C. PROCEDURE APPLICATION (FITNET)

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- **INPUTS**
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INTRODUCTION

INTRODUCTION:

The FITNET Fracture Module 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.

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The procedure can be applied during the design, fabrication or quality control as well as operational stages of the lifetime of a structure. Certainly, the procedure is also applicable for the Failure Analysis cases of the failed components.

a) FITNET at Design Phase

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

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b) FITNET at Fabrication and Quality Control Phase

The method can be used for fitness-for-purpose assessment during the fabrication phase. However, this procedure shall not be used to justify shoddy workmanship and any flaws occurring should be considered on a case by case basis with respect to fabrication standards.

If non-conforming discontinuities are detected, which cannot be shown to be acceptable to the present procedure, the normal response shall be:

(i) correcting the fault in the fabrication process causing the discontinuities and (ii) repairing or replacing the faulty product.

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c) Operational or In-Service Phase

The method can be used to decide whether continued use of a structure or component is possible and safe despite detected discontinuities or modified operational conditions.

If during in-service inspection discontinuities are found which have been induced by load fluctuations and/or environmental effects, these effects must be considered using suitable methods which may not be described in the present section (See sections 7, 8 and 9 in FITNET 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).

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In order to cover previous 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 load including secondary loads such as residual stresses.

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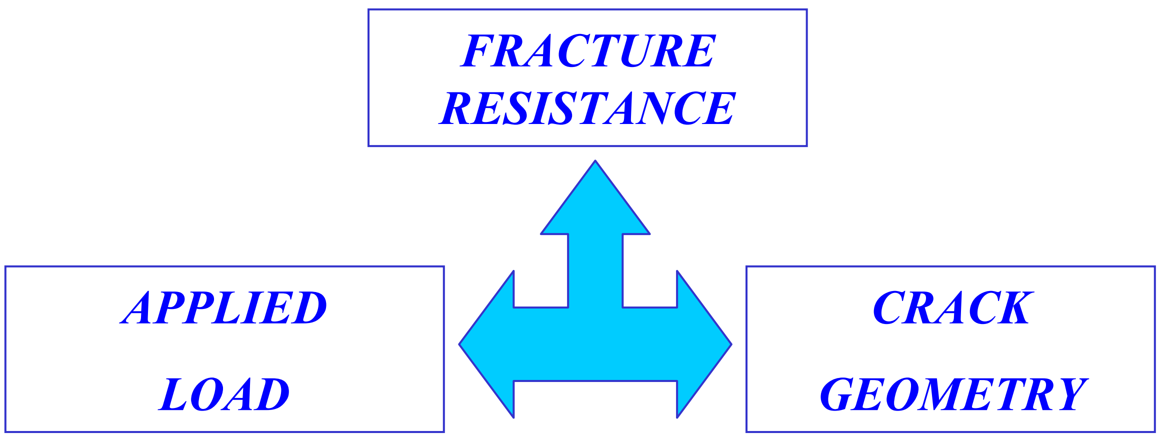
If, as is usually the case, two of these parameters are known the third can be determined by using the relationships of fracture mechanics.



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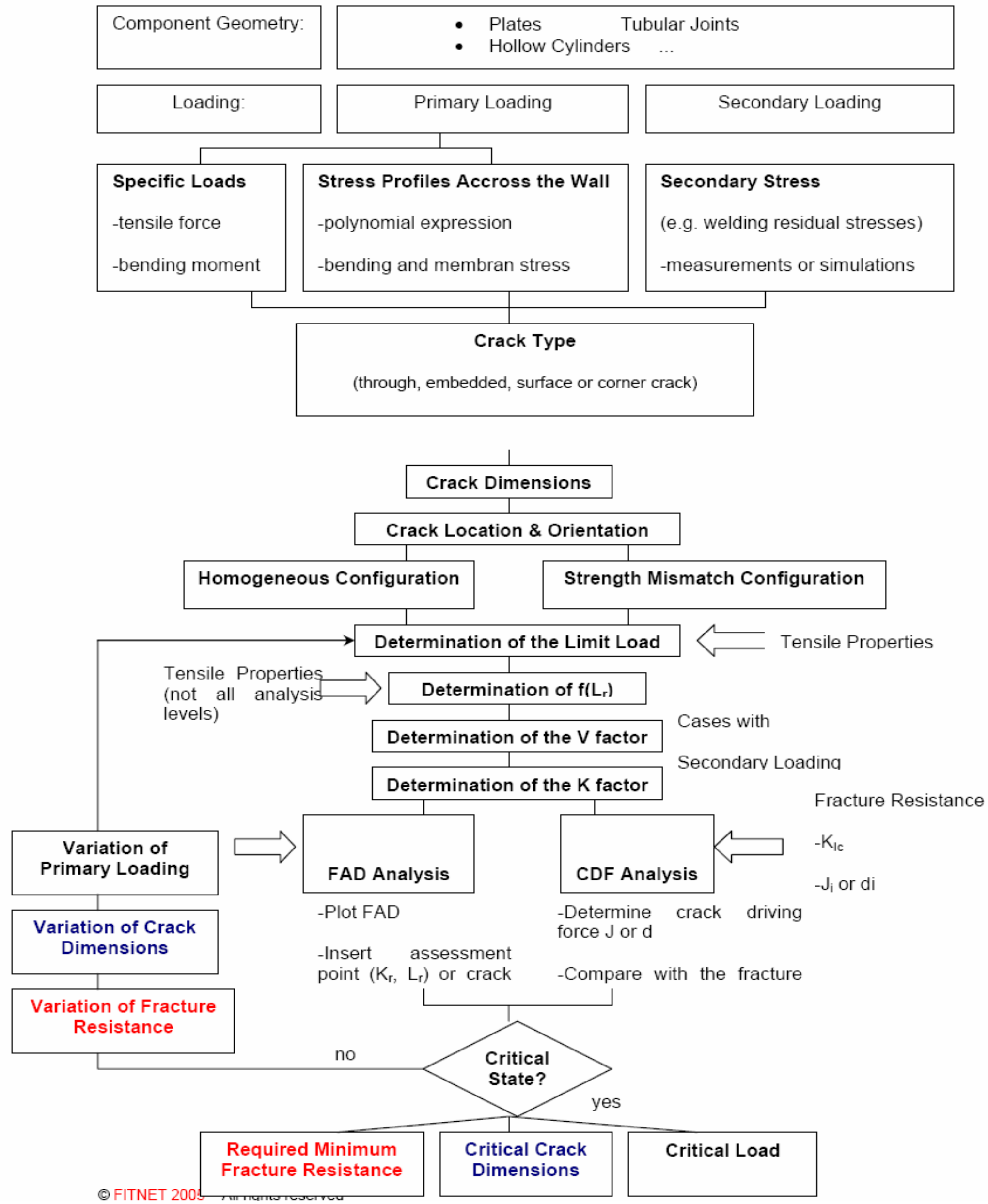
The flowchart illustrates the determination of critical crack size, critical load and required minimum fracture resistance of the material using FITNET Fracture Module



