A STATISTICAL INTERPRETATION OF THE CTOD-DESIGN CURVE AND GUIDELINES TO ASSESS HAZ-TOUGHNESS

K. Wallin*

The CTOD-design curve contains an internal safety factor, but the exact value of the factor has not been previously known. Experimental safety factors are the product of the internal safety factor and an external safety factor from the CTOD test results themselves. Here, the CTOD-design curve safety factor is determined based on a theoretical statistical treatment of experimental data.

Presently only a few crude rules exist for the assessment of HAZ fracture toughness. They are all based on a microstructural validation of each specimen after the test. Because of difficulty to obtain valid results many tests are performed in vain. New, more efficient guidelines for performing CTOD testing of HAZ with respect to assessment of local brittle zones are given, based on statistical modelling.

INTRODUCTION

Integrity assessment of welded structures is often based on the CTOD concept. Traditionally it applies the CTOD-design curve which predicts the safety of a structure based on the flaw size, structural stresses and material properties (CTOD, σ_y). Recently, steps have been taken to modify the CTOD concept to be more in line with the so called R-6 approach (Garwood et al (1)). However, the traditional CTOD-design curve still forms the base for the simplest level also in the new modification. Thus it's relevance has not been diminished. The design curve itself has a built in internal safety factor. The safety factor is often assumed to be equal to 2, but its true value has not been determined experimentally. The experimental validation of the design curve, which has been performed with wide plate tests, provides certain safety factor values. These experimental safety factors are, however, the product of the internal safety factor of the design curve and the external safety factor for the CTOD test results themselves. Thus the experimental safety factors show a large variability and their values are dependent on the CTOD value used in the assessment.

* Technical Research Centre of Finland (VTT)
Metals Laboratory

The CTOD test results in themselves show a considerable scatter, especially in the case of cleavage fracture. The scatter is large even for homogeneous materials, but in the case of inhomogeneous materials, like the heat affected zone (HAZ) in welds, the scatter can be intensified. This is especially the case if the HAZ contains local brittle microstructures. In such a case the CTOD value will depend on the probability that the crack front contains such brittle microstructures. Presently only a few crude rules exist for the assessment of HAZ fracture toughness (Denys (2)). They are all based on a microstructural validation of each specimen after the test. Because it can be quite difficult to obtain valid results many tests are performed in vain. If the goal is only to assure that the HAZ does not contain local brittle zones (LBZ) it is possible to develop more flexible rules to assess the HAZ fracture toughness.

In this paper, first the CTOD-design curve safety factor is analyzed based on a theoretical statistical treatment of experimental data. It is shown that the built in safety factor of the design curve in reality is close to 1.65. Guidelines on how to use it together with partial safety factors for the CTOD fracture toughness in order to achieve a desired total safety factor of the analysis are presented. Furthermore, guidelines for performing CTOD testing of HAZ with respect to assessment of local brittle zones are given, based on a similar statistical treatment as for the CTOD-design curve.

THE CTOD-DESIGN CURVE

Presently the normal CTOD value used with the CTOD-design curve is the minimum CTOD value of three tests (MOT). Kamath (3) who has done up to this date the probably most excessive investigation regarding the experimental safety factor of the CTOD-design curve report safety factors ranging from 0.9 to 14 based on the MOT. These experimental safety factors (SF_{TOT}) are the product of the external safety factor due to MOT (SF_{MOT}) and the internal safety factor of the design curve (SF_{INT}). The MOT CTOD value corresponds to a certain probability level, but this level is not fixed. The probability level will be the function of confidence level by the equation

$$P_{MOT} = 1 - (1 - P_{conf})^{1/3} \qquad \text{...(1)}$$

The confidence level in equation 1 can be interpreted in the following manner. $P_{conf} = 0.5$ means that 50 % of the P_{MOT} will correspond to a probability less than 20.6 %. $P_{conf} = 0.1$ means that 10 % of the P_{MOT} will correspond to a probability less than 3.5 % and $P_{conf} = 0.9$ means that 90 % of the P_{MOT} will correspond to a probability less than 53.6 %.

