5 Information Required for Assessment (Input)

5.1 Introduction

This section briefly provides the information needed for conducting fitness-for-service analysis in all four Modules. It contains basically three major groups of input parameters, namely;

1) Flaw information, 2) Stresses (loading conditions), 3) Material Properties

The FITNET FFS Procedure can be used for the design of a new component, for support of the fabrication or quality control process and for assessing the structural significance of fabrication cracks, or crack like-flaws, that are detected. Obviously, the FFS procedure also applies to the clarification of the failure case of a component. All three application areas require assessment routes with respective sets of input parameters which enable FFS analysis to be conducted with certain accuracy depending on the quality of the input information.

Therefore, it is advisable to generate relevant material properties of a component at the fabrication stage, or retain appropriate materials, especially welds for later testing. In particular, the desirability of having accurate fracture toughness data cannot be emphasised too strongly and tests on weld procedure test samples are advisable. Similarly, fatigue crack growth, creep and stress corrosion cracking data may be obtained from the actual materials of the component. The information required should take account of the material strain and thermal history and the appropriate environment.

The following input data is essential to conduct FFS assessment;

1) size, position and orientation of flaw, 2) component and weld geometry, fabrication procedure, 3) stresses of all kinds and temperatures including transients, 4) yield or 0.2% proof strength, tensile strength and elastic modulus, (in some cases a full stress-strain curve is required), 5) fatigue/corrosion fatigue, S-N and crack propagation data, 6) fracture toughness (K_{Ic} or J or CTOD values or, for some cases, R-curve) data; in some cases fracture toughness can be estimated from Charpy V-notch data.

5.1.1 Flaw Information

5.1.1.1 Postulated Flaws

The effects of postulated (not real) flaws on structural integrity for “design” and “fabrication support” purposes can be assessed by use of this document. The assessment may include treatment of some shape imperfections as planar or non-planar flaws which may need to be considered as potential failure sites.

5.1.1.2 Flaws in “Component in-Service”

Once a flaw has been detected in a component in operation, a first step is to develop a complete physical evaluation in terms of its shape and dimensions, with any uncertainty in size from the particular detection method taken into account. This evaluation should include an assessment of the flaw location in relation to local stress concentrators, welds, crevices (e.g. at fasteners, flanges), and also details of the crack path and crack orientation, if feasible. If more than one flaw is present, the flaw density and the spacing between the flaws should be noted in view of possible future coalescence. The state of the surface should also be assessed for general or localised corrosion damage. Where coatings are present, the state of the coating should be assessed. The possibility of flaws in other similar locations should be evaluated and inspection in those regions undertaken accordingly.

The following flaw types can be assessed by use of this document in terms of their effect on structural integrity;

1) PLANAR FLAWS: a) cracks, b) lack of fusion or weld penetration, c) undercut, root undercut, concavity and overlap. In some cases, weld undercut may be treated as shape imperfection.

2) NON-PLANAR FLAWS: a) cavities and pores, b) inclusions. In some cases cavities and inclusions may be treated as planar flaws.

3) SHAPE IMPERFECTIONS: a) misalignment, b) imperfect profile

Shape imperfections may sometimes be treated as planar flaws, as listed in 1) and some other shape imperfection may give rise to stress concentration effects.

5.1.2 Stresses

It is essential to analyse and define or make reasonable assumptions about the possible stresses on the component of interest. This should include normal operational stresses (static, cyclic or random cyclic), transient stresses associated with start-up and shut-down or system upsets, residual stresses at welds or on cold-worked surfaces, and the existence of multi-axial stress states. In this context, it is also essential to characterise the intended or operating service environment of the component since it is critical to recognise that it may be a local environment / temperature change which can in turn be responsible for driving the cracking or damage process.

5.1.3 Material Properties

Material properties of the structural component of interest should generally be generated using international material testing codes and standards. Alternatively they should be available based on open literature or reasonable assumptions. The latter may lead un-conservative predictions or excessive conservatism depending on the selection of the properties of interest. The mechanical properties to be used should be determined at the service temperature of the component.

Principally, material properties of the region where flaw is detected, is needed for the assessment of the significance of flaws. Efforts should be made to use the properties of the region of interest.

The material properties should include all weld metal tensile properties if the weldment is of interest. Special testing techniques (e.g. micro-flat tensile) may be needed for determination of weld metal tensile properties of the narrow welds, such as laser and electron beam welds.

5.2 Flaw Information

The flaw characterisation rules given in Annex F have in-built conservatism. In order to reduce this, alternative rules or characterisation from first principles may be appropriate provided the reserve factors of the fracture analysis are acceptable. Annex E and F are giving further details of the flaw re-characterisation, idealisation and interaction of multiple flaws.

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

Furthermore, a comprehensive classification of the various types of weld flaws which may be encountered is given in ISO 6520 (BS EN 26520).

5.2.1 Single Planar Flaws

Planar flaws should be characterised by the height and length of their containment rectangles. These dimensions can be summarised as $2a$ for through thickness flaws; a and $2c$ for surface flaws; and $2a$ and $2c$ for embedded flaws. A full range of geometries and flaw dimension definitions is presented in the FITNET Annex A and B of stress intensity factors and limit load solutions respectively. Examples of definitions of flaw dimensions for a range of common geometries are given in Figure 5.1.

Planar flaws are essentially 2D features such as cracks, laminations, lack of fusion and lack of penetration in welds, undercuts, sharp groove-like localised corrosion, branch type cracks due to environmental effects etc. Volumetric flaws are essentially 3D features such as cavities, blowholes, aligned porosity, solid inclusions and local thinning due to corrosion. Planar flaws are generally treated as cracks, however the decision when a volumetric flaw should be treated this way is much more sophisticated and has to include user's experience with respect to the structure under consideration. It should be taken into account that non-destructive examination might not be sensitive enough to determine whether microcracks have initiated from a volumetric flaw.

5.2.2 Types of Planar Cracks

It is common practice to distinguish between five types of cracks: surface cracks, through-wall cracks, buried or embedded cracks, corner cracks and edge cracks. Any FITNET analysis is based on the assumption that the crack has an ideal shape with a straight, elliptical, semi-elliptical or quarter-elliptical crack front which may be described by two dimensions, crack depth a and crack length c, Figure 5.1. In the case of buried or embedded cracks in addition the distance between the flaw and the nearest free surface, p, has to be taken into account.

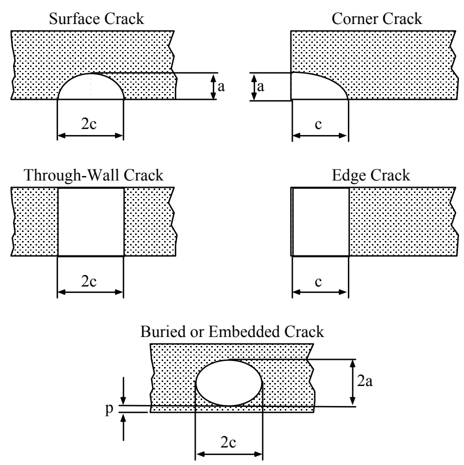

Figure 5.1 - Types of Planar Flaws (*Note: For the through-wall crack, crack length can also be defined as "a"*).

5.3 Stresses

All forms of loading, actual and postulated, should be considered in the stress analyses. In addition to applied service loading, the loading should include dead weight loads, thermal stresses, residual stresses, and stresses due to test, fault and postulated fault loads. In general, the loading is represented by stress distributions across the wall sections of the uncracked structures. Both linearized and polynomial representations are considered below. Usually the stress distributions are provided by finite element analyses but other methods are admissible provided that the resulting stress profiles are conservative. It may sometimes be more convenient to perform separate analyses to provide the inputs to stress intensity factor and limit load calculations, as required in fracture and creep analyses, for example. If stress intensity factor and limit load solutions are available for specific loads such as external forces, moments or pressures these can be used directly as load input parameters.

For some advanced levels of this procedure, both elastic and elastic-plastic analyses of the defective structure are required.

The stress component normal to the crack plane is used to determine the Mode I stress intensity factor. More generally, other stress components are needed to determine shear mode stress intensity factors, limit load and reference stress solutions, and constraint parameters.

5.3.1 Dynamic Analysis

Provided the rise time, t_r, of the applied load exceeds the fundamental period, T, of the cracked component by at least a factor of 3, then a quasi-static stress analysis of the structure is sufficient. For shorter rise times, a dynamic analysis should be performed to define the peak load, which is then used in the assessment.

5.3.2 Load Levels

Within the ASME Codes, loadings are described in terms of 4 levels, A-D. These may be briefly defined as follows.

Level D — These loadings are extremely low probability events, the consequences of which are such that plant is written off so that only considerations of public health and safety are involved

Level C — These are infrequent events that require shutdown for correction of loadings or repair of damage

Level B — These are moderate frequency events, which occur often enough for the design to include a capability to withstand Level B loadings without impairing operation. Level B loadings may or may not lead to a forced outage but corrective action does not include repair of mechanical damage

Level A — These are all loadings other than Levels B, C and D. Level A, therefore, includes service loadings; start-up, shut-down, etc.

It may be necessary to address all levels of loading in a fitness-for-purpose assessment, although for Level D it may not be necessary to avoid failure if the consequences of failure do not affect public health and safety. Clearly, however, acceptable margins or factors will differ for different Levels.

5.3.3 Stress Categorisation

The loads or resulting stresses must be separated into primary and secondary categories:

Primary stresses arise from loads which contribute to plastic collapse and

Secondary stresses arise from loads which do not contribute to plastic collapse.

The categorisation into these two types is a matter of some judgement. The primary stresses are produced by applied external loads such as pressure, deadweight or interaction from other components. Secondary stresses are generally produced as a result of internal mismatch caused by, for example, thermal gradients and welding processes. These stresses will be self-equilibrating, i.e. the net force and bending moment will be zero.

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

It is particularly difficult to decide on the magnitude of residual stresses due to welding to be included in the assessment. Among other things, these are dependent on material, weld designs and procedures, structural geometry, and post weld heat treatment. A compendium of welding residual stress profiles for common geometries and materials is provided in Annex C.

5.3.4 Stress Linearisation

If a stress component is linear through the section thickness, it may be equated to a combination of membrane and bending distributions. Where a stress component, σ is non-linear, statically equivalent membrane and bending stress components over the section, σ_m and σ_b respectively, can be determined from

$$\sigma_m = (1/t)\int_0^t \sigma dx \tag{5.1}$$

$$\sigma_b = (6/t^2)\int_0^t \sigma\,(t/2 - x)\,dx \tag{5.2}$$

where t is the wall thickness.

