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APPLICATION AND VERIFICATION OF THE SINTAP FRACTURE TOUGHNESS ESTIMATION PROCEDURE FOR WELDS AND PARENT MATERIALS

For: Sintap Task 3

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EXECUTIVE SUMMARY

Background

APPLICATION AND VERIFICATION OF THE SINTAP FRACTURE TOUGHNESS ESTIMATION PROCEDURE FOR WELDS AND PARENT MATERIALS

1. INTRODUCTION

The maximum likelihood (mml) procedure for the analysis of fracture toughness data measured in inhomogeneous materials, which has been developed for the SINTAP flaw assessment procedure, is described and validated. The mml procedure involves a series of steps to ensure that the fracture toughness distribution fitted to experimental data is conservative. The distribution is based on a three parameter Weibull distribution with a shape parameter of 4. Validation of the procedure is provided by experimental data from weld metal, HAZ and parent plate. The results of the mml procedure are compared with results from the assessments carried out to existing methods described in BSI PD6493:1991 and BS 7910. It is concluded that for small data sets, the mml procedure provides a greater level of consistency and minimises selection of potentially non-conservative fracture toughness values compared with the BS methods.

For reasons of cost and/or restrictions on the amount of material available, fracture toughness is often measured using a limited number of specimens. The determination of an appropriate statistical distribution from limited data can be arbitrary and unreliable. Consequently, the selection of a characteristic value from such a distribution for use in a flaw assessment procedure may be unconservative, or at least give inconsistent assessments. However, some of the inconsistency can be removed by assuming the fracture process is governed by a weak link process which follows a three parameter Weibull distribution. For ferritic steels this is given by:

$$P(K_c) = 1 - exp - \left[\frac{K_c - 20}{K_o - 20}\right]^4 \qquad [1]$$

where

$P(K_c)$ is the cumulative probability of fracture toughness, K_c (MPam$^{0.5}$)

K_o is the scale parameter (the 63rd percentile of the distribution)

20 is the shift parameter in the Weibull distribution (MPam$^{0.5}$)

4 is the value of the shape parameter in the Weibull distribution for small scale yielding.

Equation [1] may be re-written as follows to provide an estimate of K_c with a given probability level once K_o is known:

$$K_c = 20 + (K_o - 20)\{- ln\,(1 - P(K_c))\}^{0.25} \qquad [2]$$

Thus, the distribution fitting procedure involves finding the optimum value of the K_o for a particular set of data. However, data censoring may be necessary if some of the test results do not result in fracture or the value of fracture toughness exceeds the theoretical capacity of the specimen, i.e. the result is no longer controlled by small scale yielding. Unfortunately, the test results may be biased when specimens are extracted from inhomogeneous materials such as weld metals and heat affected zones (HAZs). Since every specimen in a series of tests is unlikely to sample local brittle zones (LBZs) that may be present, the fracture toughness distribution will be biased to the higher toughness regions that are present. Thus the fitted distribution could result in non-conservative assessments being made. To avoid this potential problem Wallin (1997, 1998) has proposed a maximum likelihood estimation procedure (mml procedure) in the SINTAP flaw assessment method. The procedure is intended to provide conservative, but realistic, estimates of fracture toughness for use in defect assessment of safety critical components. This paper outlines the SINTAP mml procedure and illustrates it using fracture toughness obtained from a weld metal, HAZ and parent plate. Furthermore, the results are compared with those obtained from procedures described in BSI PD6493:1991 (1991) and its proposed replacement BS 7910:1999 (1999). It is shown that the SINTAP mml procedure provides estimates of fracture that are conservative but still consistent with BS procedures. However, as the SINTAP procedure is based on a weak link model of fracture, it offers the possibility of establishing characteristic fracture toughness values for any thickness of interest from sub-sized specimens (i.e. specimen thickness less than original weld thickness).

2. SINTAP MML ESTIMATION PROCEDURE

The mml estimation procedure is used to obtain a lower bound K_o scale parameter which describes the Weibull fracture toughness distribution (see Eq.[1]) for inhomogeneous materials. It proceeds via a series of stages that are described below. In this paper, the procedure is used to evaluate fracture toughness obtained at a single test temperature. However, the procedure can be applied to transition curve data, and further comment about this is made at the end of this section.