In order to apply equation 1 the true CTOD distribution must be known. In the case of brittle cleavage fracture (i.e. δ_c) several statistical models (Wallin (4)) yield a simple equation for the scatter of fracture toughness. For δ_c the equation becomes

$$\delta_c = \delta_0 \cdot \left\{ \ln \frac{1}{1-P} \right\}^{1/2} \qquad \text{...(2)}$$

where δ_0 is a normalization parameter corresponding to a specimen thickness/ crack width B_0. The normalization parameter represents a failure probability of 63.2 % and is related to the median fracture toughness $\delta_{.5}$ by $\delta_{.5}=\sqrt{\ln 2}\cdot\delta_0$.

Equation 2 has been comparatively well validated for a large number of materials failing by cleavage fracture (4). When equation 2 and equation 1 are combined the CTOD value corresponding to MOT will be

$$\frac{\delta_{.5}}{\delta_{MOT}} = \left\{ \frac{3 \cdot \ln 2}{\ln \frac{1}{1-P_{conf}}} \right\}^{1/2} \qquad \text{...(3)}$$

The external safety factor due to MOT is obtained from equation 3. Ordering the safety factors by rank leads to a rank probability $P_{rank} = 1-P_{conf}$. Thus the external safety factor due to MOT can be written as

$$SF_{MOT} = \left\{ \frac{-3 \cdot \ln 2}{\ln P_{rank}} \right\}^{1/2} \qquad \text{...(4)}$$

The internal safety factor for the design curve is then finally obtained as

$$SF_{INT} = \left\{ \frac{\ln P_{rank}}{-3 \cdot \ln 2} \right\}^{1/2} \cdot SF_{TOT} \qquad \text{..(5)}$$

The data reported by Kamath (3) have been analyzed by equation 5 and the results are presented in figure 1. The mean internal safety factor for the CTOD design curve would seem to be approximately 1.6.

The problem with CTOD testing is that the critical CTOD can have different definitions. The CTOD standards recognize no less than four definitions for the critical CTOD. Only two of the definitions relate to cleavage fracture initiation i.e. δ_c and δ_u. The two other definitions relate either to ductile tearing initiation (δ_i) or maximum load (δ_m). The MOT can relate to any one of these parameters and this reduces the reliability of the analysis. The MOT is likely to correspond to cleavage fracture initiation, but this need not always be the case. Furthermore Anderson et al (5) have shown that the internal safety factor of the CTOD design curve is also a function of the load level and it is also probable that surface cracks have different safety factors than through thickness cracks. Finally also the treatment of secondary stresses affect the safety factor. Therefore the reliability of the analysis presented here should not be assumed to be impeccable, but the analysis is still expected to give a satisfactory estimate of the internal safety factor.

In order to evaluate the likelihood of the analysis more precisely, the calculated SF_{MOT} have been compared with the total safety factor SF_{TOT} in figure 2. The slope of the data represents the internal safety factor. In the figure are also the 5 and 95 % confidence limits for the rank estimates plotted. The obtained value for the internal safety factor (1.65) is in close agreement with the mean value based on equation 5. Actually the values are also in good agreement with the analysis in (5). For a surface crack they (5) obtained that the safety factor was decreasing with increasing load level, but the mean safety factor appeared to be in the range 1.5-1.7. Thus it can be assumed that the present analysis is realistic. Knowing the value of the internal safety factor makes it possible to select the CTOD values (using equation 2) so as to produce a desired total safety factor with a certain confidence.

GUIDELINES TO ASSESS HAZ-TOUGHNESS

Presently most guidelines to assess heat affected zone toughness contain a validation procedure of the test results, based on sectioning and microscopic examination of the fractured specimens (2). Because it is very difficult to locate the fatigue crack front ideally within the HAZ, many tests are judged as invalid. This causes HAZ testing to be both inefficient as well as expensive.

If the goal is only to assure that the HAZ does not contain local brittle zones it is possible to develop more flexible rules to assess the HAZ fracture toughness. It has been shown by Nevasmaa and Wallin (6) that if the HAZ contains local brittle zones that are more than 3 times more brittle than the matrix, then the LBZ microstructure determine the behavior of the whole specimen.

