. Some code solutions referred to require the stress field to be linearised into membrane and bending components. This approach can be over-conservative for highly non-linear stress distributions, which can occur particularly for secondary stresses, and there is then a benefit in going to more complex weight function solutions.
CHAPTER III: FURTHER DETAILS & COMPENDIA

III.1.7 Leak-Before-Break

Leak-before-break procedures are set out in Section IV.5

A leak-before-break assessment is most likely to be of value for:

- part-penetrating defects with a high ratio of crack depth to surface length;
- defects which grow through the wall, by fatigue say, under tension loading which produces little surface crack extension;
- defects which snap through the ligament by ductile mechanisms without a significant increase in crack length;

III.1.8 Probabilistic Fracture Mechanics

While there is a general trend of reducing failure probability with increasing reserve factor, there is no unique relationship between these two quantities. The probabilistic fracture mechanics methods in Section IV.3 may then be followed to provide guidance on acceptable reserve factors. While detailed calculations can be followed, simplified estimates can also be made based on distributions of material properties. These simplified estimates are likely to be adequate for both low values of $L_r$ ($L_r < 0.5$) and for failure governed by plastic collapse ($L_r = L_r^{\text{max}}$). For intermediate cases, reduced conservatism is obtained by following the detailed methods in IV.3.

III.1.9 Weld Residual Stresses

Section III.3 provides guidance on determination and classification of weld residual stresses for input to an assessment. Simple estimates of uniformly distributed residual stresses are conservative. Reduced conservatism may be obtained by using the more detailed estimates presented or by detailed calculation or measurement of residual stresses. The benefit of following these more detailed routes is likely to be greatest for:

- deep defects for which the distribution of residual stress leads to lower stress intensity factors than those obtained using a uniform residual stress;
- assessments for which the values of $L_r$ and $K_r$ lead to points towards the left-hand side of the failure assessment diagram ($L_r/K_r < 0.8$).

III.1.10 Load-History Effects

Section IV.6 provides guidance on the effects of load-history. Benefits arising from a proof or overload test are greatest when:

- the overpressure or overload is significantly greater than the loads considered in the subsequent assessments;
- there are no loadings, such as thermal stresses, which need to be considered during operation but which are not present during the proof test;
CHAPTER III : FURTHER DETAILS & COMPELLIA

• subcritical crack growth mechanisms do not lead to significant crack extension between the time of the proof test and the times of the subsequent fracture assessments;

• there is little reduction in the fracture toughness and tensile properties between the time of the proof test and the subsequent assessment conditions;

• there is an increase in fracture toughness or tensile properties between the proof test and subsequent assessment conditions, as a result of the former being in the transition temperature regime and the latter being on the upper shelf, for example.

For warm pre-stressing (WPS) the greatest benefits occur when:

• the pre-load is high, but not sufficient to violate small-scale yielding conditions;

• the transition fracture toughness is strongly temperature-dependent;

• the cycle is load-cool-fracture with no intermediate unloading.

III.1.11 Constraint Effects

Section IV.4 provides methods for quantifying constraint effects. In order to claim benefit from reduced constraint, it is necessary to perform additional calculations and to have more information on fracture toughness properties. As a guide to whether this additional effort is likely to be justified, the following guidance is given:

• benefit is greatest in components subjected to predominantly tensile loading rather than bending;

• tension loadings in the plane of the crack increase constraint and therefore reduce any beneficial effects; conversely compressive loads in the plane of the crack increase benefits;

• benefits are greater for shallow cracks than for deeper cracks;

• there is little benefit for an assessment for ductile materials based on initiation toughness as the fracture toughness at initiation tends to be insensitive to constraint;

• there is more benefit for cleavage fracture or for an Option 2 ductile case where fracture toughness increases with reducing constraint;

• there is little benefit at low values of $L_r$ ($L_r < 0.2$) for cases dominated by primary loads;

• there is little benefit for collapse-dominated cases.

III.1.12 Weld Mismatch

A normal assessment requires use of the tensile properties of the weakest constituent in the vicinity of the crack. The homogeneous material procedures can still be used when mismatch is greater than 10% and conservative results will be obtained if the tensile properties of the lower strength constituent are used. A procedure for estimating any change in reserve factors
arising from the presence of stronger or weaker materials, weld strength overmatch and undermatch respectively, is presented in this procedure. The homogeneous or base metal procedure should be used for the weld metal strength mis-match level smaller than 10% for both overmatching and undermatching. For higher level of undermatching case, the predictions may be unsafe if base metal properties are used. For higher (>10%) degree of overmatching cases, the use of base metal tensile properties will yield overconservative predictions, but the analysis will be safe. In order to assess whether there is likely to be value in invoking the mis-match levels, the following may be noted:

- the maximum benefit arises in collapse dominated cases and is at most equal to the ratio of the flow strength of the highest strength material in the vicinity of the crack to that of the weakest constituent;
- there is little benefit for $L_r < 0.8$, where $L_r$ is based on the tensile properties of the weakest constituent;
- there is little benefit for cracks in undermatched welds under plane stress conditions;
- for deep circumferential cracks in circumferential welds in pipes under pressure, there is benefit in taking account of overmatching. There is, however, little benefit for shallow cracks.
### TABLE III.1
SIMPLIFIED STRUCTURE OF THE SINTAP PROCEDURE

<table>
<thead>
<tr>
<th>Level</th>
<th>Title</th>
<th>Format of Tensile Data</th>
<th>Format of Toughness Data</th>
<th>Mismatch Allowance?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Default</td>
<td>Yield stress only</td>
<td>Estimation of yield/tensile ratio (Y/T) for FAD. Toughness from Charpy energy</td>
<td>No</td>
</tr>
<tr>
<td>1</td>
<td>Basic</td>
<td>Yield stress and UTS only</td>
<td>Estimation of strain hardening exponent from Y/T for FAD. Fracture toughness as equivalent Kmat.</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Mismatch</td>
<td>Yield stress and UTS of Parent Plate and weld</td>
<td>Estimation of strain hardening exponent of parent plate and weld metal from Y/T for FAD. Fracture toughness as equivalent Kmat for relevant zone.</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Stress-Strain</td>
<td>Full stress-strain curve of Parent Plate (and weld metal)</td>
<td>FAD determined from measured stress-strain values. Mismatch option based on 'equivalent material' stress-strain curve.</td>
<td>Optional</td>
</tr>
<tr>
<td>4</td>
<td>Constraint</td>
<td>Full stress-strain curve</td>
<td>Modification of FAD based on T and Q stress approaches.</td>
<td>Possible</td>
</tr>
<tr>
<td>5</td>
<td>J-Integral</td>
<td>Full stress-strain curve</td>
<td>Estimation of J-integral as a function of applied loading from numerical analysis.</td>
<td>Optional</td>
</tr>
<tr>
<td>6</td>
<td>LBB</td>
<td>Yield stress and UTS only</td>
<td>Application to pressurised components with sub-critical crack growth.</td>
<td>No</td>
</tr>
</tbody>
</table>
Fig. III.1.1 Summary of FAD regions for consideration of potential refinement of data or analysis level
SECTION III.2: STRESS INTENSITY FACTOR AND LIMIT LOAD SOLUTIONS AND ASSOCIATED CALCULATIONS

This Section describes stress intensity factor and limit load solutions for flawed components. These are presented first in III.2.1 and III.2.2, respectively, which include approaches for performing calculations, some sample solutions and sources of solutions. The primary source of solutions is the SINTAP compendium [III.2.1] which contains both stress intensity factors and limit loads.

III.2.3 describes methods for calculating the parameter $\rho$ which is used to evaluate $K_r$, $J$ and $\delta$ (see II.4). Methods for calculating the equivalent parameter $V$, described in II.4.3, II.4.4 and II.4.5, are also presented. Finally, III.2.4 contains an extensive set of references which provide background information or solutions for specific geometries.

It should be noted that it many cases the solutions given are applicable over a limited range of flaw sizes. In situations where the flaw size of interest is not contained within the range covered by the most appropriate solution, the geometry should be remodelled to the next most appropriate but conservative solution. For example, deep part penetrating flaw can be remodelled conservatively as a fully penetrating one.

III.2.1 Stress Intensity Factor Solutions

As noted above, the primary source of information for obtaining the stress intensity factor is the SINTAP compendium [III.2.1]. This generally presents solutions in the form of weight functions or influence functions so that linearisation of the stress field in the plane of the flaw is not necessary. Some specific solutions taken from [III.2.1] are reproduced below (III.2.1.1). Sources of solutions for other specific geometries and loadings are also discussed here. III.2.1.2 - 6 then briefly describe some alternative methods or references for obtaining the stress intensity factor. Finally, III.2.1.7 presents stress intensity factor solutions for through-wall flaws with completely self-balancing through-wall stress distributions. These solutions are of particular interest for leak-before-break assessments.

III.2.1.1 Solutions for Specific Geometries

The compendium [III.2.1] contains solutions for specific geometries. In some cases the solutions are specific to both the geometry and loading. For example, for a compact tension specimen of width $W$ and thickness $B$ subject to a load $F$

$$K_i = \left( \frac{F \sqrt{a}}{BW} \right) \left[ 29.6 - 185.5 \left( \frac{a}{W} \right) + 655.7 \left( \frac{a}{W} \right)^2 - 1017 \left( \frac{a}{W} \right)^3 + 638.9 \left( \frac{a}{W} \right)^4 \right]$$

(III.2.1)

for crack sizes, $a$, which satisfy $a/W < 0.701$. A solution for deeper cracks is also contained in [III.2.1].

More generally, weight or influence functions are presented in [III.2.1] so that the solutions are for a specific geometry but can be used for a wide range of loading conditions. For example, for semi-elliptical axial surface flaws of length $2c$ and depth $a$ in cylinders,

$$K_i = \sqrt{\pi a} \sum_{j=0}^{\infty} \sigma_j f_j (a/t, 2c/a, R_i / t)$$

(III.2.2)
where the stress distribution, $\sigma(u)$, as a function of distance $u$ from the inner wall through the thickness of the cylinder is represented by the third order polynomial

$$
\sigma(u) = \sum_{j=0}^{3} \sigma_j (u/a)^j \quad 0 \leq u \leq a \quad (\text{III.2.3})
$$

in the region of the flaw. The functions $f_j$ depend on the flaw depth relative to the wall thickness, $a/t$, the flaw aspect ratio, $2c/a$, the ratio of cylinder internal radius, $R_i$, to thickness, whether the defect is at the internal or external surface, and on whether the surface point or deepest point of the flaw is being considered. The compendium [III.2.1] includes tables for $f_j$ for: $0 \leq a/t \leq 0.8$; $2c/a = 2, 5, 10$; $R_i/t = 4, 10$; for both internal and external flaws and for both surface and deepest points of the flaw. Table III.2.1 reproduces the solutions for the deepest point of an internal surface flaw.

In some cases, solutions for specific loadings are combined with solutions for polynomial stress distributions. Thus, for a part-circumferential internal surface flaw in a cylinder the stress intensity factor is given in [III.2.1] as

$$
K_i = \sqrt{\pi a} \sum_{j=0}^{3} \sigma_j f_j + \sqrt{\pi a} \sigma_{bg} f_{bg} \quad (\text{III.2.4})
$$

where the global bending stress, $\sigma_{bg}$, is the maximum outer fibre elastic global bending stress and the through thickness stress distribution is again represented by equation (III.2.3). The functions $f_j, f_{bg}$ are tabulated for various $a/t, 2c/a$ and $R_i/t$.

Additional solutions to those in [III.2.1] for specific geometries, often for specific loading conditions, are contained in the literature. In some cases, the solutions are evaluated against applied mechanical loads and no stress analysis is necessary. In other cases, $K_i$ may be evaluated from an independently derived stress field in the uncracked body.

Solutions are available for both semi-elliptical and fully extended flaws, the latter providing an overestimate of $K_i$, at the deepest point of the flaw when the flaw is of a finite length. For semi-elliptical flaws some of the solutions provide values of $K_i$ at different locations around the crack front while others provide an average value.

Specific solutions for nozzle to shell intersections are contained in references [III.2.2] to [III.2.8] and there are compendia containing solutions for a wide variety of geometries in references [III.2.9] to [III.2.13]. These compendia are often consulted first for the availability of specific solutions. Care should be exercised in their use as different compendia sometimes use different normalisations for $K_i$ and it is prudent to consult the source references in cases of doubt. Other solutions for specific geometries may be found in [III.2.14] to [III.2.35]. As noted above, the primary source of information for use with this procedure is the SINTAP compendium [III.2.1] which contains a number of specific solutions, including a section covering offshore structures.

### III.2.1.2 Code Solutions

Solutions in codes may be used for both $\rho^P$ and $\rho^S$ stress fields. $K_i$ is evaluated from the elastically calculated stress field in the uncracked body at the location of the flaw. Stress gradients are taken into account by linearising the stress field over the flaw depth, $a$, and...
splitting it into membrane (tensile) and bending components. The method of linearisation should be pessimistic in that \( K_I \) is overestimated.

These methods are quick and easy, and provide a satisfactory preliminary solution. They are applicable to semi-elliptical flaws, and allow \( K_I \) to be estimated at two locations on the flaw perimeter corresponding to the major and minor axes of the ellipse. They may, however, be extremely pessimistic for very steep stress gradients.

Standardised general solutions are contained in references [III.2.36] to [III.2.39].

**III.2.1.3 Flaws at the Edge of a Notch**

There are no generalised solutions available for flaws sited at notch tips. In general, such flaws may be assessed pessimistically by considering them to have a depth equal to the sum of the depths of the flaw and the notch, and then by analysing them using one of the standard solutions. An assessment of this type is satisfactory for flaws associated with sharp notches, but may be excessively pessimistic when the notch is blunt. In such cases, standard solutions for the depth of the flaw alone may be multiplied by the stress concentration factor of the notch, or, where a stress analysis may be performed, the stress gradient due to the notch may be allowed for.

It should be noted that very short flaws at very sharp notches may require special attention because of localised plasticity effects. Methods of analysing such flaws are discussed in references [III.2.40] to [III.2.42].

**III.2.1.4 Computer Programs**

Several computer programs are available for deriving stress intensity factors for a wide range of geometries and for both \( \sigma_6 \) and \( \sigma_s \) stress fields. These programs use weight function techniques and require a knowledge of the stress field in the uncracked body. The SINTAP and R6-CODE software are examples of such software.

**III.2.1.5 Finite Element Methods**

Finite element methods are available to evaluate \( K_I \) by an elastic analysis of the flawed structure. Having performed an elastic analysis, the value of \( K_I \) may be determined by a variety of techniques, such as displacement and stress substitution, energy difference methods, virtual crack extension, contour integration and Bueckner’s formulation. These are described in references [III.2.43] and [III.2.44].

**III.2.1.6 Solutions for Multiple Flaws**

Where components contain multiple flaws, there may be interactions between neighbouring flaws which affect \( K_I \). Some solutions may be found in references [III.2.45] to [III.2.56].

**III.2.1.7 Through-thickness flaws with completely self-balancing residual stress fields**

The case of through-wall flaws with completely self-balancing through-wall stress distributions is considered in this sub-section, and is of particular interest for leak-before-break assessments (IV.5). Figure III.2.1 gives examples of such stress distributions. In general, residual stress fields may not be completely self-balancing through the wall thickness. The part of the stress distribution which is not self-balancing should then be
assessed separately using the methods of II.4.3 to II.4.5 to evaluate $\rho$. $K_r$, $J$ or $\delta$ should be evaluated for that part, and the term due to the self-balancing stress field added, following the guidelines of II.4.3 to II.4.5 as required.

The estimates for through-wall flaws with self-balancing residual stress fields are based on linear elastic methods. Therefore application of this section is limited to small values of these stresses such that $\frac{\rho}{(K_r p/L)} \leq 4$. Secondary loads outside this range will require individual consideration. Finite element analyses for the stress distribution in Figure III.2.1 have shown that, for crack lengths greater than about half the wall thickness, the stress intensity factor at the surface is approximately constant, the mid-thickness value being equal and opposite. For the cases of triangular, sinusoidal and square through-wall self-balancing stress distributions (Figure III.2.1), the contribution to $K_r$ is

$$\frac{\lambda \sigma_{\text{max}} \sqrt{\pi w}}{K_{\text{mat}}}$$

Here $\sigma_{\text{max}}$ is the surface value of the self-balancing through-wall stress, $w$ is the thickness of the flawed section and $\lambda$ is a constant equal to 0.38, 0.43 and 0.48 for the triangular, sinusoidal and square stress distributions, respectively. These values are for surface assessments; for mid-thickness assessments it is conservative to set the contribution to $K_r$ equal to zero. Other self-balancing through-wall stress distributions will require to be individually assessed in comparison with the particular solutions discussed above. It is conservative to use these values for very short flaws; in this case Figure III.2.1 should be consulted to determine the variation of non-dimensional stress intensity factor, $\lambda$, with flaw length.

**III.2.2 Limit Load Solutions**

The primary source of information for obtaining the limit load is the SINTAP compendium [III.2.1]. Some specific solutions taken from [III.2.1] are reproduced in III.2.2.1 and III.2.2.2 below. III.2.2.1 considers homogeneous components whereas III.2.2.2 considers components with strength mis-match. III.2.2.3 - III.2.2.6 then briefly describe some alternative methods for obtaining the limit load. In III.2.2.4, there is a discussion of the distinction between ‘local’ and ‘global’ limit load solutions (see also II.4.6).

**III.2.2.1 Solutions for Specific Geometries**

As an example of a solution in [III.2.1], consider the compact tension specimen for which the stress intensity factor solution is given by equation (III.2.1). Whereas there is only a single $K_t$ solution, the limit load depends on whether the specimen is in plane stress or plane strain (see III.2.2.3) and on whether the von Mises or Tresca yield criterion is adopted. Therefore, there are four solutions in [III.2.1]. For plane strain with the von Mises yield criterion the yield limit load, $F_e$, is

$$F_e = \left( \frac{2}{\sqrt{3}} \right) R_e WB \left[ \left( 2.702 + 4.599 \left( \frac{a}{W} \right)^2 \right)^{\frac{1}{2}} - 1.702 \left( \frac{a}{W} \right) \right]$$

(III.2.5)

It can be seen that the limit load is directly proportional to yield strength, $R_e$, and decreases with increasing flaw size. These observations hold quite generally.
For internal flaws in pressurised components, the limit load depends on whether or not the flaw faces are assumed to be pressurised and on whether a local or global criterion is taken. For an axial semi-elliptical surface flaw under internal pressure, the limiting pressure in the absence of crack face pressure, \( P_e \), is [III.2.1]:

\[
P_e = R_e \left[ \frac{a}{R_i M} + \ln \left( \frac{R_i + t}{R_i + a} \right) \right]
\]  

(III.2.6)

where

\[
M = \left[ 1 + \frac{1.61c^2}{R_i a} \right]^{\frac{1}{2}}
\]  

(III.2.7)

The corresponding \( K_I \) solution may be obtained from equation (III.2.2) by representing the elastic stress field in the uncracked cylinder in the form of equation (III.2.3).

For circumferential flaws in pressurised cylinders, care must be exercised as collapse of the cylinder is often governed primarily by the hoop stress rather than the lower, axial stress normal to the plane of the flaw. For example, for a fully circumferential internal surface flaw of depth \( a \) in a cylinder of internal radius, \( R_i \), and external radius, \( R_o \), the limit pressure is

\[
P_e = R_e \left[ \ell n \left( \frac{R_o}{R_i + a} \right) + \frac{1}{2} \left( \frac{R_o}{R_i + a} \right)^2 \right]
\]  

(III.2.8)

for

\[
\left( 1 - \frac{R_i}{R_i + a} \right) > \frac{1}{2} \left( \frac{R_o}{R_i + a} \right)^2
\]  

(III.2.9)

otherwise

\[
P_e = R_e \left[ \ell n \left( \frac{R_o}{R_i + a} \right) + 1 - \frac{R_i}{R_i + a} \right]
\]  

(III.2.10)

These solutions are based on the Tresca yield criterion, assume crack face pressure and that the axial stresses arise from the cylinder having closed ends. Equation (III.2.8) applies for deep flaws, greater than approximately half the wall thickness, whereas equation (III.2.10) applies for shallow flaws and reduces to the uncracked Tresca limit pressure for \( a = 0 \).

The compendium [III.2.1] contains a large number of specific limit load solutions for pressure vessels, plates, spheres and offshore tubular joints. Limit load solutions for components with strength mis-match are also presented in [III.2.1] as discussed in III.2.2.2 below.

### III.2.2.2 Solutions for Material Mis-match

The pattern of plastic deformation in the neighbourhood of a section containing a flaw may be influenced if there is material mis-match. The methods of limit analysis described in subsections III.2.2.3 - III.2.2.6 may also be applied in these cases and have led to the development of a number of solutions for plates and cylinders which are compiled in [III.2.1]. Solutions are available for geometries which may be idealised as containing two regions with differing strengths, \( R_e^B \) and \( R_e^W \), the yield strengths of base and weld metal, say. The
limit load is then proportional to $R_e B$ and depends on flaw size, in a similar manner to the homogeneous solutions in III.2.2.1. However, the limit load also depends on the ratio $R_e W / R_e B$ and the size of the region for which the strength differs from $R_e B$. A lower bound estimate of limit load is given by the homogeneous solution taking the lower of $R_e B$ and $R_e W$. The solutions in [III.2.1], then enable benefit to be claimed from the increase in limit load due to the higher strength material.

As an illustration of the solutions in [III.2.1], consider the plane strain centre cracked plate with a crack in the centre-line of weld material $W$ which is shown in Figure III.2.2. The thickness of the plate is $t$ and a convenient normalisation of the height of the central region is

$$\Psi = (w-a)/h$$

In plane strain, the limit load for the plate made wholly of material $B$, $F_e B$, is

$$F_e B = (4/\sqrt{3}) R_e B t (w-a)$$

For undermatching ($M = R_e W / R_e B < 1$), the limit load, $F_e M$, is

$$F_e M / F_e B = M$$

$$F_e M / F_e B = \min \{ [1-(1-M)/\Psi], F_e M(1)/F_e B \}$$

where

$$F_e M(1)/F_e B = M [1.0 + 0.462 (\Psi^{-1})^2/\Psi - 0.044 (\Psi^{-1})^3/\Psi]$$

$$= M [2.571 - 3.254/\Psi]$$

$$= M [0.125 \Psi^3 + 1.291 + 0.019/\Psi]$$

For overmatching ($M > 1$),

$$F_e M / F_e B = \min \{ 1/(1-a/w), F_e M(2)/F_e B \}$$

where

$$F_e M(2)/F_e B = M$$

$$= 0.04 \{24(M-1) \exp [- (M-1)/5]/\Psi + M + 24 \}$$

Some results are shown in Figure III.2.3. Quite generally,

$$M \leq F_e M / F_e B \leq 1 \quad M < 1$$

$$1 \leq F_e M / F_e B \leq M \quad M \geq 1$$

and it can be seen that the results occupy the full range of these inequalities. The use of the lower bounds in these inequalities corresponds to defining the collapse load in terms of the yield stress of the weaker material. In extreme cases of large $M$, collapse can be controlled by the undefective plate section in material $B$. 

It is apparent from Figure III.2.3 that for this geometry there is potentially significant benefit from using the mis-match limit load for overmatching at lower values of $\Psi$ or for undermatching at higher values of $\Psi$. Conversely, the value of $F_e^M$ is close to the limit load based simply on the weaker material for overmatching with high values of $\Psi$ ($F_e^M \approx F_e^B$) and for undermatching with low values of $\Psi$ ($F_e^M \approx MF_e^B$). For the plates considered in [III.2.1], the general effects of mis-match can be summarised as follows:

For overmatching ($M>1$):

- $F_e^M$ is close to $F_e^B$ for geometries with cracks close to or on the boundaries between the two material zones;
- $F_e^M$ can be significantly higher than $F_e^B$ for cracks in the centre of the material region $W$ but the effect becomes less significant as the flaw size to width ratio, $a/W$, in Figure III.2.2, decreases and the normalised ligament size $\Psi$ increases.

For undermatching ($M<1$):

- The mis-match effect is significant for plane strain, regardless of $a/W$ (Figure III.2.2) particularly when the size of the zone of material $W$ is of small extent (for example, small $h/(W-a)$ large $\Psi$ in Figure III.2.2);
- $F_e^M$ is close to $MF_e^B$ for plane stress so that there is little benefit in using the mis-match limit load.

### III.2.2.3 Use of Elastically Calculated Stresses in a Generalised Plate Model

One method for estimating the limit load if a specific solution is not available is to use the elastically calculated stresses in a plate model. The first step in this procedure is to perform an elastic analysis of the defect free structure. This is used to define the tensile, bending and shear stress resultants at the gross section containing the flaw. These resultants are then used in conjunction with plastic yield load solutions for cracked plates to define the parameter $L_r$.

Plate solutions are generally presented as either plane stress or plane strain. For a conservative approach the plane stress solution is preferable as the plane stress limit load is lower than that in plane strain and its use, therefore, leads to higher values of $L_r$. In practice, component behaviour may correspond to neither idealisation and care should be exercised in using these 2-dimensional solutions. In particular, even the plane stress solution may lead to non-conservative results if there are high shear forces or high out-of-plane membrane forces present. The plane strain solutions have limited application. They may be relevant when deformations in the plane of the flaw are highly constrained by the remainder of the component, and may also be used to indicate the sensitivity of the assessment to the choice of limit load solution.

Care should be exercised in using plate solutions based on restrained bending. When such solutions are adopted it should be demonstrated that moments can be redistributed away from the section containing the flaw without causing another part of the structure to be in a more onerous condition than the section containing the flaw.
III.2.2.4 Use of Plastic Limit Analysis Solutions

The methods of limit analysis are well developed and the upper and lower bound theorems can be used to estimate values of the limit load. The lower bound theorem leads to an underestimate of the limit load and hence to an overestimate of $L_r$ and is particularly useful for the applications of this document. The compendium [III.2.1] contains a large number of lower bound limit analysis solutions for plates, round bars, cylinders, cones and spheres. In using limit analysis solutions, the plastic yield load used to define $L_r$ is the plastic limit load calculated for the yield or 0.2% proof stress, $R_e$.

In using limit analysis solutions, there is a distinction between ‘global’ solutions and ‘local’ solutions which correspond to a local yielding of the ligament at the flaw. As the ligament thickness tends to zero the ‘local’ limit load tends to zero. However, failure of the ligament need not correspond to overall yielding: the component may be able to sustain a load equal to the limit load with a fully penetrating defect. This is the basis for the distinction between the so-called ‘local’ and ‘global’ limit loads for partial penetration flaws. The ‘local’ limit load is less than or equal to the ‘global’ limit load.

For through flaws or flaws recharacterised as through flaws, the value of $L_r$ is defined by the ‘global’ limit load. In a conservative assessment, for partial penetration flaws, the plastic yield load used to evaluate $L_r$ should be the ‘local’ limit load which is the load needed to cause plasticity to spread across the remaining ligament assuming an elastic-perfectly plastic material with a yield stress equal to $R_e$. When such an assessment leads to unacceptable results, it may be possible to recharacterise a flaw as fully penetrating. Alternatively, the conservatism arising from the use of the ‘local’ limit load may be reduced by performing detailed analysis to calculate $J$; it is worth noting that in some cases such analysis has shown the ‘global’ limit load is more appropriate.

III.2.2.5 Use of Finite-Element Analysis

The flawed component may be analysed using a small displacement finite-element method with an elastic-perfectly plastic material model. The analysis is performed for a monotonically increasing load; the maximum load attained defines the plastic yield load ratio $F_e / R_e$ for the yield stress $R_e$ used in the analysis.

As noted in sub-section III.2.2.1, the plastic yield load is directly proportional to yield stress, so the ratio $F_e / R_e$ can be used to define the plastic yield load for other values of yield stress. The elastic properties assumed in the analysis do not affect the plastic yield load in a small displacement analysis.

In the finite-element method, there can be difficulties of convergence as the load approaches the plastic yield load. Therefore, a finite-element package which has been validated for plastic collapse analysis must be used when this approach is adopted. However, a lower estimate of plastic yield load is obtained by taking any load at which the analysis remains convergent and in many cases may lead to a satisfactory assessment.

The finite-element method has not been widely used for obtaining plastic yield loads of flawed components, but has been used to determine limit loads by the methods of limit analysis rather than by performing an incremental elastic-plastic solution. However, results have been obtained largely for plate geometries rather than for complex components. With the ever increasing power of digital computers such numerical solutions are likely to become more widely available.
III.2.2.6 Use of Model Tests – Empirical Solutions

The plastic yield load may be estimated by testing a scale model of the structure, including the flaw. In order to avoid ambiguity in interpreting the results, models should be made of a material which behaves in an approximately elastic-perfectly plastic manner. Thus the material should have a well-defined yield stress and an ultimate stress/yield stress ratio close to unity. Plastic limit loads derived from experimental results are often extended to cover a range of geometric variables by means of empirical expressions.