For determination of the stress intensity factor, the linearised stress over the position of the crack is important. Figure 5.2 shows an arbitrary stress distribution through the thickness of a component. A crack is located between the co-ordinates x_A and x_B. If x_A is nonzero the crack is embedded and if x_A is equal to zero the crack is a surface flaw. The linearised stress state over the position of the crack consists of a membrane part σ_m^* and a local bending part σ_b^*. A normal force N and moment M per unit width may be defined from the actual stress distribution and related to a linearised stress state between x_A and x_B by

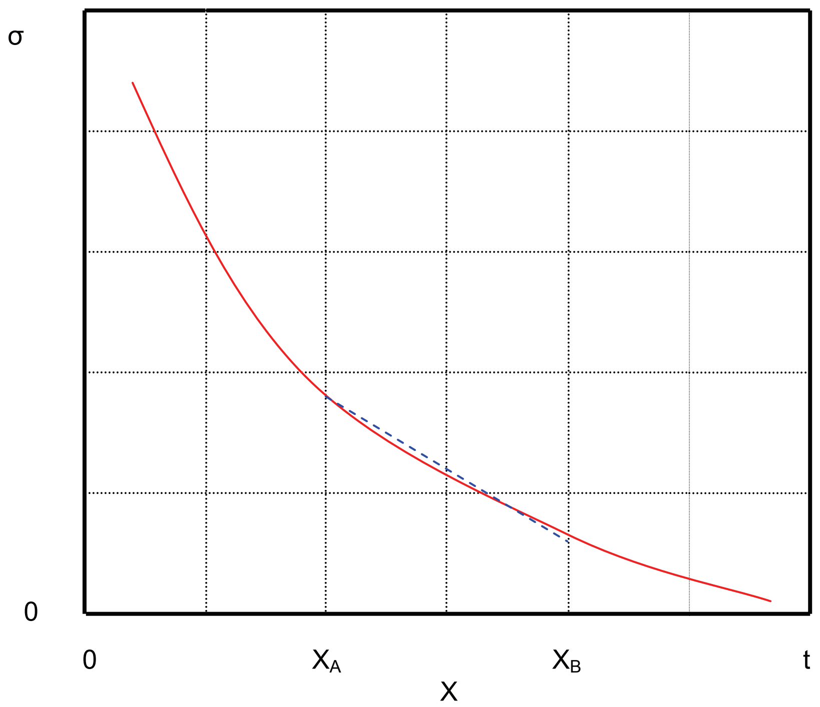

Figure 5.2 - The solid line shows an arbitrary stress distribution and the dotted line the stress linearized over the crack depth, i.e. between the co-ordinates x_A and x_B, the linearization is non-conservative near x_B.

$$N = \int_{x_A}^{x_B} \sigma(x)dx = \int_{x_A}^{x_B} (\sigma_m^* + \sigma_b^*\left(1 - \frac{2x}{t}\right))dx \tag{5.3}$$

$$M = \int_{x_A}^{x_B} x\sigma(x)dx = \int_{x_A}^{x_B} x(\sigma_m^* + \sigma_b^*\left(1 - \frac{2x}{t}\right))dx \tag{5.4}$$

Thus, σ_m^* and σ_b^* are obtained from

$$\sigma_m^* = \frac{4N(x_B^2 + x_B x_A + x_A^2) - 6M(x_B + x_A) - 3Nt(x_B + x_A) + 6Mt}{(x_B - x_A)^3} \tag{5.5}$$

$$\sigma_b^* = \frac{3Nt(x_B + x_A) - 6Mt}{(x_B - x_A)^3} \tag{5.6}$$

The normal force N and the moment M per unit width between the co-ordinates x_A and x_B are calculated from the stress distribution σ(x) by equations (5.3) and (5.4).

For calculation of the limit load parameter L_r and for calculation of K_I for a through-wall crack, x_A=0, x_B=t and equations (5.3) and (5.4) reduce to equations (5.1) and (5.2). For calculation of K_I for a surface flaw, x_A=0 and x_B=a, where a is the crack depth.

5.3.5 Polynomial Representations of Stress Fields

It is often convenient to represent the distribution of a stress component by a polynomial. For example, the fourth order polynomial stress distribution is

$$\sigma(x) = \sigma_0 + \sigma_1(x/t) + \sigma_2(x/t)^2 + \sigma_3(x/t)^3 + \sigma_4(x/t)^4 \tag{5.7}$$

For this distribution, the membrane and bending stress components are determined from equations (5.1) and (5.2) as

$$\sigma_m = \sigma_0 + \sigma_1/2 + \sigma_2/3 + \sigma_3/4 + \sigma_4/5 \tag{5.8}$$

$$\sigma_b = -\sigma_1/2 - \sigma_2/2 - 9\,\sigma_3/20 - 2\,\sigma_4/5 \tag{5.9}$$

For circumferential cracks in cylinders, it may be more convenient to represent the axial stress component by a combination of the through-thickness polynomial of equation (5.7) and a global bending stress, σ_{gb}, across the section:

$$\sigma = \sigma_0 + \sigma_1(x/t) + \sigma_2(x/t)^2 + \sigma_3(x/t)^3 + \sigma_4(x/t)^4 + \sigma_{gb}(R_i + x)/(R_i + t) \tag{5.10}$$

where R_i is the internal radius.

5.3.6 Plastic Collapse away from a Flaw

In addition to determination of the state of stress in the region of a crack, checks should be made to ensure that plastic collapse does not occur in regions away from the crack being assessed. Collapse conditions are most likely to occur in the most highly loaded regions, in locally thinned areas, or in regions of locally high temperature or locally low strength material.

5.3.7 Finite-Element Stress Analysis

Finite element analysis may be used to assist in the application of the FITNET procedures. The complexity of the finite element analysis depends on the application involved and some uses of such analysis are as follows.

Linear elastic analysis of the uncracked structure may be used to provide the stress distribution at the position where a crack is to be assessed, for input to a weight function solution for calculation of the stress intensity factor (Annex A) or the T-stress.(Annex K).

Linear elastic analysis of the cracked structure may be used to directly calculate the stress intensity factor, the T-stress, or the elastic compliance. Such analyses are more likely to be used for calculating stress intensity factors for complex secondary stresses or for mixed mode loadings, where there are fewer standard solutions available.

Inelastic analysis of the uncracked structure may be used to calculate stress and strain distributions at the position where a crack is to be assessed. These results may be used for input to a weight function solution for calculation of the stress intensity factors required when following the more complex fracture methods for treating secondary stresses (Annex J).

Elastic or inelastic analysis of a pressurised structure containing a through-wall crack may be used to evaluate the crack opening area as an input to a leak-before-break (LbB) assessment (Section 11.2).

Elastic, inelastic or elastic compensation analysis of the cracked structure may be used to evaluate the limit load. Such analyses are more likely for complex geometries or for structures with a strength mismatch, where there are fewer standard solutions available.

Inelastic analysis of the cracked structure may be used to calculate J or a constraint parameter such as the Q-stress. Calculation of J, for example, may be used: to construct a more detailed failure assessment curve; to demonstrate that simplified failure assessment curves are relevant to a surface cracked component when used with a global limit load; or for direct use of J in an assessment to refine estimates of margins.

Inelastic analysis of the cracked structure may be used to apply the local approach (Section 12) method, either for direct assessment of the structure or to estimate a constraint enhanced toughness for use in constraint based methods.

Inelastic analysis of the welding process may be used to derive the resulting residual stresses and hence refine the secondary stresses input to an assessment.

5.3.7.1 Performing Finite-Element Stress Analysis

In many cases, the stress analysis requires the use of numerical methods, namely the Finite Element Method (FEM). This method is helpful in cases where an analytical solution does not exist. The FEM can be applied to solution of a number of engineering problems including:

- Heat transfer (stationary or non-stationary)
- Elastic stress analysis
- Non-linear stress analysis (plasticity, creep, etc.)
- Fracture mechanics problems (determination of stress intensity factors, J-integral, C*-integral, etc.)

Although the FEM is widely used at present, the correct use requires some experience. To obtain accurate results, users should consider some rules, which are briefly mentioned below.

5.3.7.1.1 Heat transfer analysis

In a heat transfer analysis, the model should be built taking into account the following criteria:

- All the possible heat fluxes between the component and the external environment should be identified and properly represented. Two basic mechanisms are usually taken into account: Convection and Radiation. In this context, the expression “external environment” has been adopted to identify both the fluid contained by a pressurized component and the environment where the component itself is operated.
- The presence of insulation and refractory materials cannot be neglected, unless they do not significantly affect the temperature distribution and it is possible to demonstrate that this operation leads to conservative results.
- The conductive heat transfer between two metallic surfaces which are in contact with each other must be considered with caution: in some circumstances, for example for non-integral attachments such as pad reinforcements and saddles, because of the manufacturing tolerances, it might be conservative to neglect the heat transfer.
- In the case of transient analysis, the element size and time increment should be chosen carefully (see below)

5.3.7.1.2 Material properties

All material properties must be adequately defined. If the temperature varies, the temperature dependence of material parameters must be specified. The data are usually tabulated and it is expected that parameter values are linearly interpolated in each temperature interval. However, the nature of input data is commonly FE-code dependent and users should follow specific instructions. For plasticity and creep effects, many material models are available. The application of an adequate constitutive model is limited by FE code capabilities and material data availability. The user must ensure that the model used is adequate for the expected temperature and stress intervals.

5.3.7.1.3 Mesh design

The mesh design should be based on technical documentation of the structure to be analysed and the characteristic dimensions must be defined properly. The element model should simulate the behaviour of the real structure as far as possible. This can be ensured by using appropriately sized elements. However, fine meshes lead to extraordinary requirements on computational time. Therefore, a compromise element size should be found. The optimal mesh density (for example in the vicinity of stress concentrators, such as notches etc.) can be tested on a simple example and an adequate element size can be determined by comparison of result for different meshes. If the stress contours are sufficiently smooth, the mesh density is acceptable.

The type of element used depends on the nature of the problem and on availability within the FE code. Users should follow the recommendation of the FE code producer about implemented elements and their properties. Generally, second order elements (spatial or planar) are recommended for modelling. These elements lead to reasonable results. If there is the possibility to adjust integration options, reduced integration can accelerate calculations and suppress some negative phenomena such as element locking due to extensive creep deformation.

For crack tip stress field modelling, there are some special crack tip elements. However, these elements are not available in common FE codes. An alternative and efficient procedure is based on employing collapsed isoparametric second order elements. In the case of linear elastic analysis, these elements are able to simulate the $r^{-1/2}$ stress field singularity, which occurs in the crack tip vicinity.

In heat transfer problems, temperature oscillations are observed occasionally. The phenomenon can be a result of the element mesh being too coarse.

5.3.7.1.4 Boundary conditions

The displacements and forces (or moments, pressure etc.) should follow the real constraints on the structure (for example support positions) as well as the loadings that affect it. In creep problems, the time dependence of loading can play a significant role and hence the loading history must be known. The symmetry of a structure can significantly reduce the computational requirements and only a part (half, quarter) of the structure needs to be modelled. In this case however, appropriate nodal displacements which correspond to the assumed symmetry must be prescribed.

In heat transfer problems, the determination of heat transfer coefficients may be important. In this case, sensitivity analysis can be performed to assess the influence of the heat transfer coefficient on results. If temperature measurements on the structure to be analysed are available, the heat transfer coefficient can be fitted by a small number of simulations and an optimal value can be found.

5.3.7.1.5 Calculation control

In time-dependent problems (creep, heat transfer, etc.), the time increment plays an important role. A large time increment can cause solution instability and convergence problems. To prevent this, an implicit procedure is recommended because it is unconditionally stable. FE codes can also employ explicit algorithms with controlled time increments. The FE code manual should be consulted to identify capabilities and limits of the algorithm used.

In creep problems, the time increment should be very short (e.g. 10^{-3} hours) in the primary stage of creep. As the structure approaches the steady state, the time increment can get longer. The software usually estimates limits to the crep strain increment obtained between two subsequent solutions. These limits (expressed in terms of “creep ratio” between creep strain increment and total strain) should never been exceeded, in particular before the steady state field is reached.

Nonlinear analysis leads to a system of nonlinear equations and its solution satisfies equilibrium conditions. The system of equations is usually solved iteratively. There are several numerical methods (for example, the Newton-Raphson technique) and their convergence rate can be problem dependent. For a given problem, some methods can converge, some not. The solution is found, if convergence conditions are satisfied. The convergence conditions are usually based on vector norms (for example residual vector norm) and convergence occurs when the norms are less than a specified value. A strict convergence condition leads to an excessive number of iterations and a non-convergent solution. Therefore, the number of iterations should be limited and the convergence condition should be adjusted appropriately. It is helpful to monitor the norms during solution and if the norms do not approach the specified limit, it is better to interrupt the solution. Before restart, the convergence criterion should be weakened or loading increments can be reduced. If the FE program allows, use of another iterative method can lead to a convergent solution. Users should consult the FE code manual to find more about solution convergence. For example, line search algorithms can accelerate convergence and improve the robustness of the iterative procedure.

5.3.8 Mixed Mode Loading

Where the plane of the flaw is not aligned with a plane of principal stress, the first step is to project the flaw on to each of the three planes normal to the principal stresses and to assess each of the three projected flaws. There are, however, restrictions on proceeding in this way. Caution is needed if:

- There is a large angle (>20˚) between the plane of the actual flaw and the principal plane on which the stress intensity factor and reference stress are greatest.
- There is only a small difference between the stress intensity factors on two or more planes of projection.
- The maximum stress intensity factor occurs for the flaw projected on one plane and the maximum reference stress occurs for the flaw projected on another plane.
- One of the principal stresses is compressive with a magnitude similar to the maximum principal tensile stress.

