FRACTURE MODULE

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6 Fracture module

6.1 Introduction

The FITNET Fracture Module described in this section is based on fracture mechanics principles and is applicable to the assessment of metallic structures (with or without welds) containing actual or postulated flaws. The purpose of the analysis in this Module is to determine the significance, in terms of fracture and plastic collapse, of flaws postulated or 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 quality control as well as operational stages of the lifetime of a structure. The procedure is also applicable to Failure Analysis.

a) Design Stage

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 and Quality Control Stage

The method can be used for fitness-for-purpose assessment during the fabrication phase. However, this procedure should 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 should be: (i) correcting the fault in the fabrication process causing the discontinuities and (ii) repairing or replacing the faulty product.

c) Operational or In-Service Stage

The method can be used to decide whether continued use of a structure or component is possible and safe despite detected defects or modified operational conditions. If during in-service inspection defects 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).

In order to cover the above described cases, the fracture analysis of the component containing a crack or crack-like flaw is expected to be controlled by the following three parameters:

1) the fracture resistance of the material,

2) the component and crack geometry, and

3) the applied stresses including secondary stresses such as residual stresses.

If, as is usually the case, two of these parameters are known, the third can be determined by using the relationships of fracture mechanics. This Module aims to provide analytical procedure for this purpose. Consequently, the decisions that can be reached using this module are:

a) **For design of a new component**, structural significance of a postulated crack can be analysed. The dimensions of this crack should be chosen such that there is a high probability of its being detected in quality control or in-service inspections. If a crack of this size is demonstrated not to grow to a critical size over the projected lifetime of the component then no critical situation should be expected for the smaller undetected cracks. Alternatively, a critical crack size can be determined in order to specify requirements on NDE in quality control and in-service inspections.

b) **If a crack is detected in-service,** a decision can be made as to decide whether or not it is critical for the applied loading case. If necessary, the applied load can be reduced in order to avoid the critical state. If the analysis is combined with a fatigue crack extension analysis (Section 7, Route 4) the residual lifetime of the component can be predicted and, based on this, non-destructive examination (NDE) intervals can be specified which ensure a safe further service for a limited time.

An in-service inspection interval can be specified based on the residual lifetime that an assumed initial crack given by the NDE detection limit under service conditions requires to extend to its critical size. In this case the present module will be part of a fatigue crack extension analysis (Section 7). Finally, a minimum required fracture resistance of the material can be specified based on the critical crack size or the NDE detection limit under service conditions to avoid failure during the projected lifetime of the component.

A flowchart is shown in Figure 6.1 to illustrate the determination of critical crack size, critical load and required minimum fracture resistance of the material using the FITNET Fracture Module.

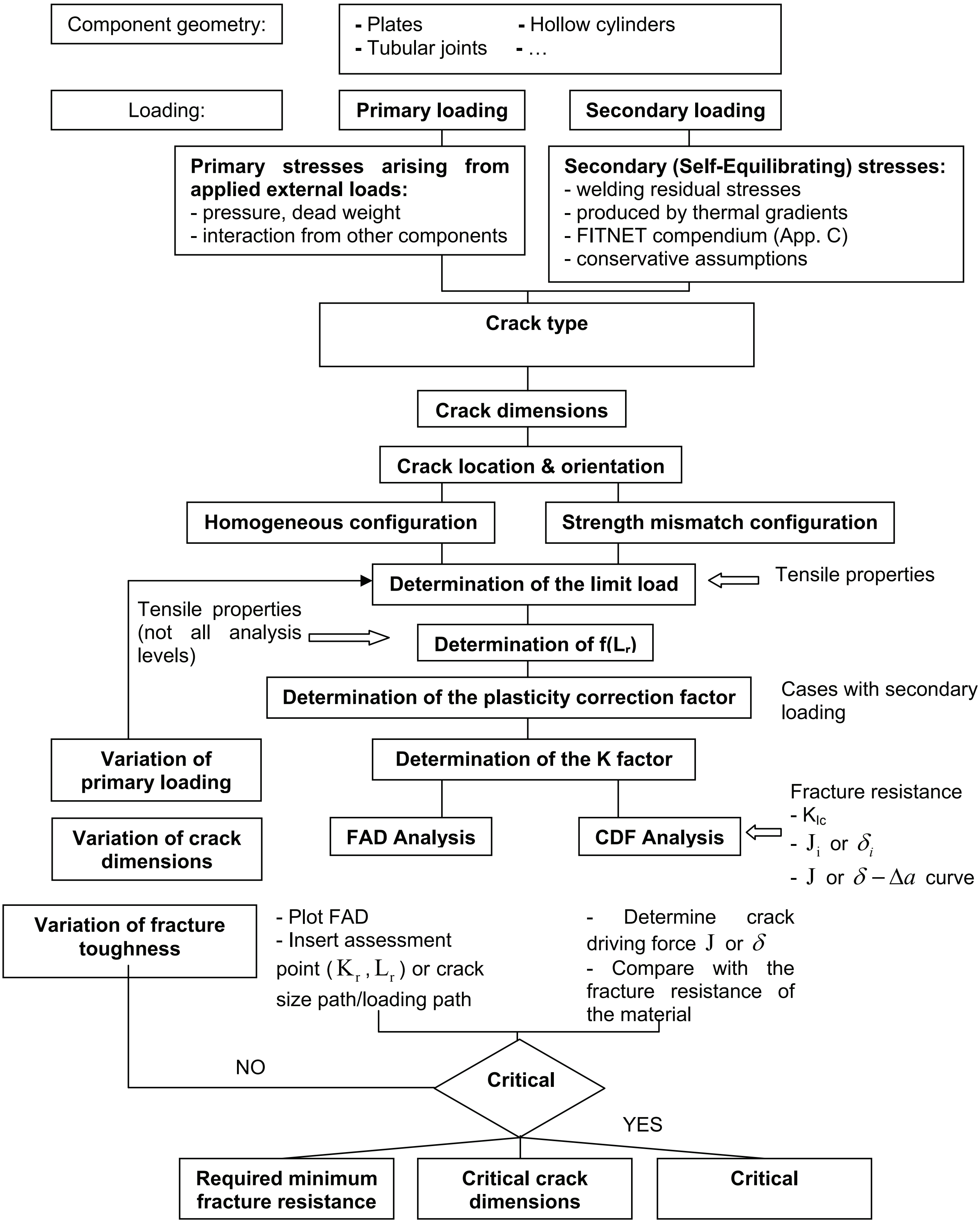


Figure 6.1 - Overall flow-chart of Fracture Module

6.2 Analysis – FAD and CDF Routes

6.2.1 FAD / CDF

Two approaches for determining the integrity of cracked structures and components have been selected for the FITNET procedures. The first uses the concept of a Failure Assessment Diagram (FAD) and the second a diagram which uses a crack driving force (CDF) curve. 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-scale 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 6.2.2, and other details of the material's stress strain curve.

A brief description of the alternative approaches follows.

6.2.1.1 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 as follows:

K_r :- The ratio of the applied linear elastic stress intensity factor, K_I, to the materials fracture toughness, K_{mat}

L_r :- The ratio of the total applied load giving rise to the primary stresses to plastic limit load of the flawed structure.

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

$$K_r = f(L_r) \tag{6.1}$$

It incorporates a cut-off at $L_r = L_r^{\max}$, 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. Figure 6.2 (a) gives an example for a structure analysed using the fracture initiation levels of analysis, and Figure 6.2(b) an example for a structure that 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 indicates 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.

6.2.1.2 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 (6.2), or in units of crack opening displacement, equation (6.3). Both are derived from the same basic parameters used in the FAD approach, the linear elastic stress intensity factor, K_r and L_r. In their simplest forms *J* is given by:

$$J = J_e\left[f(L_r)\right]^{-2} \tag{6.2}$$

where $J_e = K_e^2 / E'$ and

$$\delta = \delta_e\left[f(L_r)\right]^{-2} \tag{6.3}$$

where $\delta_e = K_I^{\,2} / (E^{/} R_e)$ and R_e is the material's yield or proof strength and $E^{/}$ is Young's modulus, E for plane stress, and $E/(1-\upsilon^2)$ for plane strain.

To use the CDF approach, for the basic option of analysis, the CDF is plotted as a function of L_r to values of $L_r \le L_r^{\max}$, 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. Figure 6.2 (c) gives an example of such a plot.

To use the CDF approach for the higher option 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 6.2 (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.

6.2.1.3 Primary and Secondary Stress Treatment Evaluation of K_r, J and CTOD

The definitions K_r, J and δ given in 6.2.1.1 and 6.2.1.2 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. However, 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, have to be taken into account. The methods for accounting for such effects are given below.

6.2.1.3.1 Evaluation of K_r From Primary and Secondary Stresses

Where loads give rise to secondary stresses, these stresses are characterised as σ^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 ρ contained in the definition of K_r in equation (6.4)

$$K_r = K_I^P(a)/K_{mat} + K_I^S(a)/K_{mat} + \rho(a) \tag{6.4}$$

where at the flaw size, *a,* of interest (taking account of any postulated flaw growth for ductile tearing, Option 1 and Option 3), $K_I^P(a)$ is the linear elastic stress intensity factor calculated for all primary stresses, $K_I^S(a)$ is the linear elastic stress intensity factor calculated for all secondary 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 primary and secondary stresses and depends not only on flaw size but also on the magnitude of the primary stresses (i.e., on L_r). A method for calculating ρ is given in Annex J.

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 σ^P or σ^S. Others are specific to only one category of loading. Procedures, solutions and references are given in Annex A, 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 ρ used for determining K_r in equation (6.4), a multiplying factor, V, can be used. If this factor is preferred, the definition of K_r changes to that in equation (6.5)

$$K_r = \left[K_I^P(a) + V.K_I^S(a)\right]/K_{mat} \tag{6.5}$$

The calculation of V is described in Annex J. The two approaches are fully compatible using the recommended definitions of ρ and V.

6.2.1.3.2 Evaluation of J_e and J from Primary and Secondary Stresses

The elastic value of *J,* is defined as

$$J_e = K^2/E' \tag{6.6}$$

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

$$J=J_e/[\,f(L_r)-\rho\,]^2 \tag{6.7}$$

Note that now the parameter ρ is separated from the elastic part of the calculation, and appears in the denominator in equation (6.7) 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 Section 6.2.1.3.1, according to equation (6.8)

$$J_e=[\,K_I^P(a)+K_I^S(a)]^2/E^I \tag{6.8}$$

and ρ is calculated following the procedures of Annex J. $f(L_r)$ is the function describing the FAD or CDF according to the Option chosen.

If the alternative to ρ, V, is to be used, equations (6.7) and (6.8) combine to become

$$J = \frac{\left[K_I^P(a)+V.K_I^S(a)\right]^2 / E^I}{F(L_r)^2} \tag{6.9}$$

6.2.1.3.3 Evaluation of δ from Primary and Secondary Stresses

The calculation of δ is a modification of the calculation of *J*. For example, δ_e, the elastically calculated value for δ, is defined as

$$\delta_e=K_I^2/E^I R_e \tag{6.10}$$

where, E^I is defined as in Section 6.2.1.3.2, and R_e is the material's yield or proof strength. δ is defined as

$$\delta=\delta_e/[f(L_r)-\rho]^2 \tag{6.11}$$

Hence, δ_e is calculated from the linear elastic stress intensity factors described in Section 6.2.1.3.1, according to equation (6.12)

$$\delta_e=[K_I^P(a)+K_I^S(a)]^2/E^I \tag{6.12}$$

and again ρ is calculated following the procedures of Annex A, and *f(L_r)* is the function describing the FAD or CDF according to the Option chosen .

As for *J* if the alternative to ρ, *V*, is to be used, equations (6.11) and (6.12) combine to become

$$\delta = \frac{\left[K_I^P(a)+V.K_I^S(a)\right]^2 / E^I}{F(L_r)^2} \tag{6.13}$$

6.2.2 Analysis Options

There are a number of different options 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, that may be chosen by the user at the outset or they may be self selected. Self selection occurs when an unsatisfactory result at one option is re-analysed at a higher option. Simple rules determine when this can be achieved, Section 6.2.3, and the optimum route minimises unnecessary work and complexity.

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

The option of analysis is characterised mainly by the detail of the material's tensile data used. There are three standardised options and two advanced options of analysis. The different standardised options produce different expressions for $f(L_r)$ which define the FAD or CDF to be used in the analysis.

A subdivision of the option 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 FITNET procedure is termed the characteristic value.

The basic option of analysis, **Option 0**, should only be used for cases where the knowledge of material is very limited. This requires values of the material's yield strength (or 0.2% proof strength) and the Charpy behaviour of the material.

