ESTIMATION LOWER BOUND CTOD FRACTURE TOUGHNESS OF HAZ NOTCHED WELDS WITH MECHANICAL MISMATCH

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High strength TMCP steels with SMYS in the range 420 to 500 MPa are investigated with respect to CTOD fracture toughness in the heat affected zone (HAZ). Different welding procedures are conducted in order to evaluate the effect upon brittle fracture initiation conditions.

A statistical approach based on binomial probability of the minimum value and Weibull weakest link statistics was applied to determine lower bound characteristic values for CTOD fracture toughness. The approach provides characteristic values in accordance with a specified fracture probability and confidence level for the data set. Validation is carried out by comparison with more comprehensive estimation procedures.

INTRODUCTION

CTOD testing of steel weldments may give rise to results with high scatter. A crucial point is how to estimate a lower bound value from a given set of test results. A simple method based only on the minimum value and the number of test specimens (1) and (2) is presented. The method is in the present paper evaluated by comparison with more comprehensive estimation procedures within a cooperative Japanese-Norwegian research project on new high strength steels for offshore applications.

The simple method is termed the SPRÖDZON method from an international cooperative research project with the same name where the method was elaborated (2). It appear as a promising candidate for implementation in specifications and international standards as a method for characterization of fracture toughness test data. The features of the method are:

- Simple closed form calculation procedure.
- The statistical significance of the data is quantified in terms of a percentile

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and a confidence level. These are the main parameters to be specified in the specification as a requirement to assure a target safety.
- The method is applicable on any number of test results (i.e. 3 or more), and data sets with different number of test results can be compared.
- If brittle microstructure in HAZ are demonstrated to be responsible for low CTOD values, the statistical significance of the data set can be related directly to the total sampled amount of this microstructure. With this approach all specimens are valid, but the contribution to the confidence level depends upon the success of the notch positioning.

The SPRÖDZON method is a simple engineering procedure applicable for small data sets and other situations where the distribution function for the whole data set is unknown due to contribution from different fracture mechanisms. It should be noted that other methods based on parametric distributions may provide more accurate estimates in situations where the data source is sufficient.

From the present test programme it is concluded that the combination of weld metal overmatch and low toughness microstructure in the grain coarsened HAZ (CGHAZ) caused low CTOD values. In this case good correlation between sampled amount of CGHAZ and fracture toughness was obtained. In cases where these two conditions were not present such as weld metal under/evenmatch, poor weld metal toughness or higher HAZ toughness, such correlation could be more difficult to detect.

For data sets where a specific microstructure was identified as brittle and responsible for brittle fracture initiation, the total amount of this microstructure sampled by all specimens in the data set can be determined by sectioning of the specimens after testing. The specimens in the data set contribute to the characteristic value by the amount of the brittle microstructure sampled. This feature is of large practical importance because present validation criteria for HAZ testing (e.g. API RP2Z and EEMUA 158) are in many cases difficult to accomplish. Expensive re-testing can be avoided by determination of a sufficient number of test specimens in advance and by subsequent calculation of a characteristic value from the test results obtained.

THE SPRÖDZON METHOD

The SPRÖDZON method consists of two basic relations. One is the binomial probability of the minimum value of a data set P_{min}. For a selected confidence level P_{conf} and number of tests included in the data set n, this probability is determined as:

$$P_{\min} = 1 - (1 - P_{conf})^{1/n} \qquad \textbf{(1)}$$

where P_{min} represents the cumulative probability of the minimum value of the data set. The binomial probability does not include any assumption of statistical distribution of the test data.

The second basic relation is the statistical distribution function related to the lower tail of the population considered. For a data set where different fracture mechanisms are included, it is not possible to relate one distribution function to the whole population. However, if the lower tail of the population is characterized by brittle fracture before ductile crack growth initiation, this part of the distribution can be described by a Weibull distribution function.

$$P(F) = 1 - \exp\left(-\left(\frac{\delta}{\beta}\right)^{\alpha}\right) \tag{2}$$

where δ is the random variable (represented by CTOD values), and where α and β are the shape and scale parameter in the two-parameter Weibull distribution respectively. An important feature provided by the Weibull distribution is the statistical crack front length correction where the CTOD value δ_2 for a specified crack front length B_2 can be determined from results for another length B_1 and its corresponding CTOD value δ_1

$$\delta_2 = \delta_1 \left(\frac{B_1}{B_2}\right)^{\frac{1}{\alpha}} \tag{3}$$

Combination of the two basic relations is carried out by assuming that the binomial probability of the minimum and the corresponding minimum CTOD value determines a point on the Weibull distribution which represents the lower tail of the population considered. In this way the scale parameter is implicitly determined. If it is furthermore assumed that the scale parameter α = 2.0, any fractile in the distribution can be determined. For a specified probability level P, the corresponding characteristic CTOD value δ_P can be determined by Equation (4).