In these circumstances, significant Mode II or Mode III loading may be present and the mixed mode procedures of Section 11.5 should be followed.

5.3.9 Warm Pre-stressing

A warm pre-stress is an initial pre-load applied to a ferritic steel structure containing a flaw, which is carried out at a temperature above the ductile-brittle transition temperature, and at a higher temperature or in a less embrittled state than that corresponding to the subsequent service assessment.

When carrying out a warm pre-stressing assessment as part of a fracture assessment, it is necessary to define the stresses corresponding to both the pre-load and the service conditions and the nature of the loading and temperature history. Advice on performing a warm pre-stress analysis is given in Section 11.4.1.3.

5.3.10 Fluctuating Stress

Fatigue crack growth and some other assessments use the applied stress range acting on the section containing the flaw, resulting from the fluctuating components of load. Thus, residual welding stresses are not included, but fluctuating thermal stresses are. The stresses may either be treated directly or after resolution into membrane and bending components as described above.

Where the stress range varies during life, a stress spectrum should be converted to discrete stress ranges using a cycle counting method, such as rainflow or reservoir. The stress spectrum should then be represented as a distribution or histogram of stress ranges.

5.3.11 Relaxation of Residual Stress

Residual stresses may be relaxed as a result of plasticity and/or creep. Relaxation due to creep may occur during post-weld heat treatment or in service, for components operating at high temperature.

5.3.12 Plastic Limit Load Analysis

5.3.12.1 Definition

The limit load is defined as the maximum load a component of elastic-perfectly plastic material is able to withstand. Above this limit ligament yielding becomes unlimited. However, real materials strain harden with the consequence that the applied load may increase beyond the value given by the non-hardening limit load. Sometimes strain hardening is taken into account by replacing the yield strength of the material by a 'flow strength' (often the mean of yield strength and ultimate tensile strength) in the limit load equation.

In the FITNET procedure, the limit load F_Y is defined as the perfectly plastic limit load for a yield stress σ_Y equal to the 0.2% proof stress of the material. The limit load is used, for example, to define the parameter L_r in a fracture analysis and a reference stress, σ_{ref}, in a creep analysis by

$$L_r = F/F_Y = \sigma_{ref}/\sigma_Y \qquad (5.11)$$

5.3.12.2 Determination of the limit load

A number of methods such as classical limit load analyses, finite element analyses and experimental techniques are available for determining the limit load. These are discussed briefly here. In the context of FITNET the primary source of information for obtaining the limit load is the compendium given in Annex B. Limit load solutions from other sources or individual determination can also be used provided they are shown be conservative. Usually plane stress and lower bound theorem limit loads can be regarded as conservative. Caution is however advisable with special applications such as leak-before-break analyses where the conservatism can be reversed. The FITNET compendium covers solutions for specific geometries, solutions based on a so-called generalised plate model and solutions for strength mismatched components.

a) Solutions for specific geometries

Annex B contains solutions for defects in plates, spheres, cylinders and bolts. The limit load is directly proportional to yield strength σ_Y, and decreases with increasing flaw size. For internal flaws in pressurised components, the limit load depends on whether or not the flaw faces are assumed to be pressurised and on whether a local or global criterion is taken.

b) Use of Elastically Calculated Stresses in a Generalised Plate Model

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

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

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

c) Solutions for weld strength mismatched components

The pattern of plastic deformation in the neighbourhood of a section containing a flaw may be influenced if there is strength mismatch, for example, when the weld metal and base metal plate of a weldment show different yield strength and/or strain hardening. This is discussed in Section 6.3.3.5 and solutions are given in Annex B for geometries which may be idealised as containing two regions with differing strengths. A lower bound estimate of limit load is given by the homogeneous solution taking the lower of the two strengths. The limit load for mismatch in Annex B enables benefit to be claimed from the increase in limit load due to the higher strength material.

d) Use of Finite-Element Analysis

The flawed component may be analysed using a small displacement finite-element method with an elastic-perfectly plastic material model. The analysis is performed for a monotonically increasing load; the maximum load attained defines the limit load ratio F_Y/σ_Y for the yield stress σ_Y used in the analysis. Since the limit load is directly proportional to the yield stress, the ratio F_Y/σ_Y can be used to define the plastic limit load for other values of yield stress. The elastic properties assumed in the analysis do not affect the quantity in a small displacement analysis.

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

The finite-element method has not been widely used for obtaining plastic limit loads of flawed components, but has been used to determine limit loads by the methods of limit analysis rather than by performing an incremental elastic-plastic solution. However, results have been obtained largely for plate geometries rather than for complex components. Examples are the strength mismatch limit load solutions in Annex B. With the ever increasing power of digital computers such numerical solutions are likely to become more widely available.

e) Use of Plastic Limit Analysis Solutions

The methods of limit analysis are well developed and the upper and lower bound theorems can be used to estimate values of the limit load. The lower bound theorem leads to an underestimate of the limit load and hence to an overestimate of L_r and is particularly useful for the applications of this document. The compendium (Annex B) contains a large number of lower bound limit analysis solutions.

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

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

5.3.13 Stress Analysis for Fatigue Assessment

5.3.13.1 Load/stress history

Loads and the resulting fatigue actions (i.e. stresses) on real structures usually fluctuate in an irregular manner and give rise to variable amplitude loading. The stress amplitude may vary in both magnitude and period from cycle to cycle. Because the physical phemomena are not chaotic but random, the stress time history can be characterized by mathematical functions and by a limited number of parameters.

The stress time history is a record and/or a representation of the fluctuations of the load in the anticipated service time of the component. It is described in terms of successive maxima and minima of the stress. It covers all loading events and the corresponding is shown in Figure 5.3.

Figure 5.3 - Typical random load/stress time history

In most cases, the load/stress time history is stationary and ergodic, which allows, from a representation of a limited length, the definition of a mean range and its variance, an energy density spectrum, a statistical histogram and distribution, and a probabilistic distribution.

The data needed to perform a fatigue analysis can be determined from measurements or time step computation conducted during a limited time, or a spectral computation. A load/stress history may be given for the full service life time or as a series of load/stress histories of typical sequence of load events for the full service life time.

A load/stress history can be represented by one of the following:

a) a record of successive maxima and minima of load/stress, as shown in Figure 5.3,

b) a load/stress cumulative range histogram (stress range cumulative distribution) determined from a) as shown in Figure 5.4,

c) a transition matrix of the stress derived from a) as shown in Figure 5.5,

d) a load/stress range histogram (stress range occurrences), as shown in Figure 7.3.

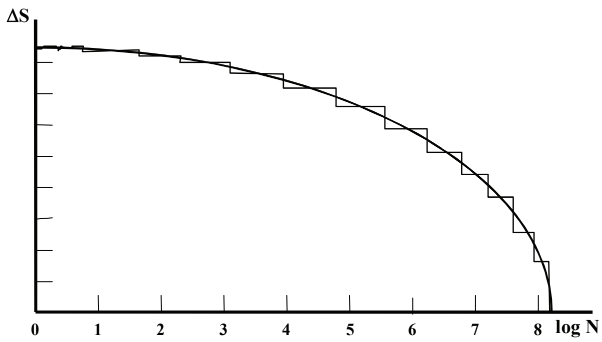

Figure 5.4 - Long term cumulative histogram

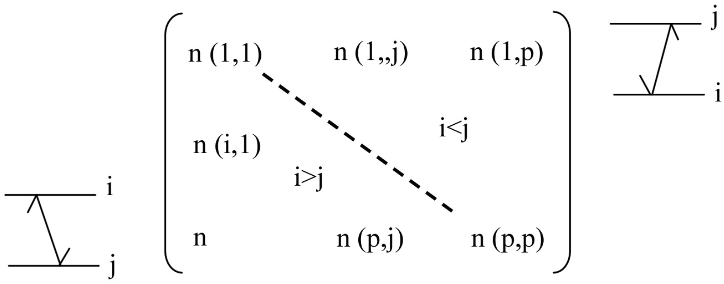

Figure 5.5 - Transition matrix

When the structural behaviour, i.e., stresses versus loads, are measured or computed by a time step method, the results provide a stress history of type a). The type b), c) and d) stress histories are then obtained using a specific counting method, such as up zero crossing or rainflow.

When the structural behaviour is computed by a spectral method, the results provide a series of short term energy density spectra. Each energy density spectrum allows determination of a short term stress cumulative histogram, and the sum of the short term histograms, taking into account their probability of occurrence, provides the long term histogram for the total service time as shown in Figure 5.4.

In general the short term energy density spectra can be assumed narrow band which leads to a Rayleigh distributed short term cumulative histogram:

$$prob\{S \geq S_0\} = \exp\left[-\frac{S_0^2}{E}\right] \tag{5.12}$$

where E is the total energy of the spectrum.

In the majority of cases the long term load/stress cumulative histogram can be represented by a 2 parameter Weibull distribution:

$$prob\{S \geq S_0\} = \exp\left[-\left(\frac{S_0}{w}\right)^{\xi}\right] \tag{5.13}$$

where

ζ is the shape factor which fixes the shape of the curve. In Figure 5.4, $\xi > 1$.

w is a characteristic value which fixes the level of the curve.

5.3.13.2 Stress concentrations

Stress concentrations due to gross structural discontinuities and misalignment are included when calculating the applied stress. The stress concentration effect of a local structural discontinuity, due for example to a welded joint geometry, is only taken into account in a notch stress approach (see Section 7.2.3.2) or a fracture mechanics assessment as part of the calculation of the stress intensity factor (see Annex A).

The peak stress due to misalignment depends only on the membrane component of applied stress. If a misaligned joint is within the stress concentration field due to a gross structural discontinuity, this membrane stress has to include the effect of the gross structural discontinuity.

5.3.13.3 Structural stress approach

Recent technical developments in the mesh-insensitive structural stress method have been discussed in detail in a number of recent publications. The mesh-insensitive structural stress definition follows the equilibrium based separation of a given through-thickness stress distribution such as at weld toe into two parts: (1) an equilibrium equivalent structural stress represented by membrane and bending components; (2) a self-equilibrating notch stress.

The equilibrium arguments can be enforced directly by using balanced nodal forces and moments from a typical finite element shell or plate model by mapping the nodal force and moment vectors into the corresponding line force and line moment vectors in the work-equivalent sense. Then, the structural stress at each nodal position along a weld line is expressed as:

$$\sigma_s = \sigma_m + \sigma_b = \frac{f}{t} + \frac{6m}{t^2} \qquad (5.14)$$

with its membrane and bending components being calculated from the line force (*f*) and line moment (*m*). In doing so, the structural stresses calculated demonstrate good mesh-insensitivity.

5.4 Material properties

5.4.1 Introduction

The scope of this section is to define the materials properties required for the implementation of the four FITNET assessment modules and to indicate, where appropriate, generic values. For convenience the sub-sections below are divided as follows:

- elastic and physical properties
- deformation and strength properties
- fracture toughness
- fatigue strength and fatigue crack growth
- creep strength and creep crack growth
- corrosion properties

Detailed information on the properties of different materials and conditions are provided in Annex M.

The material properties used in the FITNET analysis should, where possible, be obtained from the specific material concerned, in the correct product form, and at the relevant temperature and loading rate. Effects of material variability, testing and analysis procedures should be taken into account as well as potential changes in material properties in service due to thermal aging, irradiation, and other mechanisms.

5.4.2 Elastic and Physical Properties

Young's modulus and Poisson's ratio are required for the temperature at which the component is operated. If no material specific values are available, use can be made of generic data such as that shown in Table 5.1. If thermal stress analysis is to be performed, values of the material conductivity, specific heat capacity and thermal expansion coefficient will also be required.

Table 5.1 – Generic data for the elastic modulus and Poisson ratio [1]

Material	Elastic Modulus, GPa				Poisson's ratio
	20°C	200°C	400°C	600°C	
Ferritic steels	211	196	177	127	c. 0.30
Steels with approx. 12% Cr	216	200	179	127	c. 0.30
Austenitic steels	196	186	174	157	c. 0.30
Aluminium alloys	60-80	54-72	-	-	c. 0.33
Titanium alloys	112-130	99-113	88-93	77-80	0.32-0.38

5.4.3 Deformation and Strength Properties

5.4.3.1 Yield Strength and Tensile Strength

In this procedure the ultimate tensile strength of a material is designated as R_m and the yield strength by the general term σ_Y.