The standard option of analysis, **Option 1**, is the minimum recommended option. This requires values 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 or ductile fracture. For situations where data of this quality cannot be obtained, there is a basic option of analysis, which can be based on only the material's yield or proof strength and its Charpy data. The basic option uses correlations, and as such is very conservative. It should only be used where there is no alternative. These options are described in Sections 6.3.2 and 6.4.1.

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 under-matching and overmatching; in these cases the lower of the base or weld metal tensile properties should be used. For higher degrees of mismatch, and for $L_r > 0.75$, the option of using an **Option 2** analysis, mismatch option, 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 option 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 approach is given in option 3 as the SS (Stress-Strain) option. 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. However, the analysis **Option 2** allows quicker analysis to be carried out if a parametric study on the mismatch level and the weld geometry effects is required.

Table 6.1 gives guidance on the selection of analysis option from tensile data, and Table 6.2 gives guidance on the selection of options for toughness data. Determination of these parameters is described in Section 5.4 Material Properties.

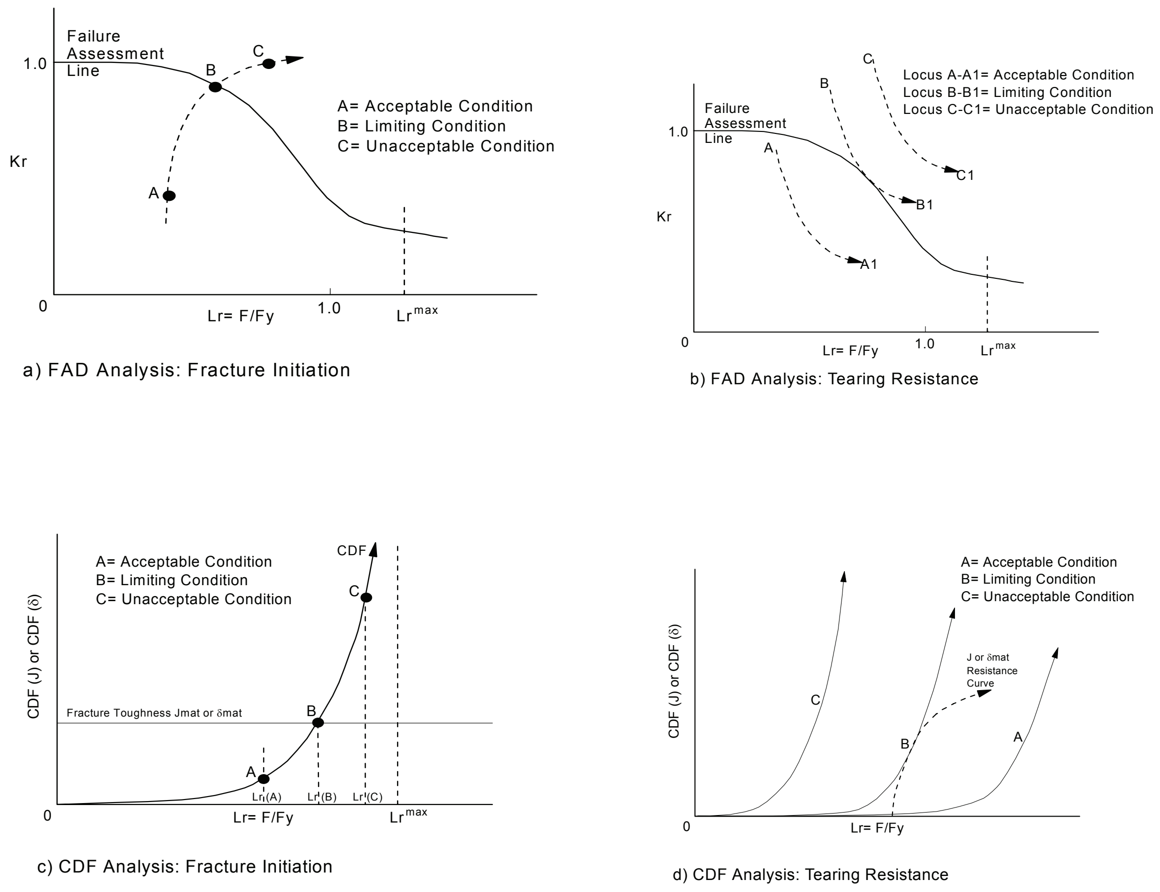
Stepwise procedures for the standard option are given in 6.3.2, and these develop to the higher standardised options as required. Procedures for the advanced options are in Sections 6.3.5, 6.3.6 and 11.2, and for the basic option in 6.4.1.

Table 6.1 - Selection of Analysis Options from Tensile Data

OPTION	**DATA NEEDED**	**WHEN TO USE**
	BASIC OPTION	
OPTION 0 Basic	Yield or proof strength	When no other tensile data available
	STANDARD OPTIONS	
OPTION 1 Standard	Yield or Proof Strength, Ultimate Tensile Strength	For quickest result. Mismatch in properties less than 10%
OPTION 2 Mismatch	Yield or Proof Strength, Ultimate Tensile Strength of both parent and weld metal. Mismatch limit loads	Allows for mismatch in yield strengths of weld and base material. Use when mismatch is greater than 10% of yield or proof strength (optional).
OPTION 3 SS (Stress-strain defined)	Full Stress-Strain Curves for both parent and weld metal.	More accurate and less conservative than options 1 and 2. Weld mismatch option included.
	ADVANCED OPTIONS	
OPTION 4 *J*-Integral Analysis	Needs numerical analysis of cracked body	
OPTION 5 Constraint	Estimates of fracture toughness for crack tip constraint conditions relevant to those of cracked structure. Needs numerical cracked body analysis	Allows for loss of constraint in thin sections or predominantly tensile loadings

Table 6.2 - Selection and Recommended Treatment of Toughness Data

	Parameters required	**Fracture mode Characterised**	**Reference in Procedure**	**Input obtained**
Basic Option	Charpy energies	All modes	5.4.8	Correlated characteristic values
Initiation Route	Fracture toughness at initiation of cracking. From three or more specimens	Onset of brittle fracture: or Onset of ductile fracture	5.4.5	Single characteristic value of toughness
Tearing Route	Fracture toughness as a function of ductile tearing From three or more specimens	Resistance curve	5.4.6	Characteristic values as function of ductile crack growth



a) FAD Analysis: Fracture Initiation

b) FAD Analysis: Tearing Resistance

c) CDF Analysis: Fracture Initiation

d) CDF Analysis: Tearing Resistance

Figure 6.2 - FAD and CDF Analysis for Fracture Initiation and Ductile Tearing

6.2.3 Guidance on Option Selection

6.2.3.1 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 sections 6.3 and 6.4 with further advice in the annexes for some of the steps.

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 options 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 or 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 Figure 6.3.

6.2.3.2 Selection of Failure Assessment Diagram - Option 0 to 5

In Section 6.3 various discrete Options are provided for deriving the shape of the failure assessment curve. A summary of these is given in Table 6.3. The Basic Option curve is the easiest to apply and requires only the yield strength to be known; Option 1 is applicable to homogeneous materials and requires a knowledge of the ultimate strength as well as the yield strength; Option 2 is a specific mis-match assessment option and requires knowledge of yield strength and ultimate tensile strength of base metal and weld metal. Option 3 requires additional information of the material stress-strain properties and can be applied either to homogeneous materials or to those cases where weld strength mis-match is an issue; Option 4 requires results of elastic-plastic finite element analysis of the defective component while Option 5 invokes constraint treatment and also requires results of detailed elastic-plastic analysis of the flawed structural component. Leak-Before-Break analysis (Section 11.2) is applicable only to fluid - containing structures. To assist in deciding whether or not to choose one of the more complex Options, 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 five Options are likely to produce similar curves. There is, therefore, likely to be little benefit in going to a higher Option 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, Option 3 curves are close to Option 1.
- For materials with Lüders strain, there is conservatism in the Option 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. Going to Option 5 may reduce this conservatism.
- 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 an Option 5 curve. In principle the Option 5 curve can be based on either the local or global 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^{max} may be imposed at loads which correspond to only small plastic strains.

6.2.3.3 Aspects of Fracture Toughness

Section 5.4.4 provides recommendations on methods for evaluating statistical bounds to fracture toughness data. The guidance in this Section should, therefore, be referred to when it is necessary to determine a value of K_{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.

6.2.3.4 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-Δa) 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.

6.2.3.5 Plastic Yield Load Analysis

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

6.2.3.6 Determination of Stress Intensity Factors

Section 5.3 (Stresses) and Annex A also contain 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.

6.2.3.7 Probabilistic Fracture Mechanics

While there is a general trend of reducing failure probability with increasing safety factor, there is no unique relationship between these two quantities. The probabilistic fracture mechanics methods in Section 11.10 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 ($L_r = L_r^{\max}$). For intermediate cases, reduced conservatism is obtained by following the detailed methods in Annex H (Reliability and Probability Principles).

6.2.3.8 Weld Residual Stresses

Annex C 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 either 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 < 0.8).

6.2.3.9 Load-History Effects

Section 11.4 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;
- Sub-critical 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 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 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-operation with no intermediate unloading.

6.2.3.10 Constraint Effects

Section 6.4 provides methods for quantifying constraint effects. In order to claim benefit from reduced constraint, it is necessary to perform the computational analysis of the cracked structural component and to have more information on fracture toughness properties. As a guide to whether this additional effort is likely to be justified, the following may be noted:

- Benefit is greatest in components subjected to predominantly tensile loading rather than bending;
- Constraint effects are more significant for structural components containing shallow 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 little benefit at low values of L_r (L_r < 0.2);
- There is little benefit for collapse-dominated cases.

6.2.3.11 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 Section. The homogeneous or base metal procedure should be used for the weld metal strength mis-match option smaller than 10% for both overmatching and undermatching. For higher option 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 over-conservative predictions, but the analysis will be safe. In order to assess whether there is likely to be value in invoking the mis-match options, 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 values of $L_r < 0.8$
- There is little benefit for cracks in undermatched welds under plane stress conditions;

Table 6.3 - Simplified Structure of the Fracture Assessment Procedure

Option	Title	Format of Tensile Data	Format of FAD and Toughness Data	Mismatch Allowance?
0	**Basic**	Yield strength only	Estimation of yield/tensile ratio (Y/T) for FAD. Toughness from Charpy energy	No
1	**Standard**	Yield strength and UTS only	Estimation of strain hardening exponent for FAD from Y/T. Fracture toughness as equivalent Kmat.	No
2	**Mismatch**	Yield strength and UTS of Parent material and weld metal	Estimation of strain hardening exponent of parent plate and weld metal for FAD from Y/T. Fracture toughness as equivalent K_{mat} for relevant zone.	Yes
3	**Stress-Strain**	Full stress-strain curves of Parent material (and weld metal)	FAD determined from measured stress-strain values. Mismatch option based on 'equivalent material' stress-strain curve.	Optional
4	**J-Integral**	Full stress-strain curve(s)	Estimation of J-integral as a function of applied loading from numerical analysis.	Optional
5	**Constraint**	Full stress-strain curve(s)	Modification of FAD based on T and Q stress approaches, Numerical analysis is required.	Possible