$$\delta_P = \left\{\frac{\ln\dfrac{1}{1-P}}{\ln\dfrac{1}{1-P_{\min}}}\right\}^{1/2} \cdot \delta_{\min} \tag{4}$$

More detailed derivation of the procedure is presented by Wallin and Hauge (2) and by Hauge (3).

EVALUATION OF LOCAL BRITTLE ZONES

If a specific microstructure can be identified as responsible for the lower bound test results, and the amount of this microstructure sampled by the crack tip can be measured on each test specimen, the statistical crack front length effect can be utilized to determine the contribution of each specimen to the estimated characteristic value as described in reference (2).

The identified brittle microstructure is denoted LBZ (local brittle zone). In accordance with the weakest link model the minimum value is related to the total volume of material sampled by the crack front, and not the number of tests.

Now, consider n test specimens each with thickness B. The minimum value of these specimens is obtained as the minimum (weakest link) of a total crack front length of $n \cdot B$. Only the part of the crack front sampling LBZ contributes to the minimum value observed. Hence, the same minimum value should be obtained by a specimen with a total crack front length equal to $\sum l_i = l_1 + l_2 + \ldots + l_n$ where l_i is the sampled length of LBZ in specimen i. We can now consider one specimen with crack front length equal to $\sum l_i$. In this case $n = 1$ and subsequently $P_{min} = P_{conf}$ (see Equation (1)).

Comparison with a toughness requirement or with other test results requires a common specimen size or crack front length reference. The resulting δ_P which is associated with the total crack front length $\sum l_i$ can now be converted to any reference crack front length by Equation (3). Introduction of a reference crack front length B_0 into Equation (4) yields:

$$\delta_P = \left\{ \frac{\ln \frac{1}{1-P}}{\ln \frac{1}{1-P_{\min}}} \right\}^{1/2} \cdot \delta_{\min} \cdot \left\{ \frac{\sum l_i}{B_0} \right\}^{1/2} \quad (5)$$

In order to simplify the calculation procedure and to avoid confusion about the value of n (please remember that $n=1$ is used for derivation of P_{min} in Equation (5)), an effective sample size n_{eff} is defined as

$$n_{eff} = \sum l_i / B_0 \quad (6)$$

By replacing n with n_{eff} in Equation (1). Equation (4) can be used without any further correction instead of Equation (5).

APPLICATION OF THE SPRÖDZON METHOD

In the above procedure, a characteristic value has been derived from a data set with specified values of confidence level P_{conf} and cumulative probability P. This is a highly relevant application in cases where the requirement to a data set is defined and for comparison of different data sets. However, the two main equations (1) and (4) are simple equations that can be manipulated and solved with respect to any parameter included.

In particular, the case where a certain fractile, cumulative probability and confidence level is defined, the required minimum value and number of parallel test specimens can be determined prior to testing. This application contributes to optimization of the test program for material qualification when the statistical requirements are defined. In the case of HAZ testing where the sampled length of LBZ is taken into account, the required number of parallels is related to the sampled LBZ length by n_{eff} .The required number of test specimens should in this case be determined by a prediction of the average length of sampled LBZ.

In the case of HAZ testing, all test specimens contribute to the final result to the extent they sample LBZ. No specimens are invalid provided that cleavage fracture is triggered by the LBZ irrespective of the LBZ size sampled by the crack front. Compared to the procedure described in API RP 2Z (4), this feature is of major importance in testing of weldments where a 15% sample of LBZ is difficult to obtain, and it provides in general a better utilization of the information contained in a data set.

TEST PROGRAMME

The introduction of high strength steels in offshore structures has increased the demand for a statistically significant characteristic value for the representation of CTOD fracture toughness. This is one of the main tasks in a Japanese-Norwegian research project on high strength steels for offshore application where a comprehensive fracture mechanics test programme on steel weldments was carried out.