III.2.3 Procedure for the Evaluation of $\rho$

The parameter $\rho$ is introduced in I.2.2.3, its role is explained in the calculation of $K_i$ in II.4.3, the calculation of $J$ in II.4.4 and in the calculation of $\delta$ in II.4.5. The steps in the procedure for calculating $\rho$ are as follows:

(a) Evaluate $K_i^S$, the linear elastic stress intensity factor for the flaw size of interest, using the elastically-calculated secondary stress distribution, $\rho^S$ (see III.2.1 above).

$K_i^S$ is positive when it tends to open the flaw. If $K_i^S$ is negative or zero, then $\rho$ is set to zero and the remainder of this section is omitted.

(b) Evaluate $K_P^S$, a plastically corrected stress intensity factor for the flaw size of interest for the secondary stresses acting alone. Methods for evaluating $K_P^S$ are described in III.2.3.1 below.

If secondary stresses act alone, then $\rho$ is set to zero and $K_i^S$ in II.4.3, II.4.4 and II.4.5, is set equal to $K_P^S$. The remainder of the steps in this section are then omitted.

(c) Evaluate the ratio $K_i^S / (K_i^P / L_i)$ where $K_i^P$ and $L_i$ are defined in II.4.

(d) Obtain the parameter $\Psi$ from Table III.2.2 in terms of $L_i$ and the parameter $K_i^S / (K_i^P / L_i)$ calculated in step (c) above. Linear interpolation should be used for values not given in the table.

If $K_i^S / K_i^P = 1$, then $\rho$ is set equal to $\Psi$ and the remaining steps in this section are then omitted.

(e) Obtain the parameter $\phi$ from Table III.2.3 in terms of $L_i$ and the parameter $K_i^S / (K_i^P / L_i)$ calculated in step (c) above. Linear interpolation should be used for values not given in the table.

(f) Evaluate $\rho$ from

$$\rho = \Psi - \phi[(K_i^S / K_P^S) - 1]$$

III.2.3.1 Advice on Calculating $K_P^S$

Step (b) above requires the calculation of an effective stress intensity factor, $K_P^S$, for the secondary stresses acting alone. Here, four methods are given in order of accuracy and reducing complexity.
III.2.3.1.1 **Cracked Body Inelastic Analysis**

The most detailed and accurate approach for calculating $K_P^S$ is to perform an inelastic analysis of the cracked body to obtain a value $J^S$ of the $J$-integral for the secondary loading alone. Then

$$K_P^S = \sqrt{E'J^S}$$

where $E' = E$ in plane stress and $E' = E/(1-\nu^2)$ in plane strain. Note, the value of $K_P^S$ is specific to the material stress-strain curve and the flaw size used as input to the inelastic analysis. Therefore, for example, inelastic calculations will need to be repeated for a range of flaw sizes with this option if a limiting flaw size is being determined.

### III.2.3.1.2 Uncracked Body Inelastic Analysis

Compared to cracked body inelastic analysis, uncracked body inelastic analyses are quicker and cheaper to perform. One inelastic analysis may then be used to evaluate $K_P^S$ for a range of flaw sizes of interest as set out below.

It is assumed that the stress $\sigma_{yy}$ and mechanical strains $\varepsilon_{xx}, \varepsilon_{yy}$ and $\varepsilon_{zz}$ across the plane of the flaw have been determined from an elastic-plastic analysis of the uncracked body. Here the $y$-axis is normal to the plane of the flaw and $x, z$ are in-plane. The strains are the mechanical components, that is, any strain due to uniform thermal expansion has been subtracted from the total strain values.

In steps (iii) and (iv), effective flaw sizes are calculated. These flaw sizes may exceed the section thickness in some cases. The calculated values should be used in all cases in step (v).

(i) Determine an effective stress intensity factor $K^S_{\sigma}(a)$ from the uncracked-body stress $\sigma_{yy}$ normal to the crack plane.

(ii) Determine an effective stress intensity factor $K^S_{\varepsilon}(a)$ from the 'stress' $\sigma_{yy}$ normal to the crack plane defined in terms of the elastic-plastic, uncracked-body mechanical strains as if the material response were linear elastic. Specifically, $\sigma_{yy}$ is given by

$$\sigma_{yy} = \frac{E}{(1+\nu)(1-2\nu)}[(1-\nu)e_{yy} + \nu(e_{xx} + e_{zz})]$$

(iii) Define an effective crack size $a_{\sigma\text{eff}}$ from

$$a_{\sigma\text{eff}} = a + \frac{1}{2\pi\beta} \left( K_{\sigma}^S(a)/R_e \right)^2$$

where $\beta$ = 1, 3 for plane stress or plane strain, respectively.

(iv) Define an effective crack size $a_{\varepsilon\text{eff}}$ from

$$a_{\varepsilon\text{eff}} = a + \frac{1}{2\pi\beta} \left( K_{\varepsilon}^S(a)/R_e \right)^2$$

where $\beta$ = 1, 3 in plane stress or plane strain, respectively.

(v) Evaluate $K_P^S$ from
III.2.3.1.3 Estimates from Plastic Zone Size Correction

In the absence of an elastic-plastic analysis, a conservative estimate of $K_P^S$ may be obtained from the linear stress intensity factor $K_I^S$ as

$$K_P^S (a) = \left( \frac{a_{eff}^\alpha a_{eff}^\beta}{a^2} \right)^{1/4} \left[ K_0^S (a) K_I^S (a) \right]^{1/2}$$

where

$$a_{eff} = a + [1/(2\pi \beta)] [K_0^S (a)/R_e]^2$$

where $\beta = 1$ in plane stress and $\beta = 3$ in plane strain. This estimate clearly leads to $K_P^S > K_I^S$ and may be over-conservative for elastically calculated secondary stresses which are not much greater than yield. However, it does provide a simple approximation without the need for inelastic analysis. Note, $a_{eff}$ may exceed the section thickness in some cases. Where $K_P^S$ is expected to be less than $K_I^S$, then this estimate should not be used; instead, either the simple elastic estimate of III.2.3.1.4 below should be used or one of the methods of III.2.3.1.1 or III.2.3.1.2 can be used to quantify the reduction in effective stress intensity factor.

III.2.3.1.4 Elastic Estimate

The most simple approach is to set

$$K_P^S (a) = K_I^S (a)$$

This direct use of the elastic calculation is likely to be adequate when the secondary stresses are low compared to the yield stress and elastic follow-up is judged not to be significant. For large secondary stresses, particularly those which are non-uniform in the region of the flaw, plastic redistribution of stress is likely to be important and the direct use of elastic calculations is likely to be over-conservative.

III.2.3.2 The Parameter $V$

The methodology set out above follows that in R6 as discussed in [III.2.57]. Further advice on the use of finite-element analysis to calculate $K_P^S$ is contained in R6. An alternative approach to the definition of $K_r$ is given in II.4.3 as

$$K_r = (K_I^P + VK_I^S) / K_{mat}$$

The parameter $V$ plays a similar role to the parameter $\rho$ in covering the effects of plasticity on secondary stresses. This definition of $K_r$ is equivalent to that using $\rho$ with $V$ taking an initial value $V_0$ for $L_r = 0$ given by

$$V_0 = K_P^S / K_I^S$$

and, for $L_r > 0$,

$$V / V_0 = 1 + \Psi / \phi$$
$V$ may also be used in the same way when performing a CDF analysis using the equations given in II.4.4 or II.4.5.

Further discussion of the use of $V$ is contained in [III.2.57]. Experimental and numerical validation of the approach adopted here, or the equivalent $V$ approach, is also discussed in [III.2.57]. While the methods proposed are well validated this is an area where further work may lead to some simplification and potentially to reduced conservatism.
III.2.4 References


[3.2.31] W Zhao, X R Wu, M G Yan, 'Stress intensity factors for small surface cracks in a commonly used small cracked specimen (retroactive coverage)', Fatigue 90, Honolulu, Hawaii, USA 15-20 July 1990.


[3.2.36] ASME Boiler and Pressure Vessel Code, Section XI, Division 1, Article A-3000 (1983). (Note, when using this code, the flaw shape parameter, Q, should be calculated by setting \( \frac{\sigma_m + \sigma_b}{\sigma_Y} = 0 \)).


### TABLE III.2.1 Geometry functions in equation (3.2.2) for a finite axial internal surface crack in a cylinder at the deepest point A.

#### 2c/a = 2, R/t = 4

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.659</td>
<td>0.471</td>
<td>0.387</td>
<td>0.337</td>
</tr>
<tr>
<td>0.2</td>
<td>0.643</td>
<td>0.454</td>
<td>0.375</td>
<td>0.326</td>
</tr>
<tr>
<td>0.5</td>
<td>0.663</td>
<td>0.463</td>
<td>0.378</td>
<td>0.328</td>
</tr>
<tr>
<td>0.8</td>
<td>0.704</td>
<td>0.489</td>
<td>0.397</td>
<td>0.342</td>
</tr>
</tbody>
</table>

#### 2c/a = 2, R/t = 10

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.659</td>
<td>0.471</td>
<td>0.387</td>
<td>0.337</td>
</tr>
<tr>
<td>0.2</td>
<td>0.647</td>
<td>0.456</td>
<td>0.375</td>
<td>0.326</td>
</tr>
<tr>
<td>0.5</td>
<td>0.669</td>
<td>0.464</td>
<td>0.380</td>
<td>0.328</td>
</tr>
<tr>
<td>0.8</td>
<td>0.694</td>
<td>0.484</td>
<td>0.394</td>
<td>0.339</td>
</tr>
</tbody>
</table>

#### 2c/a = 5, R/t = 4

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.939</td>
<td>0.580</td>
<td>0.434</td>
<td>0.353</td>
</tr>
<tr>
<td>0.2</td>
<td>0.919</td>
<td>0.579</td>
<td>0.452</td>
<td>0.382</td>
</tr>
<tr>
<td>0.5</td>
<td>1.037</td>
<td>0.622</td>
<td>0.474</td>
<td>0.395</td>
</tr>
<tr>
<td>0.8</td>
<td>1.255</td>
<td>0.720</td>
<td>0.534</td>
<td>0.443</td>
</tr>
</tbody>
</table>

#### 2c/a = 5, R/t = 10

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.939</td>
<td>0.580</td>
<td>0.434</td>
<td>0.353</td>
</tr>
<tr>
<td>0.2</td>
<td>0.932</td>
<td>0.584</td>
<td>0.455</td>
<td>0.383</td>
</tr>
<tr>
<td>0.5</td>
<td>1.058</td>
<td>0.629</td>
<td>0.477</td>
<td>0.397</td>
</tr>
<tr>
<td>0.8</td>
<td>1.211</td>
<td>0.701</td>
<td>0.523</td>
<td>0.429</td>
</tr>
</tbody>
</table>

#### 2c/a = 10 R/t = 4

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.053</td>
<td>0.606</td>
<td>0.443</td>
<td>0.357</td>
</tr>
<tr>
<td>0.2</td>
<td>1.045</td>
<td>0.634</td>
<td>0.487</td>
<td>0.406</td>
</tr>
<tr>
<td>0.5</td>
<td>1.338</td>
<td>0.739</td>
<td>0.540</td>
<td>0.438</td>
</tr>
<tr>
<td>0.8</td>
<td>1.865</td>
<td>0.948</td>
<td>0.659</td>
<td>0.516</td>
</tr>
</tbody>
</table>

#### 2c/a = 10 R/t = 10

<table>
<thead>
<tr>
<th>a/t</th>
<th>( f_0^\Lambda )</th>
<th>( f_1^\Lambda )</th>
<th>( f_2^\Lambda )</th>
<th>( f_3^\Lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.053</td>
<td>0.606</td>
<td>0.443</td>
<td>0.357</td>
</tr>
<tr>
<td>0.2</td>
<td>1.062</td>
<td>0.641</td>
<td>0.489</td>
<td>0.417</td>
</tr>
<tr>
<td>0.5</td>
<td>1.359</td>
<td>0.746</td>
<td>0.544</td>
<td>0.440</td>
</tr>
<tr>
<td>0.8</td>
<td>1.783</td>
<td>0.914</td>
<td>0.639</td>
<td>0.504</td>
</tr>
</tbody>
</table>
TABLE III.2.2 Values of $\Psi$ as a function of $L_r$ and $K_p^s/(K_I^p/L_r)$

<table>
<thead>
<tr>
<th>$K_p^s/(K_I^p/L_r)$</th>
<th>0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_r$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.020</td>
<td>0.043</td>
<td>0.063</td>
<td>0.074</td>
<td>0.081</td>
<td>0.086</td>
<td>0.090</td>
<td>0.095</td>
<td>0.100</td>
<td>0.107</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.028</td>
<td>0.052</td>
<td>0.076</td>
<td>0.091</td>
<td>0.100</td>
<td>0.107</td>
<td>0.113</td>
<td>0.120</td>
<td>0.127</td>
<td>0.137</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.033</td>
<td>0.057</td>
<td>0.085</td>
<td>0.102</td>
<td>0.114</td>
<td>0.122</td>
<td>0.130</td>
<td>0.138</td>
<td>0.147</td>
<td>0.160</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.037</td>
<td>0.064</td>
<td>0.094</td>
<td>0.113</td>
<td>0.126</td>
<td>0.136</td>
<td>0.145</td>
<td>0.156</td>
<td>0.167</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.043</td>
<td>0.074</td>
<td>0.105</td>
<td>0.124</td>
<td>0.138</td>
<td>0.149</td>
<td>0.160</td>
<td>0.172</td>
<td>0.185</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.051</td>
<td>0.085</td>
<td>0.114</td>
<td>0.133</td>
<td>0.147</td>
<td>0.159</td>
<td>0.170</td>
<td>0.184</td>
<td>0.200</td>
<td>0.215</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.058</td>
<td>0.091</td>
<td>0.117</td>
<td>0.134</td>
<td>0.147</td>
<td>0.158</td>
<td>0.171</td>
<td>0.186</td>
<td>0.202</td>
<td>0.214</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.057</td>
<td>0.085</td>
<td>0.105</td>
<td>0.119</td>
<td>0.130</td>
<td>0.141</td>
<td>0.155</td>
<td>0.169</td>
<td>0.182</td>
<td>0.190</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.043</td>
<td>0.060</td>
<td>0.073</td>
<td>0.082</td>
<td>0.090</td>
<td>0.101</td>
<td>0.113</td>
<td>0.123</td>
<td>0.129</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.016</td>
<td>0.019</td>
<td>0.022</td>
<td>0.025</td>
<td>0.031</td>
<td>0.039</td>
<td>0.043</td>
<td>0.044</td>
<td>0.041</td>
<td>0.033</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>-0.013</td>
<td>-0.025</td>
<td>-0.033</td>
<td>-0.036</td>
<td>-0.037</td>
<td>-0.042</td>
<td>-0.050</td>
<td>-0.061</td>
<td>-0.073</td>
<td>-0.084</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>-0.034</td>
<td>-0.058</td>
<td>-0.075</td>
<td>-0.090</td>
<td>-0.106</td>
<td>-0.122</td>
<td>-0.137</td>
<td>-0.151</td>
<td>-0.164</td>
<td>-0.175</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>-0.043</td>
<td>-0.075</td>
<td>-0.102</td>
<td>-0.126</td>
<td>-0.147</td>
<td>-0.166</td>
<td>-0.181</td>
<td>-0.196</td>
<td>-0.209</td>
<td>-0.220</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>-0.044</td>
<td>-0.080</td>
<td>-0.109</td>
<td>-0.134</td>
<td>-0.155</td>
<td>-0.173</td>
<td>-0.189</td>
<td>-0.203</td>
<td>-0.215</td>
<td>-0.227</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-0.041</td>
<td>-0.075</td>
<td>-0.103</td>
<td>-0.127</td>
<td>-0.147</td>
<td>-0.164</td>
<td>-0.180</td>
<td>-0.194</td>
<td>-0.206</td>
<td>-0.217</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>-0.037</td>
<td>-0.069</td>
<td>-0.095</td>
<td>-0.117</td>
<td>-0.136</td>
<td>-0.153</td>
<td>-0.168</td>
<td>-0.181</td>
<td>-0.194</td>
<td>-0.205</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>-0.033</td>
<td>-0.062</td>
<td>-0.086</td>
<td>-0.107</td>
<td>-0.125</td>
<td>-0.141</td>
<td>-0.155</td>
<td>-0.168</td>
<td>-0.180</td>
<td>-0.191</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>-0.030</td>
<td>-0.055</td>
<td>-0.077</td>
<td>-0.096</td>
<td>-0.114</td>
<td>-0.129</td>
<td>-0.142</td>
<td>-0.155</td>
<td>-0.166</td>
<td>-0.177</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>-0.026</td>
<td>-0.049</td>
<td>-0.069</td>
<td>-0.086</td>
<td>-0.102</td>
<td>-0.116</td>
<td>-0.129</td>
<td>-0.141</td>
<td>-0.152</td>
<td>-0.162</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>-0.023</td>
<td>-0.043</td>
<td>-0.061</td>
<td>-0.076</td>
<td>-0.091</td>
<td>-0.104</td>
<td>-0.116</td>
<td>-0.126</td>
<td>-0.137</td>
<td>-0.146</td>
</tr>
</tbody>
</table>
TABLE III.2.3 Values of $\phi$ as a function of $L_r$ and $K^p_p/(K^p/L_r)$

<table>
<thead>
<tr>
<th>$K^p_p/(K^p/L_r)$</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_r$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.815</td>
<td>0.869</td>
<td>0.877</td>
<td>0.880</td>
<td>0.882</td>
<td>0.883</td>
<td>0.883</td>
<td>0.882</td>
<td>0.879</td>
<td>0.874</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0.690</td>
<td>0.786</td>
<td>0.810</td>
<td>0.821</td>
<td>0.828</td>
<td>0.832</td>
<td>0.833</td>
<td>0.833</td>
<td>0.831</td>
<td>0.825</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.596</td>
<td>0.715</td>
<td>0.752</td>
<td>0.769</td>
<td>0.780</td>
<td>0.786</td>
<td>0.789</td>
<td>0.789</td>
<td>0.787</td>
<td>0.780</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0.521</td>
<td>0.651</td>
<td>0.696</td>
<td>0.718</td>
<td>0.732</td>
<td>0.740</td>
<td>0.744</td>
<td>0.745</td>
<td>0.743</td>
<td>0.735</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.457</td>
<td>0.589</td>
<td>0.640</td>
<td>0.666</td>
<td>0.683</td>
<td>0.693</td>
<td>0.698</td>
<td>0.698</td>
<td>0.695</td>
<td>0.688</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>0.399</td>
<td>0.528</td>
<td>0.582</td>
<td>0.612</td>
<td>0.631</td>
<td>0.642</td>
<td>0.647</td>
<td>0.648</td>
<td>0.644</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>0.344</td>
<td>0.466</td>
<td>0.522</td>
<td>0.554</td>
<td>0.575</td>
<td>0.587</td>
<td>0.593</td>
<td>0.593</td>
<td>0.589</td>
<td>0.587</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>0.290</td>
<td>0.403</td>
<td>0.460</td>
<td>0.493</td>
<td>0.516</td>
<td>0.528</td>
<td>0.533</td>
<td>0.534</td>
<td>0.534</td>
<td>0.535</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>0.236</td>
<td>0.339</td>
<td>0.395</td>
<td>0.430</td>
<td>0.452</td>
<td>0.464</td>
<td>0.470</td>
<td>0.475</td>
<td>0.480</td>
<td>0.486</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.185</td>
<td>0.276</td>
<td>0.330</td>
<td>0.364</td>
<td>0.386</td>
<td>0.400</td>
<td>0.411</td>
<td>0.423</td>
<td>0.435</td>
<td>0.449</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>0.139</td>
<td>0.218</td>
<td>0.269</td>
<td>0.302</td>
<td>0.326</td>
<td>0.347</td>
<td>0.367</td>
<td>0.387</td>
<td>0.406</td>
<td>0.423</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>0.104</td>
<td>0.172</td>
<td>0.219</td>
<td>0.256</td>
<td>0.287</td>
<td>0.315</td>
<td>0.340</td>
<td>0.362</td>
<td>0.382</td>
<td>0.399</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>0.082</td>
<td>0.142</td>
<td>0.190</td>
<td>0.229</td>
<td>0.263</td>
<td>0.291</td>
<td>0.316</td>
<td>0.338</td>
<td>0.357</td>
<td>0.375</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>0.070</td>
<td>0.126</td>
<td>0.171</td>
<td>0.209</td>
<td>0.241</td>
<td>0.269</td>
<td>0.293</td>
<td>0.314</td>
<td>0.333</td>
<td>0.350</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.062</td>
<td>0.112</td>
<td>0.155</td>
<td>0.190</td>
<td>0.220</td>
<td>0.247</td>
<td>0.270</td>
<td>0.290</td>
<td>0.309</td>
<td>0.325</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>0.055</td>
<td>0.100</td>
<td>0.139</td>
<td>0.172</td>
<td>0.200</td>
<td>0.225</td>
<td>0.247</td>
<td>0.267</td>
<td>0.285</td>
<td>0.301</td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>0.048</td>
<td>0.089</td>
<td>0.124</td>
<td>0.154</td>
<td>0.181</td>
<td>0.204</td>
<td>0.224</td>
<td>0.243</td>
<td>0.260</td>
<td>0.276</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>0.042</td>
<td>0.078</td>
<td>0.110</td>
<td>0.137</td>
<td>0.161</td>
<td>0.183</td>
<td>0.202</td>
<td>0.220</td>
<td>0.236</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>0.036</td>
<td>0.068</td>
<td>0.096</td>
<td>0.120</td>
<td>0.142</td>
<td>0.162</td>
<td>0.180</td>
<td>0.196</td>
<td>0.211</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>0.031</td>
<td>0.058</td>
<td>0.082</td>
<td>0.104</td>
<td>0.124</td>
<td>0.141</td>
<td>0.157</td>
<td>0.172</td>
<td>0.186</td>
<td>0.198</td>
<td></td>
</tr>
</tbody>
</table>
Fig. III.2.1 Non-dimensional stress intensity factors for through-thickness flaws with through-wall self-balancing stress distribution
Fig. III.2.2  Mis-matched Centre-Cracked Plate

\[ \psi = \frac{(W-a)}{H} \]
\[ \xi = \frac{a}{W} \]
\[ M = \frac{\sigma_{YW}}{\sigma_{YB}} \]

Fig. III.2.3  Limit Load for Mis-matched Centre-Cracked Plate in Plane Strain for \( a/W = 0.5 \)

\[ F_{YM} = \frac{4}{\sqrt{3}} \frac{\sigma_{YN}}{B} \cdot (W-a) \]
### NOMENCLATURE AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$</td>
<td>1% proof test at the appropriate temperature</td>
</tr>
<tr>
<td>$\sigma_y^{*}$</td>
<td>Lower of ($\sigma_{yp}$, $\sigma_{yw}$)</td>
</tr>
<tr>
<td>$\sigma_y^{+}$</td>
<td>Greater of ($\sigma_{yp}$, $\sigma_{yw}$)</td>
</tr>
<tr>
<td>$\sigma_{yp}$</td>
<td>Yield or 0.2% proof strength of parent metal</td>
</tr>
<tr>
<td>$\sigma_{yw}$</td>
<td>Yield or 0.2% proof strength of weld metal</td>
</tr>
<tr>
<td>$\sigma_{R,L}$</td>
<td>Longitudinal residual stress</td>
</tr>
<tr>
<td>$\sigma_{R,T}$</td>
<td>Transverse residual stress</td>
</tr>
<tr>
<td>$\sigma_{R,T,O}$</td>
<td>Transverse residual stress at outer surface</td>
</tr>
<tr>
<td>$\sigma_{R,T,B}$</td>
<td>Transverse residual stress at bore surface</td>
</tr>
<tr>
<td>$t$</td>
<td>Plate thickness</td>
</tr>
<tr>
<td>$T$</td>
<td>Plate thickness for T weld joint</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of the weld bead</td>
</tr>
<tr>
<td>$r_0$</td>
<td>Dimensions of the yield zone for a thick plate</td>
</tr>
<tr>
<td>$y_0$</td>
<td>Dimensions of the yield zone for a thin plate</td>
</tr>
</tbody>
</table>

Note: All Stress in MPa  
All Dimensions in mm
III.3.1. INTRODUCTION

Residual stresses can have a detrimental effect on the integrity of a structure and are therefore an important component of any integrity assessment of a welded structure. Although they are introduced by various manufacturing processes, those due to welding are the most common and relevant to this programme of work. Under predictions of fracture risk can occur if they are not correctly accounted for, while over-conservative estimates lead to over-estimation of fracture risk. Under-prediction is of concern to structural integrity whilst over-estimation may have severe financial implications in an industrial situation.

Primary stresses are those which contribute to collapse, such as applied loads or pressures, and also displacement controlled stresses, such as those associated with thermal expansion. Secondary stresses are those that are self-equilibrating across a weldment, producing a zero net force or bending moment. Residual stress distributions are made up of two components, the first being directly attributable to the welding process, arising from thermal contractions and phase changes that occur in the weldment, while the second component arises from mismatch and restraint within the structure itself.

This section presents a single reference source of residual stress profiles for a range of geometries in the As-Welded, Post-Weld Heat Treated and Weld-Repaired conditions.

Residual stress profiles are given in the transverse direction (stresses normal to the weld run) and also the longitudinal direction (stresses parallel to the weld run). These are termed $\sigma_R^T$ and $\sigma_R^L$ respectively. The variation of stress in both through thickness distance and normal distance from the weld centre-line are shown, although those in the through-thickness direction are considered to be negligible.

The data obtained for each geometry are fitted to upper bound tensile profiles, which in general, do not self-equilibrate across the weld section. It is therefore recommended that the literature should be consulted for assessments of borderline results in order to obtain the best residual stress profile for the specific joint and material under assessment.

III.3.2. STRUCTURE

Residual stress profiles can be determined by three methods of increasing conservatism:

(i) As a function of the welding conditions and of the mechanical properties of the materials.

(ii) According to a polynomial function representing an upper-bound fit to experimental measurements.

(iii) As equal to the yield strength of the weld metal.

The first method is preferred because it is the most accurate.
Consequently, the following clauses are proposed for determining the residual stress profiles for a welded assembly:

1. If the welding conditions are known or may be estimated ⇒ the residual stress profiles are determined from knowledge of the size of the plastic zone \((r_0, y_0)\) which is calculated from details of the welding parameters and the mechanical properties of the material.

2. If the welding conditions are unknown ⇒ the residual stress profiles are experienced as a polynomial function.

3. \(\sigma_{R_L}^T\) or \(\sigma_{R_T}^T\) = the greater of \((\sigma_{yw}, \sigma_{yp})\) in an area including the weld and its neighbourhood.

The calculation of the size parameters of the elastic zone \((r_0, y_0)\) is detailed in Section III.3.3.

Residual stress profiles are presented for cases 1 and 2 above for the following geometries:

- Plate butt welds and pipe axial seam welds
- Plate T-butt welds
- Pipe butt welds
- Pipe T-butt welds
- Set-in nozzles
- Set-on nozzles
- Repair welds

Details are given in Table III.3.1.

For each geometry considered, the variation of residual stresses in each figure is represented as follows:

- Variation of longitudinal residual stresses at the surface,
- Variation of transverse residual stresses at the surface,
- Variation of longitudinal residual stresses through the thickness,
- Variation of transverse residual stresses through the thickness.

Distance through the thickness is presented in normalised terms as \((z/t)\) where \(z\) is any depth and \(t\) is the plate, or component thickness.

The stress profiles are normalised to the yield stress \(\sigma_y\) \((\sigma_y = \text{yield or 0.2\% proof stress})\) of the weld metal or parent metal. They are presented in terms of normalised residual stress. The parameter, \(\sigma_y\), refers mainly to the yield stress of the weld \(\sigma_{yw}\) for longitudinal residual stresses except for a few cases. For transverse residual stresses, \(\sigma_y\), is the lower of the weld metal \(\sigma_{yw}\) and parent metal \(\sigma_{yp}\) yield stress except when there is a defect of the type listed below in which case it is the higher of the two yield stresses.

1. Defects in repair welds
2. Defects at weld intersections
3. Shallow defects
For austenitic steels, the high work hardening after the beginning of the plastic deformation, results in a large variability of the material properties. In this case, the yield stress $\sigma_y$ is defined as the 1% proof stress. To a first approximation $\sigma_y (\varepsilon = 1\%) = 1.5 \sigma_y (\varepsilon = 0.2\%)$

If the defect is being assessed in an area of constant and uniform temperature, the appropriate value of $\sigma_y$ is the yield stress at the temperature of assessment. If the temperature varies within the defective area, then the appropriate value of $\sigma_y$ is the maximum value of yield stress which usually corresponds to that at the minimum temperature recorded.