However, with respect to specific applications it has a slightly different meaning that varies from case to case. For materials with continuous yielding, i.e. without Lüders' strain, the yield strength σ_Y refers to the proof strength of the material $R_{p0.2}$ that is defined for a plastic strain of 0.2%, whereas for materials with a Lüders' strain it refers to the lower yield plateau R_{eL}.

In the fracture module (Section 6) for Option 0 (Basic level) and Option 1 analyses, the specified minimum yield strength as given by a manufacturer's standard can be accepted instead of individually determined values. However a distinction is not usually made between the lower and upper yield plateau, R_{eH} and R_{eH} on test certificates. Therefore, in order to avoid non-conservatism, the value of yield strength provided should be corrected by a factor of 0.95 when applied to the determination of the plastic limit load F_Y and the ligament yielding factor L_r.

N.B. In this procedure, the conservatism of the yield strength (and ultimate tensile strength) is defined quite differently depending on the further use in the analysis. For determining the plastic limit load F_Y and the ligament yielding factor L_r, conservatism is given by lower bound values. However, for estimating welding residual stresses, conservatism means upper bound. Special problems may arise for leak-before-break analyses.

In cases where more than one measurement of σ_Y is available, the lowest or highest value has to be chosen depending on what is conservative for the special application.

The flow strength, σ_f, can be understood as an effective yield strength taking into account strain hardening. In FITNET it is defined as

$$\sigma_f = 0.5\left(\sigma_Y + R_m\right). \qquad (5.15)$$

Temperature and strain rate dependency: for situations where the operating temperature is below room temperature, but only the room temperature yield strength is known, the yield strength for ferritic steels may be estimated from the following equation:

$$\sigma_{Y(T)} = \sigma_{Y(RT)} + \frac{10^5}{491 + 1.8\,T} - 189 \text{ MPa} \qquad (5.16)$$

Where σ_Y is the chosen yield strength and T is the temperature of interest in °C.

The strength parameters yield strength, tensile strength and flow strength tend to increase with increasing loading rate in the absence of dynamic strain aging effects. In cases of dynamic loading, the use of quasi-static tensile properties will ensure conservatism in the fracture assessment procedure, although the user should be aware that fracture toughness may fall with increasing loading rate.

Statistical aspects and margins: the yield and strength parameters are characterised by variations due to batch effects, different locations in the plates or bars of material and random errors in testing. These variations are taken into account in a FITNET analysis either as lower or upper bound values depending on what is conservative for the particular application or as statistical parameters characterising the respective scatter bands. Specified minimum properties for the grade of material can be treated as lower bound values. Individually determined values need statistical evaluation. An appropriate measure for this is the coefficient of variation (COV) which refers to the ratio of standard deviation to be mean value of the respective property which has to be determined in a number of tests. If no specific information is available the default values in Table 5.2 can be used.

Table 5.2 - Indicative values of the coefficient of variation for strength properties [Dowling]

Variable	Coefficient of variation (default value)
Modulus of elasticity	0.05
Yield strength	0.07
Ultimate tensile strength	0.05
Tensile strength of welds	0.10

NOTE In the SINTAP procedure the scatter in the yield strength is modelled by a log-normal distribution whereas the default values in the above table are representative for a normal distribution. The influence of this difference on the numerical values can, however, be regarded as insignificant.

5.4.3.2 Engineering and True Stress-Strain

For fracture assessment Options 3, 4 and 5 individually determined stress-strain curves have to be available. Special emphasis has to be given to well defined stress-strain values at strains less than 1%. At Option 3, true stress, true strain data have to be used. At Option 3 true stress, true strain data are mandatory for "large deformation" analyses whereas both engineering and true data may be used for "small deformation" analysis. As a rule, J integral analyses can be carried out assuming small deformation conditions, whereas for CTOD analyses large deformations conditions need to be considered. The true stress and strain data, σ_t and ε_t, can be determined from the engineering data, σ and ε, by:

$$\sigma_t = \sigma\,(1+\varepsilon) \tag{5.17}$$

and

$$\varepsilon_t = \ln\ (1+\varepsilon) \tag{5.18}$$

However, since they are based on the assumption of a homogeneous strain distribution along the gauge length of the tensile specimen, these equations are applicable only to the onset of necking. Beyond the maximum load the true stress should be determined from measurements of the actual cross section diameter in the necking region. In addition, since the neck - which by its nature is a mild notch – introduces a complex triaxial stress state further correction is needed. The so-called "Bridgman correction" provides an estimate of the uniaxial stress that would exist if no necking took place:

$$\sigma = \left(\frac{1+2R}{r}\right)^{-1} \left[\ln\ \left(1+\frac{r}{2R}\right)\right]^{-1} \sigma_x \tag{5.19}$$

In equation (5.19) σ_x is formally the axial stress (load divided by minimum cross section, the non-uniform stress state being ignored), R is the radius of the curvature of the neck which is modelled by the arc of a circle and r is the minimum radius in the neck. R and r may be measured directly during the tensile test, e.g. using photography or a tapered ring gauge.

5.4.3.3 Strain Hardening Coefficient

Generally, the strain hardening coefficient N (0 < N < 1) is defined as the slope of the plastic branch of the stress-strain curve, when plotted in log(σ) – log(ε_p)coordinates. In the FITNET procedure a conservative estimate is given by

$$N = 0.3\left[1 - \frac{\sigma_Y}{R_m}\right] \tag{5.20}$$

Equation (5.20) was obtained as a lower bound curve to a large data set of individually determined N versus σ_Y/R_m pairs for a wide range of steels with yield strengths between 300 and 1,000 MPa and σ_Y/R_m ratios between 0.65 and 0.95. Because equation (5.20) was obtained for steels its application to non-ferrous materials is not recommended. If structures made of non-ferrous materials have to be assessed, the general definition for determining N as the slope of the log(σ) – log(ε_p) part of the true stress-strain curve can be applied.

Several definitions of the strain hardening exponent are used in the literature. These are commonly also designated as N or n; however the corresponding values show considerable divergence. Therefore, no use must be made of N values provided in external sources unless it is demonstrated that the basic definition is compatible to that given in this procedure.

5.4.3.4 Lüders' Strain

For fracture analyses (except Option 0) a distinction must be made between materials with and without Lüders' strain. In many situations the data will be complete enough to establish the yielding characteristics, but there are other cases where this may not be the case. For structural steels, an indication can be obtained from the yield strength, composition, and the process route. Guidance for this decision is given in Table 5.3. where these factors have been grouped according to standard specifications. It should, however, be recognised that the presence of Lüders' strain is affected not only by the material and its test temperature but also by test method, loading rate and specimen design. Thus the information in Table 5.3 is a generalisation and applies only to the steels listed. For other materials the yielding behaviour should be individually established. If there is some doubt, it is conservative to assume the presence of Lüders' strain.

If no individual measurements of the Lüders' strain $\Delta\varepsilon$ are available a conservative estimate can be made as

$$\Delta\varepsilon = \begin{cases} 0.0375\ (1 - 0.001\ R_{eH}) & \text{for } R_{eH} \le 1000 \text{ MPa} \\ 0 & \text{for } R_{eH} > 1000 \text{ MPa} \end{cases} \tag{5.21}$$

This relation was obtained empirically, but is assumed to be conservative since the Lüders' strain is known to be smaller or even disappear in large-scale tests, in particular in the presence of bending stress components.

Table 5.3 – Guidance for determining whether a yield plateau i.e. Lüders strain should be assumed. N.B. ( ) =some uncertainty, a sensitivity analysis should be carried out.

Yield Stress Range (MPa)	Process Route	Composition Aspects	Heat Treatment Aspects	Assume Yield Plateau
	As-Rolled	Conventional Steels e.g. EN 10025 grades) without microalloy additions	NA	Yes
		Mo, Cr, V, Nb, Al or Ti present	NA	(No)
$\sigma_Y \leq 350$	Normalised	EN 10025 type compositions without microalloy additions	Conventional normalising	Yes
		EN 10113 type compositions with microalloy additions	Conventional normalising	Yes
	Controlled Rolled	EN 10113 compositions	-	Yes
	Controlled Rolled	EN 10113 compositions	Light TMCR schedules (σ_Y <400)	Yes
			Heavy TMCR schedules (σ_Y >400)	(Yes)
350<σ_Y 500≤ σ_Y	Quenched & Tempered	Mo or B present with microalloy additions Cr, V, Nb or Ti	Heavy tempering favours plateau	Yes
			Light -tempering favours no plateau	(Yes)
		Mo or B not present but microalloying additions Cr, V, Nb or Ti are (V particularly strong effect)	Heavy tempering	(Yes)
			Light tempering	(No)
	Quenched & Tempered	Mo or B present with microalloy additions Cr, V, Nb or Ti	Tempering to σ_Y < ~690	(No)
			Tempering to $\sigma_Y \geq$ ~690	No
500 <σ_Y		Mo or B not present but microalloy additions Cr, V, Nb or Ti are	Tempering to σ_Y < ~690	Yes
			Tempering to $\sigma_Y \geq$ ~690	(No)
1050 ≥YS	As-Quenched	All compositions	NA	No

5.4.4 Fracture Toughness

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

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

In all of these cases, the toughness can be characterised by the same parameter. This can be written in terms of *K, J* or CTOD parameters. Standardised methods are available for determining all fracture toughness values needed for this procedure, and the treatments for determining the characteristic values given in the following sections are designed around these standardised methods. In the absence of appropriate fracture toughness data, Charpy data can be used to give a conservative estimate of fracture toughness, by using appropriate correlations. These correlations are given in section 5.4.8.

The overall FITNET approach for the treatment of fracture toughness data is summarised in Figure 5.6.

5.4.4.1 Toughness Data Format

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

Any of the fracture toughness parameters can be described as *K, J or* δ, depending on the approach adopted by the user. However, for calculating characteristic values using the MML method, all data should first be transformed into units of *K*. They may be converted back for use in the crack driving force (CDF) approaches, when preferred. Recommended equations for conversion between fracture toughness parameters are tabulated in the MML section.

