New Unified Fracture Toughness Estimation Scheme for Structural Integrity Assessment

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Abstract

At present, treatment of fracture toughness data varies depending on the type of data (K_{IC}, J, CTOD) that are available for fracture mechanics analysis. This complicates structural integrity assessment and makes it difficult to apply any single, unified procedure. Within the Brite-Euram project 'SINTAP' a fracture toughness estimation scheme has been developed for the unified treatment of data for use in structural integrity assessment. As a procedure, it can be applied to Charpy data, as well as to fracture toughness data, and is suitable for the treatment of data at both single and different temperatures. The data sets may contain results from both homogeneous and inhomogeneous material, making the procedure applicable also to welded joints. The procedure allows fracture toughness assessment with quantified probability and confidence levels. Irrespective of the type of the original data, one material-specific K_{mat} value representing a conservative estimate of the mean fracture toughness is obtained (with its probability distribution). This information can then be applied to structural integrity assessment.

1 Introduction

At present, treatment of fracture toughness data that are to be used in fracture mechanics analysis varies depending on the type of data (K_{IC}, J or CTOD) that are available. This complicates structural integrity assessment and makes it difficult to apply any single, unified procedure. Particularly regarding welds, significance of material's inhomogeneity (LBZs) in terms of quantified probability and confidence levels is not encountered in structural integrity assessments in a unified manner. In the cases where fracture toughness data do not exist and cannot be easily obtained, it is necessary to base the estimate on Charpy data via the use of appropriate correlation between Charpy energy and fracture toughness. Many of the existing correlations, however, may only be applicable to a certain part of the transition curve or a small range of materials or just parent plate.

Within 'SINTAP', the aim was to develop a fracture toughness estimation scheme [1,2] for the unified treatment of various forms of toughness data for use in structural integrity assessments. Formulated to a procedure, one material-specific toughness parameter, K_{mat}, together with its probability density distribution $P\{K_{mat}\}$ is defined, irrespective of the type of the original data. For assessment against brittle fracture, the procedure is based upon the maximum likelihood concept (MML) [3] that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. As a result, a conservative estimate of the mean (50 %) fracture toughness (and the distribution) is obtained.

The present methodology can be applied to indirect (Charpy) data [2] or to actual fracture toughness data [1] and is suitable for treatment of data at both single and different temperatures. This way, a reliable estimate can be obtained for various forms of data sets containing results from both homogeneous and inhomogeneous material. Thus, the Procedure is expected to work well not only for base materials but, in the case of welded joints, for weld metals (WM) and heat-affected zones (HAZ). For the cases where the design of a structure against brittle fracture is not necessary, reference [4] is made to a separate approach.

The procedure represents a user-friendly step-by-step methodology which allows a reliable fracture toughness assessment with quantified probability and confidence levels. The work within 'SINTAP' is currently progressing towards the aim of establishing a unified European procedure for structural integrity assessment tailored towards the practical user.

2 Indirect Determination of Fracture Toughness

In reality, direct fracture toughness data are often not available and cannot be easily obtained, making it necessary to base the estimate of fracture toughness on the Charpy impact energy (Cv). Since no single correlation can be applied to all parts of the toughness transition curve, the SINTAP Procedure provides the following options [2]:

(i) A lower bound correlation for brittle (lower shelf) behaviour
(ii) A statistical method for the transition regime (The 'Master Curve')
(iii) A lower bound correlation for the ductile (upper shelf) behaviour.

Within this framework, guidance is also provided for:

(i) Determination of the Charpy 27/28 J temperature (T_{28J}) from data at other temperatures
(ii) Conversion of J and CTOD values into equivalent K_{mat} values

(iii) Quantification of the influence of strain rate

(iv) Treatment of Charpy data determined on sub-size specimens.

The principles of the treatment of Charpy data are described in [2] and shown as a flow-chart in Fig. 1. The selection of the appropriate correlation is based on knowledge of the expected operating regime of the material (brittle/ductile), and on the quality of the Charpy data that are available.

