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THE USE OF CHARPY/FRACTURE TOUGHNESS CORRELATIONS IN THE FITNET PROCEDURE

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ABSTRACT

In an ideal situation, fracture toughness data to be used in structural integrity assessments are generated through the use of appropriate fracture mechanics-based toughness tests. In reality, such data are often not available or cannot be easily obtained due to lack of material or the impracticability of removing material from the actual structure. In such circumstances, and in the absence of appropriate historical data, the use of correlations between Charpy impact energy and fracture toughness can provide the fracture toughness value to be used in the assessment. The FITNET (Fitness-for-Service) procedure, presently being developed in the frame of a European Thematic Network, includes a section which deals with the use of empirical correlations between Charpy and fracture toughness data. This paper will outline the contents of this chapter, along with some examples of application of selected correlations to actual test data.

Keywords: FITNET, structural integrity assessments, Charpy/toughness correlations.

INTRODUCTION

The European Fitness-for-Service (FITNET) thematic network is currently running in the framework of the "Competitive and Sustainable Growth" (GROWTH) research programme of the European Community, having started in February 2002 [1]. The objective of this concerted action is the development and extension of the use of Fitness-for-Service (FFS) procedures for assessing postulated or real damage in actual metallic structures due to fracture, fatigue, creep or corrosion.

The ultimate outcome of the network will be a comprehensive, unified FITNET FFS procedure, designed to assess the structural integrity of metallic welded or non-welded structures transmitting loads. The procedure will comprise four main modules, each dealing with one of the major structural failure modes, respectively Fracture, Fatigue, Creep and Corrosion. Within the fracture module, the problem of unavailability of direct fracture toughness measurements and the necessity to use indirect estimations based on Charpy impact test results is addressed in one of the chapters; the background to the problem is given below.

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Within the FITNET procedure, the flowchart shown in Figure 1 is given for helping the user choose the appropriate correlation(s) based on his specific situation (prediction of expected fracture behaviour of the structure, nature of Charpy impact data available, use of sub-sized Charpy test results etc).

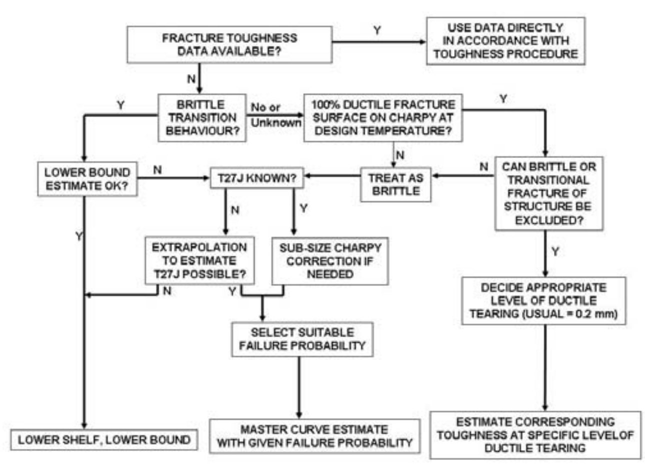

Figure 1 – Flow-chart provided by the FITNET procedure for the selection and use of Charpy/toughness correlations for estimating fracture toughness.

In the present status of the FFS procedure, several of the correlations which will be presented here are still lacking published experimental validation because they are based on ongoing work. When FITNET is completed, each equation will be supported by a statement giving its applicability (e.g. steel type) and range of validity. For the time being, we can generally say that the various approaches can be applied to ferritic structural steels.

DEFINITION OF THE APPLICABILITY REGIMES (LOWER SHELF/TRANSITION/UPPER SHELF)

One of the first problems that needs to be addressed is the definition of the different regimes of material behaviour, with reference to both the absorbed energy (KV) and the shear fracture appearance (SFA) transition curves obtained from Charpy tests and the 27 J transition temperature.