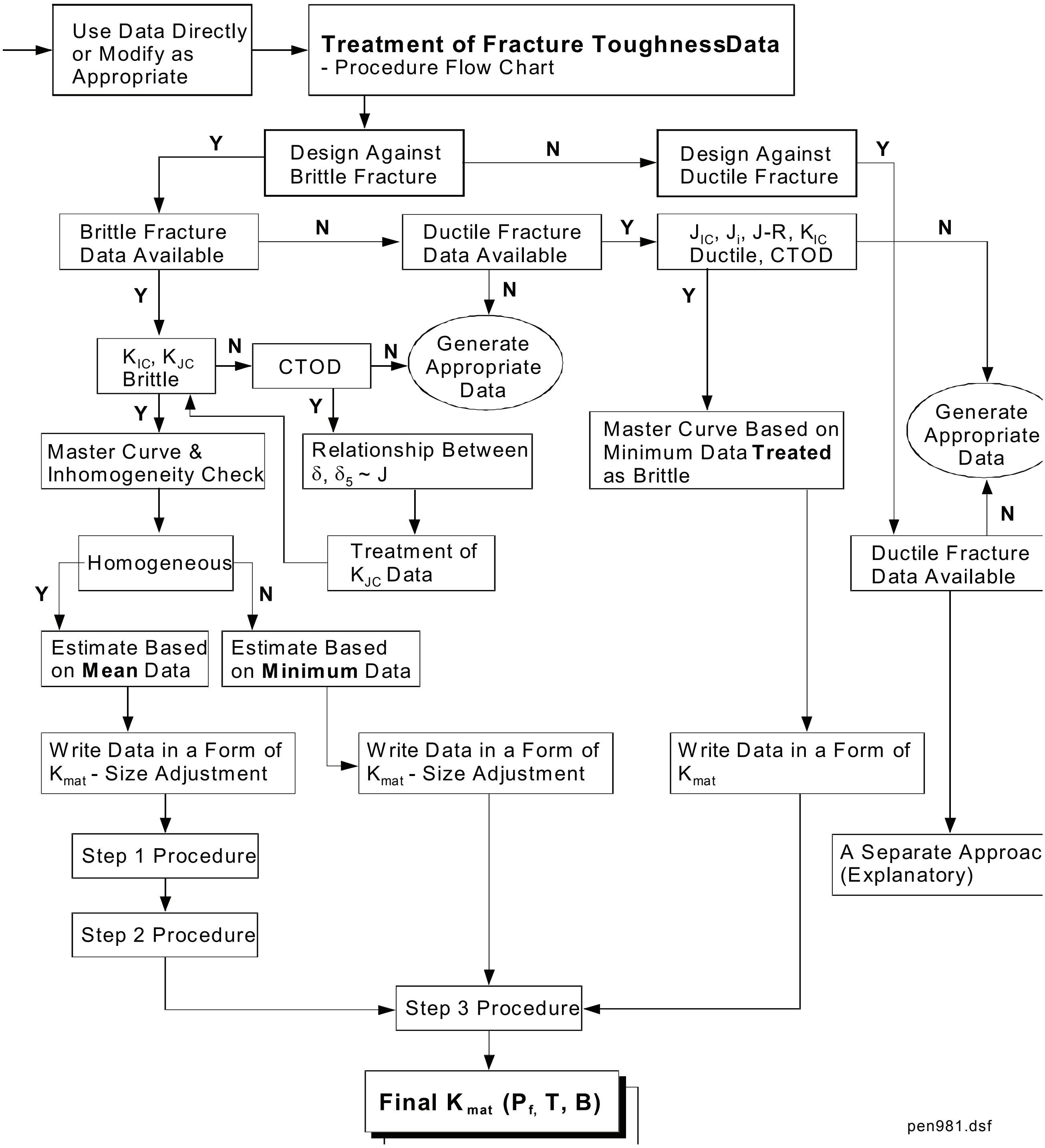

Figure 5.6: Flowchart for Treatment of Fracture Toughness Data

5.4.4.2 Fracture Initiation Toughness

The fracture toughness for initiation of brittle fracture is determined using the MML (maximum likelihood) method described in section 5.4.5.1. In principle data can be collected on any number of specimens at a single temperature representative of the temperature of interest in the structure, or at different temperatures. For practical purposes, at least three (3) test results are required, but the credibility and accuracy of the MML representation is greatly improved with a larger number. The MML method provides median fracture toughness and a statistical distribution from which the characteristic value can be obtained. Any choice of characteristic value can be made, such as the 5th or 20th percentile, depending on the reliability required of the analysis. Since the use of the MML method implies acceptance of the weakest link model of brittle fracture and a crack front length dependence, this must also be taken into account when determining characteristic values.

5.4.4.3 Fracture Data Collection

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

The fracture toughness tests should be carried out either on full thickness tests specimens, or on specimens complying with the specimen size criteria detailed in section 5.4.5.1. Various procedures, such as ASTM E1820, BS7448 and ESIS-P2 (1992), give guidance on fracture toughness testing which include validity tests to ensure that the result is compatible with the theoretical basis underpinning the tests. The screening criteria used in the MML method to censor the data are in accordance with ASTM E 1921-05 and ensure that the result is not unduly biased by unrepresentative high values. Specimens which produce a result which fail these criteria should not be discarded, since these results are used as censored data in the analysis.

Ideally fracture toughness tests for use in modern assessment methods should not be undertaken with the aim of measuring maximum load J or CTOD values, as the resistance curve (R-Curve) is a more correct way of defining fracture toughness for these cases. However in the case of maximum load data being the only available type, recommendations for using such values are given in section 5.4.7.

5.4.5 Analysis of Data for Initiation of Fracture

5.4.5.1 Brittle Fracture

The MML method given below contains three stages of analysis. Stage 1 gives an estimate of the median value of fracture toughness. Stage 2 performs a lower tail MML estimation, checking and correcting any undue influence of excessive values in the upper tail of the distribution. Stage 3 performs a minimum value estimation to check and make allowance for gross inhomogeneities in the material. In Stage 3, effectively, an additional safety factor is incorporated for cases where the number of tests is small.

It is recommended that all three stages are employed when the number of tests to be analysed is between three and nine. With an increasing number of tests, the influence of the penalty (i.e., the additional safety factor) for small data sets is gradually reduced. For 10 and more tests, only stages 1 and 2 need to be used. However, Stage 3 may still be employed for indicative purposes, especially where there is evidence of gross inhomogeneity in the material (e.g. for weld or heat-affected zone material). In such cases, it may be judged that the characteristic value is based upon the Stage 3 result, or alternatively, such a result may be used as guidance in a sensitivity analysis (see section 10.1.3.2) or used to indicate the need for more experimental data, when appropriate.

Results obtained using the MML method described here have been compared with those of the so-called 'Minimum-of three equivalent' (MOTE). For small data sets (fewer than about 12 results) the MML method provides more consistent estimates of K_{mat} when compared to values determined from the MOTE method. The reason for this is that when using, for instance, the MOTE with a 50% confidence level the overall conservatism of the estimate tends to increase with increasing number of tests, whereas the use of MOTE with a 95% confidence level leads to a decrease of the overall conservatism of the estimate. The MML method, in turn, accounts for all these effects in a more consistent manner. Because of this, the MML procedure minimises the risk of overestimating the true fracture toughness of the material particularly in the case of small data sets. For large data sets (greater than about 15 results), the values determined from the two methods are similar. The principles of the three stages of analysis according to the MML method are given in Figure 5.7, Figure 5.8 and Figure 5.9.

5.4.5.1.1 Preliminary Steps

The preliminary tasks including (1) conversion of the available fracture toughness data into units of *K*, (2) data censoring i.e. treatment of non-valid data, and (3) specimen size adjustment, are performed according to the standard Master Curve analysis given in section 11.7, in accordance with ASTM E 1921-05.

Ensure all data are in units of *K*

The relationships for converting *J* or δ to *K* are given by equations (5.22) and (5.23) respectively:

$$K = \sqrt{J.E/(1-\nu^2)} \tag{5.22}$$

where E is Young's modulus and ν is Poisson's ratio

$$K = \sqrt{mR_e\delta.E/(1-\nu^2)} \tag{5.23}$$

where R_e is yield or proof stress and m = 1.5. This value of the coefficient m was determined from a large data set on structural steels and represents the 25th percentile. As such it should give conservative estimates of toughness. It should be noted, however, that the value of m = 1.5 is only appropriate for treating data from deep notch, high constraint specimens and may not be appropriate for steels with a very low work hardening exponent i.e. N < 0.05, or for materials other than steel. Where an alternative value of m can be justified, it may be used in eqn. (5.23).

Perform Specimen Size Adjustment

For the comparison of data from different size specimens, adjust all results from specimens whose thickness is not 25 mm according to:

$$K_i = K_{25} = 20 + (K_B - 20)(B/25)^{0.25} \tag{5.24}$$

where K_B is the toughness of a specimen of original thickness *B.* Note that K_B is the original value for the fracture toughness in a specimen of thickness B (here B refers to the nominal thickness, regardless of any side-grooving etc.) and K_i is the adjusted value, equivalent to that for a specimen size of 25 mm.

5.4.5.1.2 Maximum Likelihood Method

(I) For data over a range of temperatures

MML Stage 1. Determination of MML Median Value for T_0

Stage 1 consists of a standard Master Curve determination of T_0 according to Figure 5.7. The concept of the Master Curve method is presented in detail in section 11.7.

The transition temperature T_0 corresponds to the temperature where the median fracture toughness for a 25 mm thick specimen has the value 100 MPa√m. For multi-temperature data, T_0 is estimated from the size adjusted K_{JC} data using a multi-temperature randomly censored maximum likelihood expression:

$$\sum_{i=1}^{n} \frac{\delta_i \exp\{0.019(T_i - T_0)\}}{11 + 77\exp\{0.019(T_i - T_0)\}} - \sum_{i=1}^{n} \frac{(K_i - 20)^4 \exp\{0.019(T_i - T_0)\}}{[11 + 77\exp\{0.019(T_i - T_0)\}]^5} = 0 \qquad (5.25)$$

where T_i is the test temperature of a specimen of toughness K_i adjusted to a 25 mm specimen size. Eq. (5.25) is optimised by repeatedly calculating T_0 using an iterative process, to obtain a final estimate of T_0. Note that T_i is the test temperature for a specimen *i*, with K_i as its fracture toughness, adjusted to 25 mm specimen size. For censored data whose toughness is represented by $K_{JC(cen)}$, T_i should be regarded as the temperature of that test. Perform the summations over values of *i* from 1 to *n*, where *n* is the total number of data in the set, including those censored.

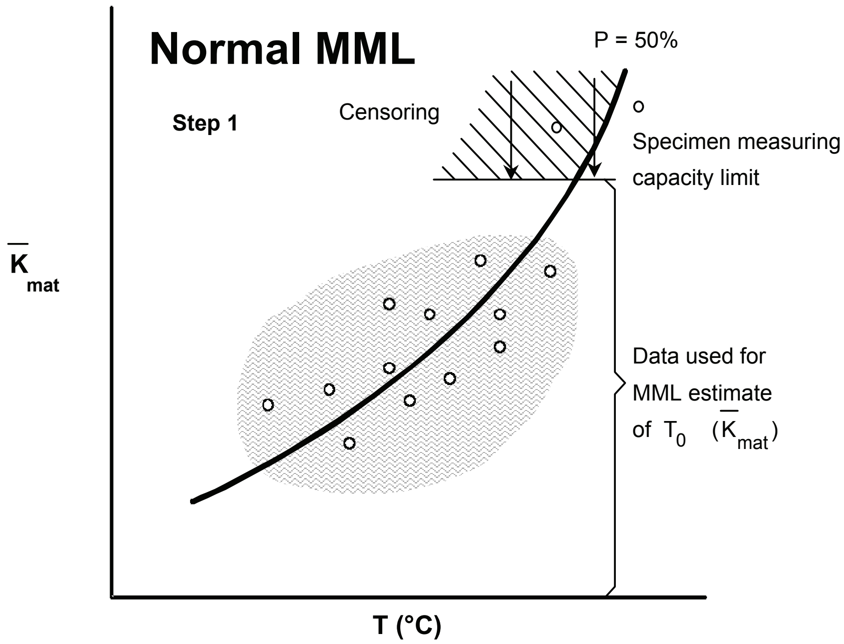

Figure 5.7 - Principle of MML Stage 1 analysis: standard Master Curve estimation

MML Stage 2. Lower Tail MML Estimation

Stage 2 performs a lower tail MML estimation in accordance with steps (a) to (c)), corresponding to the the principle given in Figure 5.8.

(a) Censor all data whose toughness K_{JC} exceeds a K_{CENS} value given by eqn. (5.26) to be equal to the K_{CENS} setting Kronecker's delta, δ_I, equal to 0 for the censored data and to 1 for all other data fulfilling the size criterion experessed by eqn. (5.27).

$$K_{CENS}(T_0) = 30 + 70\exp\{0.019(T_i - T_0)\}$$

(5.26)

where T_i is test temperature of specimen of toughness K_i adjusted to 25 mm specimen size.

$$K_{JC(cen)} = (Eb_0R_e/30)^{0.5} \qquad (5.27)$$

where b_0 is the size of the uncracked ligament.

(b) Use this "upper tail" censored data set, to obtain a new estimate of T_0 by performing a standard MML analysis in accordance with the MML Stage 1 analysis

(c) Compare the two values of T_0. If the new T_0 is higher than the previous T_0, repeat the upper-tail censoring according to equation (5.26), using the new value as a benchmark. Continue the iteration until a constant value of T_0 is obtained. This value is designated as $T_{0(stage2)}$.