The mml procedure proceeds via a series of stages. The first stage is to check that all the data meet the acceptance criteria of the relevant testing standard. The fracture toughness values are converted into stress intensity factors with $MPam^{0.5}$ units. Where CTOD data are available, these may be converted into equivalent K_c values using:

$$K_C = \left[\frac{1.5\sigma_{YS}\,CTOD\,E}{(1-\upsilon^2)} \right]^{0.5} \qquad [3]$$

where:

σ_{YS} = yield strength, MPa
CTOD = crack tip opening displacement, m
E = Young's modulus, MPa
ν = Poisson's ratio

Next, the specimen capacity limit (K_{climit}) is determined from:

$$K_{c\,limit} = (E\,b_o\sigma_{YS} / 30)^{0.5} \qquad [4]$$

where b_o (m) is the initial ligament below the notch (W-a_o) in the test specimen.

Equation [4] ensures that fracture occurs under small-scale yielding conditions. Results from specimens that exceed this limit are censored, the censoring parameter, δ, is set at 0 and the fracture toughness set at K_{climit}. Specimens that do not fracture are also censored (δ=0). Results from other specimens are not censored and δ is set at 1 for each specimen.

Next, the fracture toughness values are corrected to a reference thickness of 25mm using:

$$K_{c25} = 20 + (K_c - 20)(B/25)^{0.25} \qquad [5]$$

where B is the thickness of the specimen in which K_c was measured.

The values of K_{c25} and their associated censoring parameters are then used to make the first estimate K_o. This is STEP 1 in the mml procedure (referred to as ‘normal mml estimation’) and K_o is obtained from:

$$K_o = 20 + \left[\frac{\sum_{i=1}^{N} (K_{c25i} - 20)^4}{\sum_{i=1}^{N} \delta_i} \right] \qquad [6]$$

where:

N = number of results
i = i_{th} result

Note that the maximum likelihood procedure uses all the test results and that K_o is biased towards the uncensored data (δ=1).

If the material tested were homogeneous, the estimate of the K_o from Eq.[6] could be inserted into Eq.[2] to provide a value of K_c, for a specified probability level. For the value to be used in a defect assessment procedure, it is necessary to correct this fracture toughness for the appropriate thickness (see Eq.[5]). However, when the data are from inhomogeneous materials, further censoring is required.

STEP 2 in the mml procedure, (referred to as ‘lower tail mml estimation’) involves censoring all data above the 50th percentile of the distribution, i.e. setting $\delta = 0$ for all values above the 50th percentile. This ensures that the estimate of K_o is biased towards the lower tail of the toughness distribution so as to include results from specimens containing LBZs. Results from specimens which do not contain LBZs and that are likely to give high fracture toughness values tend to be excluded by STEP 2. The censored values are assigned the median value of toughness:

$$\overline{K}_{c25} = 20 + (K_o - 20)\,0.91 \qquad [7]$$

After censoring, K_o is re-estimated using Eq.[6]. However, since both Eq.[6] and [7] contain K_o, the procedure is iterative with K_o and $\overline{K}_{c25}$ being continually adjusted until a consistent minimum K_o is obtained.

The final step, STEP 3 (referred to as ‘minimum value estimation’), requires an estimate of the K_o using the minimum fracture toughness value in the data set. This is obtained from:

$$K_o = 20 + (K_{c25\,min} - 20)\left(\frac{N}{\ln 2}\right)^{0.25} \qquad [8]$$

The values of K_o from each of the three steps are now compared. The K_o which describes fracture toughness distribution is the lowest determined from the three steps, except when K_o from STEP 3 is not less than 90% of the lower of K_o from STEPS 1 or 2. In this case, K_o is the lowest of STEPS 1 or 2. Where K_o from STEP 3 is less than 90% of the lower of STEP 1 and 2, it would be conservative to use K_o from STEP 3. However, since the procedure is highlighting an outlier, a judgement has to be made as to its significance. If the data set is large and the fit to the assumed distribution is good, then the result from STEP 3 can be treated as representing an anomaly and can be ignored. It is then reasonable to assume that the lower of STEPS 1 or 2 are describing the fracture toughness distribution. The SINTAP procedure recognises this, and recommends that for more than 9 results, STEP 3 is unnecessary. However, if the data set is small, it would be unreasonable and unconservative to ignore STEP 3. If the result from STEP 3 is considered to be unsatisfactory then further testing should be conducted to better define the lower tail of the fracture toughness distribution.