According to the FITNET procedure, the lower shelf is defined as the temperature region where SFA $\leq$ 20% and the impact energy is less than 27 J; upper shelf as the temperature region where SFA = 100% (different criteria, such as SFA $\geq$ 95%, can be used by agreement between the parties). The range in between is defined as the ductile-to-brittle transition region.

BRITTLE BEHAVIOUR: LOWER SHELF AND EARLY TRANSITION REGION

A lower bound correlation that can be used in the lower shelf regime for a wide range of steels [2] is given by:

$$K_{mat} = \left[\left(12\sqrt{C_V} - 20\right) \left(\frac{25}{B}\right)^{0.25} \right] + 20 \qquad (1)$$

where K_{mat} is the fracture toughness of the material (MPa√m), C_V is the Charpy energy (J) and B is the thickness of the specimens (mm). Eq.(1) derives 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.(1) can also be used in the lower transition region, where cleavage is preceded by limited plastic deformation, but the impact energy is less than 27 J. The K_{mat} estimate is based on the C_V value corresponding to the minimum of three tests or its equivalence.

MIXED BRITTLE/DUCTILE BEHAVIOUR: DUCTILE-TO-BRITTLE TRANSITION REGION

The so-called Master Curve correlation [3,4] consists in relating a specific Charpy transition temperature ($T_{27J/28J}$) to a specific fracture toughness transition temperature ($T_{100MPa\sqrt{m}}$). The relationships given in the FITNET procedure were originally developed for energy levels corresponding to 28 J and 41 J. However, 27 J and 40 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}.

The application of the Master Curve approach enables consideration to be given to:

- thickness effect
- scatter
- shape of fracture toughness transition curve
- required probability of fracture.

The general relationship between the Charpy and fracture toughness transition temperatures, whose accuracy will strongly depend on the quality of the Charpy input data, is given by [5,6]:

$$T_{100MPa\sqrt{m}} = T_{27J} - 18°C \qquad (\sigma=15°C) \qquad (2a)$$

or

$$T_{100MPa\sqrt{m}} = T_{40J} - 24°C \qquad (\sigma=15°C) \qquad (2b)$$

which, if the $+\sigma$ lower confidence limit is assumed for a conservative estimate, becomes:

$$T_{100MPa\sqrt{m}} = T_{27J} - 3°C \qquad (3a)$$

or

$$T_{100MPa\sqrt{m}} = T_{40J} - 9°C \qquad (3a)$$

Figure 2 shows data from 65 different steels (base and weld, unirradiated and irradiated), for which estimations based on eq.(2a) are compared with measured values of $T_{100MPa\sqrt{m}}$ from actual fracture toughness tests [7,8]. All but one data points lie within the 95% confidence limits (±2σ).

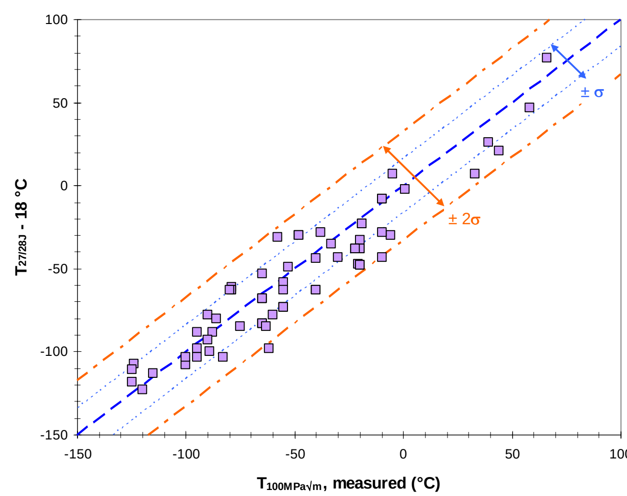

Figure 2 – Estimation of toughness transition temperature $T_{100MPa\sqrt{m}}$ using $T_{27/28J}$ for 65 different steels [7,8].