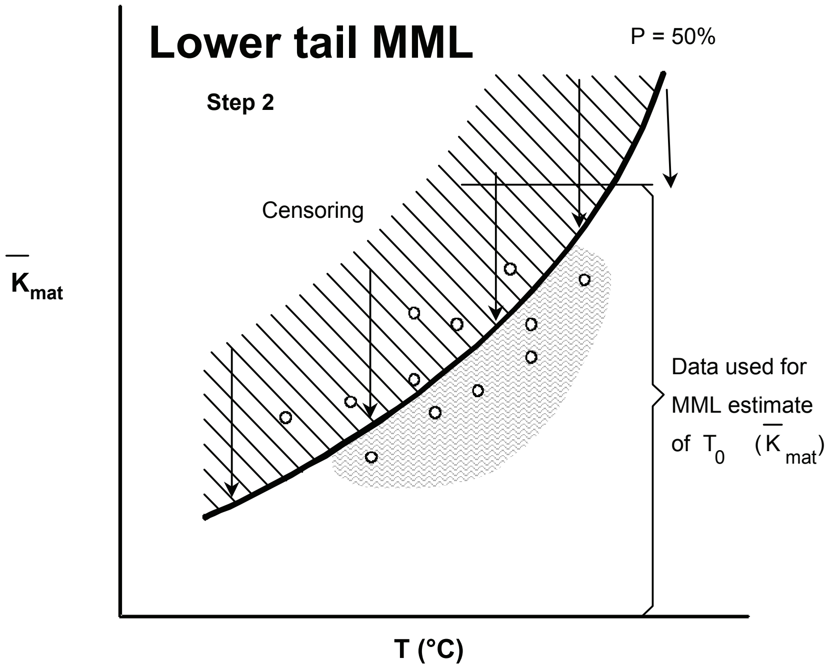

Figure 5.8- Principle of MML Stage 2 analysis: lower tail estimation

MML Stage 3. Minimum Value Estimation

If the number of data (specimens) in the data set is less than 10, perform Stage 3: “Minimum value estimation” in accordance with steps (a) to (c); the principle is given in Figure 5.9.

(a) Calculate the maximum value of T_0 (based on a single data point) according to equation (5.28) using all non-censored data, i.e., where $\delta_i = 1$. This value is designated as $T_{0(max)}$.

$$T_{0(\max)} = \max \left| T_i - \frac{\ln\left\{ \dfrac{(K_i - 20)\left(\dfrac{n}{\ln 2}\right)^{1/4} - 11}{77} \right\}}{0.019} \right. \qquad (5.28)$$

where n is total number of tests (specimens) in data set, K_i is the individual toughness value adjusted to the 25 mm specimen size and δ_i = 1.

(b) Compare $T_{0(max)}$ and T_0 obtained from Stage 2, i.e., $T_{0(stage2)}$. If $T_{0(max)}$ – 8 °C > $T_{0(stage2)}$, there is indication that the data is inhomogeneous, and $T_{0(max)}$ should be taken as the representative value of T_0. Otherwise, $T_{0(stage2)}$ may be taken as representative.

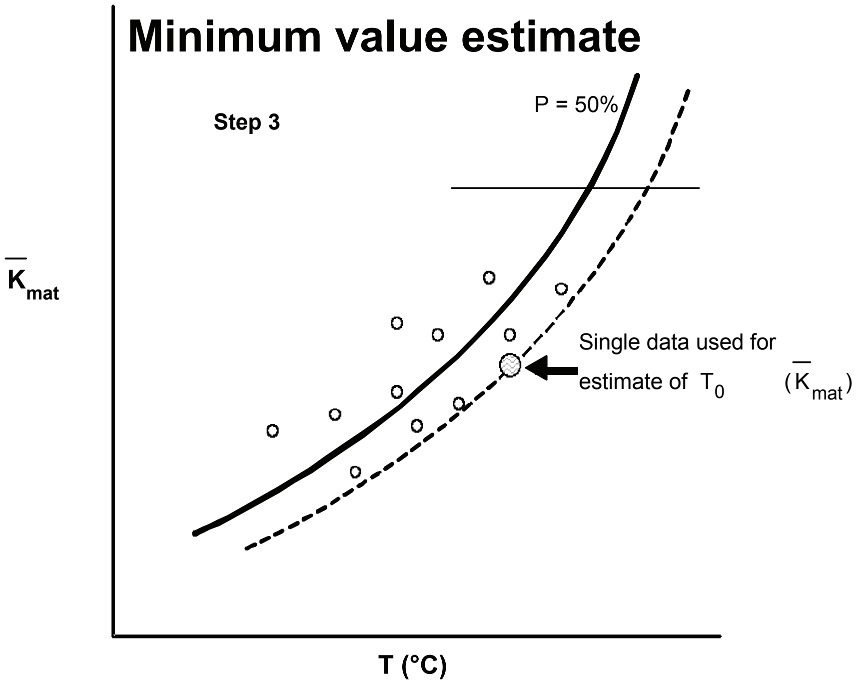

Figure 5.9- Principle of MML Stage 3 analysis: minimum value estimation

(c) Determine the final value of $T_{0(max)}$ including a small data set safety correction using equation (5.29). This value is designated as $T_{0(stage3)}$.

$$T_{0(stage3)} = T_{0(\max)} + \frac{14}{\sqrt{r}} \qquad (5.29)$$

where $T_{0(max)}$ is the value of T_0 from MML stage 3 analysis, $T_{0(stage3)}$ is the final $T_{0(max)}$ value including a small data set correction and r is the number of specimens which failed by brittle fracture.

Regarding eqn. (5.28), note that T_i is the test temperature of a specimen of toughness K_i and n is the total number of test results in the data set. With respect to eqn. (5.29) note that r is the number of specimens in the data set that failed by brittle fracture.

(II) For data at a single temperature

MML Stage 1. Determination of MML Median Value

Stage 1 consists of a standard Master Curve determination of K_0 according to Figure 5.7. For data at a single-temperature, K_0 is calculated from the size adjusted K_{JC} data using a fracture toughness description for constant temperature data according to:

$$K_0 = 20 + \left(\frac{\sum_{i=1}^{n} (K_i - 20)^4}{\sum_{i=1}^{n} \delta_i} \right)^{1/4} \qquad (5.30)$$

where K_i is the individual toughness value of specimen *i*, adjusted to a 25 mm specimen size and *n* is the total number of data in the set, including those censored. Include also each value of $K_{JC(cen)}$ (designated by $\delta_i = 0$).

MML Stage 2. Lower Tail MML Estimation

Stage 2 performs a lower tail MML estimation following steps (a) to (c), with the principle given in Figure 5.8.

(a) Censor all data whose toughness K_{JC} exceeds a K_{CENS} value given by eqn. (5.31) below to be equal to the K_{CENS}, setting δ_i for the censored data equal to 0 and δ_i for all other data fulfilling the size criterion c.f. Eq. (5.31) equal to 1.

$$K_{CENS}(K_0) = 20 + (K_0 - 20) \cdot (\ln 2)^{1/4} \qquad (5.31)$$

(b) Use this "upper tail" censored data set to obtain a new estimate of K_0 by performing a standard MML analysis.

(c) Compare the two values of K_0. If the new K_0 is smaller than the previous K_0, repeat the upper-tail censoring according to eqn (5.31), using the new value as a benchmark. Continue the iteration until a constant value of K_0 is obtained. This value is designated as $K_{0(stage2)}$.

MML Stage 3. Minimum Value Estimation

If the number of data (specimens) in the data set is less than 10, perform Stage 3: “Minimum value estimation” in accordance with steps (a) to (c); the principle is given in Figure 5.9.

(a) Calculate the minimum value of K_0 , $K_{0(min)}$, from the lowest measured $K_{i(min)}$ using all non-censored data, i.e., where $\delta_i = 1$:

$$K_{0(\min)} = 20 + (K_{i(\min)} - 20)\left(\frac{n}{\ln 2} \right)^{1/4} \qquad (5.32)$$

where $K_{i(min)}$ is minimum value of K_i and *n* is the total number of test results in the data set.

(b) Compare $K_{0(min)}$ and K_0 obtained from Stage 2, i.e., $K_{0(stage2)}$. If $K_{0(min)} < 0.9 \cdot K_{0(stage2)}$, there is indication that the data is inhomogeneous, and $K_{0(min)}$ should be taken as the representative value of K_0. Otherwise, $K_{0(stage2)}$ may be taken as representative.

(b) Determine the final value of $K_{0(min)}$ including the small data set safety correction using equation (5.33) - this value is designated as $K_{0(stage3)}$:

$$K_{0(stage3)} = 20 + \frac{K_{0(\min)} - 20}{1 + \frac{0.25}{\sqrt{r}}} \quad (5.33)$$

where $K_{0(min)}$ is the value of K_0 from MML stage 3 analysis, $K_{0(stage3)}$ is the 'final' $K_{0(min)}$ value including small data set correction and r is the number of specimens which failed by brittle fracture.

Regarding equation (5.32), note that K_{min} is the minimum value of the individual toughness values, K_i , in the data set and n is the total number of test results in the data set. With respect to equation (5.33), note that r is the number of specimens in the data set that failed by brittle fracture.

(III) Final estimates of the MML analysis procedure

As an outcome of the three stages, the MML analysis produces estimates of $\overline{K_m(T_0)}$, $\overline{K_m(K_0)}$ and K_{0m} for, respectively, the 50% (median) and 63.2% cumulative failure probabilities from which a probability distribution can be calculated. The estimates of $\overline{K_m(T_0)}$, $\overline{K_m(K_0)}$ and K_{om} are calculated from the following equations:

$$\overline{K_m(T_0)} = 30 + 70\exp\{0.019(T - T_{0(stage)})\} \quad (5.34)$$

where $T_{0(stage)}$ is the value of either $T_{0(stage2)}$ or $T_{0(stage3)}$

$$\overline{K_m(K_0)} = 20 + (K_{0(stage)} - 20)\cdot 0.91 \quad (5.35)$$

where $K_{0(stage)}$ is the value of either $K_{0(stage2)}$ or $K_{0(stage3)}$

$$K_{0m} = 31 + 77\exp\{0.019(T - T_{0(stage)})\} \quad (5.36)$$

where $T_{0(stage)}$ is the value of either $T_{0(stage2)}$ or $T_{0(stage3)}$

The characteristic values of fracture toughness are then obtained following section 5.4.5.1.3.

Regarding equations (5.34) and (5.36), note that $T_{0(stage)}$ is the final value of either $T_{0(stage2)}$ or $T_{0(stage3)}$, depending on the number of data (specimens) in the data set, and whether the MML Stage 3 analysis indicated significant inhomogeneity of the data, or not. As regards equation (5.35), this applies to $K_{0(stage)}$.

5.4.5.1.3 Determination of Characteristic Values

This section gives characteristic values of the material's fracture toughness using the outcome of the MML analysis procedure above.

(I) Determine the characteristic fracture toughness value K_{mat} :

$$K_{mat} = 20 + (K_{0m} - 20)\{-\ln(1 - P_f)\}^{0.25} \quad (5.37)$$

where P_f is the 0.05 or 0.2 fractile representing 5% or 20% cumulative failure probability of the set of specimens.

(II) Calculate the statistical distribution, $P\{K_{mat}\}$:

$$P\{K_{mat}\} = 1 - \exp - \left\{ \frac{K_{mat} - 20}{K_{0m} - 20} \right\}^4 \tag{5.38}$$

where K_{mat} is the characteristic value of material's fracture toughness and K_{0m} is the fracture toughness value for 63.2% cumulative failure probability. For data over a range of temperatures, these may be calculated at any appropriate temperature.

Note that equation (5.37) can be used to give a characteristic value for the toughness in terms of K_{mat} as a function of the desired failure probability fractile, P_f, and the value of K_{0m} obtained. In using this equation, the following factors also need to considered:

(i) The reliability required for the result: this will determine the choice of P_f, (0.05 or 0.2).

(ii) The importance of the MML Stage 3 result for data sets above 10 results: this will determine what value of K_{0m} is used. This, in turn, depends on which value of $T_{0(stage)}$: $T_{0(stage2)}$ or $T_{0(stage3)}$ was applied to calculating K_{0m}, in Eq. (5.36).