The validity ranges for the profiles presented are summarised in Table III.3.2.

III.3.3. **CALCULATION OF THE DIMENSIONS OF YIELDED ZONE**

For the determination of residual stress profiles which take account of the welding conditions, the dimensions of the yielded zone associated with the residual stress must be evaluated.

**For thick material:**

$$r_0 = \frac{K \eta q}{\sigma_{yp} v}$$  \hspace{1cm} (III.3.1)

where:

- $r_0$ = radius of yield zone, mm
- $K$ = a material constant, Nmm/J (see below)
- $\sigma_{yp}$ = yield or 0.2% proof strength of parent metal, N/mm$^2$
- $q$ = Arc power in J/sec = $IV$
- $I$ = current, A
- $V$ = voltage, V
- $v$ = weld travel speed, mm/sec
- $\eta$ = process efficiency (fraction of arc power entering plate as heat)

Qualitatively, the thick plate formula is applicable where the weld bead dimensions are small compared with the plate thickness, for example at a multi-pass weld with many passes, or at a small single-pass fillet weld on thick plate. Quantitatively, Equation III.3.1 applies if $r_0 \geq t$, where $t$ is the plate thickness. If $r_0 > t$, then the thin plate formula, given below, as eq III.3.2 is used. Iteration may be necessary to determine the correct equation.
Weld in Thin Material

\[ y_0 = \frac{1.033K \eta d}{\sigma_{yp} Vf} \]  

(III.3.2)

In a butt weld, \( t \) is the plate thickness. In a T-joint between a base plate of thickness \( t_b \) and an attached plate of thickness \( t_a \), \( t \) is taken as \((t_b + 0.5 t_a)\). In a corner joint with the same definitions of \( t_b \), \( t \) is taken as \(0.5 (t_a + t_b)\). All other variables are as defined for Equation III.3.1.

Equation III.3.2 applies if \( y_0 > 1.033 t \). If \( y_0 \leq 1.033 t \), the thick plate formula previously described is used. In general, Equation III.3.2 is applicable where the weld bead dimensions are comparable with the plate thickness, for example at single pass or two pass butt welds.

Material Constant and Process Efficiency

\( K \) is defined as follows:

\[ K = \frac{2\alpha E}{(e\pi pc)} \]  

(III.3.3)

where:

- \( \alpha \) = coefficient of thermal expansion, °C\(^{-1}\)
- \( E \) = Young's Modulus, N/mm\(^2\)
- \( \rho \) = density, kg/mm\(^3\)
- \( c \) = specific heat, J/kg°C
- \( e \) = exponential constant, 2.718

The material properties are taken at ambient temperature (20 °C). Typical values of the relevant properties are listed in Table III.3.3. Taking a typical value of process efficiency, \( \eta = 0.8 \), gives the following values of \( K\eta \):

- Ferritic steels, \( K\eta = 122 \) Nmm/J
- Austenitic stainless steels, \( K\eta = 161 \) Nmm/J
- Aluminium alloys, \( K\eta = 131 \) Nmm/J

III.3.4 RESIDUAL STRESS PROFILES

III.3.4.1 Plate Butt Welds and Pipe Axial Seam Weld

The details of distributions for plate butt welds and pipe axial seam welds are shown in Fig.III.3.1 as follows:

1. Geometry
2. Surface residual stress profiles
3. Through-thickness residual stress profiles
The calculation of residual stress decay (parameters $r_o$ and $y_o$) for use with these profiles is carried out in accordance with Section III.3.3

The equations for the through-thickness residual stress profiles are:

**Ferritic Steels;** longitudinal through-thickness stress

$$\sigma^L_R (z / t) / \sigma_{yw} = 0.82 + 2.892(z / t) - 11.316(z / t)^2 + 10.545(z / t)^3 - 1.846(z / t)^4$$  (III.3.4)

**Austenitic Steel;** longitudinal through-thickness stress

$$\sigma^L_R (z / t) / \sigma_{yw} = 0.95 + 1.505(z / t) - 8.287(z / t)^2 + 10.571(z / t)^3 - 4.08(z / t)^4$$  (III.3.5)

**Ferritic and Austenitic Steels;** transverse through-thickness stress

$$\sigma^T_R (z / t) / \sigma_{yw} = 1 - 0.917(z / t) - 14.533(z / t)^2 + 83.115(z / t)^3$$
$$- 215.45(z / t)^4 + 244.16(z / t)^5 - 96.36(z / t)^6$$  (III.3.6)

For the case of unknown or un-estimatable welding conditions the longitudinal surface residual stress profile can be determined from the polynomial expression shown in Fig. III.3.8 for this class of weld.

**III.3.4.2 Plate T-Butt Welds**

Details of the distributions for plate T-butt welds are shown in Fig. III.3.2 as follows:

1. Geometry
2. Surface residual stress profiles
3. Through-thickness residual stress profiles

The profiles shown are applicable to ferritic steels, austenitic steels and aluminium and to T-butt welds, T-fillet welds in flat plates and in tubular T-joint geometries.

Alternatively, where sufficient information on the welding process is available the polynomial expression shown in Fig. III.3.8 can be used to estimate the longitudinal surface residual stress profile.

**III.3.4.3 Pipe Butt Welds**

The details of distributions for pipe-butt welds are shown in Fig. III.3.3 as follows:

1. Geometry
2. Surface residual stress profiles
3. Through-thickness residual stress profiles
For the case of surface residual stress, there is no recommendation for transverse stress as insufficient information exists. In this case residual stress should be taken as being uniform and equal to the lower of the yield strength of parent plate or weld metal.

For through-thickness profiles, the longitudinal distribution is given as a linear profile equal to yield stress at the outer surface and \( \sigma_{R_{LB}} \) at the bore where:

\[
\sigma_{R_{LB}} = A_b \sigma_y
\]  
(III.3.7)

where:

\[
A_b = \begin{cases} 
1 & 0 < t \leq 15 \text{ mm} \\
1 - 0.0143 (t - 15) & 15 \text{ mm} < t \leq 85 \text{ mm} \\
0 & t > 85 \text{ mm}
\end{cases}
\]

For a pipe thickness of less than 15 mm, a through thickness tensile yield stress is obtained. The tensile stress at the bore decreases with increasing pipe thickness to a value of zero for a pipe thickness of approximately 85 mm, and then becomes compressive.

The transverse through-thickness residual stress profile depends on the material. For austenitic steels the profile is thickness-dependent as given by:

\[
\sigma_T(z/t) = 1.219 \sigma_y \left[ \frac{2z}{t} - 1 \right]
\]  
\( t \leq 7 \text{ mm} \)  
(III.3.8)

\[
\sigma_T(z/t) = (1.5884 - 0.05284t) \sigma_y \left[ \frac{2z}{t} - 1 \right]
\]  
\( 7 \text{ mm} < t \leq 7 \text{ mm} \)  
(III.3.9)

For pipe thickness greater than 25 mm, the profile of residual stresses is defined by the following polynomial expression:

\[
\sigma_T(z/t) = \sigma_{T,O} \left[ 0.27 + 0.91(z/t) - 4.93(z/t)^2 + 8.60(z/t)^3 - 2.03(z/t)^4 \right]
\]  
(III.3.10)

For ferritic welds, the profile depends on the heat input of the weld and the pipe thickness. For high heat inputs \( [(q/v)/t > 60 \text{ J/mm}^2] \), the following through wall cosine distribution is applicable:

\[
\sigma_T(z/t) = \sigma_{T,O} \cos(\pi z/t) : z \text{ measurement from outer surface and } \sigma_{T,O} = -1
\]  
(III.3.11)

For low heat inputs \( [(q/v)/t < 60 \text{ J/mm}^2] \) the following polynomial stress distribution is applicable.

\[
\sigma_T(z/t) = \sigma_{T,O} \left[ 1 - 3.29(z/t) - 26.09(z/t)^2 + 73.16(z/t)^3 - 45.72(z/t)^4 \right]
\]  
(III.3.12)

Where

\[
\frac{\sigma_{T,O}}{\sigma_y} = -0.5 - 0.0083 \frac{q}{vt}
\]  
(III.3.13)

It should be noted that the residual stress on the outer surface of a pipe is always in compression for all values of heat input.
III.3.4.4  Pipe T-Butt Welds

The term Pipe T-Butt weld also includes pipe on plate welds (tubular T and Y nodes). The profiles are shown for the following in Fig. III.3.4:-

1  Geometry
2  Surface residual stress profiles
3  Through-thickness residual stress profiles

The surface profiles are the same as those recommended for T-butt welds (Section III.3.4.2) although it should be noted that the profiles for pipe-on-pipe geometries are for the stresses in the chord and not the brace member.

The through-thickness stress profiles were determined from data where the ratio of chord thickness to brace thickness varied from 1.375 to 2. When \( t/T < 1.375 \), a uniform tensile residual stress of yield magnitude should be assumed. For cases where \( t/T > 2 \), the profiles for plate T-butt welds are recommended. The \( R/r \) ratios for the pipe on pipe geometries varied from 1.5 to approximately 2 and the profiles given should be used with caution outside this range. If the radii differ by a large amount (a factor of 5) then the profiles presented for plate T-butt welds should be considered as a good alternative.

The formulae for the through thickness residual stress profiles are:

**Ferritic steels**, longitudinal through-thickness stress:

\[
\frac{\sigma_R^L}{\sigma_{yw}} = 1.025 + 3.478(z/t) - 27.816(z/t)^2 + 45.788(z/t)^3 - 21.8(z/t)^4 \quad (III.3.14)
\]

**Ferritic steels**, transverse through-thickness stress:

\[
\frac{\sigma_R^T}{\sigma_{yw}} = 0.97 + 2.327(z/t) - 24.125(z/t)^2 + 42.478(z/t)^3 - 21.087(z/t)^4 \quad (III.3.15)
\]

where \( \sigma_{yw} \) is the lower of the yield stress of parent material and weld metal.

Application of these formulae to austenitic welds should be made with care.

III.3.4.5  Set-In Nozzles

The geometry and residual stress profiles are shown in Fig. III.3.5 for the following cases:-

1  Geometry
2  Surface residual stress profiles
3  Through-thickness residual stress profiles

The longitudinal surface residual stress profile is given for thick and thin material where the definition of this is made in accordance with the dimensions of the plastic zone (Section III.3.3). There is no recommendation for a transverse surface residual stress for this geometry and no polynomial expression for the longitudinal surface residual stress.
The through-thickness stress profiles are given for two different locations of the component in Part 3 of Fig. III.3.5.

III.3.4.6 Set-On Nozzles

Details for set-on nozzles presented in Fig. III.3.6 as follows:

1 Geometry
2 Surface residual stress profiles
3 Through-thickness residual stress profiles

For the surface residual stress, distributions are suggested for thin and thick material for the longitudinal orientation but no profiles are available for the transverse orientation. Section III.3.3 should be used to determine the thickness category of the component. There is no polynomial expression available for the longitudinal surface residual stress.

Through-thickness stress profiles are given for two different locations of the component in Fig. III.3.6.

III.3.4.7 Weld T-Intersections

The treatment of weld T-intersections depends on the order in which the welds were made:

a) If the terminating welds are completed first, which is normal practice, then the intersection has no particular significance and each weld is treated as it would normally be for the relevant geometry (i.e. the effect of the intersection should be ignored).

b) If the terminating weld is completed last, then the residual stress profiles must be assumed to be uniform, tensile through the thickness and of weld metal yield magnitude.

III.3.4.8 Repair Welds

Profiles for repair welds are shown in Fig. III.3.7 as follows:

1 Geometry
2 Surface residual stress profiles
3 Through-thickness residual stress profiles

The surface longitudinal residual stress profile applies to ferritic steel, austenitic steel and aluminium while all other profiles apply to ferritic steels only. If the repair weld is short the through-thickness residual stress profiles in both the longitudinal and transverse orientations are the same. The profile for the surface transverse residual stress profile should only be used for a full length repair weld.

For through-thickness stresses, the stress should be taken as the greater yield stress of the parent plate, original weld or repair weld. Below the repair, the residual stress reduces linearly with distance to zero at a distance $z_0$ below the root of the repair. $z_0$ is related to the heat input of the repair weld and is defined in Part 3 of Fig. III.3.7.
The transverse and longitudinal residual stress distributions in repair welds should be considered to be of yield magnitude throughout the depth of the repair. For part-depth repairs of depth $z_r$, the residual stresses may be assumed to decrease from yield magnitude at the bottom of the repair weld, where $z_o$ is defined by Equation III.3.16.

\[
z_o = \frac{122}{\sigma_y} \left( \frac{q}{v} \right) \tag{III.3.16}
\]

for $z \leq z_r$, \quad $\sigma_T^t = \sigma_L^t = \sigma_y$ \quad (III.3.17)

for $z_r \leq z \leq (z_r + z_o)$ \quad $\sigma_T^t = \sigma_L^t = \sigma_y \left( \frac{z_r + z_o - z}{z_o} \right)$ \quad (III.3.18)

for $z \geq (z_r + z_o)$, \quad $\sigma_T^t = \sigma_L^t = 0$ \quad (III.3.19)

where $z$ is measured from the face of the component from which the repair was made.

The residual distributions for repair welds are derived from measurements on ferritic steels and therefore may not be applicable to austenitic steels.

### III.3.4.9 Post-Weld Heat Treatment (PWHT)

The effectiveness of PWHT on the relief of welding residual stress depends on:-

- Geometry of component
- Thickness
- Steel and weld metal properties
- PWHT temperature
- Time at temperature
- Whether treatment is local or global
- Restraint of component

Invariably, PWHT does not reduce the welding residual stress to zero, the exact value depending on the complex interactions of the above factors. Experimental and modelling work supports previous recommendations that the welding residual stress after PWHT should be taken as:

- 30% of yield stress of the material in which the flaw lies for longitudinal residual stress.
- 20% of the lesser of the yield strengths of the parent plate and weld metal for transverse residual stress.

Alternative values may be used where modelling or experimental work is available for such justification.
### Table III.3.1: Geometries and Relevant Figure Numbers for Residual Stress Profiles

<table>
<thead>
<tr>
<th>GEOMETRY DESCRIPTION</th>
<th>GEOMETRY</th>
<th>SURFACE RESIDUAL STRESS PROFILE</th>
<th>THROUGH-THICKNESS RESIDUAL STRESS PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Butt Welds and Pipe Axial Seam Welds</td>
<td>III.3.1 pt. 1</td>
<td>III.3.1 pt. 2</td>
<td>III.3.1 pt. 3</td>
</tr>
<tr>
<td>Plate T-Butt Welds</td>
<td>III.3.2 pt. 1</td>
<td>III.3.2 pt. 2</td>
<td>III.3.2 pt. 3</td>
</tr>
<tr>
<td>Pipe Butt Welds</td>
<td>III.3.3 pt. 1</td>
<td>III.3.3 pt. 2</td>
<td>III.3.3 pt. 3</td>
</tr>
<tr>
<td>Pipe T-Butt Welds</td>
<td>III.3.4 pt. 1</td>
<td>III.3.4 pt. 2</td>
<td>III.3.4 pt. 3</td>
</tr>
<tr>
<td>Set-in Nozzles</td>
<td>III.3.5 pt. 1</td>
<td>III.3.5 pt. 2</td>
<td>III.3.5 pt. 3</td>
</tr>
<tr>
<td>Set-on Nozzles</td>
<td>III.3.6 pt. 1</td>
<td>III.3.6 pt. 2</td>
<td>III.3.6 pt. 3</td>
</tr>
<tr>
<td>Repair Welds</td>
<td>III.3.7 pt. 1</td>
<td>III.3.7 pt. 2</td>
<td>III.3.7 pt. 3</td>
</tr>
</tbody>
</table>

### Table III.3.2: Validity Ranges for Profiles

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>THICKNESS (mm)</th>
<th>PROOF STRESS (N/mm²)</th>
<th>HEAT INPUT (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Butt Welds</td>
<td>24 – 300</td>
<td>310 - 740</td>
<td>1.6 - 4.9</td>
</tr>
<tr>
<td>Pipe Circumferential Butt Welds</td>
<td>9 – 84</td>
<td>225 - 780</td>
<td>0.35 - 1.9</td>
</tr>
<tr>
<td>Pipe Axial Seam Welds</td>
<td>50 – 85</td>
<td>345 - 780</td>
<td>Not known</td>
</tr>
<tr>
<td>T-Butt Welds</td>
<td>25 – 100</td>
<td>375 - 420</td>
<td>1.4</td>
</tr>
<tr>
<td>Tubular and Pipe to Plate Joints</td>
<td>22 – 50</td>
<td>360 - 490</td>
<td>0.6 - 2.0</td>
</tr>
<tr>
<td>Repair Welds</td>
<td>75 – 152</td>
<td>500 - 590</td>
<td>1.2 - 1.6</td>
</tr>
<tr>
<td>PROPERTIES</td>
<td>FERRITIC STEELS</td>
<td>AUSTENITIC STAINLESS STEELS</td>
<td>ALUMINIUM ALLOYS</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------------</td>
<td>-----------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, $\alpha$, °C$^{-1}$</td>
<td>$12 \times 10^{-6}$</td>
<td>$16 \times 10^{-6}$</td>
<td>$24 \times 10^{-6}$</td>
</tr>
<tr>
<td>Young's modulus, $E$, N/mm$^2$</td>
<td>207,000</td>
<td>193,000</td>
<td>70,000</td>
</tr>
<tr>
<td>Volumetric specific heat, $\rho c$, Jmm$^3$/°C</td>
<td>0.0038</td>
<td>0.0036</td>
<td>0.0024</td>
</tr>
<tr>
<td>$K = 2\alpha E/(\pi \rho c)$, Nmm/J</td>
<td>153</td>
<td>201</td>
<td>164</td>
</tr>
<tr>
<td>$K \eta$, with $\eta = 0.8$</td>
<td>122</td>
<td>161</td>
<td>131</td>
</tr>
</tbody>
</table>

Table III.3.3: Typical Material Properties for use In Determining Dimensions of Yielded Zone
III.41

PLATE BUTT WELDS PIPE AND PIPE AXIAL SEAM WELDS
Material: Ferritic, Austenitic steels and Aluminium (only 1a)

1. Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, $\sigma^L_R$ (Fig. 1a)

For definitions of $r_0, y_0$, see Appendix 1

Fig. III.3.1a Plate Butt and Pipe Welds (Cont...)
2.2 Transverse Residual Stress, $\sigma_R^T$ (Fig 1 c)

\[
\begin{align*}
\text{Side 1: } W &= W1 \\
\text{Side 2: } W &= W2
\end{align*}
\]

unrestrained plates and pipe axial seam welds

\[
\begin{align*}
\sigma_y^* \\
t & B & W & C & t \\
2t & w & 2t
\end{align*}
\]

restrained plates

3. Through-thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress, $\sigma_R^L$ (Fig 1 b)

Distribution

Equations

FERROUS STEELS

$\sigma_R^L/\sigma_y W (z/t) = 1$

AUSTENITIC STEELS

$\sigma_R^L/\sigma_y W (z/t) = 0.95 + 1.50(z/t) - 8.287(z/t)^2 + 10.57(z/t)^3 - 4.08(z/t)^4$

3.2 Transverse Residual Stress, $\sigma_R^T$ (Fig 1 d)

Distribution

Equations

ALL STEELS

$\sigma_R^T/\sigma_y^* (z/t) = 1.0 + 0.917(z/t) - 1.533(z/t)^2 + 83.115(z/t)^3$

- 213.45(z/t)^4 + 264.16(z/t)^5 - 96.36(z/t)^6

$\sigma_y^* = \text{lower of } \{\sigma_y W, \sigma_y p\}$

Fig. III.3.1b Plate Butt and Pipe Welds (Continued)
PLATE T-BUTT WELDS
Material: Ferritic, Austenitic steels and Aluminium (only 2a))

1. Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, $\sigma_R^l$ (Fig. 2a)

Side 1: $w = w_1$
Side 2: $w = w_2$
Side 3: not applicable

a) Thick material ($r_0 \leq t$)

b) Thin material ($r_0 > t$)

(For definitions of $r_0, y_0$, see Appendix 1)
3. Through-thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress $\sigma_R^L$ (Fig. 2b)

3.2 Transverse Residual Stress $\sigma_R^T$ (Fig. 2d)

(for definitions of $r_0, y_0,$ see Appendix 1)

$\sigma y^* = \text{lower of } \{\sigma y_w, \sigma y_p\}$
PIPE BUTT WELDS
Material: Ferritic, Austenitic steels and Aluminium (only (3a))

1. Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, $\sigma_{RL}$ (fig 3a)
Distribution

Side 1: $W = W_1$
Side 2: $W = W_2$

(for definitions of $r_0, y_0$, see Appendix 1)

2.2 Transverse Residual Stress, $\sigma_{RT}$ (fig 3c)
Use uniform $\sigma_{RT} = \sigma_{g}^*$

$\sigma_{g}^* = \min(\sigma_{gW}, \sigma_{gP})$

Fig. III.3.3a  Pipe Butt Welds (Cont...)
3. Through Thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress, $\sigma^R_L$ (Fig. 3b)

Distributions

Equations

$$\sigma^L_B = Ab \sigma_{y,w}$$

Where:
- $Ab = 1$
- $Ab = 1 - 0.0143(t-15)$ for $0 < t \leq 15$ mm
- $Ab = 0$ for $15 < t \leq 85$ mm
- $t > 85$ mm

3.2 Transverse Residual Stress, $\sigma^R_T$ (Fig. 3d)

Distributions

Equations

**FERRITIC STEELS**

For Low heat inputs $(q/v)h < 60.1$ mm$^2$ and $\sigma_T^0 / \sigma_y^b = 0.5 - 0.0083(q/v)h$

$\sigma_T^0 = \sigma_T^0 (1.0 - 3.29(z/t) + 3.099(z/t)^2 + 4.9(z/t)^3 - 45.72(z/t)^4)$

For High heat inputs $(q/v)h > 60.1$ mm$^2$ and $\sigma_T^0 = -1.0$

$\sigma_T^0 = \sigma_T^0 \cos \left( \pi z/t \right)$; $z$ measured from outer surface

**AUSTENITIC STEELS**

$-7 \leq t < 25$ mm

$\sigma_T^0 = 1.219 \sigma_y^b \left( \frac{2z}{t} - 1 \right)$

$7 < t \leq 25$ mm

$\sigma_T^0 = (1.5884 - 0.05284 t) \sigma_y^b \left( \frac{2z}{t} - 1 \right)$

$t \geq 25$ mm

$\sigma_T^0 = \sigma_T^R \left[ 0.27 - 0.91(z/t) - 4.93(z/t)^2 + 8.60(z/t)^3 - 2.03(z/t)^4 \right]$ for definition of $\sigma_T^R$, see paragraph 5.3.2

For definition of $\sigma_T^R$, see paragraph 5.3.2.

$\sigma_T^0 = \text{lower of } (\sigma_{yw}, \sigma_{yp})$

**Fig. III.3.3b**

Pipe Butt Welds (Continued)
PIECE T-BUTT WELDS

Material: Ferritic, Austenitic steels (caution for (4b),(4c),(4d)) and Aluminium (only (4a))

1. Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, $\sigma_{R}^L$ (Fig 4a)

Distribution

For definitions of $r_0, y_0$, see Appendix 1

Fig. III.3.4a  Pipe T-Butt Welds (Cont...)

III.47
2.2 Transverse Residual Stress, $\sigma_R^T$ (Fig. 4c)

3. Through Thickness Profiles

3.1 Longitudinal Residual Stress, $\sigma_R^L$ (Fig. 4b)

Equations

**FERRITIC STEELS**

$$\frac{\sigma_R^L}{\sigma_{Yw}}(z/t) = 1.025 + 3.478(z/t) - 27.861(z/t)^2$$
$$+ 45.788(z/t)^3 - 21.8(z/t)^4$$

stress through thickness away from weld centre line

3.2 Transverse Residual Stress, $\sigma_R^T$ (Fig. 4d)

Equations

**FERRITIC STEELS**

$$\frac{\sigma_R^T}{\sigma_{Yw}^*}(z/t) = 0.97 + 2.327(z/t) - 24.125(z/t)^2$$
$$+ 42.485(z/t)^3 - 21.087(z/t)^4$$

$\sigma_{Yw}^*$ = lower of $\{\sigma_{Yw}, \sigma_{Yp}\}$

Fig. III.3.4b  Pipe T-Butt Welds (Continued)
SET IN NOZZLE

Material: Ferritic, Austenitic steels and Aluminium

1. Geometry

2. Surface Residual Stress Profiles

2.1. Longitudinal Residual Stress, $\sigma_R$ (Fig 5a)

Distribution

For definitions of $r_0, y_0$, see Appendix 1

Fig. III.3.5a  Set-In Nozzles (Cont...)
2.2 Transverse Residual Stress, $\sigma_R^T$ (Fig. 5c)

Use uniform $\sigma_R^T = \sigma y^*$

3. Through Thickness Profiles

3.1 Longitudinal Residual Stress, $\sigma_R^L$ (Fig. 5b)

Distribution

3.2 Transverse Residual Stress, $\sigma_R^T$ (Fig. 5d)

Distribution

$\sigma y^* = \text{lower of } \{\sigma y_W, \sigma y_p\}$

(For definitions of $r_0, y_0$, see Appendix 1)

Fig. III.3.5b  Set-In Nozzles (Continued)
3.5.1 

Fig. III.3.6a Set-On Nozzles (Cont...)
2.2 Transverse Residual Stress \((\text{fig } 6c)\)
Use uniforme \(\sigma_{R}^{T} = \sigma_{y}^{*}\)

3. Through Thickness Profiles

3.1 Longitudinal Residual Stress \(\sigma_{R}^{L} (\text{fig } 6b)\)
Distributon

3.2 Transverse Residual Stress \(\sigma_{R}^{T} (\text{fig } 6d)\)
Distributon

(For definitions of \(r_0, y_0\), see Appendix 1)

\(\sigma_{y}^{*} = \text{ lower of } (\sigma_{yw}, \sigma_{yp})\)

Fig. III.3.6b Set-On Nozzles (Continued)
REPAIR WELDS

Material: Ferritic austenitic steels and Aluminium (7a)
Ferritic steels (7b),(7c),(7d)

1. Geometry

2. Surface Residual Stress Profiles

2.1 Longitudinal Residual Stress, $\sigma_{R}^l$ (fig 7a) Distribution

Side 1: $W=W_1$
Side 2: $W=W_2$

a) Thick material ($r_0 \leq l$)
b) Thin material ($r_0 > l$)

(For definitions of $r_0$, $y_0$, see Appendix 1)
3. Through-thickness Residual Stress Profiles

3.1 Longitudinal Residual Stress (Fig 7b)

Equations

\[ \frac{\sigma_R^L}{\sigma_Y} (z/t) = 1.0 \text{ for } z < z_0 \text{ where } z_0 \text{ is the depth of the repair } \]

\[ \frac{\sigma_R^L}{\sigma_Y} (z/t) = (z_0 + z_T - 2)z_0 \text{ where } z_0 \text{ is given by } \]

\[ z_0 = \sqrt{122(q/v)\sigma_Y} \] (where \( q/v \) is in J/mm and \( \sigma_Y \) is in MPa)

for \( z > z_0 \), \( \sigma_R^L/\sigma_Y (z/t) = 0.0 \)

3.2 Transverse Residual Stress (Fig 7d)

Equations

\[ \frac{\sigma_R^T}{\sigma_Y} (z/t) = 1.0 \text{ for } z < z_T \text{ where } z_T \text{ is the depth of the repair } \]

\[ \frac{\sigma_R^T}{\sigma_Y} (z/t) = (z_0 + z_T - 2)z_0 \text{ where } z_0 \text{ is given by } \]

\[ z_0 = \sqrt{122(q/v)\sigma_Y} \] (where \( q/v \) is in J/mm and \( \sigma_Y \) is in MPa)

for \( z > z_0 \), \( \sigma_R^T/\sigma_Y (z/t) = 0.0 \)

\[ \sigma_Y^{T} \text{ = greater of } (\text{original or repair weld yield stress}) \]