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Concerning cracks, 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 shall be chosen such that it will probably be 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 NDI in quality control and in-service inspections.

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Concerning cracks, the decisions that can be reached using this module are:

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 (Fatigue Module, Section 7, Route 4) the residual lifetime of the component can be predicted and based on this non-destructive inspection (NDI) intervals can be specified which ensure a safe further service for a limited time.

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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 (Fatigue Module, 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.

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INPUTS

INPUTS

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 lands, and details of flaws and their locations, especially when associated with weld zones.

Although the procedure is aimed at establishing the integrity of a structure in the presence of planar flaws, the existence of non - planar (volumetric) flaws may also be of importance.

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INPUTS

STRUCTURAL DATA AND CHARACTERISATION OF FLAWS (cont.)

Defects treated as cracks must be characterised according to the rules given in the procedure, 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.

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INPUTS

LOADS AND STRESSES ON THE STRUCTURE

Stresses 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 and a compendium of weld residual stress profiles are given in the procedure.

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INPUTS

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.

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INPUTS

MATERIAL'S TENSILE PROPERTIES (cont.)

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 the procedure. 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.

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INPUTS

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 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.

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INPUTS

MATERIAL'S FRACTURE PROPERTIES (cont.)

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 (Δa). 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 the procedure.

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MATERIAL'S FRACTURE PROPERTIES (cont.)

Where it is not possible to obtain fracture toughness data, the analyst may use the default option for initiation where the characteristic value is based upon correlations with the material's Charpy impact data. Because this is a correlation, it is designed to provide a conservative estimate of fracture toughness.

The determination of fracture toughness from Charpy impact data is given in the Default Procedure (see Section 6.4.1. in FITNET procedure)

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ANALYSIS: FAD AND CDF ROUTES

ANALYSIS: FAD AND CDF ROUTES

Two alternative approaches are proposed in the Fracture Module:

1) The Failure Assessment Diagram (FAD) approach
2) The Crack Driving Force Diagram (CDFD) Approach

A brief description of the alternative approaches follows.

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ANALYSIS: FAD AND CDF ROUTES

THE FAD APPROACH

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

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

L_r:- The ratio of the applied stress to the stress to cause plastic yielding of the cracked structure.

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ANALYSIS: FAD AND CDF ROUTES

THE FAD APPROACH (cont.)

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:

$$K_r = f(L_r)$$

It incorporates a cut-off at $L_r = L_{rmax}$, which defines the plastic collapse limit of the structure. *f(Lr)* functions are provided in the procedure (see Section 6 in FITNET procedure).

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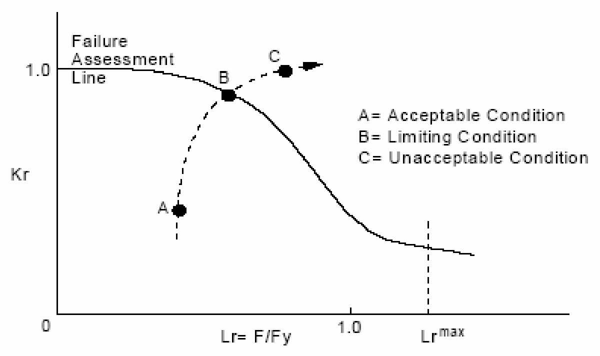
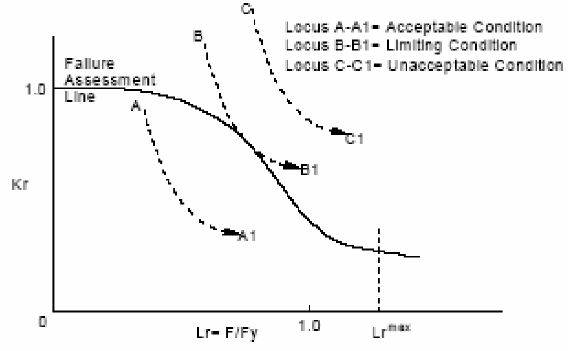
ANALYSIS: FAD AND CDF ROUTES

THE FAD APPROACH (cont.)