Besides K_{mat} from Eq. (5.37), an additional factor may be needed in cases where crack length in the structure exceeds 25 mm. The following equation can be used for this:

$$K_{mat} = K_{mat(l)} = 20 + (K_{mat(25)} - 20)(25/l)^{0.25} \tag{5.39}$$

$K_{mat(l)}$ is value of K_{mat} adjusted for length of crack front, l , in mm, for $l < 2t$. Where $l > 2t$ this correction to value of K_{mat} given by $l = 2t$, where t is section thickness. It is recommended that where the crack length in the structure exceeds the section thickness, t, a correction equivalent to a maximum crack front length of 2*t* should be applied, except in the case of excessive inhomogeneity.

(iii) When using the crack driving force (CDF) approaches, reconvert K_{mat} to units of J or δ using equations (5.22) and (5.23).

5.4.5.1.4 Bi-modal Master Curve analysis method

This method can be used as an alternative to the standard Master Curve (MC) analysis of brittle fracture in cases of significant material inhomogeneity. An introduction to the principles of the method is given in Informative Section 12 that provides non-prescriptive information for the fracture assessment.

The MML estimation method (MML Stage 2 or Stage 3) enables conservative lower bound types of fracture toughness estimates also for inhomogeneous material, in which case these estimates describe the fracture toughness of the more brittle constituent. Neither the MML analysis, nor standard MC analysis, however, can provide any information of the more ductile constituent. Therefore, a probabilistic description of the complete material is not possible. The bi-modal MC analysis method extends the standard MC analysis by describing the fracture toughness distribution of inhomogeneous material as the combination of two separate MC distributions. Thus, the bi-modal MC analysis method is particularly efficient in describing e.g. weld heat-affected zone (HAZ) data.

5.4.6 Ductile Tearing

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

In some situations, only single values of fully ductile toughness are available, measured at the maximum load obtained in the test, and there is no possibility of performing further tests. Where the possibility of brittle

fracture can be confidently excluded, such maximum load values may be used, subject to certain specimen size and ligament length considerations (see section 5.4.7).
Since the scatter in data representing the onset of ductile tearing is normally small, it is sufficient to base the characteristic value on the minimum value of three valid test results. Where results are invalid, consideration should be given to using the valid limit of toughness as the characteristic value. Alternatively, the significance of this limit could be explored by means of a sensitivity analysis (see section 10.1.3.2).

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

For ferritic or bainitic steels, it is important to ensure that the temperature of interest is high enough to avoid any risk of brittle fracture occurring from proximity to the ductile-brittle transition. Guidance is given in section 10.1.2.3.

5.4.7 Use of Maximum Load Fracture Toughness Data

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

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

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

In the case where the possibility of brittle fracture in the component can be excluded with confidence, the maximum load fracture toughness value can be treated as if it was a ductile value and the size adjustment is not applied. The characteristic value should be determined from three or more results. Care should be taken in the case of a high resistance to tearing since the maximum load fracture toughness in such cases usually exceeds the toughness corresponding to the onset of stable crack extension. In such cases, a full tearing analysis may often be more appropriate. Where resistance to ductile tearing is low, the maximum load fracture toughness is closer to the toughness level at initiation of tearing and can be used with relative confidence. Where it is possible to establish the amount of ductile tearing occurring prior to the attainment of the maximum load, this should be taken into account by increasing the flaw size in the structure by the same or a greater amount. In other situations, the maximum load toughness value should be taken to correspond to 6% crack growth relative to the ligament.

In the situation where brittle fracture of the component cannot be excluded, a MML Stage 3 analysis should be performed, treating the lowest value of maximum load fracture toughness as if it was brittle, and following the MML analysis method described in section 5.4.5.1.2. This also requires an assessment of the validity of the data.

In all cases, the user should establish that the structure is capable of withstanding any ductile tearing that may occur. Stable tearing using full thickness fracture toughness specimens up to the measured maximum load toughness value are acceptable.

5.4.8 Charpy impact energy - fracture toughness correlations

If the appropriate fracture toughness data for use in structural integrity assessments is not available, the use of correlations between Charpy impact energy and fracture toughness can provide the fracture toughness value to be used in the assessment. The flowchart given in Figure 5.10 helps the user to choose the appropriate correlation.

5.4.8.1 Definition of the applicability regimes (lower shelf / transition/ upper shelf)

For the application of the respective correlations, three different regimes of material behaviour should be defined as follows. Lower shelf is then defined as the temperature region where the shear fracture appearance (SFA) is ≤ 20% and the impact energy is less than 27J. Upper shelf is the temperature region where SFA = 100%[1]. Obviously, the range in-between is considered as the ductile-to-brittle transition region.

5.4.8.2 Lower shelf and early transition (prevalently brittle behaviour)

A lower bound correlation that can be used in the lower shelf for a wide range of steels [5.3] is given by:

$$K_{mat} = \left[\left(12\sqrt{C_V} - 20\right)\left(\frac{25}{B}\right)^{0.25} \right] + 20 \tag{5.40}$$

where K_{mat} is the fracture toughness of the material (MPa√m), C_V is the Charpy energy (J) and B is the crack front length (mm) or the specimen thickness. Eq.(5.40) was derived from the use of the Master Curve with the lower 5th percentile of fracture toughness and a 90% confidence level, at a Charpy energy of 27 J. Eq.(5.40) can also be used, where cleavage is preceded by limited plastic deformation, but the impact energy is less than 27 J. The K_{mat} estimate should be based on the C_V value corresponding to the minimum of three tests or its equivalent. If the impact energy is less than 3 J, then Eq. (5.40) is not applicable and fracture toughness tests should be performed.

In case Charpy and fracture toughness data are unavailable, a very conservative lower bound toughness for ferritic steels can be taken as: $K_{mat} = 20 MPa\sqrt{m}$.

5.4.8.3 Transition region (mixed brittle/ductile behaviour)

The Master Curve correlation [5.4, 5.5] relates a specific Charpy transition temperature ($T_{27J/28J}$)[2] to a specific fracture toughness transition temperature ($T_{100MPa\sqrt{m}}$). This relationship is then modified to account for: thickness effect, scatter, shape of fracture toughness transition curve and required probability of fracture. The general relationship between the two transition temperatures[3] is given by:

$$T_{100MPa\sqrt{m}} = T_{27J} - 18°C \quad (\pm\sigma) \tag{5.41}$$

which, if the $+\sigma$ lower confidence limit of ±15°C is assumed for a conservative estimate, becomes:

$$T_{100MPa\sqrt{m}} = T_{27J} - 3°C \tag{5.42}$$

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[1] Lower values (e.g. 95%) can also be chosen by agreement between the parties.

[2] The relationship given here was originally developed for energy level corresponding to 28 J. However, 27 J correspond to typical requirements in steel specifications and the difference (1 J) is believed to have a negligible effect on the estimated toughness K_{mat}.

[3] The accuracy of this estimation will obviously be highly dependent on the quality of the original Charpy data.

In the transition region the fracture toughness transition curve can be described as a function of T_{27J} as follows:

$$K_{mat} = 20 + \{11 + 77 \cdot \exp[0.019(T - T_{27J} + 3°C)]\}\left(\frac{25}{B}\right)^{0.25}\left(\ln\frac{1}{1-P_f}\right)^{0.25} \quad (5.43)$$

where P_f is the probability of fracture toughness being lower than K_{mat}.

Often T_{27J} may not be known but some other data describing the transition region might be given for a material. In such cases it is recommended to use the procedure involving incomplete transition curves (5.4.8.4).

Note: if other correlations are used, for the derivation of T_{27J} as given here, which were developed especially for the transition temperature in question, it is up to the user to demonstrate that the correlation used has a similar (or larger) degree of confidence as eq. (5.43).

5.4.8.4 Incomplete transition curves

When the CVN data does not allow the determination of T_{27J}, It can be conservatively estimated from:

$$T_{27J} = T_{Cv} - \frac{C}{4} \cdot \ln\frac{C_V \cdot (USE - 27J)}{27J \cdot (USE - C_V)} \quad (5.44)$$

where T_{Cv} is the temperature at which Charpy data C_V are available and the constant C is a function of the material's yield strength (σ_Y) and upper shelf energy USE (see also Figure 5.12):

$$C \approx 34°C + \frac{\sigma_Y}{35.1} - \frac{USE}{14.3} \quad (5.45)$$

with σ_Y in MPa and *USE* in J.

If the upper shelf energy is unknown, it should be estimated as being twice the highest measured impact energy value. If both impact energy and shear fracture appearance data are available, the upper shelf energy can be estimated more accurately from:

$$USE \approx 100 \cdot \frac{\sum_{i=1}^{n} \frac{C_{Vi}}{SFA_i}}{n} \quad (5.46)$$

where *n* is the number of Charpy data available.

If only upper shelf energy data is available, then the lowest test temperature, combined with the corresponding upper shelf energy, may be used for the transition temperature determination. In this case, the transition temperature is estimated from the following function, with the parameter C as defined in eq. (5.45).

$$T_{27J} = T_{US} - \frac{C \cdot \ln\left(\frac{19 \cdot (USE - 27)}{27}\right)}{4} \quad (5.47)$$

5.4.8.5 Upper shelf (ductile behaviour)

5.4.8.5.1 Estimation of point values

When Charpy tests exhibit fully ductile behaviour (SFA = 100%), this does not automatically imply that the structure itself will also be operating in the upper shelf at the same temperature. In particular, for thick sections and for some low carbon and low sulphur steels, the full thickness material may exhibit transitional behaviour at temperatures corresponding to upper shelf behaviour in Charpy specimens. If brittle behaviour can be excluded, a lower bound estimate of the upper shelf fracture toughness corresponding to a ductile crack extension of 0.2 mm ($K_{J0.2}$), taken as the engineering approximation of the onset of ductile tearing (K_{mat}), can be evaluated from [5.8]:

$$K_{mat} = K_{J0.2} = \sqrt{\frac{E\left(0.53 \cdot C_{Vus}^{1.28}\right)\left(0.2^{0.133 C_V^{0.256}}\right)}{1000\left(1-\nu^2\right)}} \tag{5.48}$$

where C_{Vus} is the upper shelf energy (J), E is Young's Modulus (MPa) and υ is Poisson's ratio. Other amounts of crack extension than 0.2 mm can be substituted into eq.(5.48) if desired. A more user friendly form of eq. (5.48) for steels can be expressed as

$$K_{mat} = K_{J0.2} \approx 11.9 \cdot C_{Vus}^{0.545} \tag{5.49}$$

The applicability of eqs. (5.48 and 5.49) is limited to yield strength values between 170 and 1000 MPa and upper shelf energies in the range 20 to 300 J.

Alternative upper shelf correlations may be used, provided they prove to have sufficient level of conservatism for the material to be assessed.

5.4.8.5.2 Estimation of the crack resistance (J-R) curve

A conservative estimate of the *J-R* curve based on the Charpy upper shelf energy (C_{Vus}) [5.8] is expressed by the following relationship:

$$J = J_{1mm} \cdot \Delta a^m \tag{5.50}$$

where J_{1mm} is the J-integral corresponding to 1 mm of ductile crack extension (Δa) and m is the exponent of the power law. The two parameters which are needed for eq.(5.50) are given by:

$$J_{1mm} = 0.53 \cdot C_{Vus}^{1.28} \cdot \exp\left(-\frac{T-20}{400}\right) \tag{5.51}$$

$$m = 0.133 \cdot C_{Vus}^{0.256} \cdot \exp\left(-\frac{T-20}{2000}\right) - \frac{\sigma_y}{4664} + 0.03 \tag{5.52}$$

This correlation was developed from the analysis of 112 multi-specimen data sets covering yield strengths in the range 171-985 MPa and C_{Vus} in the range 20-300 J. It provides a conservative estimate of the mean *J-R* curve, corresponding to an overall probability level of 5% and is applicable at temperatures from -100 to 300 °C .

5.4.8.6 Treatment of sub-size Charpy data

When the component thickness is less than 10 mm, sub-size Charpy specimens are used. In order to use the correlations previously described, however, the shift in transition temperature associated with the reduced thickness of the Charpy specimens must be accounted for. For a standard 10 mm square Charpy specimen, 28 J corresponds to 35 J/cm². The shift in this transition temperature associated with sub-size specimens, ΔT_{ss}, is given by:

$$\Delta T_{ss} = -51.4 \ln\left[2\left(\frac{B}{10}\right)^{0.25} - 1\right] \tag{5.53}$$

where B is the thickness of the sub-size Charpy specimen (mm). It should be noted that eq.(5.53) applies only to sub-size specimens which are identical to standard testpieces except for the thickness (lower than 10 mm). It doesn't work well for miniaturized Charpy specimens, where all dimensions are reduced or scaled (e.g. KLST specimens with cross section 4 × 3 mm² and length 27 mm).