Four structural steels with yield strength in the range 420 to 500 MPa were included in the investigation. A test temperature of -50°C was determined on the basis of the CTOD transition curve in order to test in the transition range. Three different heat inputs (1.5, 3.0 and 5.0 MJ/m) was applied and a total of 9 data sets was established. The number of parallel tests varied between 9 and 15. There were large individual differences between the data sets reflecting different toughness level in the HAZ and mismatching ratio. There was also a significant scatter within the data sets, reflecting the inherent scatter in toughness within the HAZ and scatter caused by variation in fusion boundary profile and notch location.

STATISTICAL CHARACTERIZATION PROCEDURE

The fracture mechanism has a large influence upon the estimated statistical distribution. Specimens with unstable fracture before initiation of ductile crack growth (δ_c) provides a distribution different from the specimens with ductile crack growth (δ_u and δ_m). In order to integrate the two fracture mechanisms in the same cumulative distribution, the data was classified in accordance with the fracture mechanism. Weibull distribution parameters was estimated for each of the two groups defined, and the cumulative distribution was determined by definition of the joint bimodal distribution. This distribution function is defined in Equation (7).

$$F_{12}(x) = f_1 \, F_1(x) + f_2 \, F_2(x) \tag{7}$$

where f_1 and f_2 define the probability of obtaining each of the two fracture mechanisms respectively (i.e. $f_2 = 1 - f_1$), and where F_1 and F_2 are the cumulative distribution function of each corresponding data set.

In addition to the bimodal distribution, the 2 parameter Weibull and lognormal distributions were estimated.

For the purpose of investigating the SPRÖDZON method including the amount of LBZ sampled, a modification of the Weibull distribution was introduced. Before estimation, each value is corrected by the statistical crack front length correction:

$$x_0 = x_i \left(\frac{l_i}{B_0} \right)^{\frac{1}{\alpha}} \tag{8}$$

where l_i is the amount of CGHAZ sampled for specimen i with CTOD value x_i, B_0 is a reference length for sampled LBZ equal to 15% of the specimen thickness and where the Weibull shape factor α is assumed to be 2.0. Estimation of the shape parameter is carried out as for Weibull distribution above. The test data are now corrected again with the new estimated shape parameter. The procedure is repeated until the difference between the shape parameters in two subsequent iterations is negligible. As for the SPRÖDZON method, this approach is only applicable if eventual LBZ is present and identified.

Characteristic values were determined from the lognormal limit by application of the non-central t-distribution in accordance with Johnson and Welch (5). From the Weibull distribution, characteristic values are determined by the estimation procedure presented by Thoman et al (6) which is based upon numerical methods. It should also be noted that the maximum likelihood method applied for the estimation provides biased shape factors. Unbiasing factors presented in reference (6) are applied in the estimation.

RESULTS

The calculated cumulative distributions are presented in Figures 1 to 8. The results from the estimation of lower bound CTOD values are presented in Table 1. In order to compare the estimation methods, the following parameters were calculated:

LNL	Lognormal 5% fractile estimated with 75% confidence
WBL	Weibull 5% fractile estimated with 75% confidence
LNL-RFC	LNL calculated for the δ_c-values in the data set and scaled by the proportion of δ_c-values in order to reflect the bimodal property.
WBL-RFC	WBL calculated for the δ_c-values and scaled as for LNL-RFC.
SZL	SPRÖDZON 5% limit with 75%confidence (Equation (4))
SZ-LBZ	SPRÖDZON 5% limit with 75% confidence incl. LBZ (Equation (5))

Steel A

Steel A had a yield strength of 440 MPa and the weld heat input was 3 MJ/m. The cumulative distribution showed a clear bimodal behaviour (Figure 1). The SPRÖDZON method overestimated the prediction by the bimodal distribution. This is caused by the fact that two CTOD values of the same magnitude represents the minimum in the data set. This is one of the effects to be covered by the included confidence level. Comparison with the expectance value for the 5% fractile indicates that safe estimation is obtained if a bimodal lognormal distribution is assumed as the correct distribution. The bimodal Weibull distribution gave a much lower estimation. The discrepancy between LNL and WBL (also between LNL-RFC and WBL-RFC) is probably related to different capability to fit test data (7). Further examination of this aspect requires even larger data sets (10 to 20 δ_c-values). In the following discussions LNL-RFC is assumed to be the best reference as a measure of the lower bound value. SZL and SZL-LBZ is evaluated on this basis.

TABLE 1 - Comparison of different methods for the estimation of characteristic CTOD values and the minimum value measured (mm).