Fig. III.3.7b Repair Welds (Continued)
<table>
<thead>
<tr>
<th>JOINT GEOMETRY</th>
<th>LONGITUDINAL SURFACE RESIDUAL STRESS PROFILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLATE BUTT WELDS AND PIPE SEAM WELDS</td>
<td>Max of $\sigma_{yw}$ or $\sigma_{yp}$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>PLATE T-BUTT WELDS</td>
<td>$\sigma_{y+}$</td>
</tr>
<tr>
<td></td>
<td>$x=2b+w$</td>
</tr>
<tr>
<td></td>
<td>where $b=T/2+(0.0082(q/v)/(T+2t))$</td>
</tr>
<tr>
<td></td>
<td>$(q/v)$ in J/mm, $T,t,x,w$ in mm</td>
</tr>
<tr>
<td>PIPE BUTT WELDS</td>
<td>Max of $\sigma_{yw}$ or $\sigma_{yp}$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>PIPE T-BUTT WELDS</td>
<td>$\sigma_{y+}$</td>
</tr>
<tr>
<td></td>
<td>$x=2b+w$</td>
</tr>
<tr>
<td></td>
<td>where $b=T/2+(0.0082(q/v)/(T+2t))$</td>
</tr>
<tr>
<td></td>
<td>$(q/v)$ in J/mm, $T,t,x,w$ in mm</td>
</tr>
<tr>
<td>REPAIR WELDS</td>
<td>$\sigma_{nL}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{y+}$</td>
</tr>
<tr>
<td></td>
<td>$w=width of repair weld$</td>
</tr>
</tbody>
</table>

Fig. III.3.8  Alternative Profiles for Longitudinal Surface Residual Stress
III.4 : COMPENDIUM OF EQUATIONS

III.4.1 LEVEL 0 : YIELD STRESS OR PROOF STRESS ONLY, HOMOGENEOUS MATERIAL

LEVEL 0A : Yield Point Elongation Expected:

\[ f(L_r) = \left[ 1 + \frac{L_r^2}{2} \right]^{\frac{1}{2}} \text{ for } 0 \leq L_r \leq 1 \tag{III.4.1} \]

LEVEL 0B : No Yield Point Elongation Expected:

\[ f(L_r) = \left[ 1 + \frac{L_r^2}{2} \right]^{\frac{1}{2}} \left[ 0.3 + 0.7 \exp(-0.6L_r^6) \right] \tag{III.4.2} \]

\[ L_r^{\text{max}} = 1 + \left( \frac{150}{R_{p0.2}} \right)^{2.5} \tag{III.4.3} \]

III.4.2 LEVEL 1 : YIELD STRESS OR PROOF STRESS AND ULTIMATE TENSILE STRESS, HOMOGENEOUS MATERIAL

LEVEL 1A : Yield Point Elongation Expected:

\[ f(L_r) = \left[ 1 + \frac{L_r^2}{2} \right]^{\frac{1}{2}} \text{ for } L_r < 1 \tag{III.4.4} \]

\[ f(1) = \left[ \lambda + \frac{1}{2\lambda} \right]^{\frac{1}{2}} \tag{III.4.5} \]

where \( \lambda = 1 + \frac{E\Delta\varepsilon}{R_{el}} \tag{III.4.6} \)

\[ \Delta\varepsilon = 0.0375 \left( 1 - \frac{R_{el}}{1000} \right) \tag{III.4.7} \]

\[ f(L_r) = f(1)L_r^{\frac{N-1}{2N}} \text{ for } 1 < L_r < L_r^{\text{max}} \tag{III.4.8} \]

where \( N = 0.3 \left( 1 - \frac{R_{el}}{R_m} \right) \tag{III.4.9} \)

and \( L_r^{\text{max}} = \frac{1}{2} \left( \frac{R_{el} + R_m}{R_{el}} \right) \tag{III.4.10} \)
LEVEL 1B : No Yield Point Elongation Expected:

\[ f(L_r) = \left[ 1 + \frac{1}{2} L_r^2 \right]^{1/2} \left[ 0.3 + 0.7 \exp(-\mu L_r^6) \right] \quad \text{for } L_r \leq 1 \]  

(III.4.11)

where \( \mu = \min \left[ 0, 0.001 \left( \frac{E}{R_p^{0.2}} \right) 0.6 \right] \) \( \text{(III.4.12)} \)

\[ f(L_r) = f(1) L_r \frac{N-1}{2N} \quad \text{for } 1 < L_r \leq L_r^{\text{max}} \]  

(III.4.13)

\[ N = 0.3 \left( 1 - \frac{R_p^{0.2}}{R_m} \right) \]  

(III.4.14)

where \( L_r^{\text{max}} = \frac{1}{2} \left( \frac{R_p^{0.2} + R_m}{R_p^{0.2}} \right) \) \( \text{(III.4.15)} \)

III.4.3 LEVEL 2 : YIELD STRESS OR PROOF STRESS AND ULTIMATE TENSILE STRESS, MIS-MATCH MATERIAL

LEVEL 2A : Both materials expected to have Yield Point Elongation:

\[ f(L_r) = \left[ 1 + \frac{L_r^2}{2} \right]^{1/2} \quad \text{for } L_r < 1 \]  

(III.4.16)

\[ f(1) = \left[ \lambda_M + \frac{1}{2\lambda_m} \right]^{1/2} \quad \text{for } L_r = 1 \]  

(III.4.17)

where

\[ \lambda_M = \frac{(F_{YM} / F_{YB} - 1)\lambda_B + (M - F_{YM} / F_{YB})\lambda_W}{(M - 1)} \]  

(III.4.18)

\[ \lambda_B = 1 + \frac{0.0375 E_B}{R_{el,B}} \left( 1 - \frac{R_{el,B}}{1000} \right) \]  

(III.4.19)

and

\[ \lambda_W = 1 + \frac{0.0375 E_W}{R_{el,W}} \left( 1 - \frac{R_{el,W}}{1000} \right) \]  

(III.4.20)

and sub-scripts ‘B’ and ‘W’ denote properties for Base Plate and Weld Metal respectively. \( M \) is the ratio of weld metal to Base Plate Yield Strengths and the corresponding \( F_{YM}/F_{YB} \) is evaluated at \( M \).

\[ f(L_r) = f(1)(L_r)^{(N_M-1)/2N_M} \quad \text{for } 1 < L_r \leq L_r^{\text{max}} \]  

(III.4.21)

where \( L_r^{\text{max}} = \frac{1}{2} \left( 1 + \frac{0.3}{0.3 - N_M} \right) \) \( \text{(III.4.22)} \)
and \[ N_M = \frac{(M - 1)}{\left( \frac{F_{YM}}{F_{YB}} \right) / N_W + \left( \frac{M - F_{YM}}{F_{YB}} \right) / N_B} \] (III.4.23)

with \[ N_B = 0.3 \left( 1 - \frac{R_{el,B}}{R_{m,B}} \right) \] (III.4.24)

\[ N_W = 0.3 \left( 1 - \frac{R_{el,W}}{R_{m,W}} \right) \] (III.4.25)

LEVEL 2B : Neither material expected to have Yield Point Elongation:
\[ f(L_r) = \left[ 1 + \frac{1}{2} L_r^2 \right]^{\frac{1}{2}} \left[ 0.3 + 0.7 \exp(-\mu_M L_r^5) \right] \] for \( L_r \leq 1 \) (III.4.26)

with \[ \mu_M = \frac{(M - 1)}{\left( \frac{F_{YM}}{F_{YB}} \right) / \mu_W + \left( \frac{M - F_{YM}}{F_{YB}} \right) / \mu_B} \] (III.4.27)

\[ \mu_B = 0.001 \frac{E_B}{R_{p0.2,B}} \] (III.4.28)

\[ \mu_W = 0.001 \frac{E_W}{R_{p0.2,W}} \] (III.4.29)

where \( \mu_M, \mu_B \) and \( \mu_W \) have maxima of 0.6.

\[ f(L_r) = f(1)\left(L_r\right)^{(N_M-1)/2N_M} \] (for \( 1 < L_r \leq L_r^{\text{max}} \)) (III.4.30)

where \[ L_r^{\text{max}} = \frac{1}{2} \left( 1 + \frac{0.3}{0.3 - N_M} \right) \] (III.4.31)

and \[ N_M = \frac{(M - 1)}{\left( \frac{F_{YM}}{F_{YB}} \right) / N_W + \left( \frac{M - F_{YM}}{F_{YB}} \right) / N_B} \] (III.4.32)

with \[ N_B = 0.3 \left( 1 - \frac{R_{p0.2,B}}{R_{m,B}} \right) \] (III.4.33)

\[ N_W = 0.3 \left( 1 - \frac{R_{p0.2,W}}{R_{m,W}} \right) \] (III.4.34)

LEVEL 2C : Base material or weld metal expected to have Yield Point Elongation:
\[ f(L_r) = \left[ 1 + \frac{1}{2} L_r^2 \right]^{\frac{1}{2}} \left[ 0.3 + 0.7 \exp(-\mu_M L_r^5) \right] \] for \( L_r \leq 1 \) (III.4.35)

where, for the case of a weld metal which does not exhibit a Yield Plateau:
\[ \mu_M = \frac{(M - 1)}{\left( \frac{F_{YM}}{F_{YB}} \right) / \mu_W} \] (III.4.36)
with \( \mu_W = 0.001 \frac{E_W}{R_{p0.2,W}} \) \hspace{1cm} (III.4.37)

\[ K_r = \left( \frac{1}{2} \frac{\lambda_M}{\lambda_M} \right)^{\frac{1}{2}} \text{ for } L_r = 1 \] \hspace{1cm} (III.4.38)

where \( \lambda_M = \frac{(M - F_{YM} / F_{YB}) \lambda_B}{(M - 1)} \) \hspace{1cm} (III.4.39)

and \( \lambda_B = 1 + 0.0375 E_B \left( 1 - \frac{R_{el,B}}{1000} \right) \) \hspace{1cm} (III.4.40)

Equations III.4.36-III.4.40 are presented above for the case of a weld metal which does not exhibit a yield plateau. For the case a base material which does not exhibit a yield plateau, these equations should be expressed in terms of base material properties.

\[ f(L_r) = f(1)(L_r)^{(N_M - 1)/2N_M} \quad \text{(for } 1 < L_r \leq L_r^{\text{max}}) \] \hspace{1cm} (III.4.41)

where \( L_r^{\text{max}} = \frac{1}{2} \left( 1 + \frac{0.3}{0.3 - N_M} \right) \) \hspace{1cm} (III.4.42)

and \( N_M = \frac{(M - 1)}{(F_{YM} / F_{YB} - 1)/N_B + (M - F_{YM} / F_{YB})/N_B} \) \hspace{1cm} (III.4.43)

with \( N_B = 0.3 \left( 1 - \frac{R_{el,B}}{R_{m,B}} \right) \) \hspace{1cm} (III.4.44)

\[ N_W = 0.3 \left( 1 - \frac{R_{p0.2,W}}{R_{m,W}} \right) \] \hspace{1cm} (III.4.45)

### III.4 LEVEL 3 : FULL STRESS-STRAIN CURVE AVAILABLE

**LEVEL 3A: Homogeneous material case:**

\[ f(L_r) = \left[ \frac{E_{ref}}{\sigma_{ref}} + \frac{1}{2} \left( \frac{L_r^2}{E_{ref}/\sigma_{ref}} \right) \right]^{\frac{1}{2}} \quad \text{for } 0 \leq L_r \leq L_r^{\text{max}} \] \hspace{1cm} (III.4.46)

where \( \varepsilon_{ref} \) is the true strain obtained from the tensile test at a true stress of \( \sigma_{ref} = L_rR_e \), where \( R_e \) is \( R_{el} \) or \( R_{p0.2} \) as appropriate, and:

\[ L_r^{\text{max}} = \frac{1}{2} \left( \frac{R_e + R_m}{R_e} \right) \] \hspace{1cm} (III.4.47)
LEVEL 3B: Mis-Match case:

\[
f(L_r) = \left[ \frac{E \varepsilon_{r, \text{ref}} + \frac{1}{2} \left( \frac{L_r^2}{E \varepsilon_{r, \text{ref}} / \sigma_{r, \text{ref}}} \right) \right]^{\frac{1}{2}} \text{ for } 0 \leq L_r \leq L_r^{\text{max}} \tag{III.4.48}\]

where sub-script 'e' denotes 'equivalent material' and \( \varepsilon_{r, \text{ref}} \) is the true strain obtained from the 'equivalent material' tensile test at a true stress of \( \sigma_{r, \text{ref}} = L_r R_{\text{e,e}} \).

The stress-strain curve for the equivalent material is given by:

\[
\sigma_{r}(\varepsilon^p) = \left( \frac{F_{YM}}{F_{YB}} - 1 \right) \sigma_w(\varepsilon^p) + \left( M - \frac{F_{YM}}{F_{YB}} \right) \sigma_{e,b}(\varepsilon^p) \tag{III.4.49}\]

where \( F_{YM}/F_{YB} \) is defined for:

\[
M = M(\varepsilon^p) = \frac{R_{w}(\varepsilon^p)}{R_{b}(\varepsilon^p)} \text{ at a number of plastic strain values } \varepsilon^p.
\]

\( L_r^{\text{max}} \) is defined by the equivalent yield stress \( \sigma_{Y,e} \) and the equivalent flow stress \( \bar{\sigma}_e \) as:

\[
L_r^{\text{max}} = \bar{\sigma}_e / \sigma_{Y,e} \tag{III.4.50}\]

where \( \bar{\sigma}_e = \left[ F_{YM}(\bar{\varepsilon}^p) / F_{YB}(\bar{\varepsilon}^p) \right] \sigma_{f,b}(\varepsilon^p) \); \( \sigma_{Y,e} = \left[ F_{YM} / F_{YB} \right] \sigma_{Y,B} \tag{III.4.51} \)

### III.4.5 LEVEL 5: FULL STRESS-STRAIN CURVE AND J-SOLUTION AVAILABLE

\[
K_r = \left( \frac{J}{J_e} \right)^{\frac{1}{2}} \text{ for } 0 \leq L_r \leq L_r^{\text{max}} \tag{III.4.52}\]

where, for homogeneous cases,

\[
L_r^{\text{max}} = \frac{1}{2} \left( \frac{R_e + R_m}{R_e} \right) \tag{III.4.53}\]

and for Mis-Match cases,

\[
L_r^{\text{max}} = \bar{\sigma}_e / \sigma_{Y,e} \tag{III.4.54}\]

and \( \bar{\sigma}_e = \left[ F_{YM}(\bar{\varepsilon}^p) / F_{YB}(\bar{\varepsilon}^p) \right] \sigma_{f,b}(\varepsilon^p) \); \( \sigma_{Y,e} = \left[ F_{YM} / F_{YB} \right] \sigma_{Y,B} \tag{III.4.55} \)
CHAPTER IV: ALTERNATIVES & ADDITIONS TO STANDARD METHODS

IV.1 DEFAULT PROCEDURE

IV.1.1 APPLICATION

The default, level zero, procedure is used for cases where the knowledge of material properties is very limited. As a minimum, it requires knowledge of the yield stress (or 0.2% proof stress) and the Charpy behaviour of the material. This level is principally applicable to homogeneous cases, where the level of weld strength mismatch is less than 10%. It can be applied to cases where the mismatch level is higher than this provided that the tensile properties of the weakest constituent of the joint are taken, and in such cases the results will be conservative. The method relies on the estimation of other properties from empirical correlations and the results will usually be conservative.

The steps involved in the application of this method to determine the significance of a postulated or existing defect are:

- Establish tensile properties.
- Determine characteristic toughness from either a small fracture toughness data set or Charpy impact energy data.
- Determine $f(L_r)$; the shape of the FAD.
- Characterise the crack, (Section II.3).
- Determine the loads and stresses, (Section II.4).
- Analyse by FAD.
- Assess the result.

IV.1.2 TENSILE PROPERTIES

IV.1.2.1 Determination of Type of Stress-Strain Curve

The yield stress is usually obtained from design information, such as the grade of material used, test certificates or knowledge of the material specification in use at the time of the design. The first step involved in analysis of such data is to determine whether or not a yield plateau is likely to be present for the particular grade of steel. This decision is necessary since the description of the FAD for materials showing discontinuous (yield plateau) behaviour is quite different to those for materials demonstrating continuous yielding characteristics. Whether or not a yield plateau should be assumed depends on yield stress, composition and process route; these factors can be grouped roughly according to standard specifications. Table II.1.1 provides guidance for making this decision. It should be recognised that this approach is a generalisation as the presence of a yield point is affected by test method as much as material type. In particular, loading rate and specimen design can greatly influence the propensity for a yield point.
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

For those materials which are assumed to show discontinuous behaviour, the value of yield stress can either be an upper or lower yield stress.

IV.1.2.2 Estimation of Lower Yield Stress

Where it is known that the value is a lower yield stress ($R_{el}$) or a proof stress ($R_{p0.2}$), these values can be used as the characteristic value of yield stress. Where it is not known whether the value is an upper ($R_{uh}$) or lower yield stress, the value should be considered as the upper and so be factored according to equation IV.1.1 to ensure that it represents the $R_{el}$ value.

$$R_{el} = 0.95 R_{el}$$  \hspace{1cm} (IV.1.1)

IV.1.2.3 Estimation of Ultimate Tensile Stress

The ultimate tensile stress, $R_m$, can be estimated from the lower yield stress ($R_{el}$) or 0.2% proof stress ($R_{p0.2}$) by a conservative relationship between yield/tensile stress ratio and yield stress:

$$R_m = R_{p0.2} \left[ 1 + 2 \left( \frac{150}{R_{p0.2}} \right)^{2.5} \right]$$  \hspace{1cm} (IV.1.2)

where for discontinuous yielding, $R_{p0.2}$ is replaced by $R_{el}$.

IV.1.3 DETERMINATION OF FRACTURE TOUGHNESS FOR USE AT DEFAULT LEVEL

IV.1.3.1 Introduction

In an ideal situation, fracture toughness data for use in structural integrity assessments are generated through the use of appropriate fracture mechanics-based toughness tests. Where more than three values of fracture toughness are available the method described in II.2 can be applied. Where only three values are available, the lowest value should be used; however, if the failure mode is not the same in all three specimens, if the minimum value is less than 70% of the average, or when the maximum is greater than 1.4 times the average, there is a need for more data. CTOD data should be converted to equivalent $K_{mat}$ values using the guidance in II.2.

In reality, such data are often not available and cannot be easily obtained due to lack of material or the impracticability of removing material from the actual structure. In such circumstances, and in the absence of appropriate historical data, the use of correlations between Charpy impact energy and fracture toughness can provide the fracture toughness value to be used in the assessment.

Three basic correlation approaches are described here.

One expression is given for a lower bound estimation of lower shelf fracture toughness based on the Master Curve.
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

One expression is given which is applicable to lower shelf and transition behaviour but with the potential to account for thickness and selection of appropriate probability levels, also based on the Master Curve. One correlation is given which enables the user to estimate the R-curve from upper shelf energy, or a fracture toughness corresponding to a specific amount of ductile tearing.

A flowchart summarising the decision steps involved in selecting and using the appropriate correlation is given in Fig. IV.1.1.

IV.1.3.2 Lower Bound Expression for Lower Shelf Behaviour

A lower bound correlation applicable to a wide range of steels is given by:

\[
K_{\text{mat}} = \left[ 12 \sqrt{C_V} - 20 \left( \frac{25}{B} \right)^{0.25} \right] + 20 \quad (\text{IV.1.3})
\]

where \( K_{\text{mat}} \) is the estimated K-based fracture toughness of the material in MPa√m, \( C_V \) the Charpy impact energy (V-notch) in J (minimum of three tests) and \( B \) is the thickness for through-thickness cracks and equal to the crack length for surface and embedded cracks (in mm) up to a maximum of twice the section thickness.

IV.1.3.3 The Master Curve Approach for Transition Behaviour

The so-called 'Master Curve Approach' is based on correlation between a specific Charpy transition temperature (\( T_{27J} \)) and a specific fracture toughness transition temperature (\( T_{100\text{MPa}/\sqrt{m}} \)). The relationship is then modified to account for:

- Thickness effect
- Scatter
- Shape of fracture toughness transition curve
- Required probability of failure

\( T_{28J} \) is considered in the context of this procedure to be equivalent to \( T_{27J} \), a value often referred to in Steel Specifications.

The fracture toughness transition curve can be described for brittle fracture as a function of \( T_{27J} \) as follows:

\[
K_{\text{mat}} = 20 + \left\{ 11 + 77 \exp \left\{ 0.019 \left[ T - T_{27J} - 3^\circ C \right] \right\} \right\} \quad (\text{IV.1.4})
\]

\( T \) = design temperature (°C)
\( T_{27J} \) = 27 J Charpy transition temperature (°C)
\( B \) = specimen thickness (mm)*
\( P_f \) = probability of failure (e.g. 5%, 50%, or 95%)

* The definition of \( B \) is subject to the same limitations as given in IV.1.3.2.

IV.1.3.4 Estimation of Charpy 27J Temperature from Other Temperatures

When the temperature corresponding to the 27 J Charpy transition temperature is not known, this can be estimated by extrapolation from Charpy impact energy.
values at other temperatures. However, because of the range of shapes of Charpy transition curves only extrapolation over a limited Charpy energy range is permitted. The recommended values for extrapolation are given in Table IV.1.1. The recommended limits to extrapolation to determine \( T_{27J} \) are \( \pm 30^\circ C \). These limits should be strictly adhered to. This approach should be used with caution for modern low-C, low-S steels which can have steeper transition curves than that suggested in Table IV.1.1. In such cases the 27 J temperature estimated from higher temperatures can be predicted unconservatively. This estimation procedure is only suitable for data measured in full size Charpy specimens.

**IV.1.3.5 Charpy Upper Shelf Behaviour**

When the Charpy test exhibits a fracture appearance of 100% shear, upper shelf behaviour is present. However, this does not implicitly mean that the structure itself will be operating on the upper shelf at the same temperature. In particular, for thick sections and for some low carbon and low sulphur steels, the full thickness material may exhibit transitional behaviour at temperatures corresponding to Charpy upper shelf behaviour.

Where such a phenomenon cannot be excluded, the material must be assessed in terms of the Charpy 27 J temperature in accordance with the method described in IV.1.3.2. If brittle behaviour for the section thickness and temperature corresponding to the design condition can be excluded, the \( K_{mat} \) fracture toughness corresponding to a ductile crack extension of 0.2 mm, \( K_{J0.2} \), (taken as the onset of stable ductile tearing), can be evaluated from:

\[
K_{J0.2} = \sqrt{\frac{E \left(0.53C_{Vus}^{1.28} \left(0.2^{0.133C_{Vus}^{0.256}}\right)\right)}{1000(1-\nu^2)}}
\]  

(IV.1.5)

where \( K_{J0.2} \) is in MPa\( \sqrt{m} \), \( C_{Vus} \) is the Charpy upper shelf energy in Joules, \( E \) is Young’s Modulus and \( \nu \) is Poisson’s Ratio.

\( K_{mat} \) values corresponding to other amounts of ductile crack extension can be evaluated by substituting specific crack extension values, in mm, in place of 0.2 in expression IV.1.5.

**IV.1.3.6 Treatment of Sub-Size Charpy Data**

When component thickness is less than 10 mm, sub-size Charpy specimens are used. In order to use the correlations described previously, however, the shift in transition temperature associated with the reduced thickness of the Charpy specimen must be allowed for. For a standard 10 mm square Charpy specimen 28 J corresponds to 35 J/cm\(^2\). The shift in this transition temperature associated with sub-size specimens, \( \Delta T_{ss} \), is given by:

\[
\Delta T_{ss} = 51.4 \ln \left(2 \left(\frac{B}{10}\right)^{0.25} - 1\right)
\]

(IV.1.6)

Where \( B \) is the thickness of the sub-size Charpy specimen.
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

Relationships for the effect of specimen thickness on upper shelf behaviour are not available but in general the effect is the reverse of that demonstrated on the lower shelf.

**IV.1.3.7 Other Guidance/Limitations**

Effects associated with weld strength mismatch are not incorporated in this level.

Where correlations between Charpy energy and fracture toughness are made for weld metal and HAZ microstructures, the Charpy specimen should sample the most brittle microstructure.

**IV.1.4 DETERMINATION OF FAILURE ASSESSMENT DIAGRAM**

(a) For materials which display or may be expected to display a lower yield plateau, $f(L_r)$ is given by equation IV.1.7, for all values of $L_r \leq 1.0$.

$$f(L_r) = [1+0.5(L_r)^2]^{-\frac{1}{2}}$$  \hspace{1cm} (IV.1.7)

For $L_r > 1.0$, $f(L_r) = 0$

(b) For materials which do not display a lower yield plateau, $f(L_r)$ is given by equation IV.1.8 for all values of $L_r \leq L_r^{\text{max}}$, where $L_r^{\text{max}} = 1+ (150/R_p)^{2.5}$ and $R_p$ is the material's proof stress in MPa.

$$f(L_r) = (1+0.5L_r^2)^{-\frac{1}{2}}[0.3+0.7 \exp (-0.6L_r^6)]$$  \hspace{1cm} (IV.1.8)

For $L_r > L_r^{\text{max}}$, $f(L_r) = 0$

Where $L_r$ and $K_r$ are described in more detail in III.2

**IV.1.5 FLAW CHARACTERISATION**

This is determined by the shape and size of the defect and the geometry of the structure, as defined in II.3.

**IV.1.6 DETERMINATION OF LOADS AND STRESSES**

These must be classified into primary and secondary stresses. Secondary stresses do not affect the failure of the structure under plastic collapse conditions, and all other stresses are primary. All forms of loading must be considered, including thermal loading and residual stresses due to welding, and fault and accidental loads. Guidance for stress characterisation is given in II.4 and profiles for welding residual stress in III.4.

As a conservative estimate of welding residual stress, the following can be assumed in place of the more accurate, but more complex, profiles of Section III.4.
Weld Condition | Plane of Flaw | Assumed Residual Stress Level
--- | --- | ---
As-Welded | Transverse to welding direction | Yield strength of material in which flaw lies.
As-Welded | Parallel to welding direction | Lower of weld metal or parent plate yield stress.
PWHT | Transverse to welding direction | 30% of yield strength of material in which flaw lies.
PWHT | Parallel to welding direction | 20% of the lesser of the yield strengths of parent plate and weld.

Once loads and stresses have been determined, the values of $L_r = \sigma_{net}/R_e$, and $K_r = K/K_{mat}$ for the structure being assessed can be obtained. For this, guidance on appropriate limit load and stress intensity factor solutions is given in Section III.2.

**IV.1.7 ASSESSMENT OF RESULTS**

The result must be assessed in terms of the reliability required taking into account the uncertainties in the input data (I.3).

If the result is acceptable the analysis can be concluded and reported as appropriate (I.5).

**IV.1.8 UNACCEPTABLE RESULT**

If the result is unacceptable, it may be possible to proceed to a higher level of analysis, following the guidelines to determine how best to proceed (III.1).

(a) If $K_r/L_r > 1.1$, the result will be unaffected by refinements in the tensile data. In this case, the result can only be made acceptable if $K_r$ can be reduced by increasing the value of the fracture toughness used in the analysis. II.2 gives guidelines on how this may be achieved by moving to a higher level $K$ analysis.

(b) If $K_r/L_r < 0.4$, the result will be unaffected by refinements in the fracture toughness data. In this case, the result can only be made acceptable by refining the tensile data thus changing the form of $f(L_r)$. II.1 and III.4 give the equations for $f(L_r)$ which depend upon the detail of the available tensile data. The analysis should then be repeated from the beginning using the refined values for the tensile data as appropriate at each step.

(c) If $1.1 > K_r/L_r > 0.4$, the result can be affected by refinements in either or both fracture toughness data and tensile data, following the guidelines given in steps (a) and (b) above.
### CHAPTER IV: ALTERNATIVES & ADDITIONS TO STANDARD METHODS

#### TABLE IV.1.1: INFERRED CHARPY VALUES FROM TEMPERATURES ABOVE AND BELOW $T_{27J}$

<table>
<thead>
<tr>
<th>Difference Between Assessment Temperature and 27 J Charpy Transition Temperature (°C)</th>
<th>Assumed Charpy Impact Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>5</td>
</tr>
<tr>
<td>-20</td>
<td>10</td>
</tr>
<tr>
<td>-10</td>
<td>18</td>
</tr>
<tr>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>41</td>
</tr>
<tr>
<td>20</td>
<td>61</td>
</tr>
<tr>
<td>30</td>
<td>81</td>
</tr>
</tbody>
</table>

Note:
1. Interpolation between temperatures is permissible.
2. Extrapolations from temperatures greater than 40°C above the 27 J temperature is not permitted.

**Example**: 51 J measured at $T = -20°C$. For this value, interpretation of data in above table gives a difference between assessment temperature, $T$, and $T_{27J}$ of 15°C, hence $T - T_{27J} = 15°C$ and $T_{27J} = -(15-(-20)) = -35°C$. 
Fig. IV.1.1 Selection and Use of Appropriate Correlation for Estimating Fracture Toughness from Charpy Impact Energy
SECTION IV.2: PROCEDURES FOR PERFORMING A DUCTILE TEARING ANALYSIS

These procedures replace steps 3, and 6, in I.4.2.2, and are to be used for performing an analysis when the fracture toughness is defined as a function of the amount of ductile tearing (See II.2.4). This form of analysis takes account of the increase in toughness as the crack extends by ductile tearing and it may be applied regardless of the analysis level determined by the tensile data.