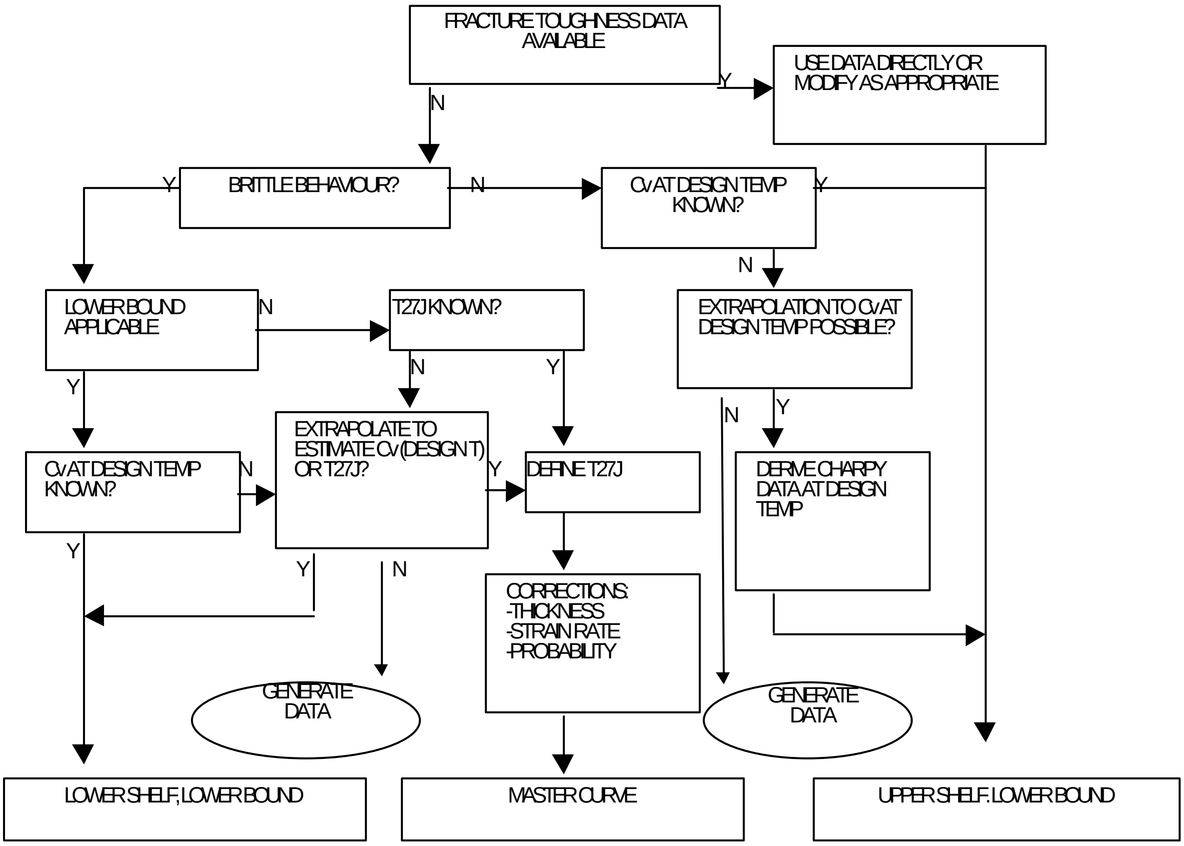

Fig. 1. Flowchart for selection of appropriate Charpy - fracture toughness - correlation [2].

2.1 Determination of fracture toughness in the brittle regime: Master Curve Concept

For materials operating in the brittle regime the determination of fracture toughness follows the 'Master Curve' concept, which is based on the correlation between the Charpy 28 J (27 J) temperature and the temperature for $K_{mat} = 100$ MPa√m. The relationship is modified to account for the required failure probability (Eq. 7), thickness effect (Eq. 8) and the shape of the fracture toughness transition curve (Eq. 9). Consequently, fracture toughness (K_{mat}) in the transition regime can be defined as [2]:

$$K_{mat} = 20 + \left\{11 + 77\exp\left(0.019\left[T - T_{28J} + 18^{\circ}C\right]\right)\right\}.(25/B)^{1/4}.\left\{\ln\left(1/\left[1 - P_f\right]\right)\right\}^{1/4} \qquad (1)$$

T = design temperature (°C)
T_{28J} = 28/27 J Charpy transition temperature (°C)
B = specimen thickness or flaw width $(2 \cdot c)$ (mm)
P_f = probability of failure
Std. dev. = 13 °C
Cv = Charpy impact energy (J)

At a Cv of 28 J the use of Eq. (1) with the lower 5th percentile of fracture toughness and a 90 % confidence level leads to a simple equation which represents a conservative lower bound estimate of fracture toughness:

$$K_{mat25} = 12 \sqrt{Cv} \tag{2}$$

where K_{mat25} is the estimated K-based fracture toughness of the material in MPa√m for a thickness or flaw width $(2 \cdot c)$ of 25 mm.

