10 Assessment and Reporting of Results (Output)

10.1 Assessment of Results

10.1.1 Introduction

Editorial Note: *This Section in its current status mainly refers to the fracture related analysis and based on the SINTAP procedure. Further development of this section with respect to fatigue, creep and corrosion will be conducted during the next revison. M. Kocak, 01. May 2006.*

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

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

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

10.1.2 Input Data

10.1.2.1 Loads and Stresses

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

10.1.2.2 Tensile Properties

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

10.1.2.3 Fracture Toughness

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

(a) Brittle behaviour (For Initiation Option of Fracture Module)

Where the fracture mechanism is brittle, the fracture toughness is often highly scattered, especially where the material is inhomogeneous, as for example in welds. For this reason, the reliability of the result is dependent on the number of specimens tested. The recommended method for treating such fracture toughness data is given in Section 6, and this provides a statistical distribution of fracture toughness, from which the characteristic value may be derived. The distribution obtained following this method is biased to produce a conservative estimate of the median, where the level of conservatism is dependent on the number of specimens tested, and the incidence of low results that do not conform to the general distribution.

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

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

(i) The incidence of inhomogeneity.

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

(ii) Adjustment for length of crack front.

The method given in Fracture Module, assumes that brittle fracture occurs via a weakest link model. This implies that the length of the crack front is important in determining the fracture toughness: the longer the crack front, the more the chance of sampling a weak link. The distribution obtained following the procedures in Section 6 is normalised to a specimen 25 mm thick.

It is recommended that this adjustment is performed in all cases, and especially where the material is inhomogeneous, and where there is doubt about the way the cracks in the test specimens sample the inhomogeneous regions. For crack front lengths exceeding the section thickness, t, a correction equivalent to a maximum crack front length of 2t is normally sufficient, except where inhomogeneity is excessive.

(b) Ductile behaviour (Initiation Option)

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

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

(c) Ductile behaviour (Tearing Option)

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

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

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

(d) Ductile behaviour (Maximum Load Values)

Where only maximum load data are available, the choice of characteristic value will depend on the number of specimens and the proximity of the test temperature to the ductile brittle transition temperature where known.

It should be noted that the use of maximum load values of toughness originated in the semi-empirical method for flaw assessment, known as the crack tip opening displacement (CTOD) design curve method, incorporated in early versions of BS.PD 6493. The justification for this was based upon the fact that the CTOD values were obtained on full section thickness tests, and the design curve included 'factors of safety' of between 2 and 10. In some cases, historic maximum load data on full-thickness specimens may only be available. It is not recommended that maximum load data are collected specially for use in the FITNET procedure, as more modern methods of tests are more appropriate. The FITNET FFS Procedure does not contain the 'safety factors' required of the CTOD design curve and use of maximum load data should correspondingly take full account of this. Guidance on the use of such data is given in Section 6.

10.1.3 Significance of Result

The limiting state, evaluated using values for the input data established following the guidelines in Fracture Module, Section 6, in principle defines a safe operating condition. However, for some engineering purposes, for example in design calculations, confidence is traditionally gained by applying safety or reserve factors on the defect free structure. When using the FITNET FFS Procedure, however, the application of previously specified numerical factors can be misleading because of the inherent and variable interdependence of the parameters contributing to fracture behaviour. Confidence in assessments is reinforced by investigating the sensitivity of the result to credible variations in the appropriate input parameters. Sensitivity analyses are facilitated by considering the effects that such variations have on reserve factors.

This section deals with sensitivity analysis in terms of reserve factors based upon the deterministic calculations of Fracture Module. An alternative approach is to perform a probabilistic fracture mechanics calculation as described in Section 6.

10.1.3.1 Reserve Factors

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

$$F^L = \frac{Load\_which\_would\_produce\_a\_Limiting\_condition}{Applied\_Load\_in\_Assessed\_Condition}$$

When using the FAD approach, for a given assessment point $\{L_r, K_r\}$ the limiting load is evaluated by changing the value of the specified load until the assessment point lies on the assessment line. When the structure is subjected to a single primary load only this may be done by scaling the assessment point along the radius from the origin, as shown in Figure 10.1. When the structure is subjected to more than one load, only the load of interest should be changed. If both primary and secondary loads exist allowance must be made for the changes in the parameter ρ, with load L_r.