The procedure described above can, in principle, be applied to data in the fracture toughness transition regime. In this case the temperature dependence of fracture toughness for ferritic steels is described by the Master Curve (Wallin, 1994) which is given by:

$$K_o = 31 + 77\,exp\left[0.019\left(T - T_o\right)\right] \qquad [9]$$

where T_o is the transition temperature for a median fracture toughness (50th percentile) of $100MPam^{0.5}$ normalised to a 25mm thick specimen. The steps in the procedure are similar to those described above but involve estimating T_o. Having established T_o, the fracture toughness at a given temperature, specimen thickness and probability level can be obtained from:

$$K_{mat} = 20\left(11 + 77\,exp\left[0.019\left(T - T_o\right)\right]\right)\left(\frac{25}{B}\right)^{0.25}\left(-ln\left(1 - P_f\right)\right)^{0.25} \qquad [10]$$

However, in the examples given in the next section, the procedure is illustrated for tests conducted at a single test temperature.

3. APPLICATION OF THE MML PROCEDURE TO EXPERIMENTAL DATA

In order to illustrate the mml procedure, three examples are given for experimental fracture toughness data obtained in a weld metal, weld HAZ and parent plate. Each data set is described and then results of the mml procedure are presented.

3.1. WELD METAL

The weld metal data set was derived from a European round-robin weld metal fracture toughness testing programme (Hadley, 1995). Tests were conducted on multipass submerged arc butt welds made from one side at a heat input of 4.5kJ/mm and in a 50mm thick normalised C-Mn steel plate with a nominal yield strength of 340MPa. Various specimen geometries were tested at different temperatures. The data set selected here represent results obtained on full-thickness, rectangular section, deeply notched bend specimens (SE(B), Bx2B, $a_O/W=0.5$, where B=50mm). The specimens were through-thickness notched along the weld centre line and the tests conducted in accordance with BS 7448:Part 1:1991. As the specimens were in the ‘as-welded’ condition, local compression was carried out to relieve residual stresses and promote growth of straight fatigue cracks. Only those specimens that met the fatigue crack front straightness and minimum fatigue crack length requirements of BS 7448:Part 1:1991 are included in the data set. (It may be noted that local compression procedures are described in BS 7448:Part 2:1997. Also, the fatigue crack front straightness requirements are more relaxed in this standard compared with BS 7448:Part 1:1991). Other details of the test data are listed below:

Number of results, N = 27; number of specimens failing by cleavage: 21

B = 50mm
b_o = 50mm
Test temperature: -20°C
Weld metal yield strength = 529MPa at –20°C.

3.2. HAZ

The HAZ data set was derived from the European ACCRIS project which examined the effect of yield strength mismatch on toughness (Fattorini, 1997). Fracture toughness tests were conducted on X butt welds in a 48mm thick TMCP steel with a yield strength of 457MPa. The welds were made by submerged arc welding at a heat input of 3kJ/mm. In the ACCRIS programme, this data set is referred to as an ‘even match’ condition, although the weld metal yield strength overmatched that of the parent plate by about 24%. Full thickness, square section specimens (SE(B), BxB, $a_o/W=0.3$) were employed which were notched from the original plate surface into HAZ close to the weld fusion boundary. Post-test metallography was conducted to establish the actual microstructures at the fatigue crack tip and at fracture initiation. The data set selected here results from those specimens in which the fatigue crack tip was located in, or fracture initiated from, the grain coarsened HAZ. In this material, this is the lowest toughness region of the HAZ. (Results from specimens with the fatigue crack tip in weld metal were included, provided that fracture initiation took place in the grain coarsened HAZ no further than 0.5mm from the crack tip). The tests were conducted in accordance with BS 7448:Part 1:1991 and CTOD values obtained. For the purpose of the present study, these have been converted into equivalent K_c values – using Eq.[3] and assuming parent plate yield strength. Other details about the data set are given below:

N = 39; all of which failed by cleavage
B = 48mm
b_o = 33.6mm
Test temperature = -10°C
Wide metal yield strength = 569MPa
Parent plate yield strength = 457MPa

3.3. PARENT PLATE

The parent plate data set represents results from a European round-robin fracture toughness programme carried out on a normalised C-Mn steel (Towers, 1984). The particular data set selected represents the so-called ‘control’ tests (replicate tests conducted under carefully controlled conditions). The tests were conducted on full-thickness, deeply notched bend specimens (SE(B) Bx2B, $a_o/W=0.5$). The specimens were notched in the through-thickness (LT) direction. Further details are given below:

N = 108; specimens that fractured 106
B = 50mm
b_o = 50mm
Test temperature = -65°C
Yield strength at –65°C = 409MPa