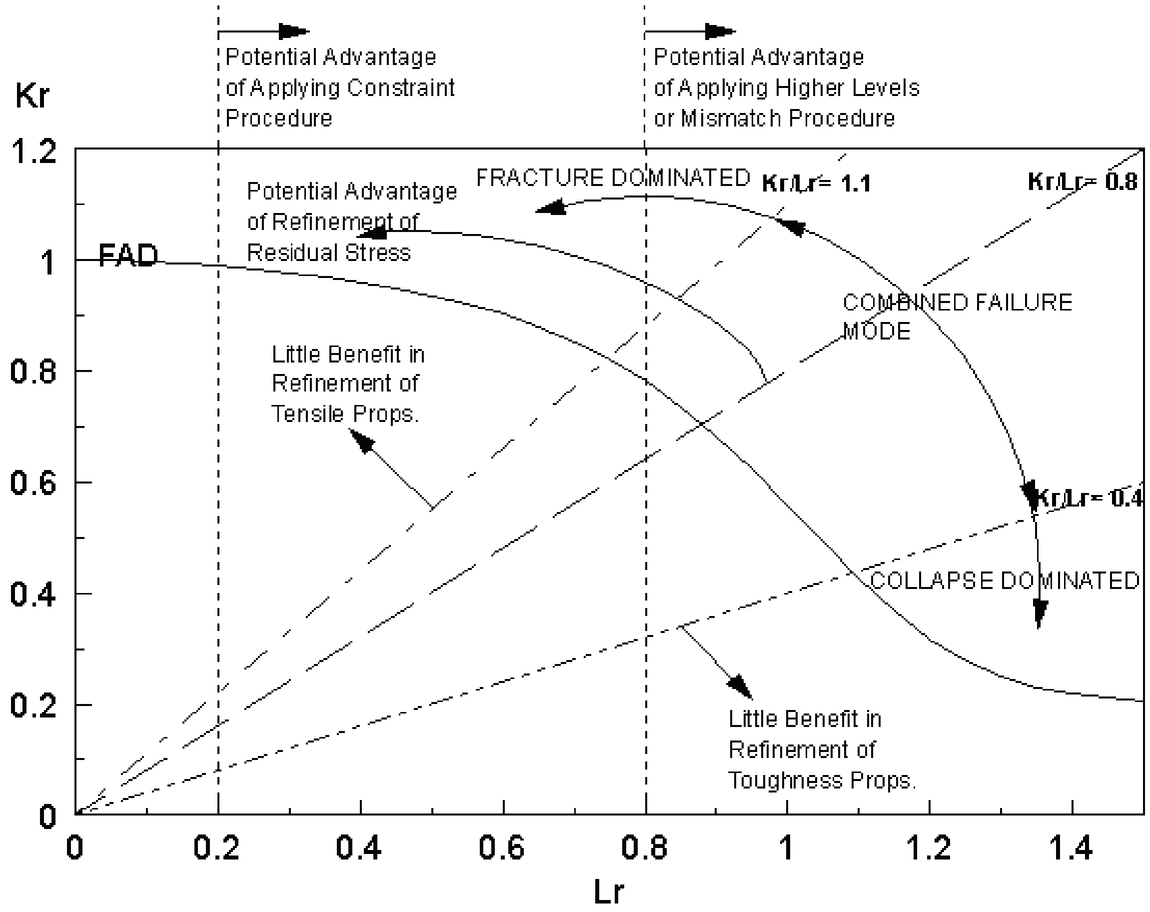


Figure 6.3 - Summary of FAD regions for consideration of potential refinement of data or analysis option

6.3 Analysis Procedures

6.3.1 Preliminary stages: assessment of objectives and available data

6.3.1.1 Objectives:

The possible objectives for using these procedures are identified in 6.1. 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 identified, 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.

6.3.1.2 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 Standard Option 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 is less than 10% and when only the yield and ultimate tensile strengths are known. This Procedure is described in detail in 6.3.2, where it deals with crack initiation only. Additional recommendations for ductile tearing analysis are given in 6.4.2. It should however be noted, 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 Option 1 Procedure may still be employed, but at the expense of additional conservatism. In such cases, the Option 2 Mismatch Procedure, 6.3.3, will give a more accurate result. Where full stress-strain curves are known, the Option 3 Stress-Strain Procedure may be employed, 6.3.4, 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 the lower constraint (6.3.6). A method for doing this is given in 6.4.3.

Equations describing the FAD and CDF for Options 1, 2 and 3 are given in detail in this section of the procedure. The advanced methods of J-integral Analysis, Constraint Analysis and Leak-Before-Break Analysis are described separately as Options 4, 5 and LBB Procedure respectively in 6.3.6, 6.3.5 and 11.2, and given in detail in 6.4.3 and 11.2. The Basic Procedure, applicable to cases where only the yield strength and Charpy data are known, is introduced and described in detail in 6.4.

The general method is the same for all options, and is outlined in the flow charts in Figure 6.5. The user may enter the procedure at any option.

6.3.2.2 gives a step-wise description of the Option 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 10.1.3. 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 option, 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 6.2.3. If a ductile tearing analysis is required, the procedures given in Section 6.4.2 can be employed fro all Standard and Advanced Options.

The treatment of tensile data to devise the parameters necessary to construct the appropriate FAD is summarised in Figure 6.5.

6.3.1.3 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, un-fused areas, 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 Annex E, 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.

6.3.1.4 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 6.2.1.3 A compendium of weld residual stress profiles is given in Annex C.

6.3.1.5 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 option of the analysis to be followed. Treatment of the tensile data is described in 5.4.3 In all cases, where scatter in the material's tensile properties exist, the minimum value should be used to calculate L_r consistent with the option of analysis, while best estimates should be used to calculate $f(L_r)$ and $L_r^{\max}$. Similarly, for mismatched cases, realistic values should be used to calculate the Mismatch Ratio, M and minimum values used for calculating L_r .

6.3.1.6 Material's Fracture Properties

All standard and advanced options 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 toughness 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_{mat}, J_{mat}, or δ_{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 (6.2.2, see also Table 6.2). The value chosen depends upon the confidence option or reliability required of the result. Appropriate procedures for determining characteristic values of toughness are given in 5.4.4

Where it is not possible to obtain fracture toughness data, the analyst may use the basic 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 Section 5.4.8.

6.3.2 The Standard Option

Option 1: Homogeneous Material - Initiation of Cracking.

6.3.2.1 Applicability

Only the simplest form of material properties data is required for this option 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.

6.3.2.2 Procedure

1. Establish Yield or Proof Strength and Tensile Strength

Mean values of these define the equation for $f(L_r)$ for both the FAD and CDF approaches and minimum values define L_r 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 5.4.3

2. Determine $f(L_r)$

The function $f(L_r)$ must be calculated for all values of $L_r \leq L_r^{\max}$. Equations for $f(L_r)$ are given in Table 6.4.

(a) For materials which have a continuous stress strain curve, $f(L_r)$ is given by equations, (6.14), with $f(1)$ defined by equation (6.15) to values of $L_r \leq L_r^{\max}$.

For $L_r > L_r^{\max}$, use equation (6.16)

(b) For materials which display or may be expected to display a lower yield plateau, $f(L_r)$ is given by the four equations (6.15), (6.16), (6.17) and (6.18).

For $L_r < 1$, use equation (6.17)

At $L_r = 1$, use equation (6.18)

For $1 < L_r < L_r^{\max}$, use equation (6.15)

For $L_r > L_r^{\max}$, use equation (6.16)

3. Determine the Characteristic Value of the Material's Fracture Toughness (5.4.4)

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 5.4.4).

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 few as three results. Recommended methods for analysing the data are given in 5.4.5.

Table 6.4 - Equations for f(L_r)

Equation No	Formula for $f(L_r)$	Definitions	Tensile Data	Range of L_r
(6.14)	$f(L_r) = (1+0.5L_r^2)^{-1/2}\left[0.3+0.7\exp(-\mu L_r^6)\right]$	$\mu = \min\left[0.001(E/R_p);0.6\right]$ E is Young's modulus R_p is proof strength in MPa	Continuous Yielding	$L_r \le 1$
(6.15)	$f(L_r) = f(1)L_r^{(N-1)/2N}$	N is an estimate of the strain hardening exponent given by $N = 0.3\left[1-(R_e/R_m)\right]$ R_e is either R_p or $0.95R_{eH}$ depending on material, in MPa. R_m is the material's ultimate tensile strength in MPa $L_r^{\max} = 0.5(1+R_m/R_e)$	Continuous And Discontinuous Yielding	$1 \le L_r \le L_r^{max}$
(6.16)	$f(L_r) = 0$		Continuous And Discontinuous Yielding	$L_r > L_r^{max}$
(6.17)	$f(L_r) = \left[1+0.5(L_r)^2\right]^{-1/2}$		Discontinuous Yielding	$L_r \le 1$
(6.18)	$f(1) = \left(\lambda + \frac{1}{2\lambda}\right)^{-1/2}$	$\lambda = (1+E\Delta\varepsilon/R_{eH})$ $\Delta\varepsilon$ is the lower yield strain given by $\Delta\varepsilon = 0.0375(1-R_{eH}/1000)$ R_{eH} is the material's upper yield strength or limit of proportionality.	Discontinuous Yielding	$L_r = 1$

Where the fracture mechanism is brittle the method, 5.4.5.1, uses maximum likelihood (MML) statistics. For between three and nine 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 to 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 crack size dependence. The characteristic value should be chosen with this in mind. Guidance is given in 5.4.5.1.2 (a) (ii), and the equation for crack size adjustment is given in Table 5.5.

Where the fracture mechanism is by ductile tearing, 5.4.5.2, 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 5.4.4 (b).

4. Characterise the Crack (Annex E)

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

5. Determine Loads and Stresses (5.3.1)

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 ρ, 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 ρ is given in Annex J.

6. Analysis

For an FAD analysis see Section 6.3.2.3 (a)

For a CDF analysis see Section 6.3.2.3 (b) when using *J* or Section 6.3.2.3 (c) when using δ.

7. Assess Result

The result must be assessed in terms of the reliability required taking into account the uncertainties in the input data (see 5.4). If the result is acceptable the analysis can be concluded and reported as appropriate (10.1.3)

8. Unacceptable result

If the result is unacceptable, it may be possible to proceed to a higher option of analysis, following the flow chart in Figure 6.5. 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 Section 6.2.1.2, Figure 6.2. More complete guidance is given in Section 6.2.3.

(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. Section 5.4.6 Ductile Tearing gives guidelines on the treatment of fracture toughness data for ductile tearing, and Section 6.4.2 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 Option 2 may give more acceptable results. For situations where the full stress strain curve is known, employment of the more accurate Option 3 analysis may provide the necessary improvements. Sections 6.3.3 and 6.3.4 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.

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 Section 6.3.6 and described in detail in Section 6.4 that also provides for a further advanced option for situations where a numerical *J*-integral is preferred (see also Section 6.3.5).

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 Section 11.10 Reliability Methods.

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

6.3.2.3 Analysis Procedures.

(a) FAD Approach

1 Plot the FAD, using mean tensile properties and the appropriate expressions for $f(L_r)$ (step 2 of Section 6.3.2.2), 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 Section 5.3.1.14 and Annex B).

3 Calculate K_r for the loading on the structure at the crack size of interest (see Annex A). 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 ρ (Section 6.2.1.3.1 and Annex K).

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 option pursued. Return to Step 7 of Section 6.3.2.2. 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 (Section 6.3.2.2).

(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 $J_e = K^2 / E'$, taking into account all primary and secondary loads (Section 6.2.1.3.2). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, ρ (Annex K).

2 Plot the CDF (J) using mean tensile properties and the appropriate expression for $f(L_r)$ (step 2 in Section 6.3.2.2) 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 $L_r \le L_r^{\max}$ (step 2 in Section 6.3.2.2). 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 (Sections 5.3.1.14 and Annex B), 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 option pursued. Return to step 7, Section 6.3.2.2.

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 Section 6.3.2.2.

(c) CDF Approach using δ

1 Calculate δ_e as a function of the applied loads on the structure at the crack size of interest, where $\delta_e = K^2 / E^/ R_e$, taking into account all primary and secondary loads (Sections 6.2.1.3.3). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, ρ (Annex K).

2 Plot the CDF (δ) using mean tensile properties and the appropriate expression for L_r (step 2 Section 6.3.2.2) where the CDF (δ) is a plot of $\delta = \delta_e[f(L_r) - \rho]^{-2}$ on L_r and δ axes for values of $L_r \le L_r^{\max}$ (step 2 in 6.3.2.2). Draw a vertical line at $L_r = L_r^{\max}$

3 Identify the point on the CDF (δ) 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 (5.3.1.14 and Annex B), and draw a vertical line at this value to intersect the CDF (δ) curve at δ_{str}.

5 If δ_{str} is less than δ_{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 option pursued. Return to step 7 – Section 6.3.2.2.

If either δ_{str} is greater than δ_{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 – Section 6.3.2.2.

6.3.3 Analysis Option 2 (Mismatch Procedure)

Option 2 Analysis - weld to base metal yield strength mismatch greater than 10%

6.3.3.1 Applicability

In the case of weldments where the differences in yield strengths between the base material and the weld metal are greater than 10 %, the joint may behave as a heterogeneous bi-metallic joint. In such cases, use of minimum values of yield strength in the joint to define L_r may be over-conservative. The mismatch option provides a method for reducing the conservatism by allowing for separate contributions of the base material (denoted B) and the weld material (denoted W). It is worth noting that the maximum decrease in the conservatism arises when failure is plastic collapse dominated.

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

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.

The Analysis Option 2 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_p^M, a value for $L_r^{\max}$ under the mismatch conditions, a value for the lower bound strain hardening exponent *N* of an equivalent material, all of which are defined in Section 6.3.3. Advice for calculating the mismatch limit load is given in Annex B, 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.

6.3.3.2 Both Base and Weld Metal Exhibit Continuous Yielding Behaviour

In this case the equations for $f(L_r)$ are those given in 6.3.2.2 para 2 (a): i.e. Eq. (6.14), (6.15) and (6.16) in Table 6.4, but with the values changed to those for an equivalent mismatch material defined by the mismatch ratio, *M,* given by Eq.(6.19).

$$M = R_p^W / R_p^B \tag{6.19}$$

where R_P^W and R_P^B are best estimates of the proof strengths. A mismatch proof strength is given by equation (6.20).