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). These points are then compared with the Failure Assessment Line. Figure on the left gives an example for a structure analysed using fracture initiation levels of analysis, and Figure on the right gives an example for a structure that may fail by ductile tearing.





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ANALYSIS: FAD AND CDF ROUTES

THE FAD APPROACH (cont.)

Used this way, the Failure Assessment Line defines the envelope for achievement of a limiting condition for the loading of the cracked structure, and assessment points lying on or within this envelope indicate that the structure, as assessed, is acceptable against this limiting condition. A point which lies outside this envelope indicates that the structure as assessed has failed to meet this limiting condition.

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

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ANALYSIS: FAD AND CDF ROUTES

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 or in units of crack opening displacement. 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:

$$J = J_e \left[f\left(L_r\right)\right]^2$$

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

and E' is Young's modulus. E for plane stress,

and $E/(1-\nu^2)$ for plane strain.

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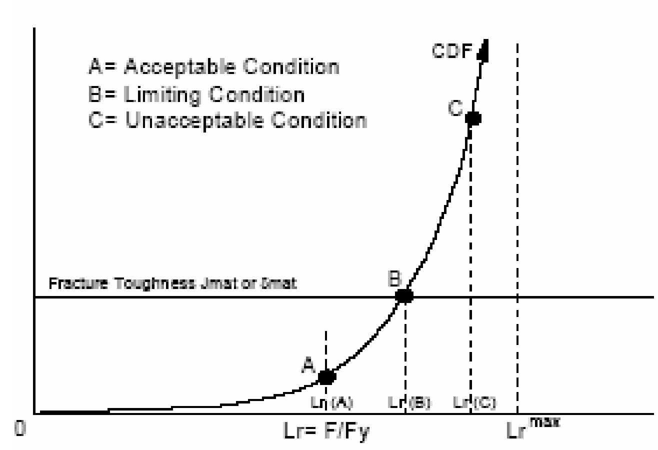
ANALYSIS: FAD AND CDF ROUTES

THE CDF APPROACH (cont.)

To use the CDF approach, for the basic option of analysis, the CDF is plotted as a function of L_r to values of $L_r \leq L_r^{max}$, 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 $L_r(B)$. A vertical line is then drawn at a value of L_r given by the loading condition being assessed.



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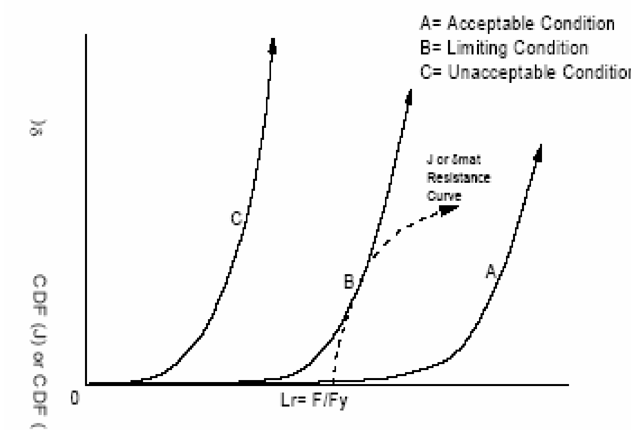
ANALYSIS: FAD AND CDF ROUTES

THE CDF APPROACH (cont.)

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 (tangent). The figure 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.

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ANALYSIS OPTIONS

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.

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.

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ANALYSIS OPTIONS

The option of analysis is characterised mainly by the detail of the material's tensile data used. There are three standardised options and three advanced options, including the special case of a leak before break analysis for pressurised systems. 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.

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ANALYSIS OPTIONS

Next table gives guidance on the selection of analysis option 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. 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.	More accurate and less conservative than options 1 and 2. Weld mismatch option included.
ADVANCED OPTIONS		
OPTION 4 Constraint	Estimates of fracture toughness for crack tip constraint conditions relevant to those of cracked structure.	Allows for loss of constraint in thin sections or predominantly tensile loadings
OPTION 5 *J*-Integral Analysis	Needs numerical cracked body analysis	

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ANALYSIS OPTIONS

And this table gives guidance on the selection of analysis option from toughness data

	Parameters required	Fracture mode Characterised	Reference in Procedure	Input obtained
Basic Option	Charpy energies	All modes	6.4.1	Correlated characteristic values
Initiation Route	Fracture toughness at initiation of cracking. From 3 or more specimens	Onset of brittle fracture: or Onset of ductile fracture	6.3	Single characteristic value of toughness
Tearing Route	Fracture toughness as a function of ductile tearing From 3 or more specimens	Resistance curve	6.4.2	Characteristic values as function of ductile crack growth

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ANALYSIS OPTIONS

The OPTION 1, is the minimum recommended option. This requires measures of the material's yield or proof strengths and its tensile strength, and a value of fracture toughness, K_{mat}, obtained from at least three fracture toughness test results which characterise the initiation of brittle fracture or the initiation of ductile tearing.

For situations where data of this quality can not be obtained, there is a 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.

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ANALYSIS OPTIONS

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 shall be used.

For higher options 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.

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ANALYSIS OPTIONS

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.