The methodology uses the minimum measured CTOD value, to estimate the likelihood of the microstructure being brittle. First one selects the desired failure probability fractile (P) e.g. 0.05, producing a CTOD value δ_P e.g. 0.1 mm, corresponding to a crack width B_0 consisting only of the microstructure in question. B_0 can be taken equal to the plate thickness for a through thickness crack or equal to $2 \cdot c$ for a surface crack. Analoguos to equation 1, the minimum CTOD value corresponds to the probability

$$P_{min} = 1 - (1 - P_{conf})^{1/N} \qquad \text{...(6)}$$

where P_{conf} is the desired confidence level e.g. 0.9. When the mean length of microstructure ($\bar{l}_i$) is used in the calculation, N is equal to the total number of specimens, but when the total length of microstructure (Σl_i) is used, N is equal to 1. Combining equations 2 and 6 one can calculate a minimum CTOD value δ_c which will guarantee that the microstructure is not brittle. The improvement of the method in relation to present analysis methods is that all specimens are "valid" regardless of the amount of LBZ in the crack front. This makes the testing much more efficient and economical.

$$\delta_e = \left\{ \frac{\ln\frac{1}{1-P_{min}}}{\ln\frac{1}{1-P}} \right\}^{1/2} \cdot \delta_P \cdot \left\{ \frac{B_0}{\sum l_i} \right\}^{1/2} \quad \text{...(7)}$$

Equation 7 yields the minimum CTOD value that gurantees that the P:th fractile of the fracture toughness for a specimen consisting only of the LBZ microstructure will be higher than δ_P. Two examples of the use of equation 7 are presented in figures 3 and 4. Figure 3 is based on the mean length of microstructure ($\bar{l}_i$), whereas figure 4 is based on the total length of microstructure ($\sum l_i$). Both figures are based on a 75 % confidence level and a 10 % lower toughness fractile corresponding to δ_P = 0.1 mm. Similar figures can be developed for any desired fractile and confidence level. These guidelines can be directly used for determining toughness criteria for welded structures.

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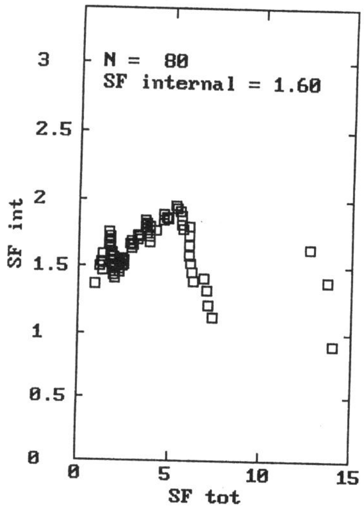

Figure 1 Internal safety factor of the CTOD design curve

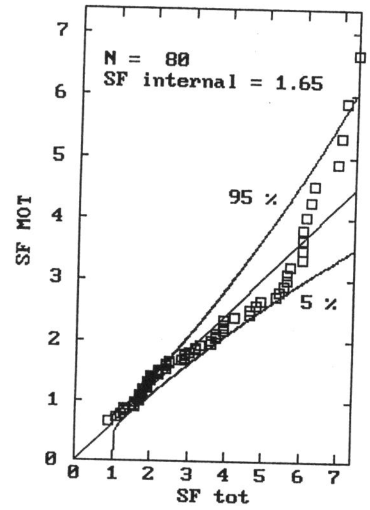

Figure 2 Relation between total safety factor and MOT safety factor

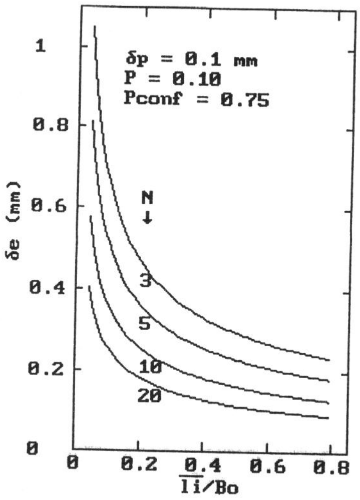

Figure 3 Requirement for minimum CTOD based on mean length of LBZ

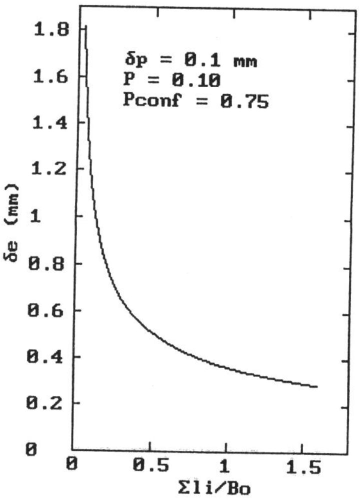

Figure 4 Requirement for minimum CTOD based on total length of LBZ