The fracture toughness transition curve can then be described as a function of T_{27J} or T_{40J} as follows:

$$K_{mat} = 20 + \{11 + 77 \cdot \exp[0.019(T - T_{27J} + 3°C)]\} \left(\frac{25}{B}\right)^{0.25} \left(\ln \frac{1}{1-P_f}\right)^{0.25} \qquad (4a)$$

or

$$K_{mat} = 20 + \{11 + 77 \cdot \exp[0.019(T - T_{40J} + 9°C)]\} \left(\frac{25}{B}\right)^{0.25} \left(\ln \frac{1}{1-P_f}\right)^{0.25} \qquad (4b)$$

where P_f is the probability of failure.

Eqs.(2),(3) and (4) are not applicable to ductile behaviour; namely, the value of SFA corresponding to 27 J or 40 J must be less than 30%.

Furthermore, a number of situations have been identified which could result in unconservative predictions; these include:

- cases where Charpy specimens exhibit unusual fracture behaviour, such as fracture path deviation;
- presence of splits on the fracture surface;
- through-thickness variation of microstructure and properties such that the Charpy specimen does not test the region of lowest toughness;
- severely cold worked material.

Incomplete transition curves

When the sparsity of Charpy data does not allow a reliable determination of T_{27J}, this parameter can be conservatively estimated from:

$$T_{27J} = T_{Cv} - \frac{C}{4} \cdot \ln \frac{C_V \cdot (USE - 27J)}{27J \cdot (USE - C_V)} \tag{5}$$

where T_{Cv} is the temperature at which Charpy absorbed energy 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) according to the following relationship:

$$C \approx 34°C + \frac{\sigma_Y}{35.1} - \frac{USE}{14.3} \tag{6}$$

with σ_Y in MPa and USE in J. Figure 3 illustrates the application of eqs.(5) and (6) to a large material data set, using different formulations of T_{Cv} (energy levels corresponding to 41 and 68 J, SFA = 50%).

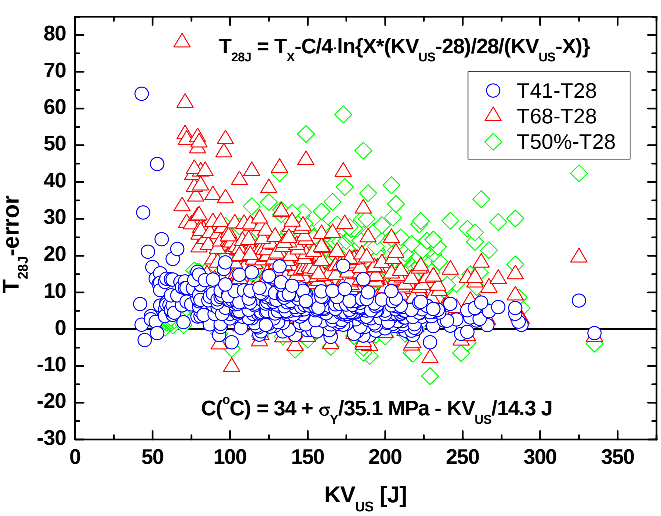

Figure 3 – Estimation of T_{28J} Charpy transition temperature based on eqs. (5) and (6). T_{28J}-error is the difference between estimated and measured values of T_{28J}.

When the upper shelf energy is unknown but both impact energy and shear fracture appearance data are available, the upper shelf energy can be estimated more accurately as:

$$USE \approx 100 \cdot \frac{\sum_{i=1}^{n} \frac{C_{Vi}}{SFA_i}}{n} \tag{7}$$

where n is number of Charpy data points available.