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ANALYSIS OPTIONS

The fracture mechanics approach given here (Options up to 3), which is intended to result in a conservative outcome for the assessment, assumes that the section containing the flaw has a high level of constraint. In some instances, especially where the section is thin, or where the loading is predominantly tensile, this assumption can be over-conservative. In such cases it may be possible to reduce the conservatism by taking account of the lower constraint. OPTION 4 (Constraint) allows it.

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ANALYSIS OPTIONS

THE BASIC PROCEDURE

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Applicability

Only the simplest form of material properties data are 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.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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.

2. Determine $f(L_r)$

The function $f(L_r)$ must be calculated for all values of $L_r \leq L_{r\ max}$. The Procedure provides formulation for different cases of stress-strain curves (see Section 6.3.2.2).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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

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.

Where there is a large scatter in the data, the most representative values will be obtained for large data sets, but values can be obtained from as little as three results. Recommended methods for analysing the data are given in the Procedure (see Section 6.3.2.2).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

Where the fracture mechanism is brittle the method uses maximum likelihood (MML) statistics.

For between 3 and 9 test results there are three stages in the statistical analysis, plus a correction for the number of specimens in the data set. This imposes a penalty on the use of small data sets, to make allowance for possible poor representation of the sample.

For 10 or more test results, only two stages need be performed. However, if it is known that the material is inhomogeneous, e.g, if it is taken from a weld or heat affected zone, it is advisable to perform the third stage for indicative purposes. The choice of characteristic value can then be made with more confidence.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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 and the equation for crack size adjustment is given in the Procedure (see Section 5.4.5.1.2).

Where the fracture mechanism is by ductile tearing, 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.

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

4. Characterise The Crack

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

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.

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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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 and which is dependent on both L_r and the stress intensity factor due to the secondary stress. Guidance for stress characterisation and the calculation of ρ is given in the Procedure (see 5.3.1.12).

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ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

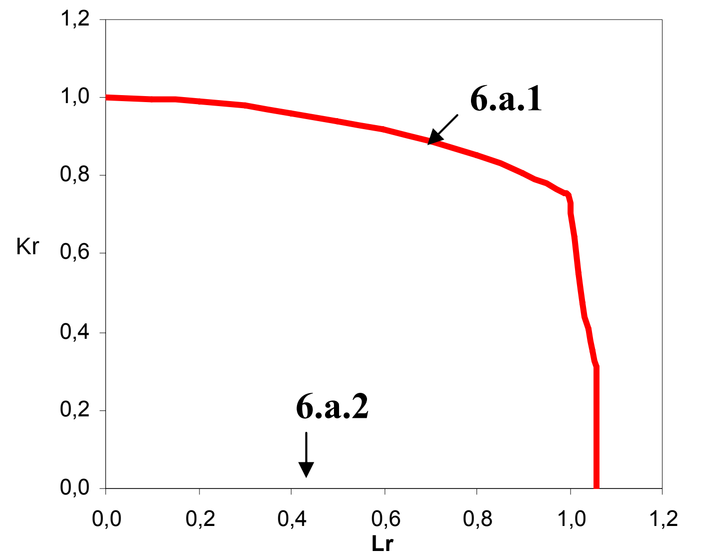
6. Analysis

Step 6 in the procedure has the following sub-steps, depending on the approach chosen:

(a) FAD Approach

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

6.a.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.



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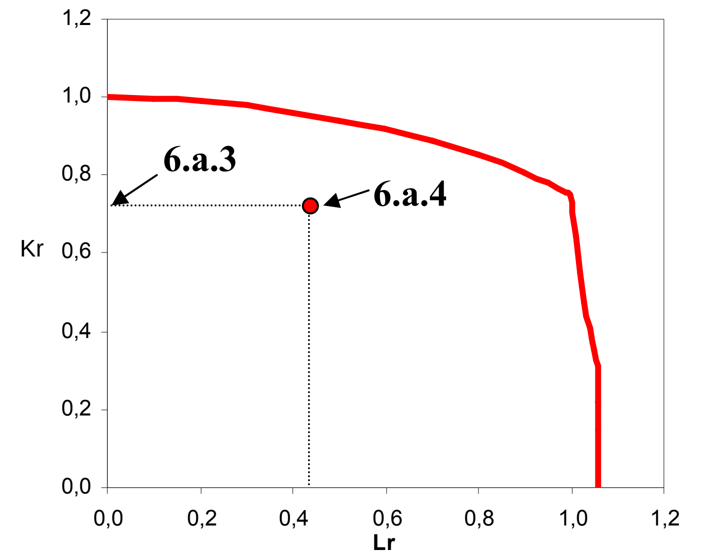
OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.a.3. Calculate Kr for the loading on the structure at the crack size of interest. In the calculation of Kr, 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.

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



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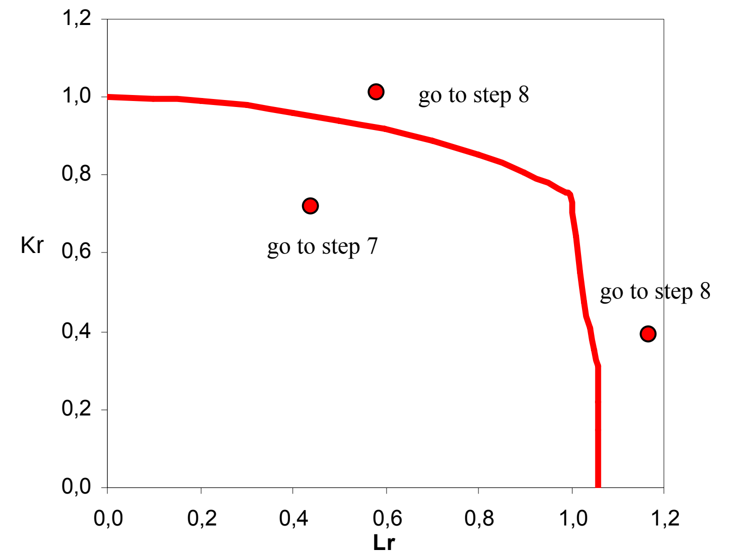
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.a.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. Go to Step 7 of the procedure. If the assessment point lies on or outside the assessment line, the structure is not acceptable in terms of the limiting conditions imposed. Go to step 8 of the procedure.