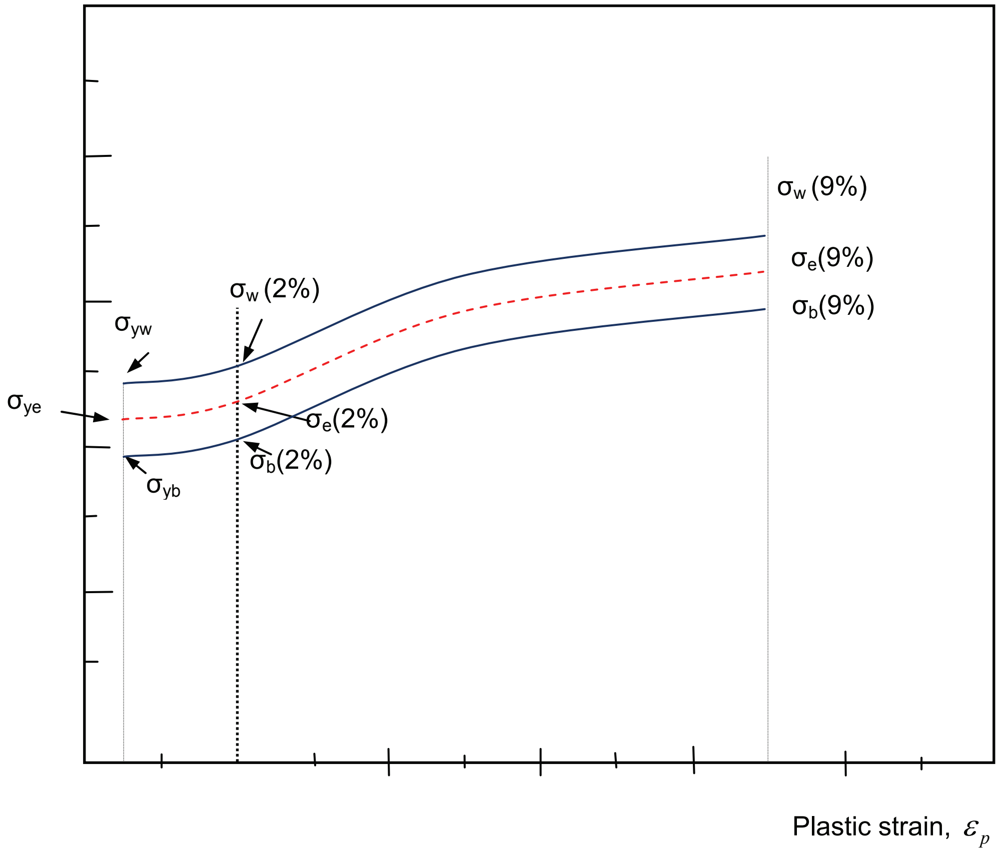
$$R_p^M = (F_p^M / F_p^B) R_p^B \tag{6.20}$$

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

In equations (6.14), (6.15) and (6.16), the values of μ , N , and $L_r^{\max}$ used are calculated for the mismatch material using equations (6.23), (6.24) and (6.25) in Table 6.5.

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

Stress, σ (MPa).



$$M(0{,}2\%) = \sigma_{yw} \ / \ \sigma_{yb}$$
$$M(2\%) \ = \ \sigma_w \ (2\%) \ / \ \sigma_b \ (2\%)$$
$$M(9\%) = \ \sigma_w \ (9\%) \ / \ \sigma_b \ (9\%)$$
$$\sigma_e(2\%) \ / \ \sigma_b(2\%) = \ P_{1\min} \ / \ P_{1b} \quad [\text{for } M = M(2\%) \ ] \text{ etc}$$

Figure 6.4 - Definition of mis-match ratio M

6.3.3.3 Both Base and Weld Metal Exhibit Discontinuous Yielding

In this case, the equations for $f(L_r)$ are those given in 6.3.2.2 paragraph 2 (b), i.e., equations (6.15), (6.16), (6.17) and (6.18), Table 6.4, with the values changed to those for an equivalent mismatch material, as described in 6.3.2.2.

The parameters are defined in terms of R_{eH}, and the relevant equations are (6.24), (6.25) and (6.26), Table 6.5 and Table 6.6.

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 (Annex B) and the mismatch proof strength, R_p^M based upon minimum properties.

6.3.3.4 One of the Constituents has a Continuous Stress Strain Curve and the Other has a Discontinuous One.

(a) When only the weld metal exhibits discontinuous yielding

In this case, $f(L_r)$ is based upon equations (6.14), (6.15), (6.16) and (6.18) listed in Table 6.4, with the input parameters changed according to equations (6.24), (6.25), (6.27) and (6.28), Table 6.5 and Table 6.6.

(b) When only the base metal exhibits discontinuous yielding

In this case, $f(L_r)$ is based upon equations (6.14), (6.15), (6.16) and (6.18) listed in Table 6.4, with the input parameters changed according to equations (6.24), (6.25), (6.27), and (6.30), Table 6.5 and Table 6.6.

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 (Annex B) and the mismatch proof strength, R_p^M, based upon minimum properties.

Table 6.5 - General Equations used in defining $f(L_r)$ for Mismatch Materials

Formulae	Formulae	Definitions	Tensile Data
(6.21)	$M = R_e^W / R_e^B$	R_e is either R_p, R_{eL}, or $0.95R_{eH}$, for weld, *W*, or base metal, *B*, depending on material	Continuous or Discontinuous
(6.22)	$R_e^M = \left(F_e^M / F_e^B\right) R_e^B$	F_e^M is the mismatch yield limit load F_e^B is the base metal yield limit load defined at R_e	Continuous or Discontinuous
(6.23)	$\mu^M = \dfrac{(M-1)}{\left(F_e^M / F_e^B - 1\right)/\mu^W + \left(M - F_e^M / F_e^B\right)/\mu^B}$	$\mu^W = 0.001E^W / R_e$ $\mu^B = 0.001E^B / R_e$	
(6.24)	$N^M = \dfrac{(M-1)}{\left(F_e^M / F_e^B - 1\right)/N^W + \left(M - F_e^M / F_e^B\right)/N^B}$	$N^W = 0.3\left(1 - R_e^W / R_m^W\right)$ $N^B = 0.3\left(1 - R_e^B / R_m^B\right)$	
(6.25)	$L_r^{max} = \left(F_e^M / F_e^B\right) R_F^M$	R_F^M is the lower of either $0.5\left(1 + R_m^W / R_p^W\right)$ or $0.5\left(1 + R_m^B / R_p^B\right)$	

Mismatch Option

For the calculation of L_r

The minimum values of yield or proof strength of both weld and base material

The minimum values of ultimate tensile strength of both weld and base material

An estimate of mismatch yield limit load

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

The mean values of yield or proof strength of both weld and base material

The mean values of ultimate tensile strength of both weld and base material

Stress-Strain Option

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 for weld and base material, plus an estimate of the mismatch yield limit load.

Table 6.6 – Equations used in defining $f(L_r)$ for Mismatch Materials with Continuous and Discontinuous Yielding

	Formulae	Definitions	Tensile data	Eq. For $f(L_r)$
(6.26)	$\lambda^M = \dfrac{(F_{eff}^M / F_{eH}^B - 1)\lambda^w + (M\text{-}F_{eff}^M / F_{eff}^b)\lambda^B}{(M\text{-}1)}$	$\lambda^W = 1 + E^W \Delta\varepsilon^W / R_{eH}^W$ $\Delta\varepsilon^W = 0.0375(1 - R_{eH}^W / 1000)$ $\lambda^B = 1 + E^B \Delta\varepsilon^B / R_{eH}^B$ $\Delta\varepsilon^B = 0.0375(1 - R_{eH}^B / 1000)$	Both Base and Weld Metal continuous	Eq (6.18)
(6.27)	$\mu^M = \dfrac{(M\text{-}1)}{(F_P^M / F_{eH}^W - 1) / \mu^B}$	$\mu^B = 0.001 E^B / R_p^B$		Eq (6.14)
(6.28)	$\lambda^M = \dfrac{(F_e^M / F_{eH}^W - 1)\lambda^W}{(M\text{-}1)}$			Eq. (6.18)
(6.29)	$\mu^M = \dfrac{(M\text{-}1)}{(F_P^M / F_{eH}^B - 1) / \mu^W}$	$\mu^W = 0.001 E^W / R_p^W$		Eq (6.14)
(6.30)	$\lambda^M = \dfrac{(M\text{-}F_e^M / F_{eH}^W)\lambda^B}{(M\text{-}1)}$			Eq (6.18)

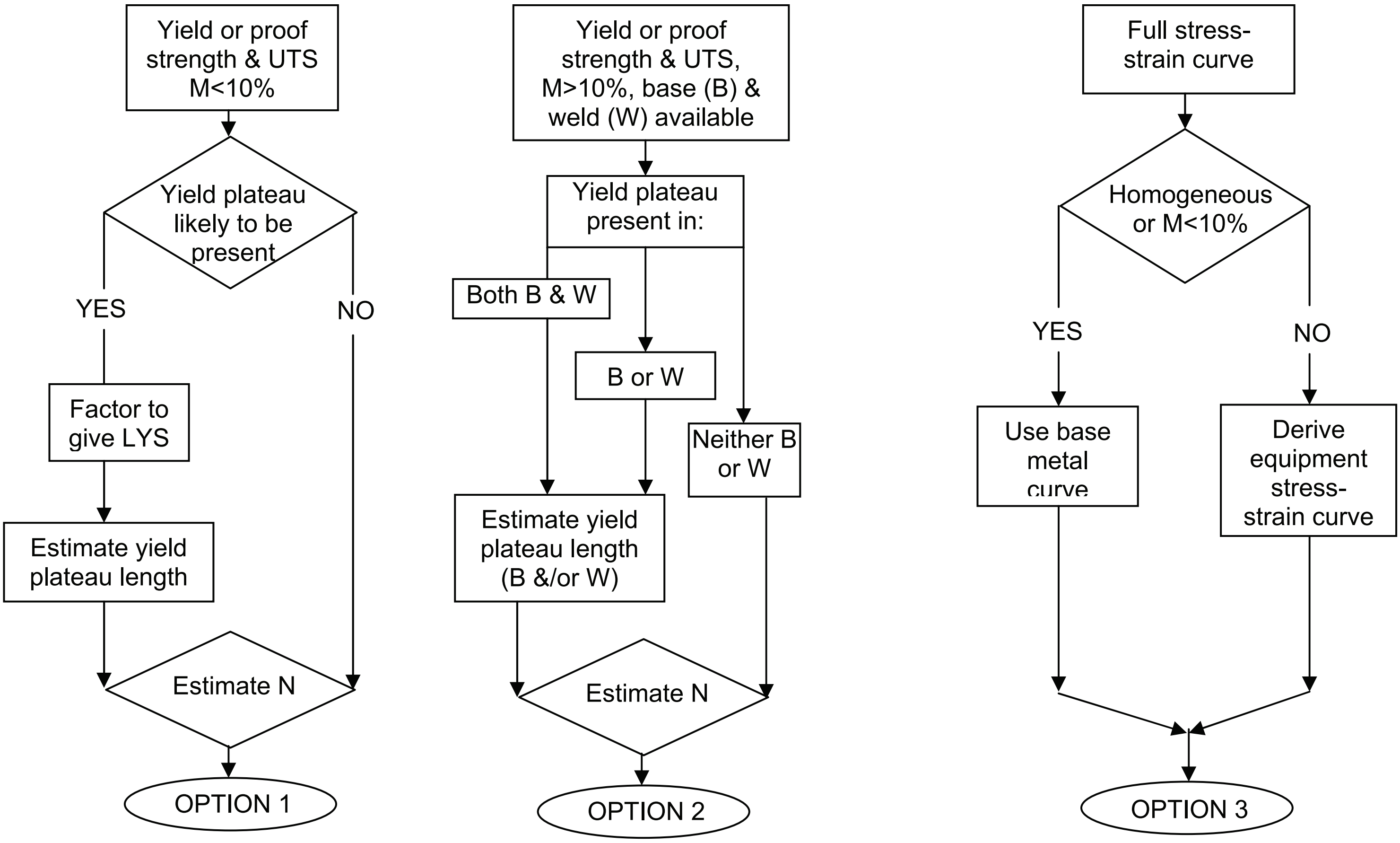


Figure 6.5 - Treatment of Tensile Data to Devise FAD at Options 1, 2 and 3

6.3.3.5 Limit Load 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 sub-sections 5.3.1.12 (b) – (e) and 5.3.1.13 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 Annex B. Solutions are available for geometries, which may be idealised as containing two regions with different strengths, R_e^B and R_e^W, the yield strengths of base and weld metal, for instance. The limit load is then proportional to R_e^B and depends on flaw size, in a similar manner to te homogeneous solutions in 5.3.1.11.2 (a). 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 Annex B,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 Annex B, consider the plane strain centre cracked plate with a crack in the centre-line of weld material W which is shown in Figure 6.6. The thickness of the plate is *t* and a convenient normalisation of the height of the central region is

$$\psi = (w-a)/h \tag{6.31}$$

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

$$F_e{}^B = (4/\sqrt{3})R_e^B t(w-a) \tag{6.32}$$

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

$$F_e^M / F_e^B = M \ldots 0 \le \Psi \le 1 \tag{6.33}$$

$$F_e^M / F_e^B = Min\left\{\left[1-(1-M)/\Psi\right], F_e^M(1)/F_e^B\right\} \ldots 1 < \Psi \tag{6.34}$$

where

$$F_e^M(1)/F_e^B = M\left[1.0+0.462(\Psi-1)^2/\Psi-0.044(\Psi-1)^3/\Psi\right] \ldots 1<\Psi<3.6 \tag{6.35}$$

$$= M\left[2.571-3.254/\Psi\right] \ldots 3.6<\Psi\le 5.0 \tag{6.36}$$

$$= M\left[0.125\Psi+1.291+0.019/\Psi\right] \ldots 5<\Psi \tag{6.37}$$

For overmatching ($M>1$),

$$F_e^M / F_e^B = Min\left\{1/(1-a/w), F_e^M(2)/F_e^B\right\} \tag{6.38}$$

where

$$F_e^M(2)/F_e^B = M \ldots \Psi \le \exp\left[-(M-1)/5\right] \tag{6.39}$$

$$= 0.04\left\{24(M-1)\exp\left[-(M-1)/5\right]/\Psi + M + 24\right\} \ldots \Psi > \exp\left[-(M-1)/5\right] \tag{6.40}$$