When using the CDF approach, for an initiation analysis the same scaling principle can be used. However, for a tearing analysis the limiting condition may need to be determined by an iterative process.

Similar methods may be used to calculate reserve factors on other parameters, sample definitions being:

$$F^a = \frac{Limiting\_Flaw\_Size}{Flaw\_Size\_of\_Interest}$$

On fracture toughness

$$F^K = \frac{Fracture\_Toughness\_of\_Material\_being\_Assessed}{Fracture\_Toughness\_which\_\mathrm{Pr}oduces\_a\_Limiting\_Condition}$$

On yield stress

$$F^R = \frac{Yield\_Stress\_of\_Material\_being\_Assessed}{Yield\_Stress\_which\_\mathrm{Pr}oduces\_a\_Limiting\_Condition}$$

10.1.3.2 Sensitivity Analysis

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

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

Sensitivity analyses may be performed in the way most convenient for the user but will be somewhat dependent on the level of analysis. Some guidance is given in 10.1.3.2.1 and 10.1.3.2.2

10.1.3.2.1 Initiation Analyses

(a) Plot a graph of the reserve factor on load, F^L , as a function of the variable of interest as shown in Figure 10.2

(b) Determine the value of F^L needed by studying the sensitivity of F^L to the variable taking into account its range of uncertainty. Guidance on making this judgement is given in 10.1.3.3.

10.1.3.2.2 Tearing Analyses

(a) Plot the reserve factor on load, F^L, as a function of postulated crack growth Δa keeping all other variables constant (Figure 10.3 a). Note that the extent of this plot will depend on the crack extension range of the resistance curve. If this is sufficiently extensive, a maximum will be obtained in the $F^L - \Delta a$ plot, Figure 10.3 b.

(b) Repeat the analysis for different values of the original flaw size, a_0, to establish the sensitivity of the results to a_0 and plot these on the same graph. Connect equivalent points on each plot to construct loci of F^L as a function of initial flaw size for different values of Δa , Figure 10.3 c.

(c) Explore the effects of changing the other variables specified in 10.1.3. In judging what reserve factors are required, account must be taken of the range of *J*-controlled crack growth and the significance of exceeding it. Further guidance is given in 10.1.3.3.

10.1.3.3 Guidance on Determining Acceptable Reserve Factors

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

If an assessment is particularly sensitive to any parameter the required reserve factor should be large enough to ensure that the limiting condition is not approached. When the graphical procedures suggested in 10.1.3.2.1 and 10.1.3.2.2 are used this state is represented by steep gradients in the region of interest. Figure 10.4 a and b qualitatively compare the preferred and non-preferred conditions.

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

The recommended method for treating fracture toughness data of brittle steels given in Section 5.4.5, can give different characteristic values depending on whether stage 2 or stage 3 is used for determining the probability distribution. The crack front length dependence arising from the weakest link model must also be considered. A sensitivity analysis which covers the variations in toughness arising from these factors is a reliable and acceptable way of judging their significance.

Sensitivity analysis is also required for the default method given in Section 6.4. This is particularly so where there is uncertainty in the definition of the Charpy values as these must provide a pessimistic measure of toughness from the correlation given.

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

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

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

2 The non destructive examination capabilities are doubtful

3 Flaw characterisation is difficult and uncertain.

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

5 Little forewarning of failure is expected. Forewarning is more likely in cases of ductile failure, than brittle failure, (the consequences of ductile failure are usually less extreme than those of brittle failure). The particular case of a Leak-Before-Break condition in a pressurised system provides explicit warning, and a high intrinsic level of confidence (Section 11.2).

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

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

8 The consequences of failure are unacceptable.

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

10.1.3.4 Partial Safety Factors

Partial Safety Factors are factors which can be applied to the individual input variables which will give a target probabilistic reliability without the need to perform a full probability analysis. Recommended partial safety factors for given values of Co-efficient of variation and probability of failure [I.3.1] are given in Section 11.12 Probability and Reliability. These can be used in place of a full probabilistic analysis where appropriate. It should be noted that the probability of failure values quoted in Table 11.5 Target failure probability are applicable to the case where partial safety factors are applied to all inputs as indicated and apply to the specific cases described in the text. The partial safety factors do not take account of any conservatism inherent in the Failure Assessment Diagram.