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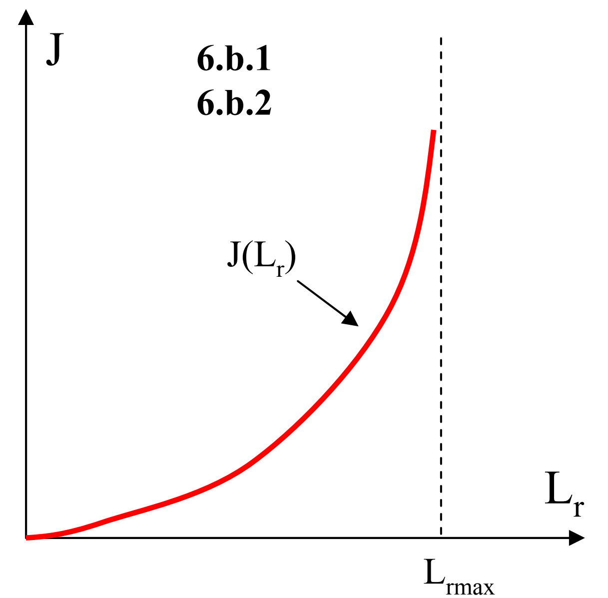
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(b) CDF Analysis using J

6.b.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. At this stage it is also necessary to calculate the allowance for plasticity due to the secondary stresses, ρ.

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



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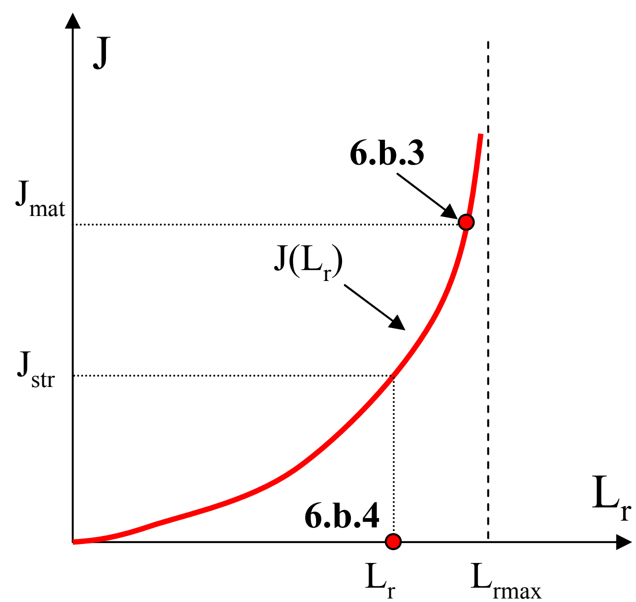
6.b.3. Identify the point on the CDF (J) curve where $J = J_{mat}$.

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



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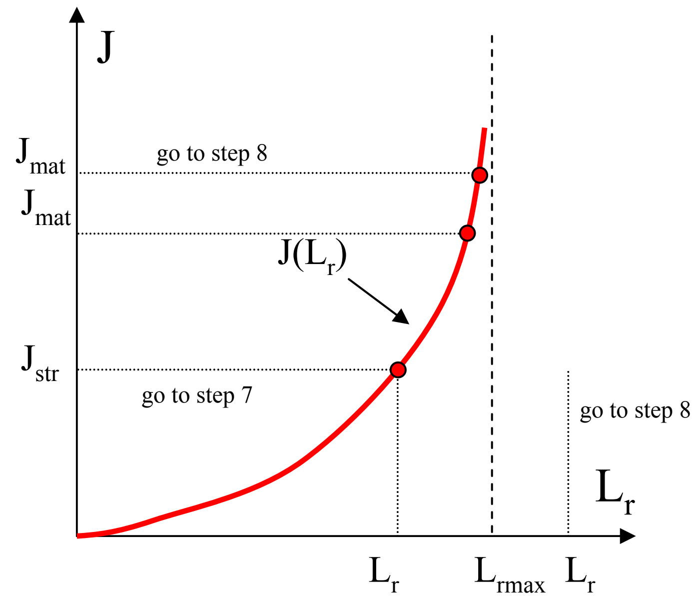
OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

6.b.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. Go to step 7.

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. Go to step 8 in procedure.