Data set	LNL	WBL	LNL-RFC	WBL-RFC	SZL	SZL-LBZ	Min. value
A - 3.0	0.032	0.015	0.062	0.029	0.064	0.089	0.10
B - 3.0	0.047	0.018	0.065	0.038	0.062	0.067	0.09
B - 5.0	0.019	0.010	0.034	0.015	0.029	0.040	0.05
C - 1.5	0.216	0.271	-	-	0.083	0.104	0.13
C - 3.0	0.064	0.062	0.047	0.034	0.052	0.076	0.09
C - 5.0	0.099	0.042	0.133	0.102	0.096	0.108	0.15
E - 1.5	0.143	0.153	0.108	-	0.087	0.121	0.13
E - 3.0	0.159	0.161	0.145	-	0.110	0.150	0.19

Steel B

Steel B had a yield strength of 467 MPa, and a heat input of 3.0 and 5.0 MJ/m was used in the welding. The test results were dominated by δ_c-values and the bimodal behaviour was not directly visible. However, after separating the data into two groups, a better fit to the experimental data was obtained (see Figures 2 and 3). For these data sets, there was a good correlation with the SPRÖDZON method and the estimate based on LNL-RFC.

Steel B was the only material where a sufficient correlation between the sampled amount of CGHAZ and CTOD value was established. The "weakest link correction" as described in Equation (8) was applied. The effect of this correction was however small since the actual sampled amount of CGHAZ was close to the reference length B_0. The Weibull shape factors calculated by iteration of Equation (8) were 1.46 and 0.99 for 3 and 5 MJ/m heat input respectively.

Steel C

Steel C had a yield strength of 496 MPa, and heat inputs of 1.5, 3.0 and 5.0 MJ/m was used in the welding. The cumulative distributions are presented in Figures 4, 5 and 6. The heat input of 1.5 MJ/m gave only one δ_c-value, and comparison with the other methods is not possible. However, the SPRÖDZON limit can easily be determined, and the method gives reasonable results. The heat input of 3.0 MJ/m gave a clear bimodal distribution and SZL overestimate LNL-RFC as for Steel A. The heat input of 5 MJ/m had a less pronounced bimodal distribution. In this case SZL-LBZ underestimated LNL-RFC slightly and correlated well with WBL-RFC.

Steel E

Steel E had a yield strength of 503 MPa, and heat inputs of 1.5, 3.0 and 5.0 MJ/m was used in the welding. The cumulative distribution for the two lower heat inputs are presented in Figures 7 and 8. The highest heat input did not reveal any δ_c-value. The toughness was generally higher than the other materials, and it was difficult to establish the distribution for the lower part of the bimodal distribution. For the two lowest heat inputs, there was still reasonable correlation between SZL-LBZ and LNL-RFC.

CONCLUSIONS

The investigated data sets represent fracture toughness results from the transition temperature range. There are evidently different fracture mechanisms leading to δ_c-values compared to δ_u and δ_m-values. By splitting the data into two groups in accordance with the fracture mechanism, a bimodal distribution can be established. This representation gives better fit to the experimental data compared to a single distribution representation.

The SPRÖDZON method gives reasonable estimates of a specified fractile with a specified confidence level in the present investigation where data sets with a wide range of toughness levels are included. This method represents a simple characterization method to treat lower tail fracture toughness test data applicable for implementation in standards and specifications.

It is concluded that the SPRÖDZON method provides a powerful tool to determine lower bound values for fracture toughness. In spite of the very simple procedure, it is considered to provide more accurate predictions than methods based on a single distribution parameter estimation in the transition temperature range. However, attention should be paid to the identification of a brittle microstructure before the amount of this microstructure is applied reference for the characteristic value.