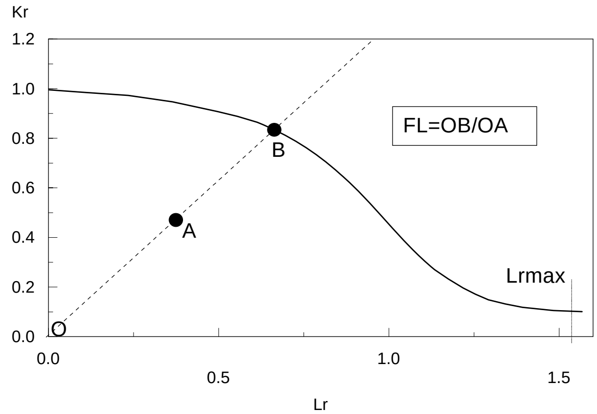
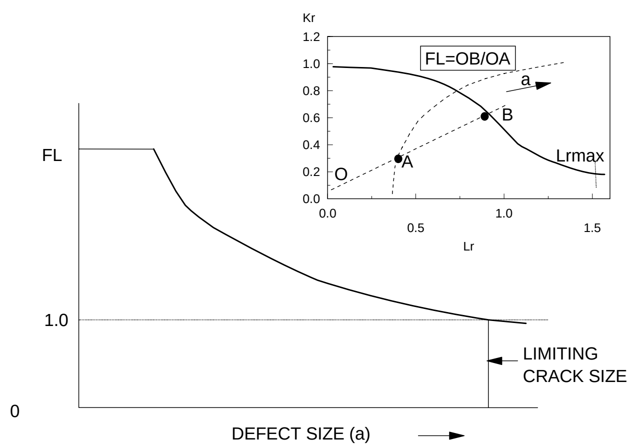
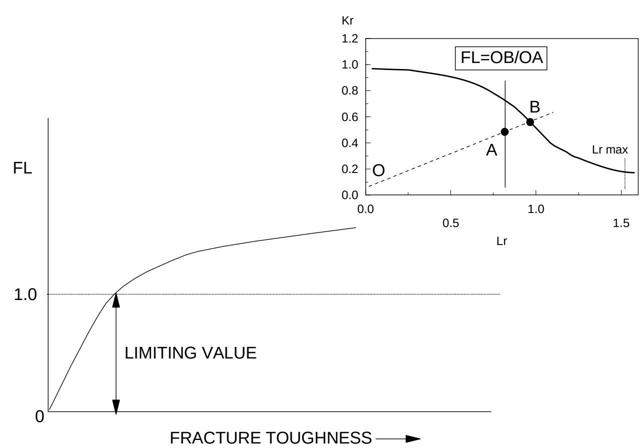