The fracture toughness evaluated in accordance with Eq. (2) applies to 25 mm thick specimens. The resultant calculated K_{mat} must therefore be corrected for the appropriate thickness (or flaw width) by:

$$K_{mat} = \left[(K_{mat25} - 20).(25/B)^{1/4} \right] + 20 \tag{3}$$

A comparison of the fracture toughness values predicted using Eq. (2) with a number of other published correlations is given in [2].

2.1.1 Validation within SINTAP

The 'Master Curve' approach has been applied [2] to a number of steels including line-pipe, ship plate, high-strength quenched & tempered steels, welds and structural steel beams and columns. The relationship between T_{27J} and $T_{100MPa\sqrt{m}}$ for this wide range of steels demonstrates the generally good description of the data by the expression.

Where discrepancies were observed, these could be attributed to dissimilar microstructures sampled in the Charpy and fracture toughness tests or to the occurrence of splits on the fracture surfaces of specimens in TMCP steels.

2.1.2 Additional Factors Applicable to the Master Curve Concept

For the cases where Charpy data corresponding to an energy level different to 28/27 J are available the use of limited extrapolation is permitted. This is based on a lower bound fit to Charpy data on a wide range of structural steels. Extrapolation from 40 °C above and 30 °C below T_{27J} can be made to estimate T_{27J} for structural steels [2].

Where a material is operating in a high loading rate regime, corrections can be made by applying a strain-rate dependent temperature shift to the transition temperature

$T_{100MPa\sqrt{m}}$ since the shape of the fracture toughness transition curve is unaffected by the strain rate [2].

The adjustment of transition temperature (by introducing a shift) becomes necessary when sub-sized Charpy specimens are used instead of standard 10 x 10mm specimens (where the 28 J value corresponds to 35 J/cm$_2$). The shift in this transition temperature associated with sub-size specimens (ΔT_{SS}) can be described as [2]:

$$\Delta T_{SS} = 51.4\ 1n\left(2[B/10]^{0.25} - 1\right) \tag{4}$$

Consequently, the Master Curve concept can be applied to a wide range of steels, the reliability of the resultant estimate of fracture toughness quantified and factors such as high loading rate or sub-size Charpy data accounted for. The method is also fully coherent with that used for the fracture avoidance clauses of Eurocode 3.

2.2 Determination of fracture toughness in the ductile regime: Deterministic Approach

There is, at present, no equivalent of the 'Master Curve' for upper shelf behaviour, consequently a deterministic approach is used. For the ductile regime the Procedure [2] provides two correlations, both of which have been validated for a wide range of steels:

$$K_{mat} = 0.54\ Cv + 55 \tag{5}$$

$$\left(K_{mat} / s_y\right)^2 = 0.52\left(\left[Cv / s_y\right] - 0.02\right) \tag{6}$$

The upper shelf fracture toughness is evaluated in accordance with both expressions and the lower value taken. Eq. (5) is only recommended when the Charpy energy is greater than 60 J. Validation exercises demonstrated that, while no statistical quantification was made, the predictions were reliably conservative [2].

3 Treatment of Fracture Toughness Data

In general, treatment of fracture toughness data (i.e. K_{IC}, K_{JC}, J_{IC}, J_i, J-R, $K_{ICductile}$) can be classified as either (i) design against brittle fracture or (ii) design against ductile fracture, with either (iii) brittle or (iv) ductile fracture data available. The procedure is described in detail in [1] and shown as a flow-chart in Fig. 2. In the case of CTOD data in the form of δ or J, the treatment is conducted using relevant K-CTOD-J conversions [2].

3.1 Assessment against brittle fracture

The 'SINTAP' Procedure [1] is based upon the MML concept [3] that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The method makes the following assumptions: (i) specimen size adjustment, (ii) distribution of scatter and (iii) minimum toughness and temperature dependence. Being equally applicable to welded joints, (iv) a data homogeneity check is included. As a result, a conservative estimate of the mean fracture toughness (and its distribution) is obtained. The method is in compliance with the recent standard ASTM E 1921-98.