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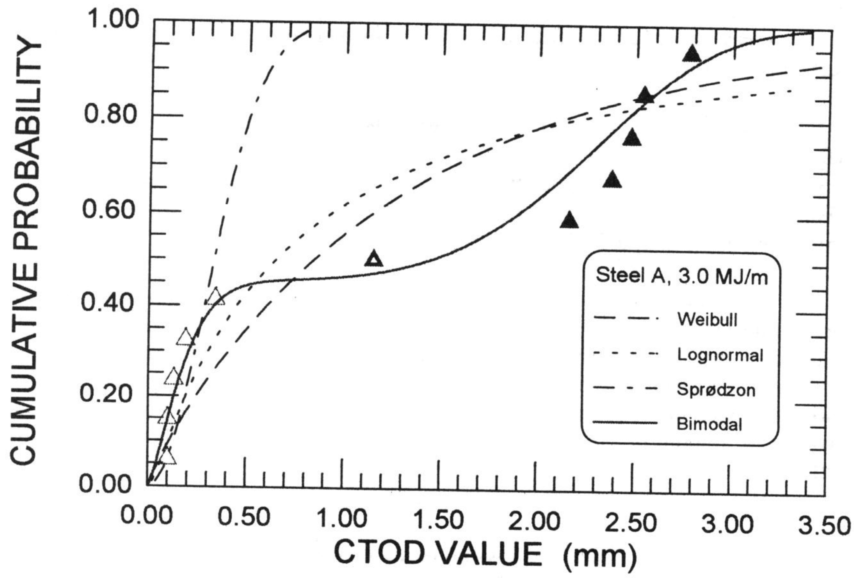