Figure 10.1 – Evaluation of FL for a Single Primary Load

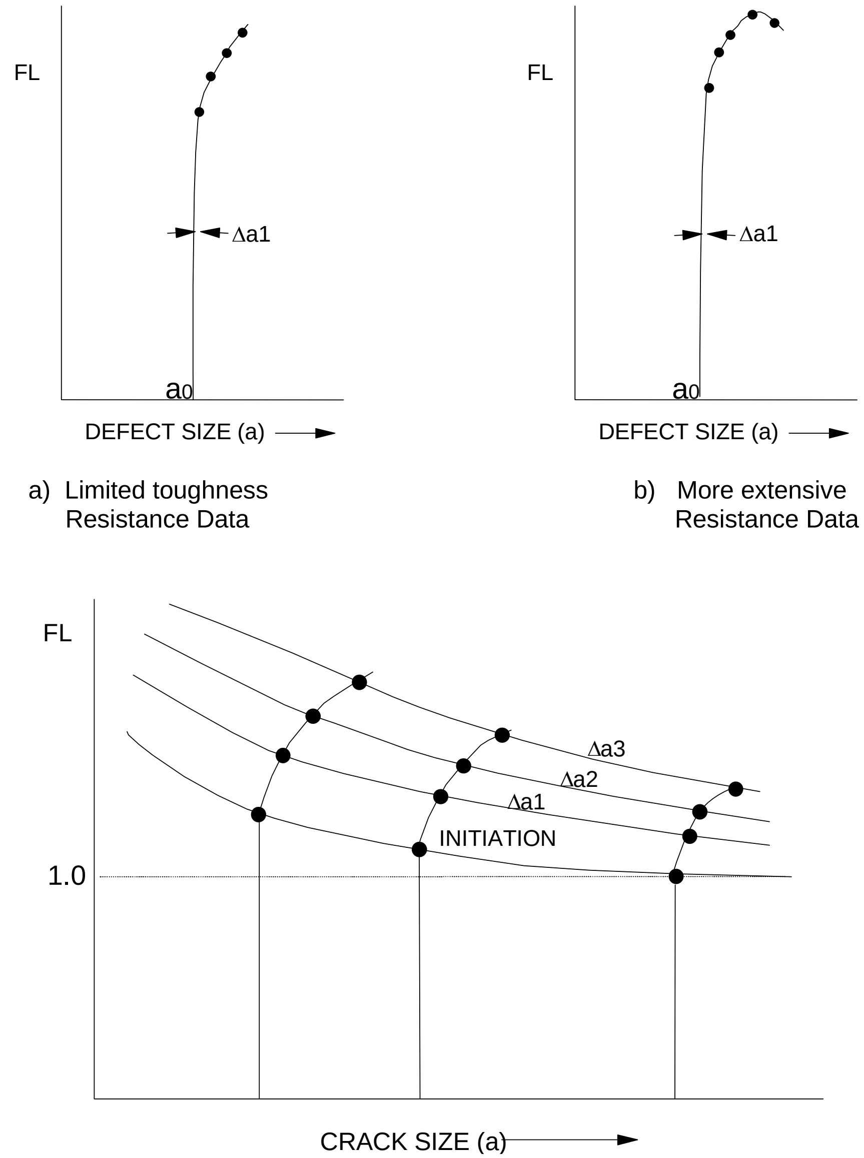


a) Defect Size



b) Fracture Toughness

Figure 10.2 – Typical Load Factor Variation Graphs



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

Figure 10.3 – Load Factor Variation with Defect Size - Ductile Tearing Analysis

Note that in both cases, the load factors in the preferred and non-preferred situations are the same, but the margin against limiting flaw size in (a) or toughness in (b) is smaller in the non-preferred situation.

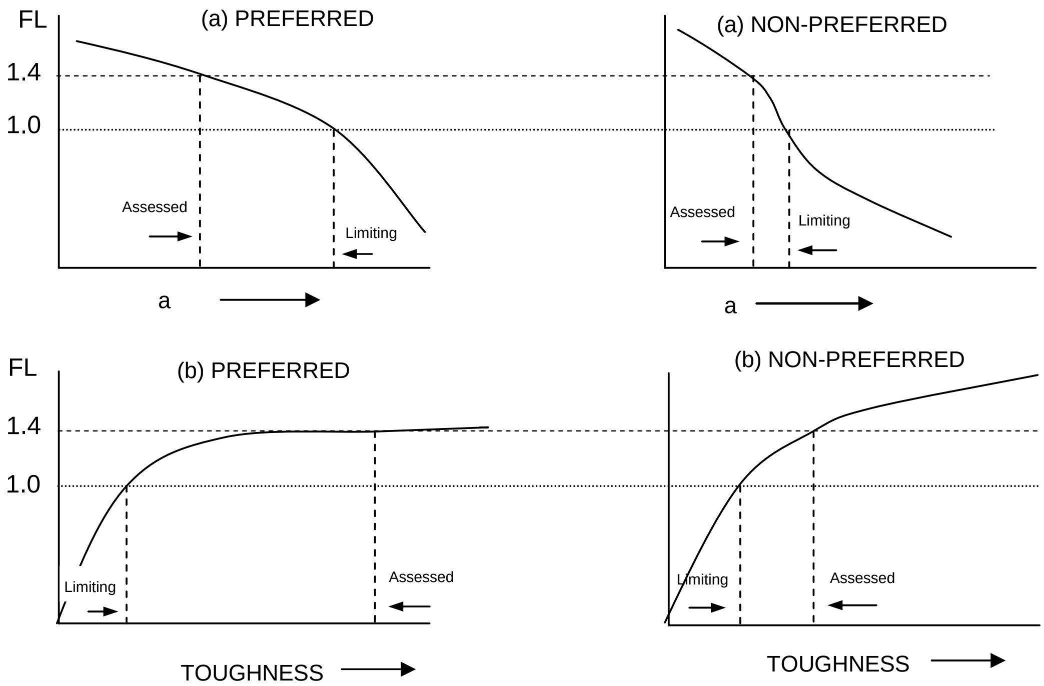


Figure 10.4 – Preferred Sensitivity Curves

10.2 Reporting of Results

10.2.1 Introduction

This part provides a checklist of issues that should be recorded to enable the full context of an analysis to be visible. This is necessary for several reasons:

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

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

10.2.2 Loading Conditions

- Structure/component Details
- Design Code (Pressure vessel, bridge, offshore)
- Normal operational stresses (primarily static, cyclic or random cyclic), R-ratio
- Fault or transient [(1)] conditions associated with start-up and shut-down or systems upsets
- Additional loads and stresses
- Existence of multi-axial stress states
- Stress analysis methods used (e.g. design code value, linearization, finite element, measured etc.)
- Residual stress value assumed and method used to determine it
- Residual stresses at welds or on cold-worked surfaces
- Application of PWHT
- Temperature
- Loading Rate
- Environmental conditions

[(1)] *Transient stresses are often critical in inducing or propagating stress corrosion cracks but historically have often been overlooked in laboratory testing.*

10.2.3 Material Properties

- Material specification
- Heat treatment, Thermal aging, Irradiation and related microstructural changes
- Yield stress, type (upper, lower, 0.2%) and how obtained (min spec, historical, test certificate, tested)
- Ultimate Tensile Stress and how obtained (min spec, historical, test certificate, tested)
- Mis-match ratio (M)
- All weld metal tensile properties (obtained from round or micro flat tensile specimens)
- Number of tensile tests carried out and whether value used is mean or lower bound
- Orientation and position of tensile specimens
- If available properties and degree, depth of cold work layer near surface
- Fracture toughness at relevant temperature and strain rate and how obtained (source of original data, Charpy correlation and associated P_f value, application of MML steps 1,2,3, comment on homogeneity, comment on specimen type and crack depths, test procedure used, constraint factor for CTOD-K conversion, validity of data, failure mechanism criteria, definition of characteristic value)
- Young's Modulus (assumed or measured)
- Poisson's Ratio (assumed or measured)

10.2.4 Definition of Postulated and Detected Flaw

- Identifying the cause of cracking in terms of the mechanistic process
- Establishing the origin and nature of the detected crack; defining the service operational conditions and history
- Flaw type, location (weld metal, fusion line etc.), position (centre line etc.) shape, size, orientation, basis for flaw size assumptions, NDE method used, quality of inspection, capabilities of method, sizing errors, probability of detection/correct sizing etc.
- Whether any flaw re-characterisation or interaction has been assumed
- If more than one crack is present, the crack density and the spacing between the cracks.
- State of the surface should be assessed for general or localised corrosion damage
- If coatings are present, the state of the coating should be reported

10.2.5 Welding / Microstructural Issues

- Welding method, parameters, heat input, consumables, joint design/geometry
- PWHT
- Tensile data for different constituents of weld (parent plate and weld metal) as per detail given in Section 5.4.

- Detailed reporting of fracture toughness determination, characteristic value and comment on inhomogeneity, metallography / fractography and site of pre-fatigue tip.
- Weld misalignment., Porosity, Weld toe geometry
- Microhardness, microstructural and microchemical aspects (features of grain boundaries or precipitate particles, elongated and clustered inclusions, local hard/soft zones)
- Orientation of the microstructure (significant differences in properties between the longitudinal and transverse directions)

10.2.6 Failure Assessment Diagram / Crack Driving Force (For Fracture Module only)

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

10.2.7 Limit Load (For Fracture Module only)

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

10.2.8 Stress Intensity Factor Solution

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

10.2.9 Significance of Results

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

10.2.10 Probabilistic Analysis

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

- Calculated failure probability

10.2.11 Summary of Assessment / Further Action

- Conclusions
- Proposed further actions in analysis (e.g. generate further material data for fatigue, creep, corrosion fracture toughness data, repeat NDE etc.)
- Proposed further actions for current structure/component (e.g. continue operation, repair, PWHT)
- Implications for other similar situations.

10.3 Bibliography

[10.1] F. M. Burdekin, A. W. Hamour, “SINTAP, Brite-Euram BE95-1426, Contribution to Task 3.5 Safety Factors and Risk”, UMIST.