FRACTURE TOUGHNESS ESTIMATION METHODOLOGY WITHIN THE SINTAP PROJECT

K. Wallin*, A.C. Bannister† and P. Nevasmaa*

At present, treatment of toughness data varies depending on the type of data (K_{IC}, J, CTOD, CVN) that are available for fracture mechanics analysis. Within the Brite-Euram project 'SINTAP' a methodology 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.

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 (δ)) that are available. This complicates structural integrity assessment and makes it difficult to apply any single, unified procedure. In reality, fracture toughness data may not exist and cannot be easily obtained. In these circumstances, it is necessary to find a reliable correlation between Charpy impact energy and fracture toughness.

Within 'SINTAP', the aim was to develop a fracture toughness estimation methodology (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. As a result, a conservative estimate of the mean fracture toughness (and the distribution) is obtained.

* VTT Manufacturing Technology, Technical Research Centre of Finland.
† Swinden Technology Centre, British Steel plc.

The 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. 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 also for welded joints. For the cases where the design of a structure against brittle fracture is not necessary, reference (1,4) is made to a separate approach.

The procedure represents a user-friendly step-by-step methodology which allows 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.

INDIRECT DETERMINATION OF FRACTURE TOUGHNESS

In reality, actual 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. Since no single correlation can be applied to all parts of the toughness transition curve, the 'SINTAP' Procedure offers the following options (2):

i) A lower bound correlation for brittle (lower shelf) behaviour. A formula representing a conservative lower bound estimate of fracture toughness has been derived.

ii) A statistical method for the transition regime. The 'Master Curve' concept is based on the correlation between T_{28J} and the temperature for $K_{mat} = 100\ MPa\sqrt{m}$. The relationship is modified to account for the required failure probability, thickness effect and the shape of the fracture toughness transition curve.

iii) A lower bound correlation for ductile (upper shelf) behaviour. Since there is no equivalent of the 'Master Curve' for upper shelf behaviour, fracture toughness is evaluated in accordance with two correlations and the lower value taken.

Within this framework, guidance is also provided for:

i) Influence of strain rate. Where a material is operating in a high loading rate regime, corrections can be made by applying a strain-rate dependent temperature shift to $T_{100MPa\sqrt{m}}$ since the shape of the fracture toughness transition curve is unaffected by the strain rate.

ii) Treatment of Charpy data from sub-size specimens. An equation for determination of the shift in transition temperature associated with sub-size Charpy specimens is provided.

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. The method is fully coherent with that used for the fracture avoidance clauses of Eurocode 3.

TREATMENT OF ACTUAL FRACTURE TOUGHNESS DATA

The treatment of fracture toughness data (K_{IC}, K_{JC}, J_{IC}, J_i, J-R, $K_{ICductile}$) can be classified as either design against brittle fracture or design against ductile fracture (with either brittle or ductile fracture data available). The principles of the methodology are given in (1) and shown as a flow-chart in Fig. 2. In the case of CTOD data (δ or J), the treatment is conducted using relevant K-CTOD-J conversions (2).

Assessment against brittle fracture

The procedure is based upon the MML concept that uses a 'Master Curve' method, making 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.

Scatter and size effect of fracture toughness. The procedure assumes the scatter to follow the statistical brittle fracture model which uses a Weibull type distribution function. The method also predicts a statistical size effect of test specimens.

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. The expression gives an *approximate* temperature dependence of the fracture toughness for ferritic structural steels.

Homogeneity check. In the case of homogeneous material the estimate can be based on the mean value of the data. 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.

Procedure description. Firstly, the original 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 3 steps, each of them setting a different validity level for that part of the data that is to be censored. The whole data set is involved, however, a certain pre-assumption is made concerning the nature of the data being censored. Finally, the $\overline{K}_{MAT}$ fracture toughness estimate is 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 (exceeding the specimen's measuring capacity limit).

Step 2 (Lower-Tail MML Estimation). The 50% upper tail of the data set is censored and the remaining used for the estimation. This ensures that the estimate is descriptive of the material, without being affected by macroscopic inhomogeneity, ductile tearing or large-scale yielding (i.e. unrealistically high 'apparent' toughness).

Step 3 (Minimum Value Estimation). Only the minimum toughness value in a data set is used for the estimation. The intention is to assess the significance of a single minimum value, with the aim at avoiding unconservative estimates in the case of locally inhomogeneous material. The procedure can hence be applied to welds exhibiting local brittle zones.

Treatment of ductile fracture data

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. For (i) materials with their operating temperature in the upper-shelf regime or (ii) materials which do not exhibit brittle cleavage fracture, a separate approach (1,4) is advised to be used as guidance.