Some results are shown in Figure 6.7. Quite generally,

$$M \le F_e^M / F_e^B \le 1 \ldots M < 1 \qquad (6.41)$$

$$1 \le F_e^M / F_e^B \le M \ldots M \ge 1 \qquad (6.42)$$

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 strengh of the weaker material. In extreme cases of large *M*, collapse can be controlled by the non-defective plate section in material B.

It is apparent from Figure 6.7 that for this geometry there is potentially significant benefit from using the mis-match limit load for overmatching at lower values of Ψ or for undermatching at higher values of Ψ. 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 Ψ ($F_e^M \cong F_e^B$) and for undermatching with low values of Ψ ($F_e^M \cong MF_e^B$). For the plates considered in Annex B and Section 5.3.2.1.12, 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 6.6, decreases and the normalised ligament size Ψ increases.

For undermatching (*M<1*):

- The mis-match effect is significant for plane strain, regardless of *a/W* (Figure 6.6) particularly when the size of the zone of material *W* is of small extent (for example, small *h/(W-a)* large Ψ in Figure 6.6);
- 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.

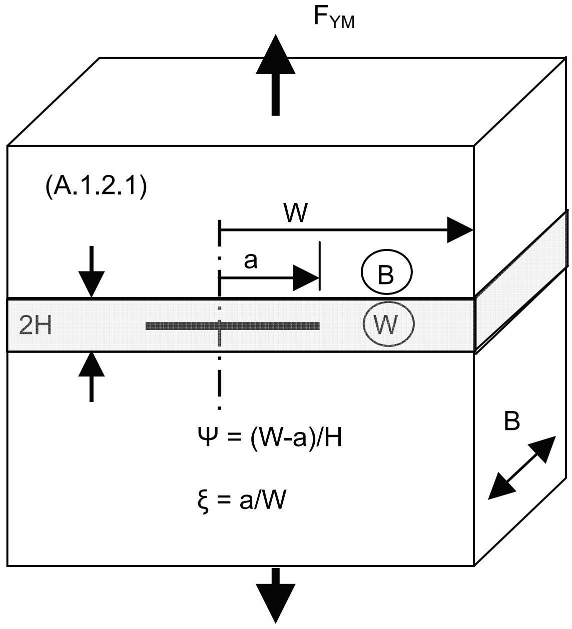


Figure 6.6 - Idealised weld geometry

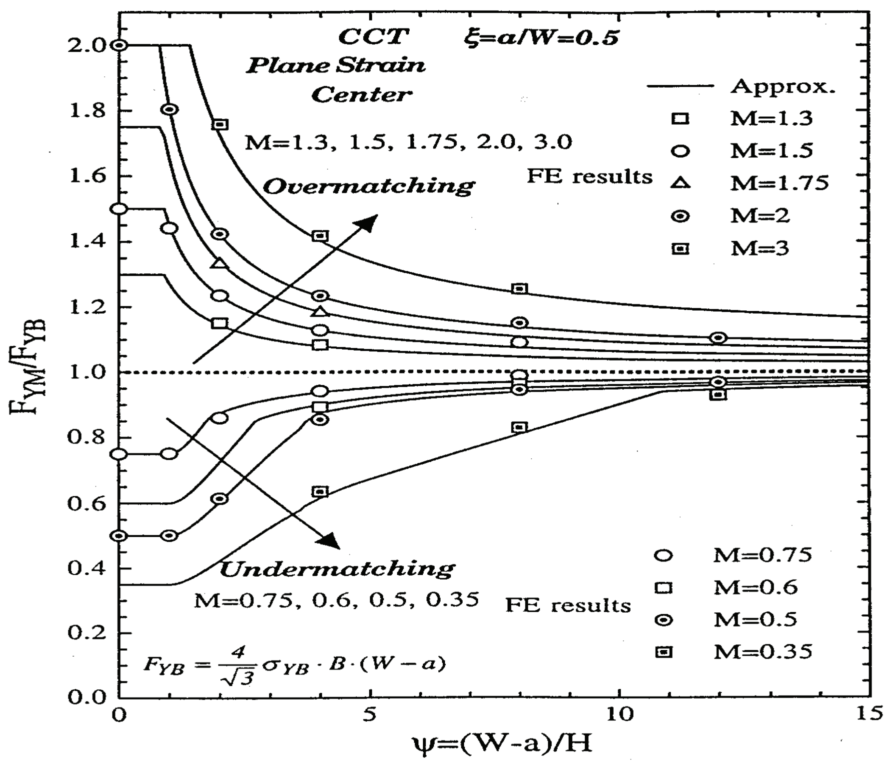


Figure 6.7 - Typical results for F_{Lmis} for centre cracked plate in plane strain for *a/W* = 0.5

6.3.4 Analysis Option 3 (Known Stress-Strain Curves)

6.3.4.1 Applicability

This option 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 mismatch conditions (Annex B)

6.3.4.2 Calculation Steps, Homogeneous Material

The equation for $f(L_r)$ is the same for all materials, at all values of $L_r \leq L_r^{max}$, 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 up to $L_r = L_r^{max}$.

For $L_r \leq L_r^{max}$, $f(L_r)$ is given by equation (6.43)

$$f(L_r) = \left[E\varepsilon_r / \sigma_r + 0.5L_r^2 / (E\varepsilon_r / \sigma_r) \right]^{-1/2} \tag{6.43}$$

where ε_r is the material's true strain obtained from the uniaxial stress strain curve at a true stress σ_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 $L_r > L_r^{\max}$, equation (6.16) applies.

6.3.4.3 Calculation Steps for Mismatch Material

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

$$M\left(\varepsilon_p\right) = \sigma^w\left(\varepsilon_p\right) / \sigma^B\left(\varepsilon_p\right) \tag{6.44}$$

where $\varepsilon^W(\varepsilon_p)$ is the stress at a plastic strain, ε_p, in the weld metal and $\sigma^B(\varepsilon_p)$ is the stress at the same level of plastic strain in the base metal as shown in Figure 6.4. If the stress strain curves are similar, the function $M(\varepsilon_p)$ will be only weakly dependent on ε_p and a value obtained at the proof strain, $\varepsilon_p = 0.002$, may be adequate.

For each value of $M(\varepsilon_p)$, evaluate the ratio of F^M/F^B where F^M is the mismatch limit load, see Annex B, 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, $\sigma^M(\varepsilon_p)$, for the mismatch material as follows

$$\sigma^M\left(\varepsilon_\rho\right) = \frac{\left(F^M / F^B - 1\right)\sigma^w\left(\varepsilon_\rho\right) + \left(M - F^M / F^B\right)\sigma^B\left(\varepsilon_\rho\right)}{\left(M - 1\right)} \tag{6.45}$$

The total strain is obtained by adding the elastic strain, σ^M/E, to the plastic strain, ε_p, from which the mismatch stress strain curve can be calculated. The function $f(L_r)$ can then be obtained by means of equations (6.43) and (6.14).

L_r for the loading on the structure should be calculated using the yield limit load for the mismatch conditions, F_e^M (Annex B) and an estimate of the minimum value for the mismatch proof strength, R_p^M , given at a value of plastic strain, $\varepsilon_p = 0.002$.

6.3.5 Analysis Option 4 (J-Integral Analysis)

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.

6.3.6 Analysis Option 5 (Constraint Analysis)

Associated with assessment procedures for analysis options 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_{mat} being derived from deeply cracked bend or compact tension specimens recommended in the testing standards. These are designed to ensure plane 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 evidence 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 compared with 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 given in 6.2.3. The procedure for determining the constraint benefit is described in detail in 6.4.3.

6.4 Special options

6.4.1 Basic Level of Analysis (Option 0)

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

Only the minimum yield stress is required

Only Charpy impact data are needed for K_{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 Option 1.

The default analysis uses lower bound correlations between Charpy data and K_{mat}, and provides the most conservative of all the analysis routines. A component which is acceptable using the basic option will therefore be acceptable using any of the higher options of analysis.

The basic option is described below.

6.4.1.1 Applications

The basic option 0 procedure is used for cases where the knowledge of material properties is very limited. As a minimum, it requires knowledge of the yield strength (or 0.2% proof strength) and the Charpy properties of the material. This option 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 option 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 fracture toughness data set or Charpy impact energy data.
- Determine $f(L_r)$; the shape of the FAD.
- Characterise the crack (Annex E).
- Determine the loads and stresses, (Section 5.3.1.14).
- Analyse by FAD.
- Assess the result.

6.4.1.2 Tensile Properties

6.4.1.2.1 Determination of Type of Stress-Strain Curve

The yield strength 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 from those for materials demonstrating continuous yielding characteristics. Whether or not a yield plateau should be assumed depends on yield strength, composition and process route; these factors can be grouped roughly according to standard specifications. provide guidance for making this decision. It should be recognised that this approach is a generalisation as the presence of a yield plateau is affected as much by test method as by material type. In particular, loading rate and specimen design can greatly influence the propensity for a yield plateau.

For those materials that are assumed to show discontinuous behaviour, the value of yield strength can either be an upper or lower yield strength.

6.4.1.2.2 Estimation of Lower Yield Strength

Where it is known that the value is a lower yield strength (R_{el}) or a proof strength ($R_{p0.2}$), these values can be used as the characteristic value of yield strength. Where it is not known whether the value is an upper (R_{EH}) or lower yield strength, the value should be considered as the upper and so be factored according to equation (6.46) to ensure that it represents the R_{el} value.

$$R_{el} = 0.95 R_{eH} \tag{6.46}$$

6.4.1.2.3 Estimation of Ultimate Tensile Strength

The ultimate tensile strength, R_m , can be estimated from the lower yield strength (R_{el}) or 0.2% proof strength ($R_{p0.2}$) by a conservative relationship between yield/tensile strength ratio and yield strength:

$$R_m = R_{p0.2}\left[1 + 2\left(\frac{150}{R_{p0.2}}\right)^{2.5}\right] \tag{6.47}$$

For discontinuous yielding, $R_{p0.2}$ is replaced by R_{el} .

6.4.1.3 Determination of Fracture Toughness for Use at Basic Level (Option 0)

6.4.1.3.1 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. In reality, fracture toughness 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 provided in 5.4.8 are described below:

One expression is given for a lower bound estimation of lower shelf fracture toughness based on the Master Curve.

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 Figure 5.11.

6.4.1.4 Other Guidance/ Limitations

Effects associated with weld strength mismatch are not incorporated in this option. 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.

6.4.1.5 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 (6.48), for all values of $L_r \leq$ 1.0.

$$f\left(L_r\right)=\left[1+0.5\left(L_r\right)^2\right]^{-1/2} \tag{6.48}$$

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 (6.49) for all values of $L_r \leq L_r^{\max}$, where $L_r^{\max} = 1+(150/R_p)^{2.5}$ and R_p is the material's proof strength in MPa.

$$f(L_r)=(1+0.5L_r^2)^{-1/2}\left[0.3+0.7\exp(-0.6L_r^6)\right] \tag{6.49}$$

For $L_r > L_r^{\max}$, $f(L_r)$ = 0

L_r and K_r are described in more detail in 5.3.1.14.2 and 5.3.1.14.3.