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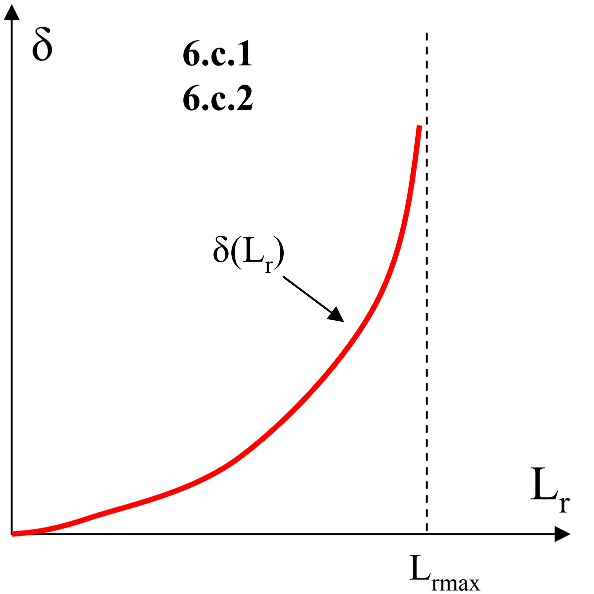
(c) CDF Approach using δ

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

6.c.2. Plot the CDF (δ) using mean tensile properties and the appropriate expression for L_r (step 2 Section I.4.2.2) 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 $L_r \leq L_{r\,max}$. Draw a vertical line at $L_r = L_{r\,max}$.



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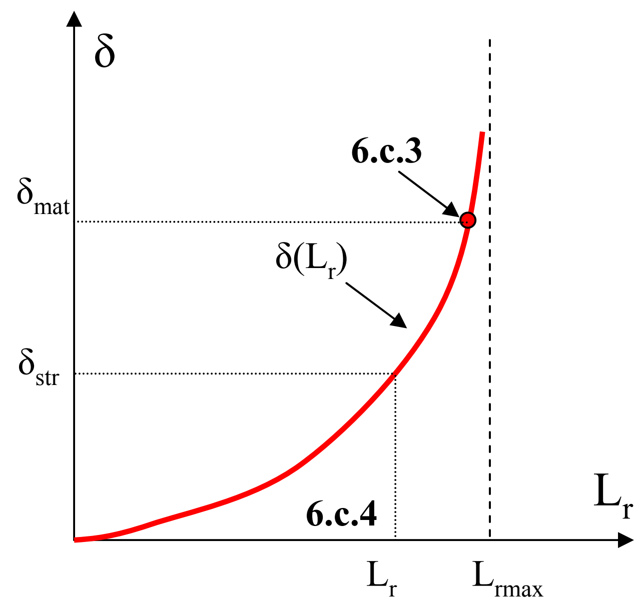
6.c.3. Identify the point on the CDF (δ) curve where $\delta = \delta_{mat}$.

6.c.4. Calculate L_r for the loading on the structure at the crack size of interest using minimum values of tensile properties and draw a vertical line at this value to intersect the CDF (δ) curve at δ_{str}.



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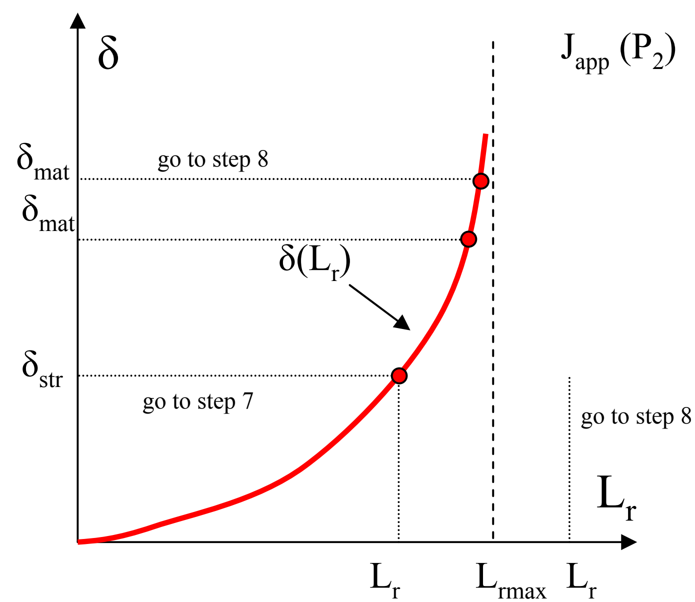
6.c.5. If δ_{str} is less than δ_{mat}, and L_r for the structure is less than $L_{r\,max}$, the analysis has shown that the structure is acceptable in terms of the limiting conditions imposed by the analysis option pursued. Go to step 7 in the procedure.

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. Go to step 8.



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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

7. Assess Result

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

8. Unacceptable result

If the result is unacceptable, it may be possible to proceed to a higher option of analysis. The Procedure gives guidelines to determine how best to proceed (see 6.3.2).

For a 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.

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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(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 accepting a higher 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.

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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

(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.

The analysis should be repeated, modifying steps 1 and 2 and details of step 6, as required.

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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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 (OPTION 4), giving guidelines on how to allow for constraint effects is described in detail in the procedure that also provides for a further advanced option for situations where a numerical J-integral is preferred (OPTION 5).