IV.2.1 FAD Analysis

1. Replacement for step 3 in I.4.2.2: Determine characteristic value of Fracture Toughness.

   In this case, the characteristic value of the fracture toughness is expressed as an increasing function of crack extension, $\Delta a$, as

   $$ K_{mat} = K_{mat}(\Delta a) $$

   $K_{mat}$ should be evaluated at the initiation of cracking (as determined following II.2.3.2) and at small increments of crack growth, typically 1 or 2 mm in extent. The choice of characteristic values should take account of the validity of the tests in terms of $J$-controlled growth and other factors (See II.2.4, I.3.3.3 and I.3.3.2.2).

2. Replacement for steps 2, 3, 4 and 5 in I.4.2.2.1(a): Analysis Procedures for FAD

   1. Calculate $L_r(\Delta a) = L_r(a_0 + \Delta a_1 + \Delta a_2 + \ldots \Delta a_i \ldots)$ for the loading on the structure where $a_0$ is the initial flaw size characterised following the procedures of II.3 and $\Delta a_i$ etc, are the small increments of postulated crack extension, corresponding to the crack extension values used to characterise $K_{mat}$ (step 1 above).

   2. Calculate $K_r(\Delta a)$ for the loading on the structure (see II.4.3)

      $$ K_r(\Delta a) = K_r^p(a_0, \Delta a)/K_{mat}(a_0, \Delta a) + K_r^s(a_0, \Delta a)/K_{mat}(a_0, \Delta a) + \rho(a_0, \Delta a) $$

      where $a_0$ is the initial flaw size and $\Delta a$ is for the small increments of postulated crack extension in $K_{mat}$.

   3. With co-ordinates $\{L_r(\Delta a), K_r(\Delta a)\}$ plot a locus of Assessment Points on the FAD.

   4. If any part of this locus lies within the assessment line the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed. If the locus only touches the assessment line at one point, or lies wholly outside of it, the structure has been shown to be unacceptable in terms of these limiting conditions.

3. Return to Step 7 in I.4.2.2; Assessment of Results.

   When assessing the results note that reserve factors depend on the amount of postulated crack extension, $\Delta a$: e.g., $F^L = F^L(\Delta a)$ (See also I.3.2.3).
IV.2.2 CDF(J) Analysis

1 Replacement for step 3, section I.4.2.2: Determine characteristic value of Fracture Toughness

In this case, the fracture toughness is expressed as an increasing function of crack extension, \( \Delta a \), as

\[
J_{\text{mat}} = J_{\text{mat}} (\Delta a)
\]

\( J_{\text{mat}} \) should be evaluated at the initiation of cracking (as determined following II.2.3.2) and at small increments of crack growth, typically 1 or 2 mm in extent. The choice of characteristic values should take account of the validity of the tests in terms of \( J \)-controlled growth and other factors (See II.2.4, I.3.3.3 and I.3.3.2.2).

2 Replacement for steps 1, 2, 3, 4 and 5 in I.4.2.2.1(b): Analysis Procedures for CDF using \( J \)

1. Calculate \( J_e \) as a function of the applied loads on the structure at the initial flaw size of interest, \( a_0 \), where \( J_e(a_0) = K(a_0)^2/E' \), taking into account all primary and secondary loads (II.4 and III.2). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, \( \rho(a_0) \) (II.4).

2. Plot the CDF(\( J \)) using the appropriate expression for \( f(L_r) \) (step 2 in I.4.2.2) where the CDF(\( J \)) is a plot of \( J = J_e(f(L_r)) - \rho \int J^2 \) on \( L_r \) and \( J \) axes for values of \( L_r \leq L_r^{\text{max}} \) (step 2 in I.4.2.2). Draw a vertical line at \( L_r = L_r^{\text{max}} \).

3. Calculate \( L_r \) for the loading on the structure at the flaw size of interest (II.4 and III.2), and draw a vertical line at this value to intersect the CDF(\( J \)) curve at \( J = J_{\text{str}}(a_0) \).

4. Repeat the above steps 1, 2 and 3 for a series of different flaw sizes above and below the initial flaw size of interest, \( a_0 \), to give a range of values of \( J_{\text{str}} \) as a function of flaw size.

5. On axes of \( J \) versus flaw size, \( a \), plot the CDF(\( J \)) as a function of flaw size where the CDF(\( J \)) is given by the values \( J = J_{\text{str}}(a) \) obtained from steps 3 and 4 above. Terminate this curve at any point where \( L_r = L_r^{\text{max}} \).

6. Plot \( J_{\text{mat}}(\Delta a) \) on this diagram, originating from \( a_0 \), the initial flaw size of interest.

7. If the CDF(\( J \)) intersects the \( J_{\text{mat}}(\Delta a) \) curve the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed. If this curve only touches the \( J_{\text{mat}}(\Delta a) \) curve, or lies wholly above it, the analysis has shown that the structure is unacceptable in terms of these limiting conditions.

3 Return to Step 7 in I.4.2.2; Assessment of Results.

Note that when assessing reserve factors on load, a family of CDF(\( J \)) curves as a function of crack size calculated for different loads can be plotted (see for example Fig I.2.2 (b)). Also, when assessing reserve factors on crack size, the \( J_{\text{mat}}(\Delta a) \) curve
can be replotted at different postulated values of $a_0$ to find the limiting condition (where $CDF(J)$ and $J_{mat}(\Delta a)$ meet at a point, See I.3.3.2.2).

### IV.2.3. CDF($\delta$) Analysis

1. **Replacement for step 3, section I.4.2.2: Determine characteristic value of Fracture Toughness**

In this case, the fracture toughness is expressed as an increasing function of crack extension, $\Delta a$, as

$$\delta_{mat} = \delta_{mat}(\Delta a)$$

$\delta_{mat}$ should be evaluated at the initiation of cracking (as determined following II.2.3.2) and at small increments of crack growth, typically 1 or 2 mm in extent. The choice of characteristic values should take account of the validity of the tests in terms of $J$-controlled growth and other factors (See II.2.4, I.3.3.3 and I.3.3.2.2).

2. **Replacement for steps 1, 2, 3, 4 and 5 in I.4.2.2.1(c): Analysis Procedures for CDF using $\delta$**

   1. Calculate $\delta_e$ as a function of the applied loads on the structure at the initial flaw size of interest, $a_0$, where $\delta_e(a_0) = K(a_0)^{2/E'}.R_\sigma$, taking into account all primary and secondary loads (II.4 and III.2). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, $\rho(a_0)$ (II.4).

   2. Plot the CDF($\delta$) using the appropriate expression for $f(L_r)$ (step 2 in I.4.2.2) where the CDF($\delta$) is a plot of $\delta = \delta_{eff}(L_r) \cdot f(L_r)$ on $\delta$ and $L_r$ axes for values of $L_r \leq L_r^{max}$ (step 2 in I.4.2.2). Draw a vertical line at $L_r = L_r^{max}$.

   3. Calculate $L_r$ for the loading on the structure at the flaw size of interest (II.4 and III.2), and draw a vertical line at this value to intersect the CDF($\delta$) curve at $\delta = \delta_{eff}(a_0)$.

   4. Repeat the above steps 1,2 and 3 for a series of different flaw sizes above and below the initial flaw size of interest, $a_0$, to give a range of values of $\delta_{eff}$ as a function of flaw size.

   5. On axes of $\delta$ versus flaw size, $a$, plot the CDF($\delta$) as a function of flaw size where the CDF($\delta$) is given by the values $\delta = \delta_{eff}(a)$ obtained from steps 3 and 4 above. Terminate this curve at any point where $L_r = L_r^{max}$.

   6. Plot $\delta_{mat}(\Delta a)$ on this diagram, originating from $a_0$, the initial flaw size of interest.

   7. If the CDF($\delta$) intersects the $\delta_{mat}(\Delta a)$ curve the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed. If this curve only touches the $\delta_{mat}(\Delta a)$ curve, or lies wholly above it, the analysis has shown that the structure is unacceptable in terms of these limiting conditions.
3 Return to Step 7 in I.4.2.2; Assessment of Results.

Note that when assessing reserve factors on load, a family of CDF(δ) curves as a function of crack size calculated for different loads can be plotted (see for example Fig I.2.2 (b)). Also, when assessing reserve factors on crack size, the δmat(∆a) curve can be replotted at different postulated values of a0 to find the limiting condition (where CDF(δ) and δmat(∆a) meet at a point, see I.3.3.2.2).
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

IV.3 RELIABILITY METHODS

IV.3.1 Introduction

The application of deterministic fracture mechanics assessment procedures to the prediction of fitness-for-purpose requires the use of data that are often subject to considerable uncertainty. The use of extreme bounding values for the relevant parameters can lead, in some circumstances, to unacceptably over-conservative predictions of structural integrity. An alternative approach is to use reliability methods to allow for the uncertainties in the parameters and to assess the probability of failure of structures containing flaws. It should be noted that the question of the required reliability or safety margin for a particular application depends on the consequences of the failure and requires an overall risk assessment to be carried out.

The procedures described in I.4 are, with the exception of the treatment of fracture toughness data, deterministic. The input data are treated as a set of fixed quantities and the result obtained is unique to these data. Different forms of a result can be obtained but in all cases a comparison of the result with a perceived critical state is performed. Since the perceived critical state is dependent on choice of analysis, and contains an inherent degree of conservatism, it is best regarded as a limiting condition rather than critical.

In this section, methods of probabilistic defect assessment are described which enable the probability of failure to be calculated for a given set of parameters and their corresponding statistical distribution. In addition, a method based on the use of recommended partial safety factors on input parameters for a range of target failure probabilities is presented. The methods described in this section are fully automated by means of the proSINTAP software; operating details for this are described in a separate users' document.\(^{(1)}\)

IV.3.2 Structure

The probabilistic procedure described here has been developed to calculate two different failure probabilities, \(P_f\):

(a) Probability of failure, defect size given by NDE.

(b) Probability of failure, defect not detected by NDE.

The procedure uses two different limit state functions, \(g(X)\):

\[
g_{R_6}(X) = g_{R_6}(K_{IC}, \sigma_y, a) = f_{R_6} - K_r \quad \text{(IV.3.1)}
\]

\[
g_{L_r}(\sigma_y, \sigma_U, a) = L_{max}^r - L_r \quad \text{(IV.3.2)}
\]

These limit state functions are based on the SINTAP 'Known YS - Known UTS' continuous yielding FAD only (Level 1). Then, to calculate the probability of failure, a multi-dimensional integral has to be evaluated:

\[
P_f = \Pr[g(X) < 0] = \int_{g(X)<0} f_x(x) dx \quad \text{(IV.3.3)}
\]

\(f_x(x)\) is a known joint probability density function of the random vector \(X\). This integral is very hard (impossible) to evaluate, by numerical integration, if there are many random parameters. As it most likely that probabilistic analyses will be made using the software proSINTAP; operating details for this are described in a separate users' document.
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

ProSINTAP, all subsequent approaches described here refer to this software. The methods included in ProSINTAP are therefore all numerical algorithms and incorporate:

(a) Simple Monte Carlo Simulation (MCS).
(b) First Order Reliability Method (FORM).

IV.3.3 Parameters

IV.3.3.1 General

Within the chosen procedure, the following parameters are treated as random parameters:

(a) Fracture Toughness
(b) Yield Strength
(c) Ultimate Tensile Strength
(d) Defect Size given by NDE
(e) Defect not detected by NDE
(f) Defect Distribution

These random parameters are treated as not being correlated with one another. The parameters can follow a normal, log-normal, Weibull or some special distributions (for the flaw size).

IV.3.3.2 Fracture Toughness

The fracture toughness can follow a normal, log-normal or Weibull distribution.

The normal probability density function has the following form:

\[
f(K_I) = \frac{1}{\sigma_{K_{IC}} \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{K_I - \mu_{K_{IC}}}{\sigma_{K_{IC}}} \right)^2 \right) \]  

(IV.3.4)

where \( \mu_{K_{IC}} \) (mean) and \( \sigma_{K_{IC}} \) (standard deviation) are input data to ProSINTAP.

The log-normal probability density function has the following form:

\[
f(K_I) = \frac{1}{K_I \sigma_{LogNor} \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left[ \ln(K_I) - \frac{\mu_{LogNor}}{\sigma_{LogNor}} \right]^2 \right) \]  

(IV.3.5)

where \( \mu_{LogNor} \) and \( \sigma_{LogNor} \) are the log-normal distribution parameters. \( \mu_{K_{IC}} \) (mean) and \( \sigma_{K_{IC}} \) (standard deviation) are input data to ProSINTAP and are related to the log-normal distribution parameters as follows:

\[\mu_{LogNor} = \ln(\mu_{K_{IC}}) - \frac{1}{2} \left( \sigma_{LogNor} \right)^2 \]  

(IV.3.6)


CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

\[ \sigma_{\text{LogNor}} = \sqrt{\ln \left[ 1 + \left( \frac{k_{IC}}{\mu_{IC}} \right)^{-1} \right]} \quad (IV.3.7) \]

The Weibull probability density function has the following form:

\[ f(K_I) = \frac{k}{\theta} \left( \frac{K_I}{\theta} \right)^{k-1} \exp \left\{ -\left( \frac{K_I}{\theta} \right)^k \right\} \quad (IV.3.8) \]

where \( \theta \) (scale) and \( k \) (shape) are the Weibull distribution parameters. \( \mu_{IC} \) (mean) and \( \sigma_{IC} \) (standard deviation) are input data to ProSINTAP and are related to the Weibull distribution parameters as follows:

\[ \mu_{IC} = \frac{\theta}{k} \Gamma\left(\frac{1}{k}\right) \quad (IV.3.9) \]

\[ \sigma_{IC} = \sqrt{\frac{\theta}{k} \left[ 2\Gamma\left(\frac{1}{k}\right) - \frac{1}{k} \Gamma\left(\frac{1}{k}\right)^2 \right]} \quad (IV.3.10) \]

where \( \Gamma(z) \) is the gamma function, defined by the integral:

\[ \Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt \quad (IV.3.11) \]

This non-linear system of equations are solved using a globally convergent method with line search and an approximate Jacobian matrix.

IV.3.3.3 Yield Strength and Ultimate Tensile Strength

The Yield strength and Ultimate tensile strength can follow a normal, log-normal or Weibull distribution. For information regarding input data and distribution parameter, see IV.3.3.2 above.

IV.3.3.4 Defect Size Given By NDE

The defect size given by NDE can follow a normal log-normal or exponential distribution. For information regarding input data and distribution parameters, using a normal or log-normal distribution, see Chapter IV.3.3.2 above.

The exponential probability density function has the following form:

\[ f(a) = \lambda \exp(-\lambda a) \quad (IV.3.12) \]

where \( \lambda \) is the exponential distribution parameter. \( \mu_a \) (mean) is input data to ProSINTAP (equal to the standard deviation, \( \sigma_a \), for this distribution) and is related to \( \lambda \) as follows:

\[ \mu_a = \sigma_a = \frac{1}{\lambda} \quad (IV.3.13) \]
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

IV.3.3.5 Defect Not Detected by NDE

The parameter defect not detected by NDE is treated as a deterministic parameter in the ProSINTAP software.

IV.3.3.6 Defect Distribution

The defects can follow a normal, log-normal, exponential or Marshall distribution. For information regarding input data and distribution parameters, see Chapters IV.3.3.2 and IV.3.3.4 above.

The Marshall distribution is a special case of a more general exponential probability density function. It has the following form:

\[ f(a) = 0.583 \cdot \exp(-0.16 \cdot a) \]  
(IV.3.14)

IV.3.4 Calculation of Failure Probabilities

IV.3.4.1 Simple Monte Carlo Simulation (MCS)

MCS is a simple method that uses the fact that the failure probability integral can be interpreted as a mean value in a stochastic experiment. An estimate is therefore given by averaging a suitably large number of independent outcomes (simulations) of this experiment.

The basic building block of this sampling is the generation of random numbers from a uniform distribution (between 0 and 1). A simple algorithm will repeat itself after approximately $2 \cdot 10^3$ to $2 \cdot 10^9$ simulations and is therefore not suitable to calculate medium to small failure probabilities. The algorithm chosen for ProSINTAP repeats itself after approximately $2 \cdot 10^{18}$ simulations (this algorithm is approximately 20 times slower than the simpler algorithms mentioned above, but it is recommended if one needs more than $1 \cdot 10^8$ simulations).

Once a random number, $u$, between 0 and 1, has been generated, it can be used to generate a value of the desired random variable with a given distribution. A common method is the inverse transform method. Using the cumulative distribution function $F_{X}(x)$, the random variable would then be given as:

\[ x = F_{X}^{-1}(u) \]  
(IV.3.15)

To calculate the failure probability, one performs $N$ deterministic simulations and for every simulation checks if the component analysed has failed (i.e. if $g(X) < 0$). The number of failures are $N_f$, and an estimate of the mean probability of failure is:

\[ P_{F,MCS} = \frac{N_f}{N} \]  
(IV.3.16)

An advantage with MCS, is that it is robust and easy to implement into a computer program, and for a sample size $N \to \infty$, the estimated probability converges to the exact result. Another advantage is that MCS works with any distribution of the random variables and there are no restrictions on the limit state functions.
CHAPTER IV : ALTERNATIVES & ADDITIONS TO STANDARD METHODS

However, MCS is rather inefficient, when calculating failure probabilities, since most of the contribution to $P_F$ is in a limited part of the integration interval.

IV.3.4.2 First-Order Reliability Method (FORM)

FORM uses a combination of both analytical and approximate methods, when estimating the probability of failure.

First, one transforms all the variables into equivalent normal variables in standard normal space (i.e. with mean = 0 and standard deviation = 1). This means that the original limit state surface $g(x) = 0$ then becomes mapped onto the new limit state surface $g_u(u) = 0$.

Secondly, one calculates the shortest distance between the origin and the limit state surface (in a transformed standard normal space $U$). The answer is a point on this surface, and it is called the most probable point of failure (MPP), design point or $\beta$-point. The distance between the origin and the MPP is called the reliability index $\beta_{HL}$. In general, this requires an appropriate non-linear optimisation algorithm. In ProSINTAP, a modified Rackwitz & Fiessler algorithm is chosen. It works by ‘damping’ the gradient contribution of the limit state function and this algorithm is very robust and converges quite quickly for most cases.

Then one calculates the failure probability using an approximation of the limit state surface at the most probable point of failure. Using FORM, the surface is approximated to a hyperplane (a first order/linear approximation).

The probability of failure is given as:

$$ P_{F,\text{FORM}} = \Pr[g_{\text{Linear}}(u) < 0] = \Phi(-\beta_{HL}) \quad \text{(IV.3.17)} $$

$$ P_{F,\text{SORM}} = \Pr[g_{\text{Quadratic}}(u) < 0] = \Phi(-\beta_{HL}) \prod_{i=1}^{N-1} (1 - \kappa_i \beta_{HL})^{-1/2} \quad \text{(IV.3.18)} $$

$\Phi(u)$ is the cumulative distribution function in standard normal space and $\kappa_i$ is the principal curvature of the limit state surface at the most probable point of failure (MPP).

FORM is, as regards CPU-time, extremely efficient as compared to MCS. Using the implementation within ProSINTAP, quite accurate results will be obtained for failure probabilities between $10^{-1}$ to $10^{-15}$. A disadvantage is that the random parameters must be continuous, and every limit state function must also be continuous.

IV.3.5 Results using ProSINTAP

Using the presented procedure, a computer program ProSINTAP has been developed. Independent of the method used (MCS, FORM), the input and output are essentially the same. The main results are:

(a) Probability of failure, defect size given by NDE.

(b) Probability of failure, defect not detected by NDE.

(c) Reliability index and the most probable point of failure (only when using FORM).

(d) Sensitivity factors for the chosen random parameters, when using FORM.
(e) Partial safety factors, given an assumed target failure probability, when using FORM.

IV.3.6 Partial Safety Factors

IV.3.6.1 Introduction

The ProSINTAP software can be used to derive appropriate partial safety factors for a given target reliability level. One issue not addressed here is the consequence of failure. Where two structures are analysed to estimate partial safety factors, that with the higher consequence of failure may require the use of more severe partial safety factors even though the probabilities of failure as calculated are the same.

Partial safety factors are factors which can be applied to the individual input variables in a design equation to give the given target reliability without having to carry out full probabilistic calculations. In effect, the overall partial safety factor for load effects is the ratio of the design point value to the value assumed to represent the loading, and the overall partial safety factor on resistance effects is the ratio of the value chosen to represent resistance effects to the design point value. However, no unique solution for partial safety factors exist and the same target reliability level can be achieved by different combinations of factors.

IV.3.6.2 Recommended Values

The partial safety factors to be applied in assessments depend both on the target reliability required and on the scatter or uncertainty of the main input data, namely fracture toughness, stress level, flaw size and yield strength.

Partial safety factors for given target reliabilities and different degrees of variability of the input data are given in this part of the procedure. The target reliability levels chosen correspond to the four conditions defined in Table IV.3.1 and an additional high reliability level, corresponding to a failure probability of $10^{-7}$, representative of very high structural integrity requirements as would be applied to highly critical components. The failure probabilities of $0.23$, $10^{-3}$, $7 \times 10^{-5}$, $10^{-5}$ and $10^{-7}$ correspond to target reliability index values of $\beta = 0.739$, $3.09$, $3.8$, $4.27$ and $5.2$, respectively.

Partial safety factors to achieve the required reliability have been derived using first order second moment reliability analysis methods for different coefficients of variation of stresses, flaw sizes, fracture toughness and yield strength. For stress levels, coefficients of variation of 0.1, 0.2 and 0.3 with a normal distribution are considered with a COV (Coefficient of Variation = standard deviation/ mean) of 0.2 representing dead load or residual stress effects and a COV of 0.3 representing live load effects. For the purposes of determining partial safety factors the results are derived in terms of different COV values so that for application purposes it is necessary to know both the best estimate (mean) value of defect size and the standard deviation to determine the appropriate COV. Weibull and lognormal distributions were adopted for fracture toughness data with coefficients of variation of 0.2 and 0.3 and a lognormal distribution for yield strength with a coefficient of variation of 0.10.

The resulting recommendations for partial safety factors to be applied to the best estimate (mean) values of maximum tensile stresses and flaw sizes, and to the characteristic (i.e. minimum specified) value of toughness and yield strength, are given in Table IV.3.2. It should be noted that the partial safety factors on fracture toughness are applicable to mean minus one standard deviation values as an approximate estimate of lowest of three. It is
recommended that sufficient fracture toughness tests should be carried out to enable the
distribution and mean minus one standard deviation to be estimated satisfactorily.

Partial factors on yield strength have little effect other than at high $L_r$ values when plastic
collapse is the dominant mechanism and hence the material factors already in use for
EuroCode 3 on yield strength are adopted for consistency. For partial safety factors on
stress, the values for $\beta = 3.8$ are chosen as 1.35 and 1.5 for stress COVs of 0.2 and 0.3 to
represent dead and live load respectively, and to be consistent with EuroCode 3.

It must be recognised that the partial safety factors will not always give the exact target
reliability indicated but should not give a probability of failure higher than the target value.
The recommended partial safety factors give ‘safe’ results for the target reliability over the
whole range.

The analyses and recommendations given above are based on the assumption that failure
will occur when an assessed defect gives rise to a point which falls on the failure
assessment diagram, whereas, in practice it is often found that the diagram gives safe
predictions rather than critical ones. Including these modelling uncertainties in the
calculations of partial factors will lead to a modified set of factors. However, it is not
intended that these modified factors be used for general safety assessments and since
further work is required prior to their implementation they are not covered in any further
detail here.

References

SAQ/SINTAP/09, June 1999.
### CHAPTER IV: ALTERNATIVES & ADDITIONS TO STANDARD METHODS

<table>
<thead>
<tr>
<th>Failure consequences</th>
<th>Redundant Component</th>
<th>Non-redundant Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
<td>$2.3 \times 10^{-1}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Severe</td>
<td>$10^{-3}$</td>
<td>$7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

**Table IV.3.1 Target failure probability**

<table>
<thead>
<tr>
<th>Stress</th>
<th>$(\text{COV})_\sigma$</th>
<th>$\gamma_\sigma$</th>
<th>$\gamma_\sigma$</th>
<th>$\gamma_\sigma$</th>
<th>$\gamma_\sigma$</th>
<th>$\gamma_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>01</td>
<td>1.05</td>
<td>1.2</td>
<td>1.25</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Dead+Res</td>
<td>0.2</td>
<td>1.1</td>
<td>1.25</td>
<td>1.35</td>
<td>1.4</td>
<td>1.55</td>
</tr>
<tr>
<td>Live</td>
<td>0.3</td>
<td>1.12</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flaw size</th>
<th>$(\text{COV})_a$</th>
<th>$\gamma_a$</th>
<th>$\gamma_a$</th>
<th>$\gamma_a$</th>
<th>$\gamma_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>1.0</td>
<td>1.4</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>1.05</td>
<td>1.45</td>
<td>1.55</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1.08</td>
<td>1.5</td>
<td>1.65</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.15</td>
<td>1.7</td>
<td>1.85</td>
<td>2.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Toughness, K</th>
<th>$(\text{COV})_K$</th>
<th>$\gamma_K$</th>
<th>$\gamma_K$</th>
<th>$\gamma_K$</th>
<th>$\gamma_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>1</td>
<td>1.3</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>(min of 3)</td>
<td>0.2</td>
<td>1.8</td>
<td>2.6</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1</td>
<td>2.85</td>
<td>NP</td>
<td>NP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yield strength</th>
<th>$(\text{COV})_M$</th>
<th>$\gamma_M$</th>
<th>$\gamma_M$</th>
<th>$\gamma_M$</th>
<th>$\gamma_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(on min spec.)</td>
<td>0.1</td>
<td>1</td>
<td>1.05</td>
<td>1.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Table IV.3.2 Recommended partial factors for different combinations of target reliability and variability of input data based on failure on the FAD.**

**Notes:**
- $\gamma_\sigma$ is a multiplier to the mean stress of a normal distribution.
- $\gamma_a$ is a multiplier to the mean flaw height of a normal distribution.
- $\gamma_K$ is a divider to the mean minus one standard deviation value of fracture toughness of a Weibull distribution.
- $\gamma_M$ is a divider to the mean minus two standard deviation value of yield strength of a log-normal distribution.
CHAPTER IV, SECTION 4: ALLOWANCE FOR CONSTRAINT EFFECTS

IV.4.1 Symbols

The following symbols are used in this Section in addition to those listed in Chapter 1.

- $B^1$ Normalised T-stress
- $g_{ij}$ Normalised elastic stress field ahead of a flaw
- $K'_{\text{mat}}$ Value of $K_{\text{mat}}$ modified by constraint
- $K'_{\text{mat}}(\Delta a_i)$ Value of $K_{\text{mat}}(\Delta a_i)$ modified by constraint
- $m$ Parameter defining influence of constraint on fracture toughness
- $r$ Distance from crack tip
- $Q$ Normalised hydrostatic stress used as a constraint parameter
- $Q^p, Q^s$ Value of $Q$ for $\sigma^p, \sigma^s$ stresses, respectively
- $T$ Elastic stress parallel to the flaw, used as a constraint parameter
- $T^p, T^s$ Value of $T$ for $\sigma^p, \sigma^s$ stresses, respectively
- $\alpha$ Parameter defining influence of constraint on fracture toughness
- $\beta$ Normalised constraint parameter
- $\delta_{ij}$ Kronecker's delta
- $\rho_i$ Parameter replacing $\rho$ in procedure of Section IV.4.4
- $\sigma_{ij}$ Stress field
- $\sigma_{ij}^{\text{sy}}$ Small-scale yielding stress field for $T = 0$
- $\theta$ Polar co-ordinate at crack tip

IV.4.2 Introduction

The procedures of Chapter I.4 enable an assessment to be made of the structural integrity of a component containing a flaw. Associated with an assessment are reserve factors which indicate the closeness to the limiting conditions. However, these limiting conditions incorporate an element of conservatism so that, in general, reserve factors tend to be underestimated.

A particular conservatism implicit in the procedure is that the value of fracture toughness, $K_{\text{mat}}$, is normally derived from deeply cracked bend specimens using recommended testing standards and validity criteria. These are designed to ensure plane strain conditions and high hydrostatic stresses near the crack tip to provide a material property independent of specimen size and geometry. However, there is considerable evidence that the material resistance to fracture is increased when specimens with shallow flaws, or specimens in tension, are tested [IV.4.1-5]. These conditions lead to lower hydrostatic stresses at the crack tip, referred to as lower constraint.