Figure 1 Cumulative distribution of CTOD results, Steel A 3.0 MJ/m heat input

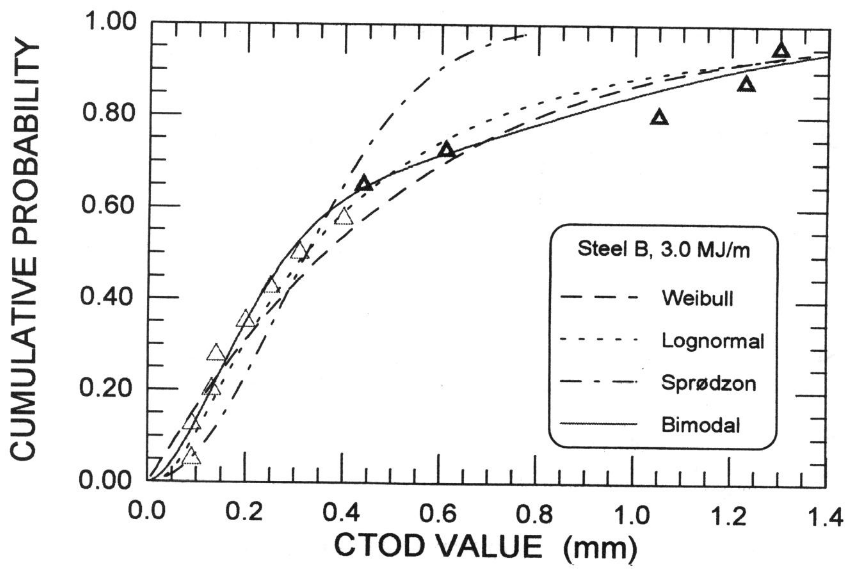

Figure 2 Cumulative distribution of CTOD results, Steel B 3.0 MJ/m heat input

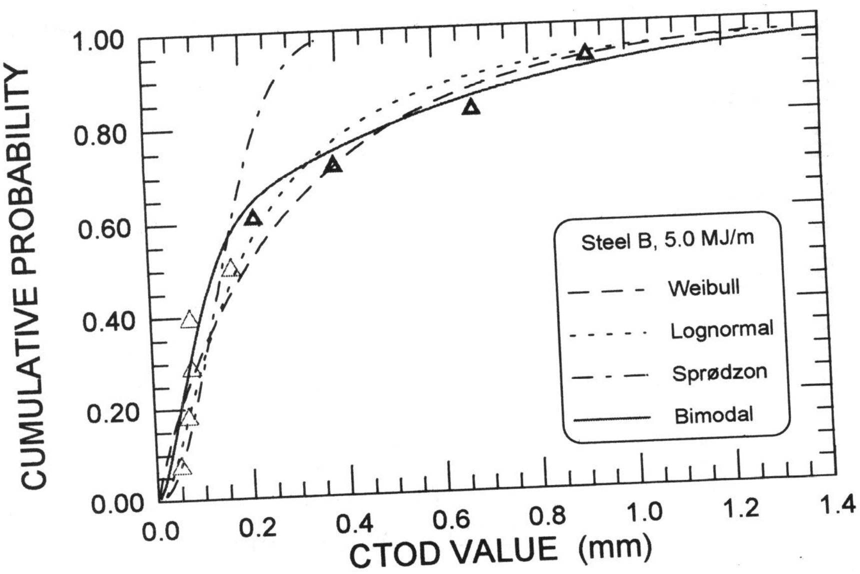

Figure 3 Cumulative distribution of CTOD results, Steel B 5.0 MJ/m heat input

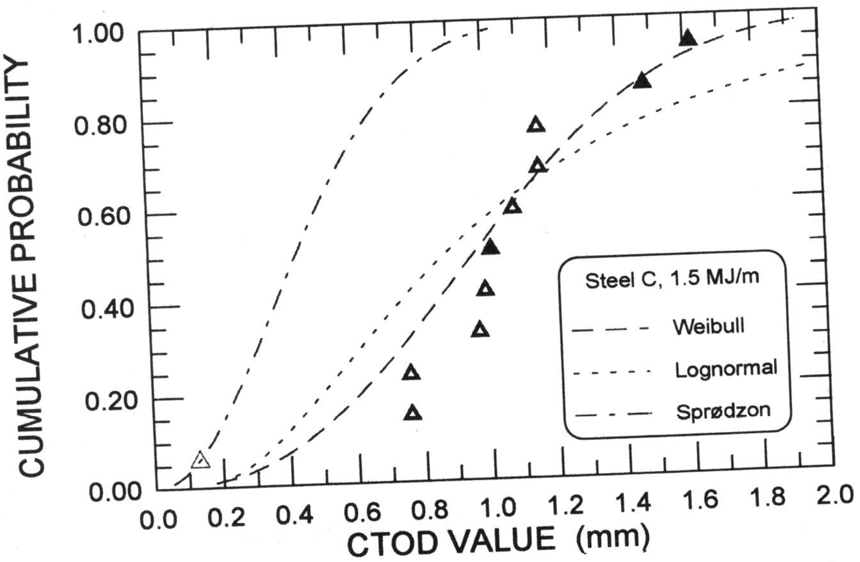

Figure 4 Cumulative distribution of CTOD results, Steel C 1.5 MJ/m heat input