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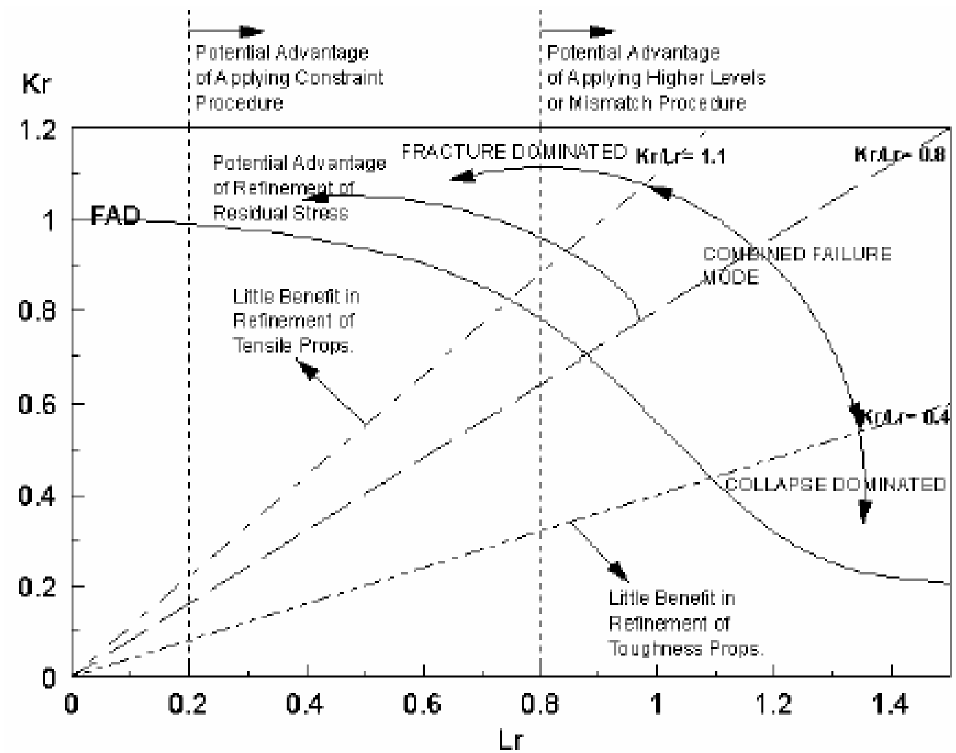
ANALYSIS OPTIONS

OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

A summary of FAD regions for consideration of potential refinement of data or analysis option is shown in the figure.



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OPTION 1: HOMOGENEOUS MATERIAL - INITIATION OF CRACKING

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 FITNET (see Section 11.10).

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

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ANALYSIS OPTIONS

THE MISMATCH PROCEDURE

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

Applicability

In the case of weldments where the differences in yield strengths between the base material and the weld metal is greater than 10 %, the joint may behave as a heterogeneous bi-metallic joint. In such cases, use of minimum values of yield strength in the joint to define Lr 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).

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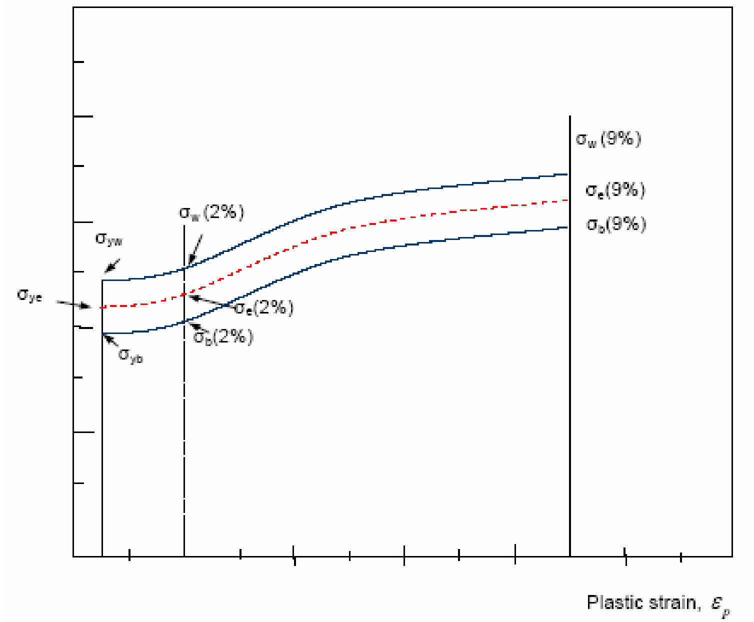
ANALYSIS OPTIONS

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

The mis-match ratio is defined by the relation between yield or proof stress in weld material and yield or proof stress in base material



$M(0,2\%) = \sigma_{yw} / \sigma_{yb}$

$M(2\%) = \sigma_w (2\%) / \sigma_b (2\%)$

$M(9\%) = \sigma_w (9\%) / \sigma_b (9\%)$

$\sigma_e(2\%) / \sigma_b(2\%) = P_{1min} / P_{1b}$ [for M = M(2%)] etc

Definition of mis-match ratio M

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ANALYSIS OPTIONS

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

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

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ANALYSIS OPTIONS

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

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 Option 2 analysis is performed using FADs and CDFs derived using values of L_r and $f(L_r)$ for an equivalent material with tensile properties derived under the mismatch conditions (see 6.3.3).

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ANALYSIS OPTIONS

OPTION 2 ANALYSIS - WELD TO BASE METAL YIELD STRENGTH MISMATCH GREATER THAN 10%

In general, for all combinations of yield behaviour, this requires calculation of the mismatch ratio, M, a mismatch limit load, F_e^M, a value for $L_{r\ max}$ under the mismatch conditions, a value for N under the mismatch conditions and similar values for μ or λ, all of which are defined in the procedure (see Section 6.3.3).

Advice for calculating the mismatch limit load is given and this also contains solutions for some typical geometries (see Annex B).

Note that the mismatch limit load depends not only upon the mismatch ratio but also on the location of the flaw within the weldment.

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ANALYSIS OPTIONS

FE BASED PROCEDURE

OPTION 3, KNOWN STRESS-STRAIN CURVES

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 the mismatch conditions.