In recent years, there has been considerable effort to quantify the geometry dependence of the material resistance to fracture using so-called constraint parameters [IV.4.6-8]. This has led to proposals for incorporating constraint in fracture assessments [IV.4.9-12]. This Section uses these proposals to set out procedures for including constraint in the overall procedure of Chapter I. It is not intended that these procedures replace those of I.4; rather that they can be used in conjunction with that approach to estimate any increase in reserve factors likely to arise under conditions of low constraint.
Section IV.4.4 describes the procedures to be followed, within the scope set out in Section IV.4.3. Section IV.4.5 then provides guidance on how to perform the additional calculations and how to obtain the additional materials data required to follow the procedures. Validation of the approach is discussed in Section IV.4.6 and in the Status Notes of Section IV.4.7 which should be read before using the methods of this Section.

**IV.4.3 Scope**

The procedures of this Section are limited to mode I loading. Combinations of $\sigma^p$ and $\sigma^s$ stresses are included.

This Section addresses the loss of constraint under plane strain conditions. An increase in resistance to fracture is also expected due to loss of out-of-plane constraint or loss of constraint under plane stress conditions. Use of a specimen thickness, where practicable, equal to the component thickness can cover the first of these. The latter effect would be expected to be capable of a similar description to the plane strain situation but with the overall effect on structural behaviour being somewhat less because of the lower constraint under small-scale yielding in plane stress. However, methods for treating this case have not yet been developed and it is, therefore, beyond the scope of this Section.

There is considerable debate about the most appropriate parameter to describe constraint effects. This Section is written in terms of the parameters $T$ and $Q$, where the latter parameter can be evaluated in a number of ways [IV.4.13]. The principles can equally be applied for other constraint parameters provided their load dependence and their influence on fracture toughness can be quantified.

**IV.4.4 Procedures**

When the failure assessment diagram route of Chapter I.4 is followed, the constraint procedures involve a modification to the failure assessment diagram but retain the definition of $K_r$ in Chapter 2 in terms of the fracture toughness, $K_{mat}$, obtained from test specimens with high constraint. With the crack driving force approach of I.4, a modified toughness is used. The procedures follow the steps in Chapter 1 apart from steps detailed below. Guidance on how to perform these steps is contained in Section IV.4.5 along with guidance on assessing the significance of the results.

The additional requirements to assess constraint effects are as follows.

(a) Evaluate a normalised constraint parameter, $\beta$ (Section IV.4.5.2).

(b) Define the influence of constraint on material resistance to fracture, relative to the data determined in I.4, in terms of $\beta$ and the material parameters, $\alpha$ and $m$ (Section IV.4.5.3).

(c) If the FAD route is being followed,

(i) Modify the failure assessment diagram of I.4 using the parameters $\beta$, $\alpha$ and $m$ (Section IV.4.5.4).

(ii) Calculate $K_r$. For primary loading only, $K_r$ is calculated as in II.4, with $K_{mat}$ as defined from data obtained under conditions of high constraint. For combined
primary and secondary loading, $K_r$ is also defined with respect to $K_{mat}$ but the parameter $\rho$ is replaced by a related parameter $\rho_I$.

For an Option 1 Analysis, the definition of $K_r$ becomes

$$K_r = K_1(a_o)/K_{mat} + \rho_1(a_o)$$

For an Option 2 Analysis

$$K_r = K_1(a_j)/K_{mat}(\Delta a_j) + \rho_1(a_j)$$

Advice on calculation of the parameter $\rho_I$ is given in Section IV.4.5.5

(iii) plot points $(L_r, K_r)$ on the modified failure assessment diagram and assess in the usual way.

(d) If the CDF route is followed, then $K_{mat}$ is simply replaced by $K_{mat}^c$. For an Option 1 analysis, this is a single value whereas for an Option 2 analysis this is a function of ductile crack extension.

IV.4.5 Background Notes and Guidance on Using the Procedure

IV.4.5.1 Definition of Loads

The procedure of I.4 requires loads to be categorised and defined. It is important that the loads are conservatively represented in the following respects.

(i) Bending effects should be properly included. Constraint levels are higher under bending than tension and, therefore, a representation of a stress distribution which overestimates the tension component but underestimates the bending component may provide a conservative estimate of $L_r$ but underestimate the level of constraint. In cases of uncertainty, sensitivity studies should be carried out.

(ii) Biaxial loading should be included. Stresses parallel to the crack plane do not affect $K_I$ but they do affect constraint. Therefore, it is important that these stresses are assessed correctly when using the procedures of this Section.

IV.4.5.2 Evaluation of Structural Constraint, $\beta$

Guidance is given in this sub-section on the evaluation of a normalised measure of structural constraint, $\beta$. As there is considerable debate about the most appropriate parameter to describe constraint, advice is given on the calculation of $\beta$ for constraint described by both the elastic T stress and the hydrostatic Q stress. Whichever parameter is adopted, materials data are required (sub-section IV.4.5.3) as a function of that parameter. As the T stress requires only elastic calculation, it is recommended that this approach is adopted for initial calculations. The Q stress is expected to provide more accurate assessments, particularly when plasticity becomes widespread (higher $L_r$), and should be used when more refined estimates of load margins are required or as part of sensitivity studies.
(a) The T-stress definition of β

The stresses $\sigma_{ij}$ close to a crack tip, calculated elastically, may be written as

$$\sigma_{ij} = \frac{K_i}{(2\pi r)^\frac{1}{2}} g_{ij}(\theta) + T \delta_{ij} + \mathcal{O}(r^\frac{3}{2})$$

as $r \to 0$, for polar co-ordinates $(r, \theta)$ centred at the crack tip. Here, $g_{ij}$ are angular functions of $\theta$, $\delta_{ij}$ is Kronecker's delta and the T stress is the second order term which can be regarded as the stress parallel to the crack flanks. The value of T is influenced by remote stresses parallel to the flaw as well as geometry, flaw size and loading.

The value of T may be calculated from elastic finite-element analysis using a number of different methods which are described in [IV.4.14]. This reference also contains normalised T-stress solutions for a range of two and three dimensional geometries. The value of T may be calculated from elastic finite-element analysis using a number of different methods which are described in [IV.4.14]. This reference also contains normalised T-stress solutions for a range of two and three dimensional geometries. The value of $\beta$ is then defined by

$$\beta = \frac{T^p}{L_r \sigma_y} + \frac{T^s}{L_r \sigma_y} \quad \text{(IV.4.1)}$$

where, $T^p$, $T^s$ are the values of T-stress for the $\sigma^p$ and $\sigma^s$ stresses, respectively, and $T = T^p + T^s$. As both $T^p$ and $L_r$ are proportional to load and $L_r$ is inversely proportional to $\sigma_y$, $\beta$ is independent of both the load magnitude and the value of $\sigma_y$ for $\sigma^p$ stresses acting alone: it is then a function of geometry, flaw size and the type of loading only.

For combined $\sigma^p$ and $\sigma^s$ stresses, $\beta$ reduces with increasing $\sigma^p$ loads (increasing $L_r$) for constant $\sigma^s$ loading. In the limit $L_r \to 0, \beta \to \infty$ but the product $\beta L_r$ remains finite and equal to $T^p/\sigma_y$ in the limit. It is this product $\beta L_r$, which is required in Sections IV.4.5.3, IV.4.5.4 and IV.4.5.5.

In the literature, values of $T^p$ are often presented, normalised by the stress intensity factor and flaw size as

$$B^p = T^p \sqrt{\pi a} / K^p_i$$

or in terms of some nominal applied stress. As values of $K^p_i$ and $L_r$ are required to perform an assessment, it is straightforward to convert these solutions into values of $\beta$ [IV.4.15].

(b) The Q-stress definition of β

For elastic-plastic materials, the stresses close to a crack tip may be written approximately as

$$\sigma_{ij} = \sigma_{ij}^{\text{suy}} + Q \sigma_y \delta_{ij}$$

where $\sigma_{ij}^{\text{suy}}$ is the stress field close to a crack tip under small-scale yielding, for the same
value of $J$ as that used to evaluate $\sigma_{ij}$, and for a remote stress field corresponding to $T = 0$. The $Q$ stress actually varies slightly with distance from the crack tip and has been defined in [IV.4.9, 16] at the normalised distance $r/(J/\sigma_y) = 2$ directly ahead of the crack.

The value of $Q$ may be calculated from elastic-plastic finite-element analysis using methods described in [IV.4.9, 13, 16-18]. In practice, the value of $Q$ may be evaluated from principal or hydrostatic stresses or from the ratio of the hydrostatic to equivalent stress ahead of the crack tip. Different notations $Q$, $Q_m$ and $H$ are used in the literature [IV.4.13, 18] to denote constraint parameters evaluated in different ways. Here, the single notation $Q$ is used for simplicity but the approach is applicable provided the same parameter is used to define the normalised constraint parameter $\beta$ defined by

$$\beta = Q / L_r \quad (IV.4.2)$$

and to quantify the effect of constraint on material toughness in Section IV.4.5.3.

In general, the value of $Q$ is a function of geometry, flaw size, type of loading, the material stress-strain curve and the magnitude of the loading. Therefore, available solutions in the literature [IV.4.9-10, 13, 15, 17-20] are of more restricted application than the corresponding solutions for $T$.

For combined $\sigma_p$ and $\sigma_s$ stresses, a value of $Q$ is required for the particular combination being examined. In the absence of a detailed evaluation of $Q$, it may be estimated for $Q^p > 0$ from

$$Q = Q^p + Q^s \quad Q^s \geq 0 \quad (IV.4.3a)$$

and, for $Q^s < 0$, as

$$Q = Q^p + Q^s(1 - L_r) \quad Q^s < 0 \text{ and } L_r \leq 1 \quad (IV.4.3b)$$

$$Q = Q^p \quad Q^s < 0 \text{ and } L_r > 1$$

or more conservatively as

$$Q = Q^s \quad Q^s < 0, Q^p < 0, Q^p > Q^s \quad (IV.4.3c)$$

$$Q = Q^p \quad Q^s < 0, Q^p < 0, Q^p \leq Q^s$$

where $Q^p$ is the value of $Q$ under the $\sigma_p$ stresses alone and $Q^s$ is the value of $Q$ under the $\sigma_s$ stresses alone. These estimates are illustrated in Figure IV.4.1.

For $L_r \leq 0.5$, the value of $Q^p$ may be estimated [IV.4.10] from

$$Q^p = T^p/\sigma_y \quad -0.5 < T^p/\sigma_y \leq 0 \quad (IV.4.4)$$

$$Q^p = 0.5 T^p/\sigma_y \quad 0 < T^p/\sigma_y < 0.5$$

Where more detailed information about the material strain hardening characteristics is
known, these estimates may be improved by using small-scale yielding approximations in [IV.4.9]. From eqn (IV.4.4), for \( \sigma \) stresses acting alone at low values of \( L_r \) and for negative values of T-stress such that \( \left| T/\sigma_y \right| < 0.5 \), the value of \( \beta \) is identical to that defined from the T-stress. Ainsworth and O'Dowd [IV.4.10] have shown that defining \( Q_p \) from \( T^p \) also provides a conservative estimate of constraint for a number of cases at \( L_r > 0.5 \). However, they also showed that for a centre-cracked tension geometry under biaxial loading the constraint level was higher when defined in terms of \( Q_p \) than \( T^p \) at higher loads (\( L_r > 0.5 \)). Therefore, solutions in the literature should be consulted to assess whether the use of \( T^p \) is likely to lead to conservative over-estimates of \( Q_p \) at high loads.

In the absence of a detailed inelastic analysis of the body containing a flaw under \( \sigma^s \) stresses, an estimate of \( Q^s \) may be obtained from \( T^s \), the value of T-stress from an elastic analysis of the \( \sigma^s \) stresses:

\[
Q^s = T^s / \sigma_y
\]  

Note, weight function methods may be used to evaluate \( T^s \) for non-linear distributions of secondary stress [IV.4.21, 22].

**IV.4.5.3 Influence of Constraint on Material Resistance to Fracture**

To use the procedure of Section IV.4.4 it is necessary to define the material fracture resistance at the level of constraint evaluated using the methods of Section IV.4.5.2. This constraint dependent toughness is denoted \( K^c_{mat} \) and is dependent on \( \beta L_r \).

At high values of constraint (\( \beta L_r > 0 \)), \( K^c_{mat} \) may be simply taken as equal to \( K_{mat} \) obtained from conventional deeply cracked bend specimens. For negative levels of constraint (\( \beta L_r < 0 \)), the influence of constraint may be broadly summarised as follows:

(i) in the cleavage regime, \( K^c_{mat} \) increases as \( \beta L_r \) becomes more negative;

(ii) in the ductile regime, there appears to be little influence of constraint on the fracture toughness, \( K_{0.2} \), relating to initiation of ductile tearing but the fracture toughness after crack growth increases as \( \beta L_r \) becomes more negative;

(iii) in view of (i) and (ii), for ferritic steels there is a shift in the brittle to ductile transition region to lower temperatures as \( \beta L_r \) becomes more negative [IV.4.23,24].

Ainsworth and O'Dowd [IV.4.10] have shown that the increase in fracture toughness in both the brittle and ductile regimes may be represented by an expression of the form

\[
K^c_{mat} = K_{mat} \quad \beta L_r > 0
\]

\[
K^c_{mat} = K_{mat} \left[ 1 + \alpha(-\beta L_r)^n \right] \quad \beta L_r < 0
\]  

(IV.4.6)
where $\alpha$, $m$ are material and temperature dependent constants. Some illustrative values of $\alpha$, $m$ taken from [IV.4.25,26] are given in Table IV.4.1. In the ductile regime, it can be seen that $\alpha$ and $m$ are, additionally, functions of ductile crack growth. However, other forms have been used in the literature (for example, [IV.4.11, IV.4.17]) and the principles of this Section are not restricted to any particular relationship between $K_{\text{mat}}^c$ and $K_{\text{mat}}$.

Values of $K_{\text{mat}}^c$, or equivalently values of $\alpha$, $m$ in equation IV.4.6, may be obtained by

(i) testing specimens having different geometries and flaw sizes to obtain data in the range of $\beta L_r$ of interest;
(ii) mechanistic modelling [IV.4.7, IV.4.8];
(iii) a combination of limited materials testing with mechanistic modelling to interpolate/extrapolate to different constraint levels.

Test specimens which have been used to generate fracture toughness data at low constraint levels include three point bend specimens with shallow flaws, centre cracked plates under tension and plates under tension with semi-elliptical surface flaws. Standards are not currently available for testing such specimens and, therefore, care needs to be exercised in order to obtain values of $K_{\text{mat}}^c$. However, some limited advice has recently been given in [IV.4.4, IV.4.27] for testing centre cracked tensile panels and shallow cracked specimens and in [IV.4.28] for evaluating $J$ from load and load-line displacement values.

Corresponding advice on evaluating the level of constraint in the specimens at fracture is contained in [IV.4.29].

**IV.4.5.4 Construction of Modified FAD**

The failure assessment diagram should initially be constructed according to one of the levels in I.4. This is denoted

\[ K_r = f(L_r) \quad \text{for} \quad L_r \leq L_r^{\text{max}} \]

\[ K_r = 0 \quad \text{for} \quad L_r > L_r^{\text{max}} \]  \hspace{1cm} (IV.4.7)

where $f(L_r)$ can take one of the forms summarised in I.4. Then the modified failure assessment diagram is

\[ K_r = f(L_r)(K_{\text{mat}}^c / K_{\text{mat}}) \quad \text{for} \quad L_r \leq L_r^{\text{max}} \]

\[ K_r = 0 \quad \text{for} \quad L_r > L_r^{\text{max}} \]  \hspace{1cm} (IV.4.8)

Where $K_{\text{mat}}^c$ is defined by equation IV.4.6 for $\beta < 0$, this becomes

\[ K_r = f(L_r)(1 + \alpha (-\beta L_r)^m) \quad \text{for} \quad L_r \leq L_r^{\text{max}} \]  \hspace{1cm} (IV.4.9)
Some modified FADs using $\alpha$, $m$, $\beta$ taken as constants are shown in Figure IV.4.2 taken from [IV.4.28]; note, the cut-off $L_r^{\text{max}}$ is not depicted but this is independent of constraint. Some properties of these modified FADs should be noted:

(i) whereas the level 1 curve is independent of geometry and material, the level 1 curve modified by equation IV.4.8 or IV.4.9 is dependent on geometry (through $\beta$), on material toughness properties (through $\alpha, m$) and also on material tensile properties if $\beta$ is defined in terms of $Q$;

(ii) whereas the level 2 curve is independent of geometry and dependent only on material tensile properties, the modified level 2 curve is additionally dependent on geometry and material toughness properties;

(iii) whereas the level 3 curve is dependent on geometry and material tensile properties, the modified level 3 curve is additionally dependent on material toughness properties;

(iv) In view of (i)-(iii), when performing a tearing analysis the failure assessment line is a function of ductile flaw growth through its influence on geometry ($\beta$ depends on flaw size) and material ($\alpha$, $m$ or $K_{c\text{mat}}/K_{\text{mat}}$ may depend on $\Delta a$). Some care is then needed in defining the instability condition and this is discussed in Section IV.4.5.6;

(v) for combined loading where $\beta$ increases with reducing $L_r$, the value of $\beta L_r$ is finite at $L_r \to 0$ [IV.4.12, IV.4.30]. Consequently the failure assessment curves intersect the axis at a values of $K_r$ greater than unity in contrast to the curves shown in Figure IV.4.2 for constant $\beta$.

IV.4.5.5 Calculation of Parameter $\rho_1$

The value of $\rho_1$ is

$$\rho_1 = \rho \left(\frac{K_{\text{mat}}}{K_{\text{c\text{mat}}}}\right) \quad \text{(IV.4.10)}$$

where $\rho$ is defined in III.2.3. When $K_{c\text{mat}}$ is defined by equation IV.4.6 for $\beta < 0$, this becomes

$$\rho_1 = \rho \left[1 + \alpha (\beta L_r)^m\right] \quad \text{(IV.4.11)}$$

IV.4.5.6 Assessment of the Significance of Results

Assessing the significance of results follows the principles set down in I.3 with reserve factors defined in terms of the assessed conditions and those which produce a limiting condition.

When analyses are performed for a single $\sigma^p$ load, a graphical construction may be used to define the load factor. More generally, the limiting condition, and hence the reserve factor, is
obtained by finding the intersection with the failure assessment curve of the locus of assessment points \((L_r, K_r)\) for different values of load.

When performing a tearing analysis the reserve factor on load, \(F^L\), should be calculated as a function of postulated flaw growth. Following the procedure in Section IV.4.4, the load factor may change as a result of changes in \(L_r, K_r\) and in the failure assessment curve. The limiting condition is obtained by plotting \(F^L\) as a function of postulated growth. When extensive flaw growth data are available, a maximum in this plot is obtained. This corresponds to a tangency condition, but with the failure assessment curve changing with flaw extension [IV.4.31-33].

Sensitivity studies should be performed to establish confidence in any increased reserve factors obtained by following the procedures in this Section. Parameters of interest which may be explored are:

(i) the constraint parameter \(\beta\) - its sensitivity to any assumptions about the nature of the loading (tension, bending), its definition in terms of \(T\) or \(Q\), and any estimate used for combined \(\sigma_\text{n}\) and \(\sigma_\text{s}\) stresses;

(ii) the material property \(K_\text{mat}\) - the extent to which lower bound properties have been used, uncertainties in modelling predictions, and uncertainties in fitting equations such as 4.4.6 to data.

IV.4.6 Validation

IV.4.6.1 Experimental Validation

Experimental validation of the procedures of this Section is presented first. Validation has been addressed for both cleavage and ductile fracture conditions but it should be recognised that the extent of the validation is currently more limited than that for the procedures of Chapter 1. This is primarily because detailed information on material properties under low constraint conditions is rarely available for large-scale tests performed in the past.

Recently, experimental validation has been addressed in [IV.4.11] for centre-cracked and three-point-bend specimens for a range of materials: cleavage fracture of a grade 43A normalised plain carbon steel at -50ºC; cleavage in a high strength weld metal at -30ºC; cleavage fracture of a quenched plain carbon steel at room temperature; cleavage fracture of a normalised CMn steel at temperatures below -140ºC; ductile flaw initiation in an A710 pressure vessel steel at room temperature. The results have been assessed using a modified toughness in the definition of \(K_r\) which is equivalent to the procedure of Section IV.4.4. The results demonstrate that points \((L_r, K_r)\) lie close to, but outside, the level 1 failure assessment line. In contrast, analysis using the procedures of Chapter 1 leads to points well outside the failure assessment line.

Experimental validation on small- and large-scale tests has been addressed in [IV.4.8, IV.4.25, IV.4.28 and IV.4.34]. In [IV.4.8], the cleavage fracture results on a grade 43A normalised plain carbon steel at -50ºC, also analysed in [IV.4.11], have been compared with the procedure of Section IV.4.4 using the local approach to obtain a lower bound to the
constraint modified fracture toughness, $K_{c_{\text{mat}}}$ . The results again demonstrate conservatism in the approach of this Section which is less than that using the procedures of Chapter 1.

Cleavage fracture in two low constraint biaxial bend experiments on A533B steel plates in the lower transition region has been addressed in [IV.4.25]. The constraint modified approach reduced the conservatism of the conventional level 1 and level 2 failure assessment curves leading to a 30-40% benefit in terms of load margin for the lower constraint geometry, whilst maintaining conservatism. When the approach was applied to ductile fracture of a large scale single edge notched A533B plate at 20ºC, the load margin was unchanged at about 1.1 because the structural constraint was not particularly low [IV.4.10]. This result demonstrates that for higher constraint conditions, the basic approach is not unduly conservative and application of the approach in this Section is little different from the basic method.

In [IV.4.35] it has been shown by testing SENB specimens of A533B steel at -100ºC with crack depth to specimen width ratios in the range of 0.1 to 0.5 there that there is a marked increase (a factor of about 2) in cleavage toughness in the shallow cracked specimens. Recently, these data interpreted in the form of equation IV.4.6, have been shown to lead to conservative estimates of fracture in uniaxial and biaxial wide plate tests, thus, providing further experimental validation for the procedures of this Section.

Validation for the use of micromechanistic modelling to estimate $K_{c_{\text{mat}}}$ is given in [IV.4.7,8]. Use of the local approach to assess the effect of constraint on cleavage fracture is described in [IV.4.7]. This approach predicts an upswing in cleavage fracture toughness as a function of decreasing crack tip constraint when applied to a BS 4360 mild steel. Damage modelling to assess the effect of constraint on ductile fracture is described in [IV.4.7]. This modelling is in agreement with experimental data showing little effect on initiation fracture toughness but a large increase in the slope of the resistance curve and hence $K_{\text{mat}}$ for low constraint conditions.

**IV.4.6.2 Finite Element Validation**

Validation for combined $\sigma^p$ and $\sigma^s$ stresses has been addressed by performing finite element calculations for a number of geometries [IV.4.21] and types of $\sigma^p$ and $\sigma^s$ stresses:

A single edge cracked plate subject to uniform tension with bending restrained along the back face opposite the crack tip (essentially equivalent to a double edge cracked plate). The ratio of flaw size, $a$, to plate width, $w$, was $a/w = 0.05, 0.1, 0.2, 0.3$ and 0.5. Secondary stresses were imposed by application of a temperature profile leading to either a linear or quadratic distribution of stress across the uncracked plate.

A centre cracked plate under uniform tension with $a/w = 0.1, 0.5$ and 0.9. A secondary stress was imposed in the same way as in the edge cracked plate.

The finite-element analyses led to the following conclusions.

For secondary loadings which lead to loss of constraint in the absence of primary loading (negative $Q^s$), the differences between the values of $Q$ for the combined loading and for primary loading alone are reduced as plasticity increases under...
primary loading such that \( Q \) for the combined loading is approximately equal to that for the primary loading alone at high loads \( (L_r > 1.0) \).

Secondary loadings which have little influence on crack tip constraint \( (Q^s \approx 0) \) also have little influence on crack tip constraint in the presence of primary loads.

For secondary stresses which produce high constraint \( (Q^s > 0) \), the increase in constraint is maintained in the presence of primary loads even at high levels of plasticity \( (L_r > 1.0) \).

These results have provided validation for, and been used to select, the estimation approach of equations IV.4.3, IV.4.5 from a number of candidate methods [IV.4.30].

**IV.4.7 Status Notes**

There has been considerable effort world wide on development of approaches for assessing constraint effects on fracture. There is still some debate on the most appropriate parameter(s) to use to describe constraint. In this Section, the \( T \) and \( Q \) parameters have been adopted as these are established to the extent that solutions are available for a number of geometries [IV.4.13-15,18,20] and methods for their evaluation are well defined. However, other parameters are under development and the user is referred to [IV.4.20] for a summary of the relative merits of different parameters.

Validation for the procedures in this Section is available as discussed in Section IV.4.6. This covers experimental data for test specimens and a few well characterised large scale tests; and, finite-element analyses for combined \( \sigma^p \) and \( \sigma^s \) stresses. However, the validation evidence is limited and further work is underway to extend the available validation.

An alternative approach to incorporate constraint effects in an assessment is by the use of micromechanistic models of fracture (local approach) within a finite-element model of a defective component. Such methods have been set out in procedural form in R6 Appendix 17 [IV.4.36]. As indicated in Section IV.4.5.3, these methods may also be used to estimate the constraint dependent fracture toughness for use within the procedures of this Section. Some recent developments in this area are described in [IV.4.37].

**IV.4.8 References**


(1997)


[IV.4.13] I Sattari-Far, Solutions of Constraint Parameters Q, Q^m and H in SEN(B) and SEN(T) Specimens, SAQ Report SINTAP/SAQ/01 (1996).


[IV.4.18] I Sattari-Far, Solutions of Constraint Parameters $Q, Q_m$ and $H$ in Surface Cracked Plates under Uniaxial and Biaxial Loading, SAQ Report SINTAP/SAQ/04 (1997).


**TABLE IV.4.1 Illustrative Constants in Equation IV.4.6 for Various Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature</th>
<th>Fracture Mode</th>
<th>$\alpha$</th>
<th>m</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A533B</td>
<td>-75°C</td>
<td>Cleavage</td>
<td>1.0</td>
<td>1.0</td>
<td>Lower bound</td>
<td>[IV.4.25]</td>
</tr>
<tr>
<td>A533B</td>
<td>-90°C</td>
<td>Cleavage</td>
<td>1.1</td>
<td>1.0</td>
<td>Lower bound</td>
<td>[IV.4.25]</td>
</tr>
<tr>
<td>A533B</td>
<td>-45°C</td>
<td>Cleavage</td>
<td>1.3</td>
<td>1.0</td>
<td>Limited data</td>
<td>[IV.4.25]</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>-50°C</td>
<td>Cleavage</td>
<td>1.3</td>
<td>2.0</td>
<td></td>
<td>[IV.4.25]</td>
</tr>
<tr>
<td>A515 Steel</td>
<td>RT</td>
<td>Cleavage</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
<td>[IV.4.26]</td>
</tr>
<tr>
<td>ASTM 710 Grade A</td>
<td>20°C</td>
<td>Ductile</td>
<td>0.0</td>
<td>1.0</td>
<td>$\Delta a = 0$</td>
<td>[IV.4.26]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>1.0</td>
<td>$\Delta a = 0.2\text{mm}$</td>
<td>[IV.4.26]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>2.0</td>
<td>$\Delta a = 0.4\text{mm}$</td>
<td>[IV.4.26]</td>
</tr>
</tbody>
</table>
Fig. IV.4.1 Estimate of $Q$ for Combined Primary and Secondary Stresses
FIGURE IV.4.2 Modifications to the Level 1 Failure Assessment Curve for Various Values of the Material Parameters, $\alpha$, $m$, and Constraint Levels, $\beta$ (<0), Using Equation IV.4.9: (a) $m = 1$, (b) $m = 2$, (c) $m = 3$. For $\alpha = 0$ or $\beta = 0$ the Curves Reduce to the Level 1 Curve.
CHAPTER IV, SECTION 5 : LEAK-BEFORE-BREAK ASSESSMENT

IV.5.1 Symbols

The following symbols are used in this Section in addition to those listed in the nomenclature in Chapter I.