3.1.1 Scatter and size effect of fracture toughness

The procedure [1] assumes the scatter to follow the statistical brittle fracture model which uses a Weibull type distribution function to describe scatter as:

$$P\left[K_{IC} \le K_I\right] = 1 - \exp\left(- \left[\frac{K_I - K_{min}}{K_0 - K_{min}} \right]^4 \right) \tag{7}$$

where $P[K_{IC} \le K_I]$ - i.e. P_f - is the cumulative failure probability at a K_I level, K_I is the stress intensity factor level, K_{min} is the lower bound to the fracture toughness and K_0 is a temperature (T_0) and specimen thickness (B) dependent normalisation fracture toughness which corresponds to a 63.2 % cumulative failure probability (and is approximately 1.1 $\overline{K}_{IC}$, where $\overline{K}_{IC}$ is mean fracture toughness).

The methodology [1] predicts a statistical size effect of fracture toughness test specimens of the form:

$$K_{B2} = \left(K_{B1} - K_{min}\right)\left(B_1 / B_2\right)^{1/4} + K_{min} \tag{8}$$

where B_1 and B_2 correspond to respective specimen thickness (length of crack front). Although "K_{min}" itself can be regarded as "theoretical" in nature, it has been found that for structural steels, a fixed, experimental value of K_{min} = 20 MPa√m can be used.

The model here is based upon the assumption that brittle fracture is primarily initiation controlled, even though it contains a conditional crack propagation criterion, which among other factors results in the lower bound fracture toughness K_{min}. Close to the lower shelf of fracture toughness (K_{IC} < 50 MPa√m), the equations are expected to be inaccurate because the initiation criterion is no longer dominant, and the macroscopic fracture is propagation controlled. In this case there is no statistical size effect [1].

In the ductile-to-brittle transition region the equations presented here should be valid as long as loss of constraint and/or ductile tearing do not play a significant role [1].

3.1.2 Temperature dependence of fracture toughness

The 'Master Curve' is used in the new ASTM standard (E 1921-98) for fracture toughness testing in the ductile-to-brittle transition region. It gives an approximate temperature dependence of the fracture toughness, K_0, for ferritic structural steels as [1]:

$$K_0 = 31 + 77.\exp(0.019.[T - T_0]) \tag{9}$$

where T0 (°C) is the transition temperature where the mean fracture toughness, corresponding to a 25 mm thick specimen, is 100 MPa√m and $K_0(T_0)$ which is a normalisation fracture toughness at 63.2 % cumulative failure probability, is 108 MPa√m.

3.1.3 Homogeneity check

In the case of 'homogeneous' material the estimate can be based on the mean value of the data. In the cases where the 'brittle microstructure' is substantially more brittle than the 'matrix microstructure', the fracture behaviour will be dominated by the former, consequently the estimate must be based on the minimum value of the data [1].