6.4.1.6 Flaw Characterisation

This is determined by the shape and size of the defect and the geometry of the structure, as defined in Annex E.

6.4.1.7 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 5.3.1 and profiles for welding residual stress in Annex C.

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 Annex C.

	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 strength.
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 and K_r for the structure being assessed can be obtained. For this, guidance on appropriate limit load and stress intensity factor solutions is given in Annex B and A, respectively.

6.4.1.8 Assessment of Results

The result must be assessed in terms of the reliability required taking into account the uncertainties in the input data (10.1.3). If the result is acceptable the analysis can be concluded and reported as appropriate (10.2).

6.4.1.9 Unacceptable Result

If the result is unacceptable, it may be possible to proceed to a higher option of analysis, following the guidelines to determine how best to proceed (6.2.3).

(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. Section 5.4.4 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 $f(L_r)$. Section 6.2.3.2 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.

6.4.2 Ductile tearing analysis

These procedures replace steps 3 and 6 in Section 6.3.2.2 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 5.4.6). 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.

6.4.2.1 FAD analysis

1.) Replacement for step 3 in Section 6.3.2.2: 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, Δa, as

$$K_{mat} = K_{mat}(\Delta a) \tag{6.50}$$

K_{mat} should be evaluated at the initiation of cracking (as determined following (5.4.5) and at small increments of crack growth, typically 1 or 2mm 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 5.4.4).

2.) Replacement for steps 2, 3, 4 and 5 in Section 6.3.2.3 (a): Analysis Procedures for FAD

1. Calculate $L_r(\Delta a) = L_r(a_0 + \Delta a_1 + \Delta a_2 + ...\Delta a_i...)$ for the loading on the structure where a_0 is the initial flaw size characterised following the procedures of 5.1.1 and Δa_1 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 6.2.1.3.1)

$$K_r(\Delta a) = K_I^P(a_0, \Delta a) / K_{mat}(a_0, \Delta a) + K_I^S(a_0, \Delta a) / K_{mat}(a_0, \Delta a) + \rho(a_0, \Delta a) \tag{6.51}$$

where a_0 is the initial flaw size and Δa 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 Section 6.3.2.2; Assessment of Results.

When assessing the results note that reserve factors depend on the amount of postulated crack extension, Δa: e.g., $F^L = F^L(\Delta a)$ (See also 5.4.4).

6.4.2.2 CDF(J) analysis

1) Replacement for step 3, Section 6.3.2.2: Determine characteristic value of Fracture Toughness

In this case, the fracture toughness is expressed as an increasing function of crack extension, Δa, as

$$J_{mat} = J_{mat}(\Delta a) \tag{6.52}$$

J_{mat} should be evaluated at the initiation of cracking (as determined following 5.4.5.2) 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 5.4.6).

2) Replacement for steps 1, 2, 3, 4 and 5 in Section 6.3.2.3 (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 (5.3.1.14 and Annex A). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, $\rho(a_0)$ (Annex K).

2. Plot the CDF(J) using the appropriate expression for $f(L_r)$ (step 2 in 6.3.2.2) 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 $L_r \le L_r^{\max}$ (step 2 in Section 6.3.2.2). 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 (5.3.1.14.2 and Annex B), and draw a vertical line at this value to intersect the CDF (J) curve at $J = J_{str}(a_0)$.

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_{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 $J = J_{str}(a_0)$ obtained from steps 3 and 4 above. Terminate this curve at any point where $L_r = L_r^{\max}$

6. Plot $J_{mat}(\Delta a)$ on this diagram, originating from a_0, the initial flaw size of interest.

7. If the CDF(J) intersects the $J_{mat}(\Delta a)$ curve the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed. If this curve only touches the $J_{mat}(\Delta a)$ 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 Section 6.3.2.2; 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 Figure 6.2). Also, when assessing reserve factors on crack size, the $J_{mat}(\Delta a)$ curve can be re-plotted 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 Section 6.3.2.3).

6.4.2.3 CDF(δ) analysis

1) Replacement for step 3, section 6.3.2.2: Determine characteristic value of Fracture Toughness

In this case, the fracture toughness is expressed as an increasing function of crack extension, Δa , as

$$\delta_{mat} = \delta_{mat}(\Delta a) \tag{6.53}$$

δ_{mat} should be evaluated at the initiation of cracking (as determined following 5.4.5.2) 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 5.4.6).

2) Replacement for steps 1, 2, 3, 4 and 5 in 6.3.2.3 (c): Analysis Procedures for CDF using δ

1 Calculate δ_e as a function of the applied loads on the structure at the initial flaw size of interest, a_0, where $\delta_e(a_0) = K(a_0)^2/(E'\cdot R_e)$, taking into account all primary and secondary loads (5.3.1.14 and Annex A). At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, $\rho(a_0)$ (Annex K).

2 Plot the CDF(*δ*) using the appropriate expression for $f(L_r)$ where the CDF(*δ*) is a plot of $\delta = \delta_e[f(L_r) - \rho]^{-2}$ on L_r and *δ* axes for values of $L_r \le L_r^{\max}$ (step 2 in section 6.3.2.2). Draw a vertical line at $Lr = L_r^{\max}$

3 Calculate L_r for the loading on the structure at the flaw size of interest (5.3.1.14.2 and Annex B), and draw a vertical line at this value to intersect the CDF(*δ*) curve at $\delta = \delta_{str}(a_0)$

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 δ_{str} as a function of flaw size.

5 On axes of *δ* versus flaw size, a, plot the CDF(*δ*) as a function of flaw size where the CDF(*δ*) is given by the values $\delta = \delta_{str}(a)$ obtained from steps 3 and 4 above. Terminate this curve at any point where $Lr = L_r^{\max}$

6 Plot $\delta_{mat}(a)$ on this diagram, originating from a_0, the initial flaw size of interest.

7 If the CDF(*δ*) intersects the $\delta_{mat}(a)$ curve the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed. If this curve only touches the $\delta_{mat}(a)$ 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 6.3.2.2; 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 Figure 6.2). Also, when assessing reserve factors on crack size, the $\delta_{mat}(a)$ curve can be re-plotted at different postulated values of a_0 to find the limiting condition (where CDF(δ) and $\delta_{mat}(a)$ meet at a point, See 6.3.2.3).

6.4.3 Allowance for Constraint Effects

6.4.3.1 Introduction

The basic procedures of Section 6.3 enable an assessment to be made of the structural integrity of a defective component. Associated with an assessment are reserve factors (Section 10) 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_{mat} , used to define K_r, 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 [6.1]-[6.5]. 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 [6.6]-[6.8]. This has led to proposals for incorporating constraint in fracture assessments [6.9]-[6.12]. This Section uses these proposals to set out procedures for including constraint in the overall procedure of Section 6.3. It is not intended that these procedures replace those of Section 6.3, 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 0 describes the procedures to be followed, within the scope set out in Section 6.4.3.2. Section 6.4.3.2.4 then provides guidance on when and how to perform the additional calculations and how to obtain the additional materials data required to follow the procedures.

6.4.3.2 Scope

The procedures of this section are limited to Mode I loading. Combinations of primary and secondary stresses are also included in the procedures.

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 (Section 5.3) 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 limited in scope to the parameters T and Q. However, a similar approach could be developed for other constraint parameters provided their load dependence could be quantified (i.e., [6.13]).

Procedures

When the failure assessment diagram route of section 6.2.1.1 is followed, two alternative procedures set out in Sections 6.4.3.2.1 and 6.4.3.2.2 can be used. The first involves a modification to the failure assessment diagram but retains the definition of K_r in Section 6.2.1.1. The second retains the failure assessment diagram of Section 6.3.2 but modifies the definition of K_r. Here the procedures are presented with K_r defined using the parameter ρ but the principles also apply to definition of K_r using the parameter V. Each procedure follows the steps in Section 6.3.2.2 apart from steps 2 and 3, which are replaced by steps 2a-d and steps 3a-e as detailed in Sections 6.4.3.2.1 and 6.4.3.2.2, respectively. Guidance on how to perform these steps is contained in Section 6.4.3.2.4 along with guidance on assessing the significance of the results. This latter guidance, in Section 6.4.3.2.4.6, may be useful in deciding which of the two procedures to follow.

With the crack driving force approach of 6.2.1.2, a modified toughness procedure is used. The procedure follows the steps in Section 6.3.2.3 apart from steps detailed in Section 6.4.3.2.3.

6.4.3.2.1 FAD Procedure I: Modification to the FAD

a Evaluate a normalised constraint parameter, β (Section 6.4.3.2.4.2).

b Define the influence of constraint on material resistance to fracture, relative to the data determined in step 3, in terms of β and the material parameters, α and m (Section 6.4.3.2.4.3).

c Modify the failure assessment diagram of step 2, Section 6.3.2.2, using the parameters β, α and m (Section 6.4.3.2.4.4).

d Calculate $\mathrm{K_r}$. $\mathrm{K_r^p}$ is calculated as in Section 6.3.2.2, with K_{mat} or $K_{mat}(\Delta a_i)$ as defined at step 3 from data obtained according to the procedures of Section 6.3.2.2. Thus, $\mathrm{K_r^p}$ is defined with respect to the fracture toughness, $K_{mat}(\Delta a_i)$, relevant to conditions of high constraint. $\mathrm{K_r^s}$ is also defined with respect to K_{mat} or $K_{mat}(\Delta a_i)$ but the parameter ρ is replaced by a related parameter ρ_1.

For an initiation analysis

$$\mathrm{K_r^s = K_I^s\,(a_o)/K_{mat} + \rho_I\,(a_o)} \tag{6.54}$$

For a ductile tearing analysis

$$\mathrm{K_r^s = K_I^s\,(a_j)} / K_{mat}\,(\Delta a_j) + \rho_I(a_j) \tag{6.55}$$

Advice on calculation of the parameter ρ_1 is given in Annex K.

6.4.3.2.2 FAD Procedure II: Modification to K_r

a Evaluate a normalised constraint parameter, β (Section 6.4.3.2.4.2).

b Evaluate βL_r, a measure of structural constraint.

c Evaluate the material toughness, K^{c}_{mat}, appropriate to the level of constraint βL_r (Section 6.4.3.2.4.3).

d Calculate K_r. The procedures of Section 6.3.2.2 are **not** followed. Instead, the definition of K_r is as follows:

For an initiation analysis

$$\begin{aligned} K^{p}_{r} &= K^{p}_{I}(a_o)/K^{c}_{mat} \\ K^{s}_{r} &= K^{s}_{I}(a_o)/K^{c}_{mat} + \rho(a_o) \end{aligned} \tag{6.56}$$

For a ductile tearing analysis

$$\begin{aligned} K^{p}_{r} &= K^{p}_{I}\left(a_j\right)/K^{c}_{mat}\left(\Delta a_j\right) \\ K^{s}_{r} &= K^{s}_{I}(a_j)/K^{c}_{mat}\left(\Delta a_j\right) + n(a_j) \end{aligned} \tag{6.57}$$

for flaw sizes $a_j + a_o + \Delta a_j$. $K^{c}_{mat}(\Delta a_j)$ is the fracture toughness after the given amount, Δa_j, of ductile tearing, allowing for the influence of constraint (Section 6.4.3.2.4.3). Note, for this procedure, ρ is evaluated according to Annex K and the modifications in Section 6.4.3.2.4.5 are not required.

e Plot points (L_r, K_r) on the failure assessment diagram, Section 6.3.2, and assess in the conventional way.

6.4.3.2.3 CDF Route Procedure

a Evaluate a normalized constraint parameter, β (Section 6.4.3.2.4.2).

b Define the influence of constraint on material resistance to fracture, relative to the data determined in step Y, in terms of β and the material parameters, α and m (Section 6.4.3.2.4.4).

c The crack driving force (K, J or δ) is calculated as function of the normalized load L_r as described for the high-constraint case but then compared with the constraint adjusted fracture toughness (when J is used as CDF, $J_{mat}(\beta,\alpha,m)$). For the higher analysis required for ductile tearing the constraint adjusted fracture toughness after the given amount of stable tearing $J_{mat}(\beta,\Delta a,\alpha,m)$ should be adopted.

6.4.3.2.4 Background Notes and Guidance on Using the Procedure

6.4.3.2.4.1 Definition of Loads

Step 5 of the procedure of Section 6.3.2 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.

6.4.3.2.4.2 Evaluation of Structural Constraint, β

Guidance is given in this sub-section on the evaluation of a normalised measure of structural constraint, β. As there is considerable debate about the most appropriate parameter to describe constraint, advice is given on the calculation of β for constraint described by both the elastic T stress and the hydrostatic Q stress. Whichever parameter is adopted, materials data are required (sub-section 6.4.3.2.4.3) 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. As broad guidance, the T stress is recommended for use for $L_r \le 1$ while for $L_r > 1$, the Q stress is recommended. It should be noted that T and Q give very similar results for $L_r \le 1$.