- \( A \) Crack opening area
- \( a_1, a_2 \) Flaw semi-lengths at breakthrough
- \( a, a' \) Flaw depth
- \( C_D \) Discharge Coefficient
- \( d \) Ligament thickness (\( d = t-a \))
- \( E' \) \( E' = E \) for plane stress; \( E' = E/(1 - \nu^2) \) for plane strain
- \( f \) Fluid friction factor
- \( f_{max} \) Maximum value of \( f \)
- \( K \) Stress intensity factor
- \( L \) Flaw length used in flow rate calculations
- \( \ell \) Flaw length
- \( \ell_b \) Flaw length at breakthrough
- \( \ell_c \) Limiting length of through-wall flaw
- \( \ell' \) Enhanced flaw length
- \( P \) Operating pressure
- \( Q \) Volumetric flow rate
- \( R \) Radius
- \( R_a \) Surface roughness parameter
- \( S \) Ratio of membrane stress to flow stress
- \( t \) Section thickness
- \( W \) Flaw width used in flow calculations
- \( \alpha(\lambda) \) Bulging factor
- \( \lambda \) Shell parameter, \( \lambda = [0.75(1 - \nu^2)]^{1/4}/(Rt)^{1/2} \)
- \( \rho \) Fluid density
- \( \sigma_m \) Membrane component of stress acting normal to flaw plane
- \( \nu \) Poisson's ratio

Abbreviations

- COA Crack Opening Area
- TWB Through-Wall Bending

IV.5.2 Introduction

There are several options by which it may be possible to demonstrate the safety of a structure containing flaws when an initial analysis has failed to show that adequate margins exist. For pressurised components one of these options is to make a leak-before-break case by demonstrating that a flaw will grow in such a way as to cause, in the first instance, a stable detectable leak of the pressure boundary rather than a sudden, disruptive break.
The various stages in the development of a leak-before-break argument may be explained with the aid of the diagram shown in Figure IV.5.1, [IV.5.1]. This diagram has axes of flaw depth, $a$, and flaw length, $l$, normalised to the pipe or vessel wall thickness, $t$. An initial part-through flaw is represented by a point on the diagram. The flaw may grow by fatigue, tearing or any other process until it reaches some critical depth at which the remaining ligament ahead of the flaw breaks through the wall. The flaw then continues growing in surface length until there is sufficient opening to cause a detectable leak or until the flaw becomes unstable. A leak-before-break argument is aimed at demonstrating that leakage of fluid through a flaw in the wall of a pipe or vessel can be detected prior to the flaw attaining conditions of instability at which rapid crack extension occurs.

This Section sets out procedures for making a leak-before-break case and recommends methods for carrying out each of the steps involved, including advice on the development of a part penetrating flaw.

When applying the approach, it is important that additional calculations are carried out to assess the sensitivity of the results to likely variations in the input data. Guidance on this and other aspects of the analysis is given in Section IV.5.5 and it is important that this is read before using the procedures.

The starting point for the leak-before-break procedure is usually a surface flaw which has yet to break through the pipe or vessel wall. In order to make a leak-before-break case for this type of flaw, it is necessary to show that:

(i) the flaw penetrates the pressure boundary before it can lead to a disruptive failure;

(ii) the resulting through-wall flaw leaks at a sufficient rate to ensure its detection before it grows to the critical length at which disruptive failure occurs.

Several steps are involved in establishing each of these requirements. First, the flaw must be characterised and the mechanisms by which it can grow identified. The next step is to calculate the length of the through-wall flaw formed as the initial defect penetrates the pressure boundary; this is then compared with the critical length of a fully-penetrating flaw. Finally it is necessary to estimate the crack-opening area, the rate at which fluid leaks from the flaw, and whether or not the leak will be detected before the flaw grows to a critical length. These steps form the basis of the leak-before-break procedure described in Section IV.5.4 of this Section.

IV.5.3 Scope

Where possible the leak-before-break procedures make use of methods and guidance already contained in other sections of this document. Where this is the case, for example, in the critical flaw size calculations, reference is made to the appropriate parts of the document. Methods other than those recommended in this procedure may be used but it is the responsibility of the user to ensure that the use of such methods can be justified and appropriate validation exists.

In contrast to the procedures of Chapter I, which are concerned with failure avoidance, part of the leak-before-break case involves failure prediction. It is therefore recommended that best-estimate values of stresses and material properties, rather than pessimistic values, are used to estimate the flaw length at breakthrough when part-through flaws are being considered. However, to ensure conservatism, pessimistic values should be used to calculate the critical length of the resulting through-wall flaw, in accordance with the procedures of Chapter I. For the purpose of this leak-before-break procedure the term ‘limiting length’ is used in this Section for the critical length of the through-wall flaw.
In assessing leakage, advice is offered which tends to underestimate flow rates as this is conservative. However, in some instances there may be consequences of leakage that have to be considered. In these cases an upper bound to leakage may be required, but this is outside of the scope of this Section.

Leak-before-break assessments for a pressure boundary should be conducted for locations judged to be most at risk. Some guidance on the selection of assessment sites is given in Table IV.5.1. The selection of assessment sites can be based on an elastic uncracked pipework system stress analysis, and the guidance given in Table IV.5.1. However, it may be necessary to examine several locations to ensure that the worst combinations of flaw orientation, loadings and material properties (eg. weld properties) have been accounted for. Although using stresses from an uncracked elastic pipework analysis may slightly underestimate the size of flaw to give a specified leak rate, several studies have shown that the conservatism associated with the determination of the limiting flaw length is overriding so that, overall, the use of uncracked stresses should be conservative in leak-before-break assessments [IV.5.2].

The procedures are primarily aimed at the assessment of discrete flaws, either postulated or known to exist in a component, for which breakthrough would occur in a ductile manner. The procedures can in principle be used when the ligament beneath the flaw fails in a brittle manner but the re-characterisation rules following brittle ligament failure are such that it may not be possible to make a leak-before-break case without recourse to crack-arrest arguments.

A leak-before-break case may not be tenable in plant that is prone to cracking mechanisms that may lead to very long surface flaws. Also, the risk of transient water hammer loading in piping containing high energy fluid can preclude leak-before-break arguments, unless the peak loads can be adequately assessed and then considered in the limiting flaw size evaluation. Where there is significant risk of damage to piping from impacting (missiles or dropped loads), other whipping pipes or arising from equipment failure then such considerations should override any leak-before-break case.

### IV.5.4 Leak-Before-Break Procedure

The leak-before-break procedure is summarised in the form of a flow chart in Figure IV.5.2 and set out as a series of steps below. More detailed guidance on carrying out each of the steps is given in Section IV.5.5, the number in brackets after each step indicating the appropriate sub-section.

1. **Characterise the Flaw (Section IV.5.5.1)**

To use this procedure the defect must be characterised as a surface (or through wall) flaw in accordance with II.3. For extended, irregular defects where a narrow ligament exists over only a small fraction of the overall flaw length the characterisation may be based on that part of the flaw where the narrow ligament exists. Embedded flaws must first be re-characterised as surface flaws in order to use the procedure.

2. **Determine Limiting Length of Through-Wall Flaw (Section IV.5.5.2)**

The limiting length at which a through-wall flaw at the position of the initial flaw would become unstable should be determined using the procedures contained in Chapter I. The minimum limiting length should be determined for the most onerous loading condition using lower-bound values for materials properties. Where appropriate, stable tearing can be invoked in this part of the assessment.
3. **Estimate Flaw Length at Breakthrough (Section IV.5.5.3)**

The flaw length at breakthrough can be estimated using the procedures of Chapter I and the re-characterisation rules in II.3. To determine the length at breakthrough:

(i) assess the shape development of the characterised surface flaw (for example an inspection indication or postulated flaw) arising from potential crack growth mechanisms. Alternatively, a range of surface flaws at the threshold of penetration may be considered;

(ii) calculate the flaw length at which ligament failure is predicted to occur using the procedures in I.4;

(iii) re-characterise the flaw for which ligament failure is predicted to occur as a through-wall flaw using the rules of II.3.

The flaw length at breakthrough is given by the length of the through-wall flaw resulting from this re-characterisation. Ligament failure should be assessed under steady state operating conditions. Best estimate material properties and loads should be used, together with local collapse solutions and ductile tearing. This provides a best estimate of the breakthrough length. Use of lower bound material properties, and failure based on initiation, reduces the breakthrough length and enhances the margin on flaw stability. The calculated leak rate is, however, reduced by this means. Because it is not clear which factor dominates, the use of best estimate data is advocated. Where necessary, the mechanisms of flaw growth (fatigue, creep, etc) should be identified and crack shape development examined. When assessing ligament failure, the stability of the surface points should be assessed along with that of the deepest point on the crack front. If the flaw becomes unstable at the surface, a leak-before-break case cannot be made.

4. **Calculate Crack-Opening Area of Flaw (Section IV.5.5.4)**

The crack opening area of a potential through-wall flaw is required to estimate leakage flow rates. The crack opening area depends on the flaw geometry (effective length, shape, orientation, etc.), the component geometry, the material properties and the loading conditions.

A best estimate approach to calculating crack opening area is advocated to establish the viability of a leak-before-break case, and provide a basis for the assessment of margins. However, crack opening area calculations are not simple and a bounding approach which minimises flow rates can offer alleviation of effort.

Advice on the calculation of crack opening area for idealised flaws in flat plates, pipework components and spheres is given in Section IV.5.5.4.

5. **Calculate Leak Rate from Flaw (Section IV.5.5.5)**

Several computer codes are available to predict leakage rates for single and two-phase flows through a wide range of through-wall flaws. Details of these codes and approximate analytical solutions for isothermal and polytropic flow of gases are given in Section IV.5.5.5. An alternative means of estimating the leakage rate is to use relevant experimental data if these are available.

6. **Estimate Time to Detect Leak from Flaw (Section IV.5.5.6)**

The leak detection system must be selected with due regard to the nature of the leaking fluid and the calculated leak rate. The detection time is then assessed from knowledge of the...
sensitivity of the equipment and its response time with due allowance for the need, if any, to check that the signal is not spurious.

The time for detection and the execution of the subsequently required actions must be less than that required for the flaw to go to the limiting length.

7. **Calculate Time to Grow to Limiting Length (Section IV.5.5.6)**

If the through-wall flaw can continue to grow in length as a result of fatigue or other mechanisms then the time required for the flaw to grow to a limiting length must be calculated by integrating the appropriate crack growth laws.

8. **Assess Results (Section IV.5.5.7)**

In principle, a leak-before-break case has been made provided that the calculations carried out in the preceding steps show that:

(i) the flaw length at breakthrough is less than the limiting length of a through-wall flaw;

(ii) the time to detect the leak is less than the time for the flaw to grow to a limiting length.

However, it is recommended that a sensitivity analysis be carried out to determine the extent to which changes in the input data affect the results of the calculations. Only if the above two conditions can be satisfied with adequate margins throughout the range of variations likely to occur in the input data can a satisfactory leak-before-break case be claimed. A sensitivity study can include failure based on initiation, with allowable tearing, and on instability. Also, upper bound material properties can be used, if known.

It should be noted that failure to demonstrate in the initial analysis that the flaw length at breakthrough is less than the limiting length, that the leak is detectable before the flaw grows to a limiting length, or that adequate margins exist does not necessarily mean a leak-before-break case cannot be made. As indicated in the flow chart of Figure IV.5.2, it may be possible to refine calculations, for example, by reducing any conservatisms that have been introduced into the calculations, by going to a more detailed analysis such as a finite element representation, or selecting a more sensitive leak detection system, and as a result make a satisfactory leak-before-break case.

**IV.5.5 Background Notes and Guidance on Using the Procedures**

The following sections are intended to provide more detailed guidance on the methods recommended for carrying out the various steps in the leak-before-break procedure. It is recommended that these are read before using the procedure. Where it is relevant, background information on various aspects of the procedure is also included.

**IV.5.5.1 Flaw characterisation**

The aim of flaw characterisation is to represent a known or postulated flaw by a relatively simple shape which adequately models the flaw and can be readily analysed. It is recommended that the flaw characterisation rules of II.3 are used for this purpose.

It is recognised that for extended, irregular flaws, where a narrow ligament may exist over only a small fraction of the overall flaw length, the characterisation rules of II.3 are likely to be unnecessarily pessimistic when making a leak-before-break case. For flaws of this nature it may be more realistic to base the initial characterisation on that part of the flaw where the narrow ligament exists. If this is done, however, it will be necessary to characterise and separately assess the remainder of the flaw to ensure that a critical part penetrating flaw
cannot arise that would lead to a double edged guillotine break. Figure IV.5.3 illustrates such an example where a complex flaw has been separately characterised as the superposition of an extended, part-through flaw and a semi-elliptical flaw in a section of reduced thickness. Provided the extended flaw cannot grow to penetrate the wall before the semi-elliptical flaw breaks through, it is acceptable in this example to assess the leak-before-break behaviour of the complex flaw in terms of the behaviour of the more simple semi-elliptical flaw. If stable crack growth is to be invoked then provided that the flaw growth used in an analysis is compatible with the validity limits then the above re-characterisation is adequate. However, for large flaw growth the user should refer to [IV.5.3], and its supporting references, where differences in a modified J parameter (defined in [IV.5.4]) are reported as a function of crack growth and a′/t. The study goes on to suggest a constant ratio (for a given a′/t) between the value of J determined for the complex cracked pipe and that for the through wall flaw.

If this approach is adopted care will be needed in several areas to ensure that the leak-before-break case remains conservative. In reducing the section thickness, for example, the stresses in the remaining section must be increased to compensate for the loss of load-bearing area. Although this is conservative when calculating the limiting length of a through-wall flaw, the flaw length at breakthrough could be under-predicted as a result of the increased stresses. In this example it is therefore recommended that the breakthrough length is also calculated for a semi-elliptical flaw of length l′ and depth (t-d) having the same aspect ratio but based on the full section thickness; the larger of the two breakthrough lengths should be used in the subsequent calculations. In practice the limit load is unlikely to vary significantly and it may only be necessary to compare the stress intensity factor values at the deepest points of the two semi-ellipses to determine which has the greater length at breakthrough. Also, since the crack-opening area is proportional to the applied stress and any flow reduction due to friction is proportional to the flow path length (and therefore the wall thickness) the crack-opening area and leak rate calculations should be based on a through-wall flaw in the full section thickness in order to ensure that the predicted leakage remains conservative.

The flaw discussed above is just one example of a whole class of possible complex flaws which might require analysis. Other flaws may well need to be characterised in different ways in order to make satisfactory leak-before-break cases.

**IV.5.5.2 Calculation of limiting flaw lengths**

As part of the leak-before-break procedures, the limiting length of a through-wall flaw at the position of the initial surface flaw must be calculated. It is recommended that this is done using the procedures of I.4. It is important that the minimum limiting length is calculated for the most onerous loading condition, (this could be a frequent or seismic loadings case) using lower bound material properties relevant to the flaw location (eg. weld, parent or heat affected zone material). Where appropriate, stable ductile tearing can be invoked within validity limits.

In determining the most onerous loading conditions, secondary stresses need to be considered. The treatment in III.2 includes Stress Intensity Factors (SIF’s) for completely self balancing through-wall residual stress distributions, representative of those which might arise from some welding processes. These SIF’s are dependent on wall thickness rather than flaw length. Results of an experimental programme designed to investigate the influence of in-plane self-balancing residual stress fields on the limiting flaw length of through thickness flaws is reported in [IV.5.5].
IV.5.5.3 Calculation of flaw length at breakthrough

Since the flaw length at breakthrough determines whether the initial failure results in a leak or a break it is important to correctly predict the shape of the flaw as it grows to penetration.

Ligament failure should be assessed using the stresses associated with normal operating conditions unless some other operating regime, prolonged operation at reduced pressure for example, leads to an increased flaw length at breakthrough. In calculating the breakthrough length it is assumed that ligament failure is not preceded by instability at the surface-breaking points of the flaw. However, the growth calculations may indicate that unstable growth in the length direction can occur before the flaw has grown fully through the wall. This result may be an artefact of the assumed flaw shape (e.g., a semi-circular flaw), or the use of limited ductile tearing. These aspects should be considered before concluding that a leak-before-break case cannot be made.

To ensure that a leak can be detected, it is important that flaw lengths (and hence crack opening areas) at, and following, breakthrough are not over predicted. It is recognised that when ligament failure first occurs, the flaw may not penetrate the wall along its entire length with a rectangular shape, as shown in Figure IV.5.4(a). Furthermore, it is recognised that the crack length at breakthrough, defined in terms of the flaw re-characterisation rules of II.3, is itself likely to be an over-estimate of the actual flaw length. Immediately following breakthrough, therefore, a cross-section of the flaw might appear as shown in Figure IV.5.4(b) for example. As a consequence, the initial rate of leakage from the flaw may be significantly less than predicted on the assumption of a uniform flaw length equal to the flaw length at breakthrough, as determined by ligament instability and flaw re-characterisation rules. In general this is not of concern since before the flaw can grow to a limiting length it will first grow to the breakthrough length, as determined by ligament instability and re-characterisation rules. This argument though relies on the fact that if the flaw extends in length it will grow in such a way as to tend towards a rectangular shape. However, the stress distribution may be such that the flaw can increase in length whilst not tending towards a rectangular shape, but rather maintaining the flaw shape at breakthrough, as shown in Figure IV.5.4(b) without re-characterisation. The above argument no longer holds for such cases and estimates of crack opening area based on a rectangular shape are non-conservative.

Recommendations are therefore given here for the flaw shape before, at and after breakthrough for cracked plates or cylinders subjected to either subcritical fatigue/stress corrosion or ductile tearing situations. Figs. IV.5.5 and IV.5.6 show the typical flaw shapes for subcritical crack growth both during the surface crack growth (Fig. IV.5.5) and at and after wall penetration (Fig. IV.5.6). The recommendations are based on the investigation in [IV.5.6] in which both experimental and analytical studies on cracked pipes and plates are reported.

In Figs. IV.5.5 and IV.5.6 a distinction is made between initially short flaws and very long flaws and also between predominantly tensile loading and through-wall bending. For mixed situations with both tensile and through-wall bending or moderately long initial flaws, interpolation between each case can be made. In general it is assumed that the load levels are below yield so that plasticity effects should only have a small influence on the results. For fatigue crack growth, the through-wall bending is assumed to be imposed at an R-ratio near zero. The flaw shapes in Figs. IV.5.5 and IV.5.6 denoting bending are for pure bending. As soon as there exists a small membrane component of the stresses perpendicular to the flaw, the flaw shape will behave more as the tensile loaded geometries.

With reference to Fig. IV.5.5, the following observations are made for the flaw shapes for subcritical surface flaws starting from initially shallow flaws:
Surface flaw growth

a) Short surface flaw, tensile loading, Fig. IV.5.5a.  
The flaw grows both in the depth and length direction and does not significantly change its original aspect ratio (length to depth) during growth. The aspect ratio tends to 2.6 as the flaw reaches the back surface.

b) Long surface flaw, tensile loading, Fig. IV.5.5b.  
The flaw grows mainly in the depth direction so that the aspect ratio decreases during growth. This case is valid for very long initial surface flaws.

c) Short surface flaw, through-wall bending, Fig. IV.5.5c.  
The flaw grows both in the depth and length directions but much more rapidly in the length direction, especially for deep surface flaws. This makes the aspect ratio quite large before wall penetration.

d) Long surface flaw, through-wall bending, Fig. IV.5.5d.  
Also in this case the flaw tends to grow more along the free surface than at the deepest position. However, depending on the initial flaw size the aspect ratio may decrease as the flaw approaches the back surface. The final aspect ratio before wall penetration is similar to the case in Fig. IV.5.5c.

Wall penetration

Supported by the experiments at AEA Technology, [IV.5.7-9], and at Yokohama National University, [IV.5.10-15], the back surface flaw length at wall penetration will be small, at least if the nominal stress is below yield. In addition, the front surface flaw length at breakthrough will not be significantly different from the flaw length immediately before wall penetration. From the comparative analyses of these experiments reported in [IV.5.6], the following flaw shape is recommended for the through-wall flaw immediately after breakthrough with reference to Fig. IV.5.6:

\[ 2a_1^* = \text{surface crack length} \ 2a_1 \ \text{just before wall penetration} \]

\[ 2a_2^* = \min(2t, 2a_1/4) \]

Here \( 2a_1 \) and \( 2a_2 \) are the front and back face flaw lengths, respectively and \( t \) is the wall thickness. The asterisk represents the conditions at wall penetration. Thus, the flaw shape at breakthrough is defined basically from the flaw shape immediately before wall penetration. The back face flaw length is set to a sufficiently small value which compares well with the reported fatigue experiments. This procedure is believed to work well if the load levels are sufficiently low to prevent significant ductile tearing after wall penetration. The back face flaw length at wall penetration is dependent on two parameters because for very long surface flaws, a back surface length \( 2a_1/4 \) would still be quite large, in conflict with experimental observations. On the other hand, for short surface flaws, e.g. a semicircular flaw, a back surface length equal to \( 2t \) will in general be larger than experimental observations.
**Flaw growth after wall penetration**

After wall penetration, the flaw shapes again depend on the type of loading and the flaw shape before wall penetration. With reference to Fig. IV.5.6, the following comments are made for the flaw shapes for subcritical through-wall flaws after wall penetration starting from deep surface flaws of different lengths just before breakthrough:

a) **Short flaw, tensile loading, Fig. IV.5.6a.**
   Flaw growth takes place both at the front and back surfaces. The flaw growth at the back surface is faster than at the front surface so that the flaw tends towards a rectangular shape. For pure tensile loading the relative difference between the flaw lengths (flaw angles for cylinders) at the back and front surfaces is, in general, less than 10% after the crack at the front surface has grown to 1.5 times its length at wall penetration. A rectangular flaw shape is reached after the flaw at the front surface has grown to twice its length at wall penetration.

b) **Long flaw, tensile loading, Fig. IV.5.6b.**
   Flaw growth takes place mainly at the back surface until the flaw has reached a near rectangular shape. This refers to the case with a very long starting flaw.

c) **Short flaw, through-wall bending, Fig. IV.5.6c.**
   Here the flaw grows much faster along the front surface compared to the back surface and a rectangular flaw shape is not reached. Note that here the starting case is a short surface flaw would grow to a long and deep flaw before wall penetration, compare Fig. IV.5.5c.

d) **Long flaw, through-wall bending, Fig. IV.5.6d.**
   The starting flaw is here a long and deep surface flaw. Also in this case the flaw grows faster along the front surface compared to the back surface even if it is not as pronounced as in Fig. IV.5.6c. For both cases shown in Fig. IV.5.6c and IV.5.6d, the stress intensity factor is negative at the back surface points at wall penetration and this, in general, causes a small back face flaw length at wall penetration. Gradually, as the front surface flaw length is expanded, the back surface flaw length start to increase. However, the flaw length at the back surface always lags behind the front surface.

**Flaw shapes at breakthrough for ductile tearing situations**

**Fig. IV.5.7** is applicable when the loads during the subcritical flaw growth are very large (compared to yield), or if the cracked component is subjected to an increasingly high monotonic load.

The recommended back surface flaw length at wall penetration for high tensile loading is half the front surface flaw length just before wall penetration, **Fig. IV.5.7a**. This is based on both numerical studies and experimental observations reported in [IV.5.6]. In [IV.5.6] it was observed from the finite element study that the plastic zone size in the ligament in front of the deep surface flaw developed very quickly up to a distance corresponding to half the front surface flaw length for each flaw geometry considered. Furthermore, the J-integral values

WEM/SINTAP/PROC_7/CHAP_IV/IV_5 REGP (05/11/99)
were quite high and uniform over this distance for tensile loading. Also, the ductile tearing experiments at AEA Technology and CEA support Fig. IV.5.7a. For the ductile tearing experiment SSTP12 [IV.5.7], after an increase of the load by 2% from that at wall penetration, the back surface flaw length increased to 90 mm or 35% of the front surface flaw length at wall penetration. For the CEA pipe test [IV.5.16], immediately after breakthrough due to ductile tearing, the outer flaw angle reached 55% of the inner surface flaw angle immediately before wall penetration.

The recommended back surface flaw length at wall penetration for high through-wall bending is set to a distance equal to the plate thickness, Fig. IV.5.7b. Very little experimental verification exists for this type of loading. However, the numerical study reported in [IV.5.6], where the J-integral values are suppressed at the deepest points of the surface flaw for plates subjected to high through-wall bending, supports a small distance of the back surface flaw length at wall penetration.

For both types of loading, the front surface flaw length at wall penetration is set to its length immediately before breakthrough plus a distance equal to the plate thickness. This is to allow for some ductile tearing also at the front surface at wall penetration which is supported by the numerical results in [IV.5.6] (high J-integral values as well as large plastic zones at the flaw intersection with the front surface) and by the CEA pipe test [IV.5.16]. For simplicity, the recommendations in Fig. IV.5.7 are valid irrespective of the initial aspect ratio of the flaw.

**IV.5.5.4 Calculation of crack-opening areas**

Crack opening area (COA) estimates for postulated through-wall flaws can vary widely depending on how the flaw is idealised, which flaw opening model is used and what material properties are assumed. This section provides outline advice on the factors which must be considered, and will influence whether or not the simplified procedure of assuming a through wall flaw can be used. For example, the methods for calculating COA in the presence of residual stress fields will show the feasibility, or otherwise, of developing a detectable through-wall flaw. It is also important to consider time dependant changes in material properties, and loadings arising from, for example, stress relaxation and redistribution processes.

Estimation methods for COA can be classified into three categories: linear elastic models; elastic models incorporating a small scale plasticity correction; and elastic-plastic models. A wide range of published solutions are available for idealised slot-like cracks in simple geometries subject to basic loadings (pressure, membrane and bending). Their accuracy varies with geometry (eg. R/t ratio), flaw size, type of load and magnitude of load. Generally the models, except for results based on detailed finite element analysis, estimate COA at the mid-thickness position; that is they do not account for crack taper arising from through-wall bending loads.

\[
A = \alpha(\lambda) \frac{\pi \sigma_{\text{m}} l^2}{2E'} \left( \left( \frac{S^2}{2} \right)^{3/2} - \left( \frac{S^2}{2} \right)^{3/2} \right) \quad \text{(IV.5.1)}
\]

If through wall bending stresses are absent or can be ignored, [IV.5.17] gives a lower bound approximation for the COA as for a through-wall flaw of length \( l \). The term in brackets
represents a first-order correction for the effects of crack tip plasticity. The factor $a(\lambda)$ is a correction to allow for bulging in terms of the shell parameter $\lambda$. For axial flaws in cylinders:

$$\alpha(\lambda) = 1 + 0.1\lambda + 0.16\lambda^2$$  \hfill (IV.5.2)

for circumferential flaws in cylinders:

$$\alpha(\lambda) = (1 + 0.117\lambda^2)^{1/2}$$  \hfill (IV.5.3)

and for meridional flaws in spheres:

$$\alpha(\lambda) = 1 + 0.02\lambda + 0.22\lambda^2$$  \hfill (IV.5.4)

The first expression is valid for $\lambda \leq 8$, the second and third expressions for $\lambda \leq 5$. These expressions for the COA were derived using thin-walled, shallow-shell theory and are strictly valid only when $R/t \geq 10$ and flaw lengths do not exceed the least radius of curvature of the shell.

Some alternative COA models in [IV.5.17 - IV.5.23] for plates, cylinders and spheres are summarised in Table IV.5.2. Background and validation to these models, specifically for cylinders with circumferential cracks, is given in reference [IV.5.24]. For circumferential flaws in cylinders the more accurate elastic-plastic model of [IV.5.18] is recommended for best estimate leak-before-break calculations where stress levels are high enough to induce significant plasticity (ie. $L_\gamma$ greater than about 0.4). However, this method requires a description of the material stress-strain curve. For bounding calculations, the linear elastic finite element results presented in [IV.5.19 and IV.5.23] are recommended. These results cover a wide range of cylinder geometries ($R/t$ from 5 to 100) and flaw lengths. Where high accuracy elastic estimates are required it should be noted that non-linear geometric deformation effects can be important in some circumstances [IV.5.25]. The solutions for plates and cylinders effectively assume that the flaws are in the centre of an "infinite" body. For many geometries this will be a reasonable approximation. However, if the flaw is close to a significant geometric constraint (eg. a pipe nozzle intersection) then local effects can influence COA; see for example references [IV.5.3], [IV.5.26-IV.5.28].

For complex geometries (such as elbows and branch junctions), unusual flaw configurations, or for high confidence calculations, it is necessary to use finite element methodology to give accurate COA results.

Mean material properties should be used to provide a best estimate of COA. Reference [IV.5.29] analyses a circumferential through wall flaw in a weld. For this situation it shows that the best estimate of COA is given by using the base metal properties (but for flaw stability $K_{\text{mat}}$ for the weld metal should be used). It is also important to allow for time dependent changes in properties.

The plant loading conditions used for COA and leakage rate estimates are usually those associated with normal operation. For pipework subjected to global transverse bending, the orientation of the resultant bending moment with respect to the potential through-wall flaw must be considered. Off centre loads can cause asymmetric crack opening (and hence non elliptical openings), partial closure or complete closure if the flaw lies totally on the compressive side (see [IV.5.3 and IV.5.30]).
For thick-walled geometries the effect of crack-face pressure, which acts to open the flaw, will be a function of crack opening: for tight flaws the mean pressure will be lower than for wide flaws. To assess the significance of such effects it is recommended that 50% of the internal pressure should be added to the membrane stress on the crack face. This value should then be reassessed when undertaking the leakage flow calculations (which usually output exit pressures), and the results iterated if necessary.