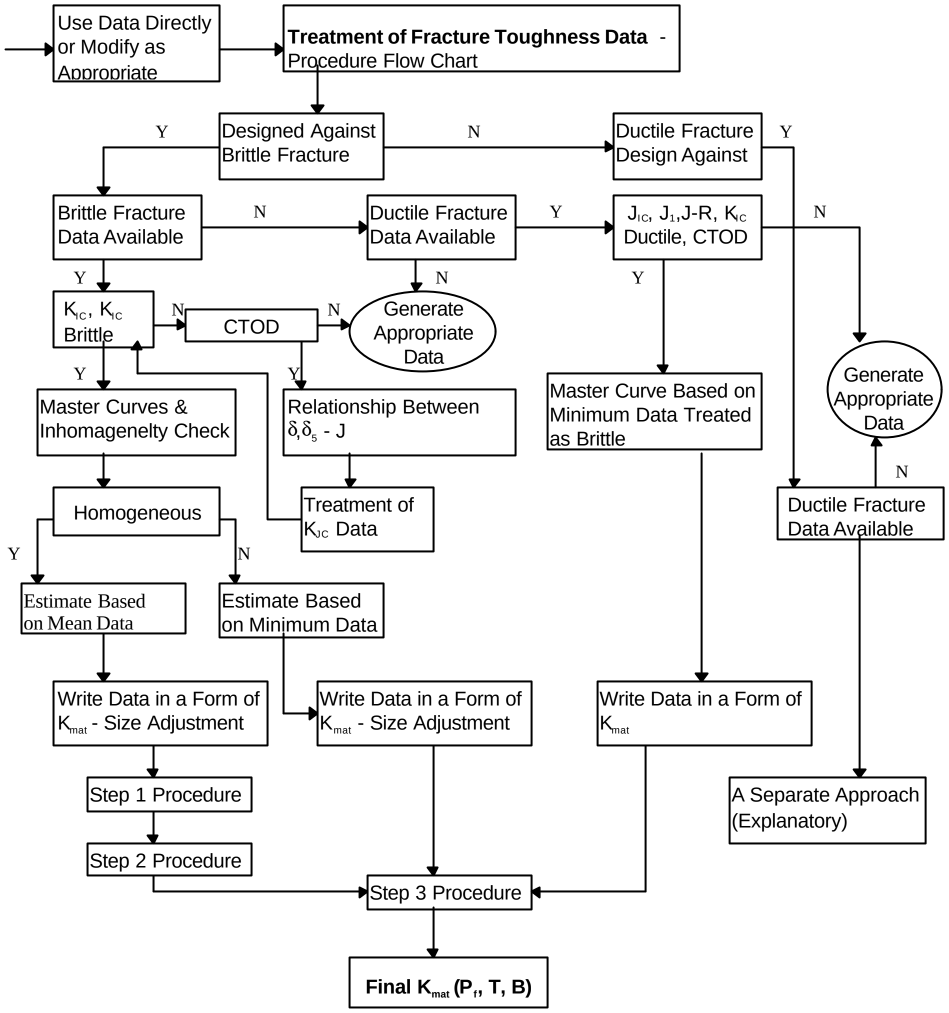

Fig. 2. Flowchart for treatment of fracture toughness data [1].

3.1.4 Procedure description

Firstly, the original fracture toughness data is written in the form of K_{mat}, with size-adjustment made for specimens of thickness other than 25 mm. The procedure progresses according to three steps, each of them setting a different validity level for that part of the data that is to be censored. It should be emphasised that censoring the data does not mean neglecting the data. The whole data set is involved in the analysis, however, a certain pre-assumption is made concerning the nature of the data being censored.

Depending on the characteristics of the original data available, the procedure guides the user towards the Step that gives the most appropriate toughness estimate K_{mat} for the fracture toughness analysis to the particular case being assessed. In the last stage, the final $\overline{K}_{MAT}$ fracture toughness estimate (and its probability distribution) are calculated either according to Step 1, 2 or 3.

Step 1: Normal MML Estimation. All the available data is used for the estimation, with the exception of ductile results ending in non-failure, and those results which are affected by large-scale yielding (thereby exceeding the specimen's measuring capacity limit). Censoring can be made e.g. according to: $K_{JC(limit)} = (E \times b_0 \times \sigma_{ys} / 30)^{0.5}$, defined by the new ASTM standard (E 1921-98).

Step 2: Lower-Tail MML Estimation. The 50 % upper tail of the data set is censored and the remaining data (corresponding to a cumulative probability of 50 % or lower) is used for MML estimation of K_{mat} or $T_0(K_{mat})$. This ensures that the estimate is descriptive of the material (i.e. microscopic properties), without being affected by macroscopic inhomogeneity, ductile tearing, or large-scale yielding (i.e. unrealistically high 'apparent' toughness values).

The Step 2 then proceeds as a continuous iteration process, until the 'constant' level for either K_0 or T_0 has been reached.

Step 3: Minimum Value Estimation. Only the minimum toughness value (i.e. one value corresponding to one single temperature) in the data set is used for the estimation. The intention is to assess the significance of a single minimum test result, with the aim at avoiding unconservative fracture toughness estimates which may arise if median (50 %) fracture toughness is used for a material expressing significant microscopic inhomogeneity.

Consequently, Step 3 sets a criteria to the allowable difference between the median (50 %) and the lower-bound (5 %) fracture toughness levels. Provided that the obtained K_{mat} or $T_0(K_{mat})$ estimate according to Step 3 is more than 10 % lower or 8 °C higher, respectively, than the corresponding estimate according to Step 1 or Step 2 - whichever of them is lower: K_{mat} (or higher: $T_0(K_{mat})$), this single minimum value is regarded as significant and the estimate according to Step 3 is taken as a final estimate of material's fracture toughness. Otherwise, the lowest (highest) one of the estimates given by Step 1 and Step 2 is taken as a final estimate.