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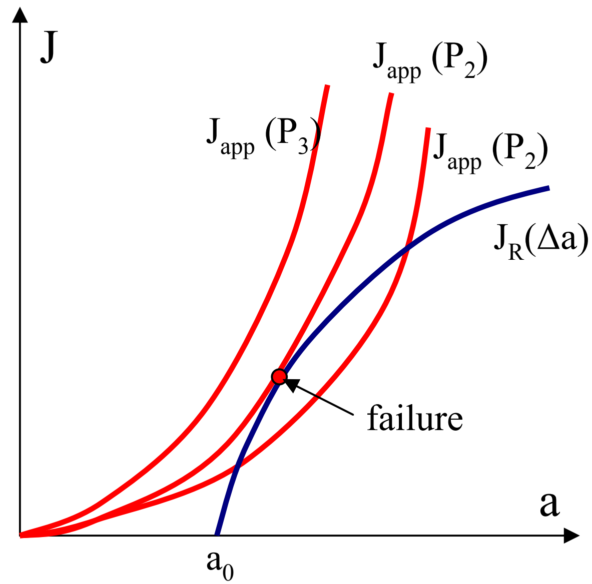
ANALYSIS OPTIONS

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.



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ANALYSIS OPTIONS

CONSTRAINT ANALYSIS

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

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 plain strain conditions and/or high hydrostatic stresses near the crack tip to provide a minimum value, and then, a conservative estimate of the material's resistance to fracture which is relatively independent of geometry.

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ANALYSIS OPTIONS

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

However, there is considerable experience that the material's resistance to fracture increases when the loading is predominantly tensile, and when the crack depths are shallow. These situations lead to lower hydrostatic stresses at the crack tip, referred to as lower constraint.

In order to claim benefit for a situation where the constraint is reduced over that in the test specimen, it is necessary to perform additional calculations and to have more information on fracture toughness properties.

Benefits are usually greatest for shallow cracks subject to tensile loads, but guidance on the cases where greatest benefit can be obtained is contained in the procedure. The methodology for determining the constraint benefit is also described in detail in the FITNET procedure (see Section 6.4.3).

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ANALYSIS OPTIONS

OPTION 5: ALLOWING FOR REDUCED AMOUNTS OF CONSTRAINT

When the FAD route is followed, two alternative procedures set out in Sections 6.4.3.3.1 and 6.4.3.3.2 can be used. The first involves a modification to the FAD but retains the definition of K_r. The second retains the FAD of Section 6.3.2 but modifies the definition of K_r. Guidance on how to perform these steps is contained in Section 6.4.3.3.4 along with guidance on assessing the significance of the results. This latter guidance, in Section 6.4.3.3.4.6, may be useful in deciding which of the two procedures to follow.

With the CDF approach, a modified toughness procedure is used. The procedure follows the steps in Section 6.3.2.3 apart from steps detailed in Section 6.4.3.3.3.

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GUIDANCE ON OPTION SELECTION

GUIDANCE ON OPTION SELECTION

Introduction

FITNET Procedure sets out a step-by-step procedure for assessing the integrity of structures containing defects.

To assist the user, the 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 (similar situations can be obtained in CDF analysis).

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GUIDANCE ON OPTION SELECTION

Selection of Failure Assessment Diagram

•The BASIC OPTION curve is the easiest to apply and requires only the yield stress 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 stress and ultimate tensile stress of base metal and weld metal.

•OPTION 3 requires additional information on the material stress-strain properties and can be applied to homogeneous materials or those cases where weld strength mis-match is an issue;

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GUIDANCE ON OPTION SELECTION

Selection of Failure Assessment Diagram

•OPTION 4 requires results of detailed elastic-plastic analysis of the defective component while OPTION 5 invokes constraint treatment.

Option	Title	Format of Tensile Data	Format of Toughness Data	Mismatch Allowance?
0	Basic	Yield stress only	Estimation of yield/tensile ratio (Y/T) for FAD. Toughness from Charpy energy	No
1	Standard	Yield stress and UTS only	Estimation of strain hardening exponent fromY/T for FAD. Fracture toughness as equivalent Kmat.	No
2	Mismatch	Yield stress and UTS of Parent Plate and weld	Estimation of strain hardening exponent of parent plate and weld metal from Y/T for FAD. Fracture toughness as equivalent Kmat for relevant zone.	Yes
3	Stress-Strain	Full stress-strain curve of Parent Plate (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	Estimation of J-integral as a function of applied loading from numerical analysis.	Optional
5	Constraint	Full stress-strain curve	Modification of FAD based on T and Q stress approaches, Numerical analysis is required.	Possible

Simplified Structure of the Fracture Assessment Procedure

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GUIDANCE ON OPTION SELECTION

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 four 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.

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• For materials with a 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 4 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 a Option 4 curve. In principle the Option 4 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.

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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 J_R 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.

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SPECIAL OPTIONS

The FITNET Procedure presents methodologies for the assessment of specific common technical problems:

- Basic Level of analysis, Option 0 (see Section 6.4.1)
- Ductile tearing analysis (see Section 6.4.2)
- Allowance for constraint effects (see Section 6.4.3)

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SPECIAL OPTIONS

Also, the Procedure provides alternative and specific assessments for fracture:

- Leak before break (see Section 11.2)
- Crack arrest (see Section 11.3)
- Load history effect (see Section 11.4)
- Evaluation under Mode I, II and III loads (see Section 11.5)
- Master Curve (see Section 11.6)
- Probability and Reliability (see Section 11.7)

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