(a) The T-stress definition of β

The stresses σ_{ij} close to a crack tip, calculated elastically, may be written as

$$\sigma_{ij} = \frac{K_I}{(2\pi r)^{1/2}} g_{ij}(\theta) + T\,\delta_{1i}\,\delta_{1j} + O(r^{\frac{1}{2}}) \tag{6.58}$$

for polar co-ordinates (r,θ) centred at the crack tip. Here, g_{ij} are angular functions of θ, δ_{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 [6.14]. This reference also contains normalised T-stress solutions for a range of two and three dimensional geometries. The value of β is then defined by

$$\beta = \frac{T^p}{L_r \sigma_y} + \frac{T^s}{L_r \sigma_y} \tag{6.59}$$

where, T^p, T^s are the values of T-stress for the σ^p and σ^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 yield strength, β is independent of both the load magnitude and the value of yield strength for σ^p stresses acting alone: it is then a function of geometry, flaw size and the type of loading only.

For combined primary and secondary stresses, β reduces with increasing σ^p loads (increasing L_r) for constant σ^s loading. In the limit $L_r \to 0, \beta \to \infty$ but the product βL_r remains finite and equal to T^s/σ_y. It is this product βL_r which is required in Sections 6.4.3.2.4.3, 6.4.3.2.4.4 and 6.4.3.2.4.5.

In the literature, values of T^p are often presented, normalised by the stress intensity factor and flaw size as

$$B^* = T^p \sqrt{\pi a} \,/\, K_I^p \tag{6.60}$$

or in terms of some nominal applied stress. As values of K_I^p and L_r are required to perform an assessment, it is straightforward to convert these solutions into values of β [6.15].

A compendium of β_T solutions is given in Annex K.

(b) The Q-stress definition of β

For elastic-plastic materials, the stresses close to a crack tip may be written approximately as:

$$\sigma_{ij} = \sigma_{ij}^{ssy} + Q\sigma_y \delta_{ij} \tag{6.61}$$

where σ_{ij}^{ssy} is the stress field close to a crack tip under small-scale yielding, for the same value of J as that used to evaluate σ_{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 [[6.9], [6.16]] 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 [6.9] -[6.16]. The value of β is then defined by

$$\beta = Q / L_r \tag{6.62}$$

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 [6.9],[6.10],[6.13],[6.15],[6.17]-[6.20] are of more restricted application than the corresponding solutions for T.

For combined primary and secondary 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

$$Q = Q^p + Q^s \qquad Q^s > 0 \tag{6.63}$$

and, for $Q^s < 0$, as

$$\begin{aligned} Q &= Q^p + Q^s(1-L_r) \qquad && Q^s<0 \text{ and } L_r \le 1 \\ Q &= Q^p && Q^s<0 \text{ and } L_r > 1 \end{aligned} \tag{6.64}$$

or more conservatively as

$$\begin{aligned} Q &= Q^s \qquad && Q^s<0,\ Q^p<0,\ Q^p>Q^s \\ Q &= Q^p && Q^s< 0,\ Q^p<0,\ Q^p \le Q^s \end{aligned} \tag{6.65}$$

where Q^p is the value of Q under the primary stresses alone and Q^s is the value of Q under the secondary stresses alone. These estimates are illustrated in Figure 6.8.

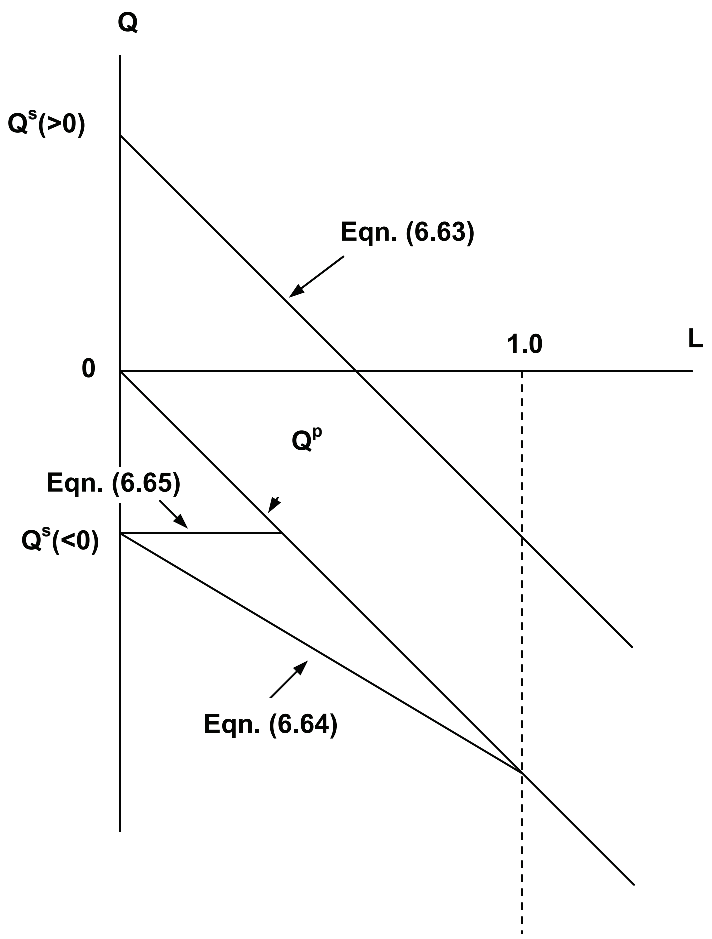


Figure 6.8 - Approximate methods for estimation of Q for combined σ^p and σ^s stresses according to equation (6.63).

For $L_r \leq 0.5$, the value of Q^p may be estimated [6.10] from

$$Q^p = T^p / \sigma_Y$$
$$0.5 < T^p / \sigma_Y \leq 0^y \tag{6.66}$$

$$Q^p = 0.5T^p / \sigma_Y$$
$$0 < T^p / \sigma_Y < 0.5 \tag{6.67}$$

Where more detailed information about the material strain hardening characteristics is known, these estimates may be improved by using small-scale yielding approximations in [6.9]. From Equation (6.67), for σ^p stresses acting alone at low value of L_r and for negative values of T-stress such that $\left| T / \sigma_y \right| < 0.5,$ the value of β is identical to that defined from the T-stress. Ainsworth and O'Dowd [6.10] 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 σ^s stresses, an estimate of Q^s may be obtained from T^s, the value of T-stress from an elastic analysis of the secondary stresses:

$$Q^s = T^s / \sigma_y \tag{6.68}$$

Note, weight function methods may be used to evaluate T^s for non-linear distributions of secondary stress [6.21].

6.4.3.2.4.3 Influence of Constraint on Material Resistance to Fracture

To use the procedure of Section 0 it is necessary to define the material fracture resistance at the level of constraint evaluated using the methods of Section 6.4.3.2.4.2. This constraint dependent toughness is denoted K^c_{mat} and is dependent on βL_r.

At high values of constraint ($\beta L_r > 0$), K^c_{mat} may be simply taken as equal to K_{mat} obtained using the procedure of Section 5.4.4. 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 βL_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 βL_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 βL_r becomes more negative [6.20].

The following equation was suggested in [6.21] to estimate the shift in the Indexing Temperature T_0:

$$T_0 \approx T_{0deep} + T_{stress} / 10 \cdot Mpa / °C \tag{6.69}$$

$T_{0\,deep}$ is the Indexing Temperature obtained from high constrained specimens. The above equation provides a simple tool for the application of the master curve technology also to low constraint geometries. The fracture toughness of the structure will normally be conservatively estimated by (6.3.2) so the integrity of the safety assessment is not in jeopardy even when the structure specific constraint is accounted for.

This shift leads to the following expression for K^c_{mat}:

$$K^c_{mat} = 20\,\mathrm{MPa}\sqrt{\mathrm{m}} + (K_{mat} - 20)\exp(0.019[-T_{stress}/10\,\mathrm{MPa}]) \quad \text{for T-stress<0} \tag{6.70}$$

Ainsworth and O'Dowd [6.10] have shown that the increase in fracture toughness in both the brittle and ductile regimes may be represented by an expression of the form

$$\begin{aligned} K^c_{mat} &= K_{mat} \\ \beta L_r &> 0 \end{aligned} \tag{6.71}$$

$$K^c_{mat} = K_{mat}\left[1+\alpha(-\beta L_r)^k\right]$$
$$\beta L_r < 0 \qquad (6.72)$$

where α , k are material and temperature dependent constants. In the ductile regime, α and m are, additionally, functions of ductile crack growth. However, other forms have been used in the literature (for example, [6.11], [6.17]) and the principles of this Section are not restricted to any particular relationship between K^c_{mat} and K_{mat}.

Values of K^c_{mat}, or equivalently values of α , k in Eqn. (6.71) and (6.72), may be obtained by

(i) testing specimens having different geometries and crack sizes to obtain data in the range of βL_r of interest [6.24];

(ii) mechanistic modelling [6.7], [6.8], [6.23];

(iii) a combination of limited materials testing with mechanistic modelling to interpolate/extrapolate to different constraint levels. A series of Lookup Tables were derived in [6.38] which enable the parameters α and k to be readily established based on a knowledge of the yield and work hardening behaviour of the material at the temperature of interest and the Beremin fracture model parameter m (see Section 12.1). The Lookup Tables are provided in Annex K.

Test specimens which have been used to generate fracture toughness data at low constraint levels include three point bend specimens with shallow cracks, 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^c_{mat} . Some advice is contained in Section 5.4.4, including procedures for evaluating K^c_{mat} , given in [6.24].

6.4.3.2.4.4 Construction of Modified FAD

The failure assessment diagram should initially be constructed according to one of the options in Section 6.6. If this is denoted

$$K_r = f(L_r) \text{ for } L_r \le L_r^{\max} \qquad (6.73)$$

$$K_r = 0 \text{ for } L_r > L_r^{\max}$$

where $f(L_r)$ can take one of the forms summarised in Section 6. Then the modified failure assessment diagram is

$$K_r = f(L_r)(K^c_{mat}/K_{mat}) \quad \text{for} \quad L_r \le L_r^{\max} \qquad (6.74)$$

$$K_r = 0 \text{ for } L_r > L_r^{\max}$$

Where K^c_{mat} is defined by equation (6.72) for β < 0, this becomes

$$K_r = f(L_r)\left[1+\alpha(-\beta L_r)^m\right] \quad \text{for } L_r \le L_r^{\max} \qquad (6.75)$$

Some modified FADs using the Option 1 curve and α, m, β taken as constants are shown in Figure 6.9 taken from [6.24]; note, the cut-off $L_r^{\max}$ is not depicted but this is independent of constraint. Some properties of these modified FADs should be noted:

(i) whereas the Option 1 curve is independent of geometry and material, the Option 1 curve modified by equation (6.74) or (6.75) is dependent on geometry (through β), on material toughness properties (through α,m) and also on material tensile properties if β is defined in terms of Q;

(ii) whereas the Option 2 curve is independent of geometry and dependent only on material tensile properties, the modified Option 2 curve is additionally dependent on geometry and material toughness properties;

(iii) whereas the Option 3 curve is dependent on geometry and material tensile properties, the modified Option 3 curve is additionally dependent on material toughness properties

(iv) In view of (i)-(iii), when performing a ductile tearing analysis the failure assessment line is a function of ductile crack growth through its influence on geometry (β depends on crack size) and material (α, m or $K^c{}_{mat}/K_{mat}$ may depend on Δa). Some care is then needed in defining the tangency condition the procedure of Section 6.4.2 (see [6.25-27]) and this is discussed in Section 6.4.3.2.4.6.

(v) For combined loading where β increases with reducing L_r, the value of βL_r is finite at $L_r \to 0$ [6.12], [6.28]. 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 6.9 for constant β.