Local through-wall bending stresses can induce elastic crack face rotations which reduce effective crack opening area. If complete crack closure occurs, no leak-before-break case can be made. Significant local through-wall bending stresses may be associated with weld residual stresses, geometric discontinuities, thermal gradients, or primary loads (for example hoop stresses in a pressurised thick cylinder). References for estimating elastic crack face rotations in simple geometries are included in Table IV.5.2.

Most leak-before-break assessments are likely to be concerned with the existence or potential existence of flaws at welds. The variation in material properties at welds, the influence of the weld preparation angle and the presence of residual welding stresses all affect the COA, (see eg. [IV.5.31]).

The initial leakage rate through a flaw, which has just broken through the pressure boundary, may be significantly less than that predicted assuming a uniform flaw length equal to the re-characterised flaw length, (see discussion in Section IV.5.5.3 and Figure IV.5.4(b)). This is because when ligament failure first occurs, the flaw may not penetrate the wall along its entire length, and because the re-characterisation rules may over-estimate the actual flaw length. In general this is not of concern, since before the flaw can grow to a limiting length, it must first extend to the break-through length assumed in the COA calculations. However, for cases where through-wall bending stresses predominate, and development of a rectangular shape is unlikely, COA can be estimated using the approximation given in [IV.5.32].

### IV.5.5.5 Leak rate calculations

The calculation of the fluid flow or leak rate through a flaw is in general a complex problem involving the flaw geometry, the flow path length, friction effects and the thermodynamics of the flow through the flaw. Several computer codes have been written to predict leakage rates through flaws for a variety of fluids. Some of the more readily available codes are described below. The codes are of necessity complex and may have physical limitations as to their use; care must be taken to ensure that codes are not used in regions for which they are not valid.

For a single-phase flow the program DAFTCAT [IV.5.33, IV.5.34] calculates flow rates through rectangular-section flaws and includes the effects of friction. The crack-opening area must be input as a rectangular planform. For a diverging or converging flaw, such as might occur if significant through-wall bending is present, the program uses the approximations given in [IV.5.35]. This reference also presents simple, approximate solutions for isothermal or polytropic flows of gases in the form:

\[
Q = C_D (P_p)^{\frac{1}{2}} W L
\]  

(IV.5.5)
where $Q$ is the mass flow through an equivalent rectangular flaw of mean width $W$ and length $L$; $P$ and $\rho$ are the pressure and density of the fluid. Friction effects can be included via a variable discharge coefficient $C_D$. The above formulation can be used for parallel or tapered flaws. For the latter a lower bound to flow rate can be calculated based on the smaller of the crack-opening areas.

For two-phase flow of steam/water mixtures, PICEP [IV.5.36] and SQUIRT [IV.5.37] can be used to calculate leak rates through a variety of flaws. The two programs are similar and use the same thermal-hydraulic model for the flow. In PICEP the leaking fluid can be wet steam or initially sub-cooled or saturated water; SQUIRT requires initially sub-cooled or saturated water. SQUIRT can also account for varying flaw lengths on the outside compared to the inside of a cracked plate or shell. Both programs allow the flaw shape to be elliptical or rectangular and the crack-opening area to vary linearly through the wall thickness if required. Friction losses are included and additional losses due to path tortuosity included in an indirect manner.

All of these programs have been validated to some extent against a variety of experimental data and reasonable agreement with experiment was obtained [IV.5.33], [IV.5.36], [IV.5.37]. In the case of the two-phase flow, programs and validation includes comparisons with flow rates through artificial flaws in the form of machined slots or parallel plates and flow rates through circular pipes.

Whilst flow rate measurements have been made on real cracks [IV.5.8-9, IV.5.38-40], the extent of validation for such flaws is relatively small and the agreement with theory generally less good. The likely accuracy of the leak rate predictions for both single and two-phase flows depends on a variety of factors and must be judged by examining the available validation data.

Friction effects are important and there is a difference in approach between the various codes. For example, PICEP and SQUIRT use an established correlation between sand roughness (but converted to surface roughness, $R_a$) and friction factor, $f$, based on pipe experiments, together with an empirical tortuosity term. However, relevant information on tortuosity is limited. In DAFTCAT, an empirically derived relationship between surface roughness and friction factor is used, and this is validated for $f \leq 0.25$ [IV.5.41]. In principle, the DAFTCAT approach is simpler, as only one parameter, $R_a$, is required. It should be noted that expert guidance may be required in interpretation, as roughness measurements depend on a number of parameters; in particular the measured $R_a$ value increases as the sampling length over which it is measured increases. This is illustrated in [IV.5.42] which presents data for surface roughness for a number of different flaw types. In the absence of specific $R_a$ data the lower values quoted in [IV.5.42], corresponding to the shorter traverse length measurements, can be used as indicative values for the determination of $f$ in flow rate calculations using DAFTCAT, or similar codes. These values are reproduced in Table IV.5.3 which includes, where appropriate, mean values and standard deviations, and these data can be used in sensitivity studies.

Formulations for friction factor, $f$, show it to be a continuous function which increases as roughness increases or flaw width reduces. However, there is a lower bound to friction, corresponding to smooth flow (see eg [IV.5.43]), and there is experimental evidence which shows that $f$ reaches an effective maximum; these aspects are discussed more fully in [IV.5.44]. The effective maximum friction factor, $f_{\text{max}}$, is dependent upon surface geometry.
In [IV.5.45] a theory is advanced to justify the existence of $f_{\text{max}}$ and this is assessed against experiments using relatively large scale conforming surfaces (i.e., one surface is manufactured and the opposing one is a replica). For the surface of most relevance to structural flaws, the random roughness, $f_{\text{max}}$ was approximately 0.2. For a very regular and stepped surface $f_{\text{max}}$ was unity. This range of values has been confirmed by experimental data on flow through real flaws: references [IV.5.36] and [IV.5.39] report experiments on fatigue cracks; [IV.5.46] reports measurements of flow through a flaw in a defective weld. These results are discussed collectively in [IV.5.44]. It should be noted that the above discussion on $f$ values relates to fully developed turbulent flow; higher values can occur in laminar flow, but, in general, these are of little interest in leak before break. To estimate $f$ for a LbB calculation an appropriate value for $R_a$ should be selected and input into an equation for $f$ (DAFTCAT will do this automatically). If $f \leq 0.25$ then the sensitivity of the flowrate calculation to $f$ should be investigated using values between 0.25 and 1. If low values for $f$ ($<\approx 0.01$) are calculated then again remedial action is required. DAFTCAT will do this automatically, otherwise $f$ needs to be set to the minimum value appropriate to the flow Reynolds Number (see eg [IV.5.43]), and this is an iterative process.

Finally, in assessing flow rate calculations consideration should be given to the potential for flow reduction mechanisms such as blocking of the flaw by oxide growth or by particle or debris entrapment. No firm advice can be offered on how to assess such effects, and any judgements will have to be based on knowledge of the particulate and/or oxidation mechanisms, and the calculated COA.

**IV.5.5.6 Leak detection and flaw stability following breakthrough**

Any leak-before-break procedure must show that the leaking flaw remains stable for a sufficient time to allow the leak to be detected. This time for detection should include that necessary to ensure that the signal is not spurious, or that to unambiguously identify the source of the leak and the subsequent action required. The stability of the leaking flaw needs to be assessed in terms of the margins to criticality and the potential for further flaw growth. If further time dependent flaw growth can occur then margins on length and time to failure need to be demonstrated. The assessed time to failure, in conjunction with the estimated flow rate, permits a suitable leak detection system to be selected.

A wide range of leak detection systems is available. References [IV.5.47] and [IV.48] give some information and guidance on systems that are available; here only a brief outline is given in terms of two broad categories: global and local. In the former category are leak detection systems that monitor large areas of plant or segregated regions. Examples include sump pumps, pumps for water systems, humidity detection for steam leaks, gas levels in air for gaseous systems, and radiation monitors for nuclear systems. All global systems detect all leaks (including, for example, valve glands, seals, etc), and hence any leakage identified by the monitoring equipment needs to be investigated and the source established. The response times for such systems are relatively long and depend on plant segregation.

Local leak detection systems monitor specific plant features (e.g., a weld) or a well defined area (e.g., length of pipe). Some detectors are medium or plant specific. For example, moisture sensitive tapes only work in water or steam systems where condensation can take place on the outer surface.
Leakage through flaws generates acoustic emission that is transmitted through the structure, and, in some circumstances, through the air. Wave guide and microphone systems have been developed which offer flexible and sensitive leak detection capabilities for a wide range of fluids. Details of design and deployment depend on applications.

IV.5.7 Assessment of results

The final step in undertaking the recommended leak-before-break procedure is to carry out a sensitivity analysis. The sensitivity analysis must take into account the range of likely variations in the main parameters used in the calculations. It is particularly important to ensure that the sensitivity of the results to variations in material properties, applied loads and the predicted crack-opening areas and leak rates is investigated.

In carrying out the sensitivity analysis it is important to realise that, unlike the procedures in Chapter 1, where the use of upper-bound loads and stress-intensity factors together with lower-bound material properties and collapse solutions helps ensure that the integrity assessment is always conservative, a leak-before-break case made in this way would not necessarily be conservative. Although these bounding values provide conservative estimates of critical flaw length and are therefore recommended for the calculation of limiting lengths they minimise the flaw length at breakthrough and maximise the crack-opening displacement both of which are non-conservative when making a leak-before-break case. Best-estimate values should therefore be used to calculate the flaw length at breakthrough and crack-opening area and then the effect of varying input parameters examined.

When considering flaw stability at breakthrough, maximum conservatism is ensured by the use of lower bound material properties for the calculation of flaw growth in the surface direction, and the use of upper bound material properties for the calculation of through-thickness flaw growth and ligament instability. For conservatism in the prediction of crack-opening area, however, the reverse conditions could be adopted: the use of upper bound material properties for the calculation of flaw growth in the surface direction and the use of lower bound material properties for the calculation of through-thickness flaw growth and ligament instability. The sensitivity of results to methods used for the determination of flaw length at breakthrough (such as the use of local or global limit load solutions) should also be examined separately for stability and crack-opening area considerations.

Care should be taken to properly account for all loadings that may be imposed. Residual welding stresses and fit-up stresses, for example, are often not known to the same degree of precision as thermal, pressure and other operational stresses. It is important therefore that the sensitivity calculations reflect this uncertainty by allowing a suitably wide range of variation for these parameters.

The requirement to use best-estimate data should be borne in mind when choosing the analysis level. Where ductile tearing is likely to occur the use of such tearing provides more accurate estimates of limiting and breakthrough flaw lengths than an analysis based on initiation toughness. In practice the choice of level is likely to depend on other factors such as the availability of materials data. Nevertheless it is important from the point of view of assessing appropriate margins that any excessive conservatisms or possible non-conservatisms in the analysis are recognised and accounted for.

Prescribed margins are not advocated in this Section, and it is for the user to determine what margins are acceptable. It also needs to be recognised that what constitutes an adequate
margin in one particular application may not be appropriate in another. Thus whether or not the margins demonstrated by the sensitivity analysis are deemed adequate is left to the judgement of the user. Although no direct guidance is given on quantifying what constitutes an adequate margin there are certain factors which should be taken into account when assessing the adequacy or otherwise of margins. These include the levels of confidence in the input data used in the calculations, any simplifying assumptions or approximations that may have been necessary, and whether or not the consequences of a sudden, break failure are tolerable.

When the procedure is used to assess discrete flaws, a possible result is that ligament failure may not be predicted under the prescribed loading conditions and neither a leak nor a break occurs. In such a case the sensitivity analysis should be used to determine the limiting conditions for ligament failure to occur and whether the failure would result in leak or a break.
IV.5.6 References


[IV.5.31] P Dong, S Rahman, G Wilkowski, B Brickstad and M Bergman, Effects of weld residual stresses on crack-opening area analysis of pipes for LBB applications, LBB 95; Specialist meeting on Leak Before Break in Reactor Piping and Vessels; Lyon, France, October (1995).


[IV.5.42] G Wilkowski, S Rahman, N Ghadiali and D Paul, Determination of crack morphology parameters from service failure for leak-rate analyses, LBB 95; Specialist meeting on Leak Before Break in Reactor Piping and Vessels; Lyon, France, October (1995).


[IV.5.44] T C Chivers, Assessments of fluid friction factors for use in leak rate calculations, LBB 95; Specialist meeting on Leak Before Break in Reactor Piping and Vessels; Lyon, France, October (1995).


[IV.5.48] T C Chivers, Aspects of leak detection, LBB 95; Specialist meeting on Leak Before Break
## Consideration Influence on Leak-before-break Arguments

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Influence on Leak-before-break Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Size</td>
<td>For given operating conditions and operating stress, leak rates will be less for smaller pipes.</td>
</tr>
<tr>
<td>Stresses</td>
<td>For a given geometry, material and temperature, LbB margins tend to reduce as stress levels increase.</td>
</tr>
<tr>
<td>Components (Elbows, tees, valves, etc)</td>
<td>Likely to have complex stress fields which complicate leak-before-break arguments and geometric stress raisers which can promote in-service degradation.</td>
</tr>
<tr>
<td>Welds and Castings</td>
<td>Flaws are more likely to occur in these features than in straight forged pipe made to modern standards.</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Low yield stress and low fracture toughness make it more difficult to demonstrate a leak-before-break case.</td>
</tr>
<tr>
<td>Susceptibility to Degradation</td>
<td>Locations should be ranked against mechanisms such as fatigue, continuum damage, ageing, etc. Other mechanisms such as stress corrosion cracking, erosion corrosion, etc may preclude a leak-before-break case.</td>
</tr>
<tr>
<td>Leak Detection</td>
<td>The detection system used may have to change for different potential flaw locations, and leak rates.</td>
</tr>
<tr>
<td>Consequences</td>
<td>Acceptability of guillotine failure may determine which locations should be assessed.</td>
</tr>
<tr>
<td>Inspection</td>
<td>History or feasibility of future inspections may be a crucial factor in choosing locations for assessment.</td>
</tr>
</tbody>
</table>

**TABLE IV.5.1 GUIDANCE ON SELECTION OF ASSESSMENT SITES AROUND A PIPE SYSTEM**
<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>PRIMARY LOADING</th>
<th>ELASTIC OR SMALL-SCALE YIELDING</th>
<th>ELASTIC-PLASTIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>Membrane</td>
<td>Westergaard [IV.5.21]</td>
<td>Wuthrich [IV.5.17] (Dugdale model) -</td>
</tr>
<tr>
<td></td>
<td>Membrane + TWB</td>
<td>Miller [IV.5.20]</td>
<td>-</td>
</tr>
<tr>
<td>Spheres</td>
<td>Pressure</td>
<td>Wuthrich [IV.5.17] R/t &gt; 10, λ ≤ 5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pressure + TWB</td>
<td>Miller [IV.5.20]</td>
<td>-</td>
</tr>
<tr>
<td>Cylinders</td>
<td>Global loads + TWB</td>
<td>Add elastic components</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Axial Cracks</td>
<td>Knowles &amp; Kemp [IV.5.19] 5 ≤ R / t ≤ 100</td>
<td>Wuthrich [IV.5.17] (Dugdale model) -</td>
</tr>
<tr>
<td></td>
<td>TWB</td>
<td>Knowles &amp; Kemp [IV.5.19] 5 ≤ R / t ≤ 100</td>
<td>-</td>
</tr>
<tr>
<td>Cylinders with</td>
<td>Pressure</td>
<td>Knowles &amp; Kemp [IV.5.19] 5 ≤ R / t ≤ 100</td>
<td>Wuthrich [IV.5.17] (Dugdale model) Langston IV.5.18 5 ≤ R / t ≤ 20</td>
</tr>
<tr>
<td></td>
<td>Pressure &amp; Global Bending</td>
<td>Add elastic components</td>
<td>Wuthrich [IV.5.17] (Dugdale model) Kumar [IV.5.22] 5 ≤ R / t ≤ 20</td>
</tr>
<tr>
<td></td>
<td>TWB</td>
<td>Knowles &amp; Kemp [IV.5.19] 5 ≤ R / t ≤ 100</td>
<td>-</td>
</tr>
</tbody>
</table>

Where the estimation model gives centre-crack opening displacement rather than area, an elliptical crack opening shape should be assumed (i.e. Crack Opening Area = \( \frac{\delta}{\Pi / 4} \)).

**TABLE IV.5.2 CRACK OPENING AREA METHODS FOR SIMPLE GEOMETRIES AND LOADINGS**
<table>
<thead>
<tr>
<th>Crack Mechanism</th>
<th>Material</th>
<th>$R_a$ Range ($\mu m$)</th>
<th>Average $R_a$ ($\mu m$)</th>
<th>Standard deviation ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intergranular stress corrosion cracking</td>
<td>Stainless Steel</td>
<td>0.64 to 10.5</td>
<td>4.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Fatigue (air)</td>
<td>Stainless Steel</td>
<td>8.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue (air)</td>
<td>Carbon Steel</td>
<td>3 to 8.5</td>
<td>6.5</td>
<td>3</td>
</tr>
<tr>
<td>Corrosion Fatigue</td>
<td>Carbon Steel</td>
<td>3 to 11</td>
<td>8.8</td>
<td>3</td>
</tr>
</tbody>
</table>

**TABLE IV.5.3** SUMMARY OF SHORT WAVE LENGTH SURFACE ROUGHNESS VALUES, FROM REFERENCE [IV.5.42]
\( l_c \) IS THE CRITICAL LENGTH OF A FULLY-PENETRATING THROUGH-WALL CRACK

**FIGURE IV.5.1** THE LEAK-BEFORE-BREAK DIAGRAM
Fig. IV.5.2  Flow Chart For Leak-Before-Break Procedure
THE COMPLEX DEFECT IN (a) MAY BE SEPARATELY ASSESSED AS THE TWO SIMPLE DEFECTS IN (b) AND (c)

FIGURE IV.5.3 EXAMPLE CHARACTERISATION OF A COMPLEX DEFECT
FIGURE IV.5.4  SCHEMATIC FLAW PROFILES AT BREAKTHROUGH
a) Tension, short crack

b) Tension, long crack

c) Bending, short crack

d) Bending, long crack

FIGURE IV.5.5 DEVELOPMENT OF FLAW SHAPES FOR SUBCRITICAL SURFACE FLAW GROWTH
FIGURE IV.5.6 DEVELOPMENT OF FLAW SHAPES FOR SUBCRITICAL THROUGH-WALL FLAW GROWTH

a) Tension, short crack

b) Tension, long crack

c) Bending, short crack

d) Bending, long crack
FIGURE IV.5.7  RECOMMENDED RE-CHARACTERIZATION OF FLAWS AT BREAKTHROUGH SUBJECTED TO DUCTILE TEARING LOADING

a) Tensile Loading

b) Through-Wall Bending
IV. 6 : CONSIDERATION OF PROOF TESTING AND WARM PRESTRESSING

IV.6.1 Introduction

This section describes how the loading history due to i) proof or overload tests or ii) warm prestressing of a structure containing flaws may be taken into account when performing an integrity assessment using the Fracture Procedures described in this document. The effect of loading history is considered with regard to mechanical relaxation of residual stresses and enhancement of lower shelf fracture resistance. The latter is only applicable where the pre-load constitutes a warm prestress (see clause IV.6.3).

Procedures are set out below which enable these effects to be quantified. In practice, the different phenomena may interact and it may not be possible to separate the different effects simply. This section does not cover sub-critical crack growth in service.

IV.6.2 Proof or overload testing

In the assessment of a cracked component that has been proof tested, the residual stress level assumed in the fracture analyses can be taken [IV.6.1] as the lower of:

\[ \sigma'_{\text{Y}}, \text{or} \left( 1.4 - \frac{\sigma_{\text{ref}}}{\sigma_f} \right) \sigma'_{\text{Y}} \]  

(IV.6.1)

where

- \( \sigma_{\text{ref}} \) is the reference stress under the proof load conditions;
- \( \sigma'_{\text{Y}} \) 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.

Note that the assumed residual stress level should always be \( \geq 0 \).

Where a crack in a proof loaded structure is believed to have initiated in service, after the proof loading, the residual stress level in fracture analysis should be taken as [IV.6.2] the lower of

\[ \sigma_{\text{Y}}, \text{or} \left( 1.1 \sigma'_{\text{Y}} - 0.8 \sigma_a \right) \]  

(IV.6.2)

where

- \( \sigma'_{\text{Y}} \) is the appropriate material yield strength at the proof test temperature and \( \sigma_a \) is the applied stress due to the proof loads at the location of interest. \( \sigma_a \) is a stress normal to the plane of the flaw and should be taken as the lower of the membrane stress in the section containing the location of interest, or the total stress at the location of interest including membrane, bending and stress concentration effects. The total stress can be lower than the membrane stress if the bending stress is negative or if there is a stress de-concentration effect, such as at the convex side of a welded joint with angular misalignment.
IV.6.3 Warm prestressing

A warm prestress (WPS) is an initial pre-load applied to a ferritic steel structure containing a pre-existing flaw which is carried out at a temperature above the ductile-brittle transition temperature, and at a higher temperature or in a less-embrittled state than that corresponding to the subsequent service assessment. A WPS argument differs from a proof-test argument in conferring added resistance to fracture under the assessment conditions; that is, it is considered to elevate the stress intensity factor at failure, $K_f$, above the corresponding fracture toughness, $K_{mat}$, in the absence of the WPS [IV.6.3- IV.6.8].

Although there is some evidence [IV.6.2, IV.6.8] that warm prestressing may produce benefits in terms of both residual stress relaxation and improvement in fracture resistance, the evidence is not conclusive. It is therefore recommended that where some relaxation in residual stress has been adopted in accordance with equation (IV.6.1), no improvement in fracture toughness should be claimed in the same assessment through the WPS argument.

The WPS review presented in Ref. [IV.6.2] suggests that repeated prestressing does not significantly increase fracture resistance above the level after a single prestress. It is recommended that no extra benefit above that obtained from a single prestress should be claimed in such cases.

The WPS effect is most beneficial at low values of $K_{mat}$. Hence, this procedure is most effective for material exhibiting toughness values determined using $K_I$ and $K_Q$ values directly and not where $J_{mat}$ or $\delta_{mat}$ values are applicable due to the extent of plasticity exhibited at the service temperature.

In service assessments using the procedure of the main document, the fracture toughness used in evaluating $K_f$ is then taken as the enhanced value, $K_{mat}$.

Warm prestressing can involve three basic types of cycle (Fig. IV.6.1). $T_1$ and $T_2$ denote the temperatures at which the pre-load and re-load to failure occur, respectively, in each case. Similarly, the stress intensity factors due to the pre-load and following the unload are denoted $K_1$ and $K_2$, respectively.

a) Load-Unload-Cool-Fracture (LUCF), where the structure is pre-loaded at temperature $T_1$ to stress intensity factor $K_1$, unloaded to stress intensity factor $K_2$, cooled to temperature $T_2$ and re-loaded to fracture. The case where $T_2 = T_1$ is permissible if hardening mechanisms have occurred prior to the re-load to fracture.

b) Load-Cool-Unload-Fracture (LCUF), where cooling to $T_2$ takes place prior to unloading and re-loading to fracture.

c) Load-Cool-Fracture (LCF). This is similar to the LUCF cycle except that no unloading occurs prior to the imposition of extra load to fracture.

The greatest benefit in terms of maximising $K_f$ is given by the LCF cycle, the least by the LUCF cycle with full unloading. Intermediate forms of cycle, where partial unloading occurs prior to re-loading to failure, and where the temperature and pressure are simultaneously reduced, give benefits lying between these two limits.

This sub-Clause gives advice on quantifying the benefit of a WPS. Two levels of argument are set out: firstly, a simplified lower-bound approach; and secondly, a more detailed route.
based on calculations, which may be of value when the simplified route is insufficient. The detailed route is consistent with a best-estimate prediction of fracture load.

For a WPS argument to be made according to the Procedure of this Clause, the following conditions should be met:

a) the failure mechanism at the service condition should be by cleavage.

b) The flow properties of the material should increase between the WPS and the service failure condition.

c) There should be no significant sub-critical crack growth between the WPS and the service failure condition.

d) The stress intensity factor $K_1$ due to the WPS loading should exceed the baseline fracture toughness $K_{\text{mat}}$ at the re-load condition.

There is evidence [IV.7.5, IV.7.2] that, for increasing pre-loads, the benefits on the apparent re-load fracture toughness lessen. Indeed, in the limit of extensive plasticity, the toughness determined in terms of CTOD or $J$ after WPS loading may actually be reduced compared to its value in the absence of the WPS. Ref. [IV.7.5] should be consulted for further advice in cases of large pre-loads.

e) Small-scale yielding conditions hold, that is $(K_1/\sigma_{Y1})^2/2\beta\pi$ is much less than the size of the uncracked ligament and any relevant structural dimensions. Here $\sigma_{Y1}$ is the yield strength at the pre-load and $\beta=1$ or 3 in plane stress or plane strain, respectively. The stress intensity factor $K_1$ is based on the elastic loads induced by the WPS only. No account should be taken of any plasticity induced in the preload by using $J$ or CTOD approaches for the applied conditions.

f) The pre-load and re-load should be in the same direction; that is, both tensile or both compressive at the crack tip. A compressive pre-load followed by a tensile re-load may reduce the apparent fracture toughness.

**IV.6.4 Simplified WPS argument**

Failure is avoided if the stress intensity factor during cooling is constant or monotonically falling to a value $K_2$. This corresponds to a benefit if $K_2$ exceeds $K_{\text{mat}}$, the fracture toughness in the absence of a WPS, and is consistent with maximum benefit from an LCF cycle. Margins against failure are not in general given by this simplified argument. In order to quantify margins it is necessary to use the detailed approach of IV.6.5.

A particular example of this simplified WPS argument is in the assessment of thermal transients (e.g. downshocks or blow-down conditions), where cleavage fracture would otherwise be predicted. The loading history during the thermal shock event is regarded as a WPS. It is argued that failure does not occur when the instantaneous stress intensity factor $K_i$ exceeds the corresponding $K_{\text{mat}}$ if $K_i$ is then reducing with temperature. The maximum size of flaw that satisfies this criterion can be compared with the size of the largest flaw that may have escaped detection to derive a margin on crack size. Any sub-critical growth of the latter flaw between inspection and the service assessment time should be allowed for.
### IV.6.5 Full WPS procedure

The argument is based on the LUCF cycle, allowing for partial unloading. This provides a conservative prediction of the stress intensity factor at failure, $K_f$, during the re-load compared with the other forms of WPS cycle. The fracture toughness used in service assessments using the fracture procedures of this document is then $K_f$.

The following steps should be carried out in quantifying the effect of the WPS on $K_f$ for a given structural geometry and flaw dimensions:

a) Determine the temperature and pressure corresponding to the WPS.

b) Determine the stress intensity factor decrement due to the unload, $K_1 - K_2$. It follows that $K_1 - K_2$ is independent of the magnitude of any system or residual stresses incorporated in the total stress intensity factors $K_1$ and $K_2$ at the pre-load and unload phases, and depends on the contribution due to the varying load only.

c) Evaluate the fracture toughness, $K_{mat}$, of the material at the assessment time, but neglecting the effects of the WPS. The effects of any degrading mechanisms, such as strain ageing or irradiation / hydrogen embrittlement that may have occurred between the time of the WPS and the subsequent assessment, should be taken into account. A lower bound value of $K_{mat}$ should be adopted to predict the elevation of $K_f$ conservatively (see equation IV.6.3 and IV.6.4 below).

d) Evaluate the stress intensity factor at failure (IV.6.3) from:

$$\frac{K_f}{K_{mat}} = \left( \frac{\sigma_{Y2}}{\sigma_{Y1} + \sigma_{Y2}} \right) \left( 1 + \frac{\sigma_{Y1} K_1}{\sigma_{Y2} K_{mat}} \right)$$

(IV.6.3)

where $\sigma_{Y2}$ is the yield strength corresponding to the final fracture condition. Then $\sigma_{Y2} < \sigma_{Y1}$. This Equation satisfies $K_f = K_{mat}$ when $K_1 = K_{mat}$ and $K_f \geq K_{mat}$ for $K_1 \geq K_{mat}$, as expected. Alternative equations developed and reported in Ref [IV.6.4], are shown in Ref. [IV.6.3] to give similar results to Equation (IV.6.3) on a plot of $K_f/K_{mat}$ against $K_1/K_{mat}$, with each equation predicting results within the scatter band of experimental data.

Work reported in Ref. [IV.6.9] confirms that this approach generally gives conservative predictions of toughness even after hydrogen exposure. However, it was also noted in the same reference, that the safety margins on the predictions may be slightly reduced when compared to cases without hydrogen effects. Therefore, for components that have been exposed to hydrogen, the value of $K_{mat}$ and $\sigma_{Y2}$ used in equation (IV.6.3) should be those appropriate to the hydrogen-embrittled state.

References


Figure IV.6.1  Typical laboratory warm prestress cycles  
(a) LUCF  (b) LCUF  (c) LCF