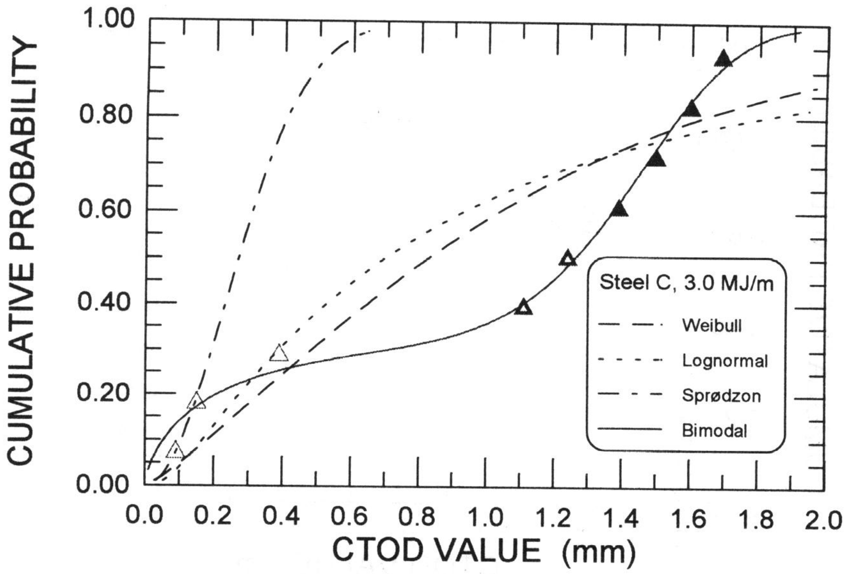

Figure 5 Cumulative distribution of CTOD results, Steel C 3.0 MJ/m heat input

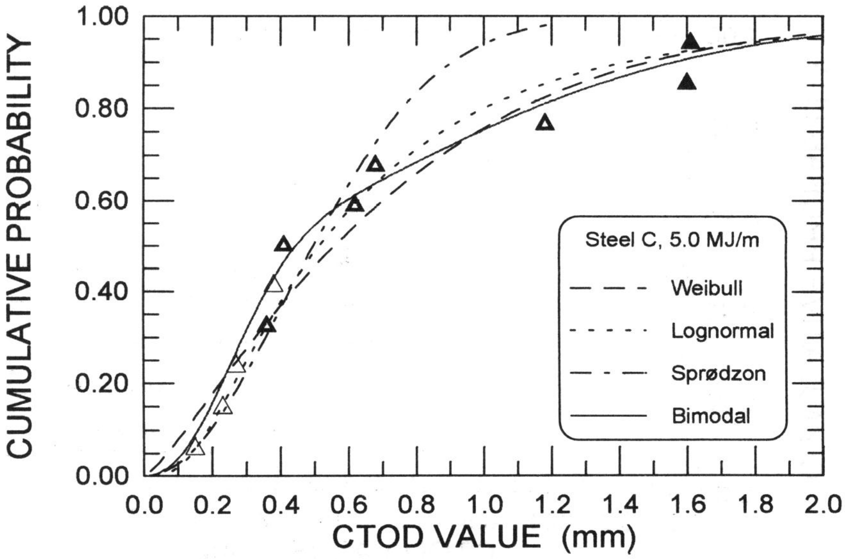

Figure 6 Cumulative distribution of CTOD results, Steel C 5.0 MJ/m heat input

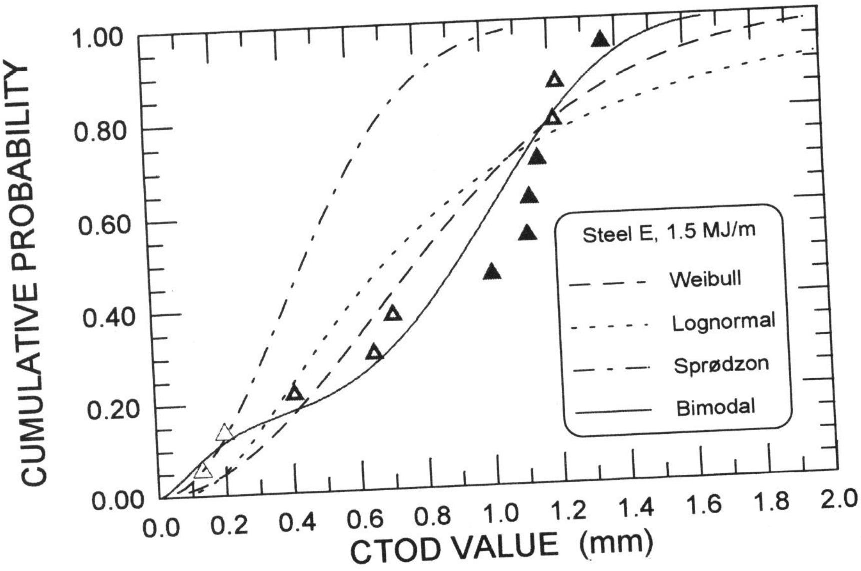

Figure 7 Cumulative distribution of CTOD results, Steel E 1.5 MJ/m heat input

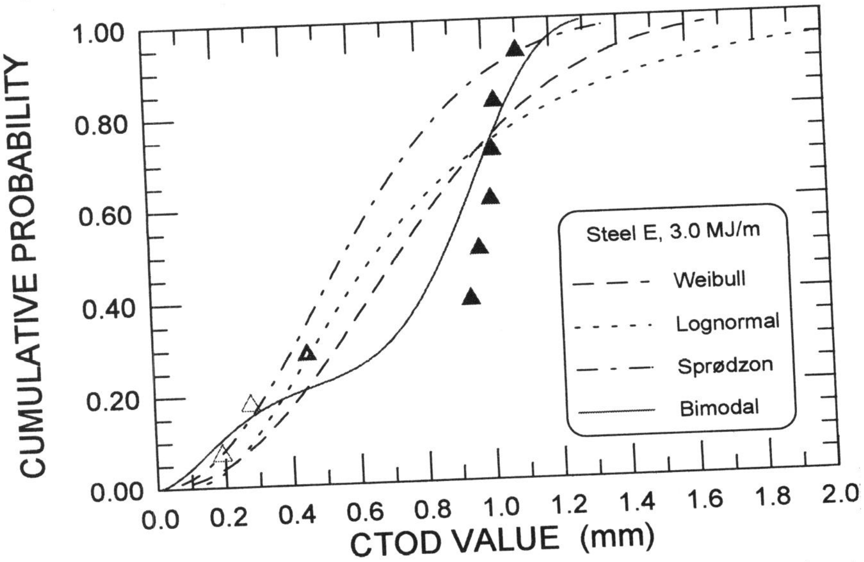

Figure 8 Cumulative distribution of CTOD results, Steel E 3.0 MJ/m heat input