If only upper shelf energy data are available, then the lowest temperature in the relevant test range (T_{US}), combined with the corresponding value of upper shelf energy, shall be used for the transition temperature determination. In this case, the transition temperature is estimated from eq. (8), where parameter C is derived from eq.(6):

$$T_{27J} = T_{US} - \frac{C \cdot \ln\left(\frac{19 \cdot (USE - 27)}{27}\right)}{4} \tag{8}$$

FULLY DUCTILE BEHAVIOUR: UPPER SHELF REGIME

Estimation of point (critical) values

When Charpy tests exhibit fully ductile behaviour (i.e. SFA = 100%), this does not automatically imply that the structure itself will be operating in upper shelf conditions 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 Charpy upper shelf behaviour.

However, if brittle behaviour for the structure can be safely excluded, an estimate of the upper shelf fracture toughness corresponding to a ductile crack extension of 0.2 mm ($K_{J0.2}$), often taken as the engineering approximation of the onset of ductile tearing (K_{mat}), can be evaluated from:

$$K_{mat} = K_{J0.2} = \sqrt{\frac{E\left(0.53 \cdot USE^{1.28}\right)\left(0.2^{0.133 \cdot USE^{0.256}}\right)}{1000\left(1-\nu^2\right)}} \tag{10}$$

where USE is in 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.(10) if desired.

At the present time, however, there are indications that eq.(10) might not always yield a conservative estimate of K_{mat} for all ferritic steels.

Estimation of the crack resistance (J-R) curve

An estimate of the J-R curve based on the Charpy upper shelf energy (USE) [9] is expressed by the following relationship:

$$J = J_{1mm} \cdot \Delta a^m \tag{11}$$

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.(11) are given by:

$$J_{1mm} = 0.53 \cdot USE^{1.28} \cdot \exp\left(-\frac{T-20}{400}\right) \tag{12}$$

$$m = 0.133 \cdot USE^{0.256} \cdot \exp\left(-\frac{T-20}{2000}\right) - \frac{\sigma_y}{4664} + 0.03 \tag{13}$$

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

TREATMENT OF SUB-SIZE CHARPY DATA

When the component thickness is less than 10 mm, sub-size Charpy specimens have to be used. However, in order to use the correlations previously described, based on T_{27J} and/or USE, the shift in transition temperature associated with the reduced thickness of the sub-size Charpy specimens must be accounted for.

For a standard 10 ×10 mm² cross section Charpy specimen, 27 J corresponds to 35 J/cm². The shift in this transition temperature associated with sub-size specimens, ΔT_{ss}, is given by [10]:

$$\Delta T_{ss} = T_{27J} - T_{ss} = -51.4 \ln\left[2\left(\frac{B}{10}\right)^{0.25} - 1\right] \tag{14}$$

where T_{ss} is the temperature corresponding to 35 J/cm² for the sub-size Charpy specimens and B is their thickness (mm).

In the case of plate materials used in pressure vessels, piping and tankage, API 579 [11] additionally reports the following correlation:

$$\Delta T_{ss} = \frac{1}{1.8}\left[\frac{10.13 - 9.73\left(\frac{B}{10}\right)}{1 + 0.3532\left(\frac{B}{10}\right)}\right]^2 \tag{15}$$

It should be emphasized that eqs.(14) and (15) only apply to sub-size specimens which are identical to standard testpieces except for the thickness (lower than 10 mm). They should not be used on 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 conservatively be estimated from:

$$USE_{10mm} \geq USE_B \cdot \frac{10}{B} \tag{16}$$

where USE_{10mm} and USE_B are the values of upper shelf energy for the standard and the sub-size Charpy specimens respectively.

CONCLUSION

The section on correlations between Charpy and toughness results is intended to provide the FITNET user the best possible guidance for conservatively estimating fracture toughness properties whenever actual toughness tests results are unavailable or cannot be produced.

The contents are based on the latest state-of-the-art knowledge on this topic according to the members of the FITNET consortium. The addition of open literature references, which will reflect the extensive qualification work presently ongoing for several of the most recent correlations, will hopefully make even more valuable the finalized version of this document, which is expected at the completion of the FITNET thematic network (mid 2006).

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