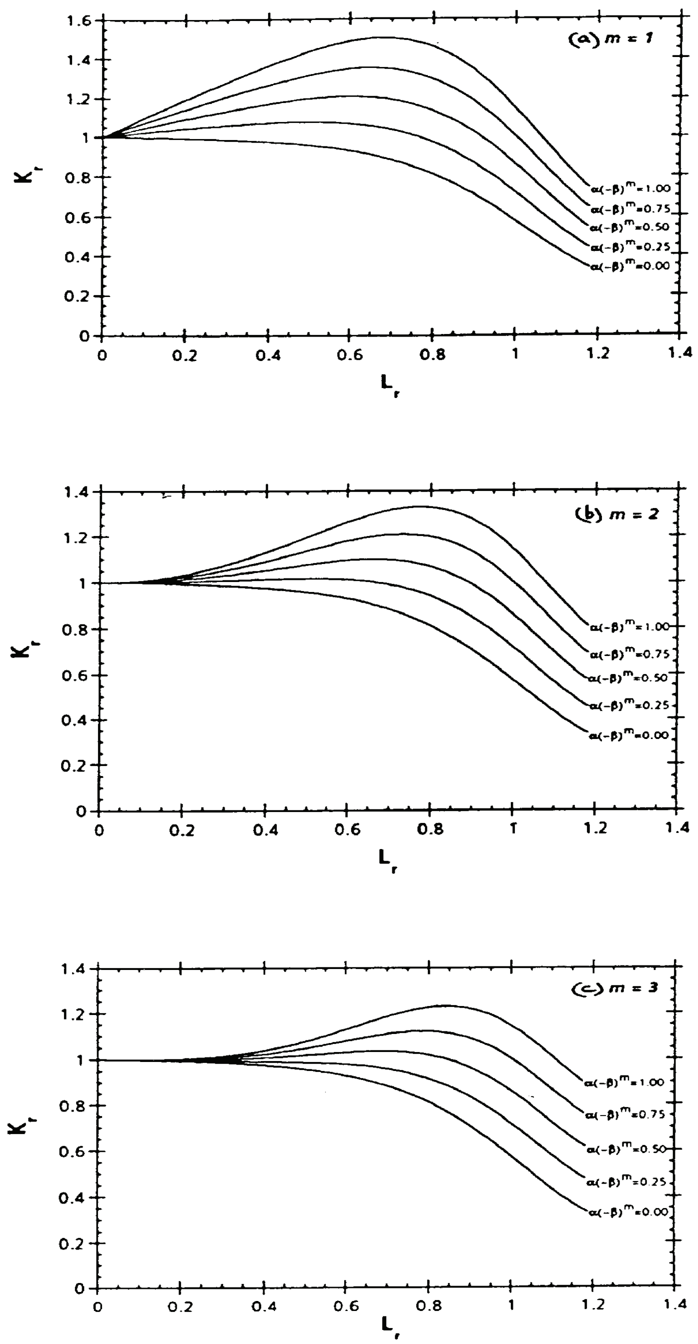


Figure 6.9 - Modifications to the Option 1 failure assessment curve for various values of the material parameters, α, m, and constraint levels, β (<0), using equation (6.75): (a) m = 1, (b) m = 2, (c) m = 3. For α=0 or β=0 the curves reduce to the Option 1 curve

6.4.3.2.4.5 Calculation of Parameter ρ_I

The value of ρ_I is

$$\rho_I = \rho\,(K^c_{mat} / K_{mat}) \tag{6.76}$$

where ρ is defined in Annex J. When K^c_{mat} is defined by equation (6.72) for β < 0, this becomes

$$\rho_I = \rho\,[1 + \alpha(-\beta\,L_r)^m]$$

6.4.3.2.4.6 Assessment of the Significance of Results

Assessing the significance of results follows the principles set down in Section 6.4.3.2.4.6 with reserve factors defined in terms of the assessed conditions and those which produce a limiting condition.

When an initiation analysis is performed for a single primary load, the graphical construction of Figure 6.2 may be used to define the load factor when following Procedure I of Section 6.4.3.2.1. When following Procedure II this construction may not be used as K_r is no longer directly proportional to load because of the dependence of $K^c{}_{mat}$ on βL_r. 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 Procedure I, the load factor may change as a result of changes in L_r , K_r and in the failure assessment curve. Following Procedure II, the failure assessment curve does not change unless an Option 4 curve is constructed at each crack extension (Section 6.4.2). The limiting condition is obtained by plotting F_L as a function of postulated growth as depicted in Figure 6.2 (b, d). When extensive crack growth data are available, a maximum in this plot is obtained. This corresponds to the tangency condition cited in Section 6.4.2, but with the failure assessment curve changing with crack extension [6.25]-[6.27].

It is important that sensitivity studies following the principles of Section 6.4.3.2.4.6 are 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 β - 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 primary and secondary stresses;

(ii) The material property K^c_{mat} - the extent to which lower bound properties have been used, uncertainties in modelling predictions, and uncertainties in fitting equations such as (6.72) to data by assessing the sensitivity to values of α , m .

6.5 Bibliography

[6.1] W A Sorem, R H Dodds and S T Rolfe, Effects of crack depth on elastic plastic fracture toughness, Int J Fract **47**, 105-126 (1991).

[6.2] J D Landes, D E McCabe and H A Ernst, Geometry effects on the R-curve, in non linear fracture mechanics: Volume 2 - Elastic Plastic Fracture (eds J D Landes, A Saxena and J G Merkle) ASTM STP 905, 123-143 (1989).

[6.3] J D G Sumpter and J W Hancock, Status of the J Plus T Stress, in Proceedings of the 10th European Conference on Fracture (eds K-H Schwalbe and C Bergers) Vol I, 617-626, EMAS, Warley, UK (1994).

[6.4] K-H Schwalbe and J Heerens, R-curve testing and relevance to structural assessment, Fatigue Fract Engng Mater Struct **21,** 1259-1271 (1998).

[6.5] D P G Lidbury, R P Birkett and D W Beardsmore, Validation of transition temperature behaviour in full-size components, AEA Technology Report 0802 (1997).

[6.6] J W Hancock, W G Reuter and D M Parks, Constraint and toughness parameterized by T, in Constraint Effects in Fracture (eds E M Hackett, K-H Schwalbe and R H Dodds), ASTM STP 1171, 21-40 (1993).

[6.7] M C Burstow and I C Howard, Predicting the effects of crack tip constraint on material resistance curves using ductile damage theory, Fatigue Fract Engng Mater Struct **19**, 461-474 (1996).

[6.8] A H Sherry, D J Sanderson, D P G Lidbury, R A Ainsworth and K Kikuchi, The application of local approach to assess the influence of in-plane constraint on cleavage fracture, ASME Pressure Vessels and Piping Conference; ASME PVP Volume 304, 495-501 (1995).

[6.9] N P O'Dowd and C F Shih, Family of crack tip fields characterised by a triaxiality parameter: part II - fracture applications, J Mech Phys Solids **40**, 939-963 (1992).

[6.10] R A Ainsworth and N P O'Dowd, Constraint in the failure assessment diagram approach for fracture assessment, ASME J Pres Ves Technol **117**, 260-267 (1995).

[6.11] I MacLennan and J W Hancock, Constraint based failure assessment diagrams, in Proc Roy Soc Lond **A451**, 757-777 (1995).

[6.12] R A Ainsworth, Constraint effects in R6 for combined primary and secondary stresses, Nuclear Electric Report EPD/GEN/REP/0013/96 (1996).

[6.13] 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).

[6.14] A H Sherry, C C France and M R Goldthorpe, Compendium of T-stress solutions for two and three dimensional cracked geometries, Fatigue Fract Engng Mater Struct **18**, 141-155 (1995).

[6.15] D J Sanderson, A H Sherry and N P O'Dowd, Compendium of β solutions for use with the R6 modified framework, AEA Report AEA-TSD-0981 (1996).

[6.16] N P O'Dowd and C F Shih, Family of crack tip fields characterised by a triaxiality parameter: part I - structure of fields, J Mech Phys Solids **39**, 989-1015 (1991).

[6.17] N P O'Dowd and C F Shih, Two-parameter fracture mechanics: theory and applications, ASTM 24th National Symposium on Fracture Mechanics, Gatlinburg, Tennessee, USA (1992).

[6.18] 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).

[6.19] I Sattari-Far, Solutions of constraint parameters Q, Q_m and H for surface cracks in cylinders under internal pressure and combined internal pressure and thermal load, SAQ Report SINTAP/SAQ/07 (1998).

[6.20] I Sattari-Far, Solutions of constraint parameters Q, Q_m and H in different cracked geometries, SAQ Report SINTAP/SAQ/08 (1998).

[6.21] K Wallin, Quantifying Tstress controlled constraint by the Master Curve Transition Temperature, Eng. Fract. Mech., Volume 68, Issue 3, 303-328 (2000).

[6.22] D G Hooton, A H Sherry, D J Sanderson and R A Ainsworth, Application of R6 constraint methods using weight functions for T-stress, ASME Pressure Vessels and Piping Conference; ASME PVP Volume 365, 37-43 (1998).

[6.23] M R Goldthorpe and C S Wiesner, Microchemical predictions of fracture toughness for pressure vessel steel using a coupled model, ASTM STP 1332 (1998)

[6.24] A H Sherry, Constraint effects on fracture assessment within an R6 framework, AEA Report AEA RS 4544 (1994).

[6.25] B A Bilby, I C Howard and Z H Li, Failure assessment diagrams I: the tangency condition for ductile tearing instability, Proc Roy Soc Lond **A444**, 461-482 (1994).

[6.26] B A Bilby, I C Howard and Z H Li, Failure assessment diagrams IV: the inclusion of constraint parameters, Proc Roy Soc Lond, **A448**, 281-291 (1995).

[6.27] B A Bilby, I C Howard and Z H Li, The use of constraint-modified failure assessment lines in failure assessment diagrams, Int J Fract **75**, 323-334 (1996).

[6.28] R A Ainsworth, D J Sanderson, D G Hooton and A H Sherry, Constraint effects in R6 for combined primary and secondary stresses, ASME Pressure Vessels and Piping Conference, Montreal; ASME PVP Volume 324 (1996).

[6.29] R6, Assessment of the Integrity of Structures Containing Defects, Revision 4, British Energy, September 2000

[6.30] RA Ainsworth, A Constraint Based Failure Assessment Diagram for Fracture Assessment, Int J Press Ves a& Piping 64, 277-285 (1995)

[6.31] Validation of Constraint Based Assessment Methodology in Structural Integrity (VOCALIST), FIKS CT-2000-00090.

[6.32] Smith, E., A comparison of Mode I and Mode III results for the elastic stress distribution in the immediate vicinity of a blunt notch, International Journal of Engineering Science 42, 473-481 (2004).

[6.33] Spink, G.M., Worthington, P.J., Heald, P.T., The effect of notch acuity on fracture toughness testing, Materials Science and Engineering 11 (1973), 113-117.

[6.34] Kim, J.H., Kim, D.H., Moon, S.I., Evaluation of static and dynamic fracture toughness using apparent fracture toughness of notched specimens, Materials Science and Engineering (2004) *Article in press*.

[6.35] O. Akourri, M. Louah, A. Kifani, G.Gilgert and G. Pluvinage, The effect of notch radius on fracture toughness J_{Ic}, Engineering Fracture Mechanics 65 (2000), 491-505.

[6.36] D Taylor, P Cornetti and N Pugno, The fracture mechanics of finite crack extension, Engineering Fracture Mechanics, Article in press (2004)

[6.37] McClung, R.C., Chell, G.G., Lee, Y.D., Russell, D.A., Orient, G.E., Development of a Practical Methodology for Elastic-Plastic and Fully Plastic Fatigue Crack Growth, NASA/CR-1999-209428 (1999).

[6.38] AH Sherry, MA Wilkes, DW Beardsmore and DPG Lidbury, Material Constraint Parameters for the Assessment of Shallow Defects in Structural Components-Part I: Parameter Solutions, Engineering Fracture Mechanics, v.72, pp.2373-2395

[6.39] FM Beremin, A local criterion for cleavage fracture of a nuclear pressure vessel steel, Met. Trans., Vol. 14A, 2277-2297 (1983)

[6.40] AH Sherry, MA Wilkes, DW Beardsmore and DPG Lidbury, Material Constraint Parameters for the Assessment of Shallow Defects in Structural Components-Part II: Constraint-Based Assessment of Shallow Cracks, Engineering Fracture Mechanics.

[6.41] K Wallin, Master Curve analysis of ductile to brittle transition region fracture toughness round robin data: the “EURO” fracture toughness curve, VTT Publication 367, Technical Research Center of Finland (1998).

[6.42] G Harlin and J R Willis, The influence of crack size on the ductile-brittle transition, Proc R Soc Lond A415, p197-226

[6.43] T Fett, *T*-Stresses in rectangular plates and circular disks, Engng Fract Mech 60, p 631-652 (1998)

[6.44] R D Patel, Determination of β_T solutions for various geometries using elastic finite element analyses, British Energy Report E/REP/ATEC/0040/GEN/02 (2002).

[6.45] X Wang, Elastic *T*-stress for cracks in test specimens subjected to non-uniform stress distributions, Eng. Fracture Mech 68, p.1339-1352 (2002)

[6.46] A G Miller, Review of limit loads of structures containing defects, 3rd edition, CEGB Report TPRD/B/0093/N82 – Revision 2 (1987); see also Int J Pres Ves Piping **32**, 191-327 (1988).

[6.47] R D Patel, Determination of β_T solutions for various geometries using elastic finite element analyses – part II, British Energy Report E/REP/BDBB/0019/GEN/03 (2003).