ADVANTAGES AND LIMITATIONS

Validation exercises have shown the advantages of the SINTAP Procedure in obtaining fracture toughness estimates for various forms of data sets from base materials and welds:

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 data, the more it will be penalised in the assessment.
iii) By relating the penalty to the quality of the original data any additional data improving the accuracy of previous data can be utilised in terms of reduced conservatism.
iv) The procedure enables the quantification of probability and confidence levels of K_{mat}.
v) Multiple safety margins that could lead to unnecessary conservatism, are avoided.
vi) The whole data set can be used, regardless of whether the results are ductile or brittle.

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

i) The data set must be representative to the application of the structure being assessed.
ii) In the case of welds, data should be available for all the 'critical' zones (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/structure.
iv) Should the structure's operating temperature lie close to the material's upper shelf, but only brittle fracture data are available, appropriate ductile fracture data should be generated.

CONCLUSIONS

A fracture toughness estimation methodology for the unified treatment of various forms of toughness data for use in structural integrity assessments has been described:

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 in ferritic structural steels, the procedure is based on the MML concept using the Master Curve method, producing a conservative estimate of the mean (50%) 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 properties. The verification calculations show that with as few as 6 tests, 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.

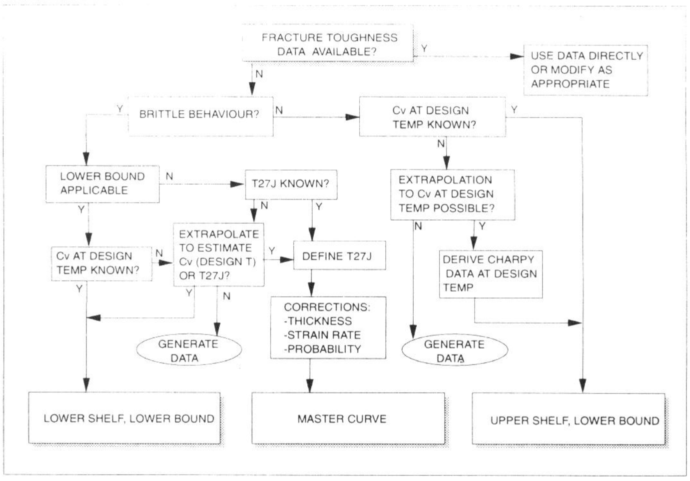

Fig. 1 - Flowchart for selection of appropriate Charpy - fracture toughness correlation (2).

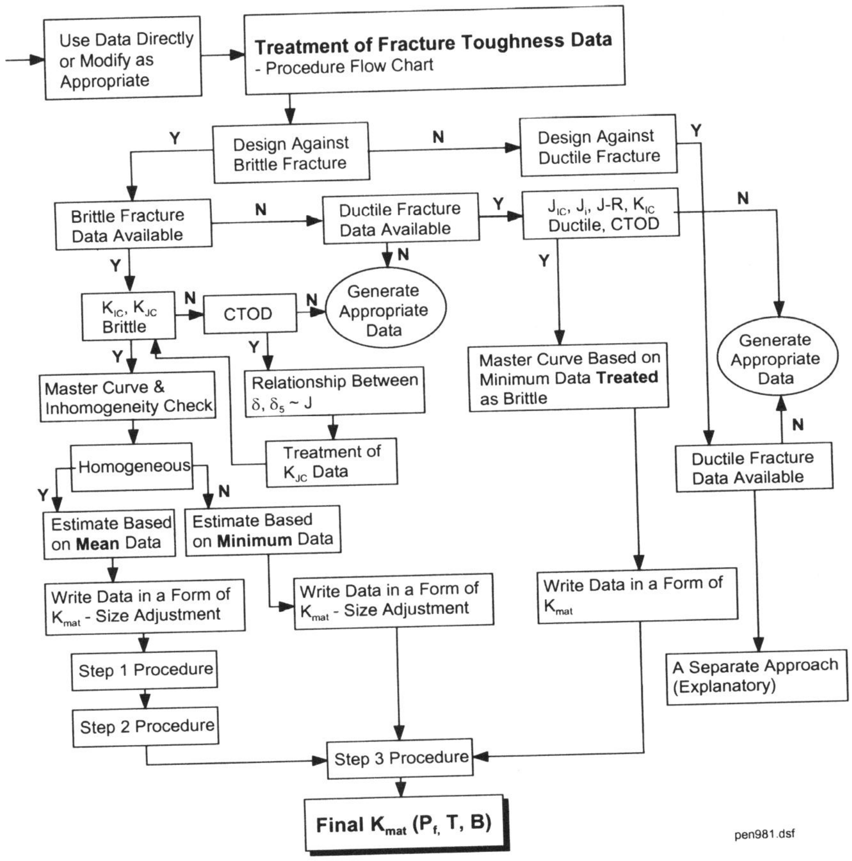

Fig. 2 - Flowchart for treatment of fracture toughness data (1).

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