For upper shelf estimates based on sub-size Charpy specimens, the upper shelf energy can be conservatively estimated from:

$$C_{V10} \geq C_{VB} \cdot \frac{10mm}{B} \tag{5.54}$$

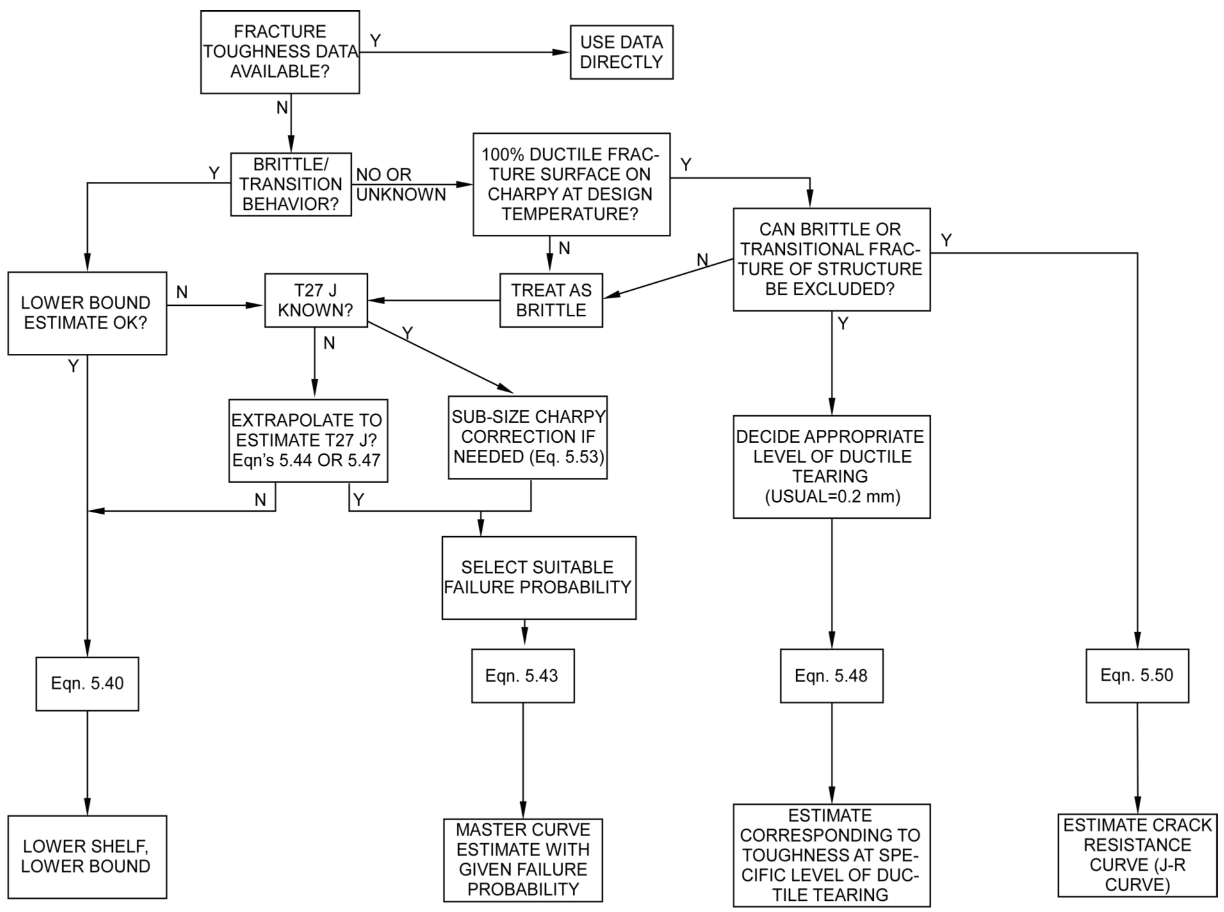

Figure 5.10 - Selection and use of appropriate correlation for estimating fracture toughness from Charpy impact energy.

5.4.9 Fatigue strength and fatigue crack growth

5.4.9.1 Fatigue Resistance

Fatigue resistance is defined in different forms depending on the fatigue assessment route adopted:

a) Material-specific S-N curves
b) Component and/or welded feature S-N curves
c) Material-specific strain range – cyclic life curves e.g. as described by the Manson-Coffin relation.

5.4.9.2 Fatigue Crack Growth Properties

The fatigue assessment module for planar flaws offers two fatigue crack growth laws to describe the rate of crack growth per cycle with the flaw stress intensity factor range. The fatigue growth threshold, ΔK_{th} , may also be required.

5.4.9.2.1 Paris Law

The basic fatigue crack growth equation is specified in the conventional Paris Law form as:

$$da / dN = A(\Delta K)^m \tag{5.55}$$

where *A* and *m* are constants which depend on the material and the applied conditions, including environment and cyclic frequency.

5.4.9.2.2 Forman-Mettu Law

The Forman-Mettu crack growth rate law reproduces the full sigmoidal shape of the log cyclic growth rate vs. log stress intensity factor relationship and is given by:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_c}\right)^q} \tag{5.56}$$

where *N* is the number of applied fatigue cycles, *a* is the crack length, *R* is the stress ratio, ΔK is the stress intensity factor range, and *C*, *n*, *p*, and *q* are empirically derived constants. Explanations of the crack opening function, *f*, the threshold stress intensity factor, ΔK_{th} and the critical stress intensity factor, K_c are presented in the fatigue module section 7.4. Values of the constants are available for several materials are given in Annex M. For other materials, these must be obtained from appropriate fatigue crack growth experimental data.

5.4.10 Creep strength and creep crack growth data

5.4.10.1 Creep rupture

Creep rupture data in the form of stress vs. time to rupture curves are required to calculate the rupture life of the remaining ligament and to estimate the current continuum damage level in the ligament as the defect grows.

5.4.10.2 Creep deformation

Creep deformation data are required for steady loadings to estimate the creep crack incubation time and subsequent creep crack growth rates using reference stress techniques. For cases with steady primary load or large elastic follow-up, forward creep data collected under constant load conditions are appropriate. For essentially strain-controlled conditions, in the absence of follow-up, stress relaxation data may be more appropriate than forward creep data. Reliable constitutive equations are needed to provide a smooth transition between these extremes. For creep-fatigue loadings, a description is required of the creep deformation of the material in the relevant cyclic condition in order to estimate creep crack growth rates during the dwell periods. Creep deformation data may also be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface for use in a creep-fatigue crack growth law. Often a simple power law expression is used to describe creep strain rate:

$$\dot{\varepsilon}_c / \dot{\varepsilon}_o = \left(\sigma / \sigma_o\right)^n \tag{5.57}$$

5.4.10.3 Creep ductility

Creep ductility data may be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface. In addition, creep ductility data may be used to estimate creep crack growth rates for situations in which explicit crack growth data are not available.

5.4.10.4 Creep crack initiation

For situations where fatigue is insignificant, it may be possible to take account of an incubation period prior to crack extension. Creep crack incubation data may be expressed in terms of a critical crack tip opening displacement, δ_i, or, for widespread creep conditions, by a relationship of the form:

$$t_i (C^*)^\beta = \gamma \tag{5.58}$$

where t_i is the incubation time and β and γ are material constants. In situations where explicit incubation data are not available, it is possible to estimate the incubation time for widespread creep conditions using approximate expressions given in Section 9.

5.4.10.5 Creep crack growth

The creep crack growth rate is specified as a function of the C* parameter by the equation:

$$\dot{a} = A(C^*)^q \tag{5.59}$$

where A and q are constants which determined from creep growth data for the appropriate material and testing conditions. A range of data sources is provided in Annex M.

Complementary to the C* approach, the creep crack growth law above can be generalised to:

$$\dot{a} = A[C(t)]^q \tag{5.60}$$

where the parameter $C_t(t)$ allows the description of the increased amplitude of the crack tip strain fields at short times below that required for full redistribution due to creep. In principle the values of A and q are equivalent whether the C* or C_t parameters are used, providing that they are determined from appropriate experimental data.

5.4.10.6 Cyclic Creep Crack Growth

Method 1: The cyclic component of creep-fatigue crack growth is described by

$$\left(\frac{da}{dN}\right)_f = C \Delta K_{eff}^{\ell} \tag{5.61}$$

where C and ℓ are material and temperature dependent constants. ΔK_{eff} is the stress intensity factor range for which the crack is judged to be open. In situations where cyclic crack growth data have been obtained from tests with significant plasticity, it is preferable to evaluate ΔK_{eff} from experimental estimates of ΔJ.

However, it will be pessimistic to use data which have been correlated with elastically calculated ΔK_{eff} values.

Method 2: the cyclic component of creep-fatigue crack growth is described by a high strain fatigue crack growth law of the form

$$\left(\frac{da}{dN}\right)_f = B'a^Q \text{, for } a_{min} \le a \le r_p \quad (5.62)$$

where a_{min} = 0.2 mm is the crack depth below which the crack growth rate is assumed to be constant. B' and Q depend on material, strain range and environment and can be determined experimentally. These laws apply for a total surface strain range $\Delta\bar{\varepsilon}_t$, while the defect is embedded in the cyclic plastic zone of size r_p at the surface of the coupon

5.4.11 Corrosion properties

5.4.11.1 K_{ISCC} determination

When the crack is of a length commensurate with the application of fracture mechanics, a threshold stress intensity factor for stress corrosion crack propagation, K_{ISCC}, is often defined. However K_{ISCC} should not be regarded as an intrinsic characteristic of the material as it will depend sensitively on the environment and loading conditions, which should reflect those for the service application. Also, there may be long-term changes in the material due to exposure that are not reflected in short term laboratory tests. The definition implies no crack growth, or crack arrest, below this value, which intrinsically brings in issues of resolution of the crack size measuring method and the patience of the experimenter.

It is common to conduct K_{ISCC} tests under static load conditions and accordingly results unrepresentative of service are often obtained. Structures are seldom subjected to purely static loading and it is well known that the value of K_{ISCC} can be considerably reduced if a dynamic loading component is involved; for example a thermal transient, following an outage, or superimposed cyclic loading, even of small magnitude.

Should it be decided that K_{ISCC} values obtained under static loading are appropriate, these can be determined using the procedures described in ISO 7539 Part 6. This document describes both crack initiation and crack arrest methods using fatigue pre-cracked, fracture mechanics type specimens tested under constant load or constant displacement. For some systems, the value will may vary depending n the method of measurement, e.g. increasing K or decreasing K experiments. As a fatigue precrack is somewhat artificial and may affect the transition to a stress corrosion crack, a decreasing K, crack arrest, type of experiment may be more pertinent.

The procedure for testing under rising load or rising displacement conditions is described in ISO 7539 Part 9. The loading or crack mouth opening displacement rate is the critical parameter and it is best to test over a range to obtain conservatively the minimum, lower shelf, value of K_{ISCC}. This may be lower than that obtained by conventional static loading or fixed displacement test under otherwise identical test conditions.

When there is a cyclic component to the loading, tests should appropriately incorporate that feature, with the loading frequency and waveform sensibly reproduced.

5.4.11.2 Stress corrosion crack growth determination

The crack velocity during stress corrosion testing of pre-cracked fracture mechanics specimens can be measured using the procedures given in ISO 7539-6 and the crack monitoring methods given in BS 7910. These techniques enable the stress corrosion crack velocity, da/dt, to be determined as a function of the stress intensity factor, K. It is most relevant to obtain crack growth date for the conditions of practical relevance and to then fit the data with a growth law appropriate to the data. The following relation is often applicable:

$$da/dt = C(K_I)^n \text{ , for } K_{ISCC} \le K \le K_c \quad (5.63)$$

where C and n are fitting parameters and K_c is the dynamic fracture toughness. However, the detailed functional relationship will be system dependent and may not be as simple as this power relationship.

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