By taking into account the possibility that a single minimum value in a data set can become significant (i.e. capable of triggering brittle failure) due to material's microscopic inhomogeneity, the procedure can be applied in the cases where the HAZ of an otherwise tough steel exhibits LBZs [1].

3.2 Treatment of ductile fracture data

The treatment of data in the case that only ductile fracture data is available depends on whether the possibility of brittle fracture in a particular structure can be excluded or not.

3.2.1 Design against brittle fracture

For the cases where only ductile fracture data are available, but the possibility of brittle fracture in a structure cannot be excluded, Step 3 which treats the minimum initiation value as a brittle cleavage fracture event, can be reliably used for fracture toughness estimation [1]. This is often the case in structures with their operating temperature in the material's transition regime or close to the lower shelf.

3.2.2 Design against ductile fracture

For materials with their operating temperature in the upper shelf regime, or materials which do not exhibit brittle cleavage fracture, a separate approach [4] is advised to be used. Due to insufficient knowledge of the extent to which e.g. constraint, mismatch, scatter, definition of 'initiation', testing etc. influencing the fracture behaviour should be considered, this approach is not meant as a procedure, but is suggested as guidance [1].

4 Advantages and Limitations

Validation exercises have demonstrated the advantages of the 'SINTAP' Procedure in obtaining fracture toughness estimates for various forms of data sets from base materials and welds [1,2]:

(i) The various treatments including specimen size adjustment, inclusion of strain rate effects etc. can be applied directly to K_{mat} data.

(ii) Even the estimate derived from 'lowest quality data' is always 'safe' because the less sufficient/accurate the original data, the more it will be penalised in the probabilistic fracture mechanics assessment.

(iii) By relating the penalty to the quality of the original data any additional data improving the accuracy of a previously existing data set can be readily utilised in terms of reduced conservatism.

(iv) The procedure enables the quantification of probability and confidence levels of the K_{mat} estimate.

(v) Multiple safety margins that could lead to unnecessary conservatism, are avoided.

(vi) The whole data set can be fully utilised in the analysis, regardless of whether the results are ductile or brittle.

To ensure the reliable use of the procedure, the following premises must be fulfilled [1]:

(i) The data set must be representative to the application of the structure/ component being assessed.

(ii) In the case of welds, data should be available for all the 'critical' zones (e.g. HAZ, WM).

(iii) For the final structural integrity assessment, suitable confidence and probability levels should be chosen in relation to the criticality of the particular component/structural member.

(iv) Should the structure's operating temperature lie close to the material's upper shelf and only brittle fracture data being available, appropriate ductile fracture data should be generated.

5 Conclusions

A fracture toughness estimation methodology for the unified treatment of various forms of toughness data for use in structural integrity assessments of ferritic structural steels has been described. The most important findings can be drawn:

(1) Reliable correlations between Charpy and fracture toughness have been established: (i) a lower-bound correlation for lower shelf behaviour, (ii) Master Curve based correlation for transition regime incorporating thickness adjustment and statistical scatter and (iii) a correlation for upper shelf behaviour.

(2) The influence of loading rate and treatment of sub-sized Charpy data can be numerically incorporated to the indirect evaluation of fracture toughness.

(3) Relationships describing K-CTOD-J conversions, as well as guidance for approximating T_{27J} from Charpy data at other temperatures have been determined.

(4) A 'SINTAP' Procedure for the treatment of fracture toughness data in three Steps has been developed, in which one material-specific K_{mat} value (and its probability distribution) is defined. For assessment against brittle fracture, the procedure is based on the MML concept using the Master Curve method, producing a conservative estimate of the mean fracture toughness. The procedure has been verified to work well for various forms of data sets containing results for both homogeneous and inhomogeneous materials. For cases where only ductile fracture data are available, but the possibility of brittle

fracture cannot be excluded, Step 3, treating the minimum value as brittle, can be reliably used.

(5) The procedure allows fracture toughness assessment with quantified probability and confidence levels. With a confidence of 75 %, a conservative and hence 'safe' estimate is obtained., irrespective of the type of the original data. The procedure thereby produces a realistic description of the lower tail probabilities. The verification calculations show that with as few as 6 tests (i.e. 6 parallels), the probability of having a conservative estimate of the mean is ≈ 75 %. This would be considered quite adequate for the majority of structural integrity assessment purposes.

(6) The work within SINTAP is currently progressing towards the aim of establishing a unified European procedure for structural integrity assessment tailored towards the practical user.

6 References

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