4. RESULTS

The results from the mml procedure are summarised in Table 1. The fracture toughness distributions predicted from each of the three steps are compared with the experimental data points (all for a reference thickness of 25mm) in Fig.1 to 3. Each step involves a rotation of the fitted curve in an anti-clockwise direction when K_o predicted from STEP 1>STEP 2> STEP 3; as illustrated by the results from the parent plate, see Fig.3. It will be noted that this sequence does not occur in every case and for the submerged arc weld and HAZ, STEP 2 provides the lowest K_o. Furthermore, STEP 1, the normal mml procedure, does not always provide a good description of the data set as a whole. This indicates that the Weibull distribution shape parameter of 4 is not optimum. Nevertheless, STEP 2 or STEP 3 does appear to provide a conservative description of the lower tail to the fracture toughness distribution. The appropriate values of toughness at a given probability level can be obtained from K_o using Eq.[2]. In the next section values of fracture toughness estimated from Eq.[2] are compared with those predicted from the procedures described in BSI PD6493:1991 and BS 7910 (draft).

5. COMPARISON OF MML PROCEDURE WITH BS PROCEDURES

The procedures for estimating a characteristic fracture toughness for use in flaw assessment is given in Appendix A of BSI PD6493:1991 and Annex L of BS 7910 (draft). Both are similar and two methods are given. The first method is intended for small data sets, typically involving less than 15 specimens, and is based on the minimum of three equivalent (MOTE) concept. The MOTE procedure requires that when there are between 3 and 5 results, the minimum value is used; between 6 and 10 results, the second lowest; and between 11 and 15 results, the third lowest. These characteristic values represent the 20th percentile of the distribution with 50% confidence (approximately). In order to guard against excessive scatter, the BS procedures require the minimum to be not less than 70% of the average toughness (in terms of K) or the maximum to be no more than 1.4 times the average. If scatter is excessive, further testing is recommended. However, in many cases this is not practical and the user must base his analyses on the data available. The second procedure is recommended when there are more than 15 results. Both the BS procedures recommend that a statistical distribution (e.g. log-normal or Weibull) is fitted to the data and the mean minus one standard deviation used in a flaw assessment.

In this section, predictions made from the mml and BS procedure are compared. In order to provide a consistent comparison criterion with the MOTE procedure, the K_{mat} obtained from the mml procedure was the 20th percentile of the Weibull distribution described by appropriate K_o. The procedure was as follows. For each set of test data, sub-sets of 3, 6, 9 and 12 results were selected at random, and MOTE and mml procedures applied to each sub-set. This process was repeated 100 times for each sub-set. With the mml procedure, a small sample correction was applied to K_o before calculating the 20th percentile, designated K_{mat}.

$$K_{ocor} = 20 + \frac{K_o - 20}{1 + \left(\frac{0.25}{r^{0.5}} \right)} \qquad [11]$$

where r = the number of specimens that fractured.

The MOTE results (K_{mat} values) were corrected for a common thickness of 25mm using Eq.[5], in order to facilitate comparison with the mml results (also for 25mm).

The results from these calculations are presented in Fig.4 to 6. Also included are the 20th percentile K_{mat} predictions made from the complete data set. For the BS procedure, various statistical distributions were fitted to the censored experimental data using a maximum likelihood method. Results from specimens that did not fracture were censored. However, censoring does not mean the result was ignored. In all cases the $\log_e$-normal distribution was found to provide the best fit, and the fitted parameters together with the 20th percentile and mean minus one standard deviation values are given in Table 2.

Figures 4-6 clearly show that the mml procedure reduces the risk of overestimating fracture toughness compared with the MOTE procedure, especially for small data sets, e.g. 9 or less. When the data set comprise only 3 results, both procedures show that a very wide range of fracture toughness estimates is possible. Actual toughness can be significantly overestimated or underestimated, although large overestimates are less likely with the mml procedure. As expected, when the number of results in a data set increases, scatter decreases. The mean values of fracture toughness tend to be lower with the mml procedure compared with the MOTE procedure, but the lower bound values are similar for both procedures.

When the results from the whole data set are compared (for the present purposes, this represents the whole population), the 20th percentile predictions from both procedures are similar, despite the fact that the mml procedure is based on a 3 parameter Weibull distribution with a shape parameter of 4, and the BS procedure is based on a ‘best-fit’ $\log_e$-normal distribution.

An apparent exception is indicated by the result from the parent plate where the 20th percentile K_{mat} from the mml procedure is 25% lower than the K_{mat} from the BS procedure. In this case, the mml prediction is based on STEP 3, and the lowest result from 108 tests; this result is likely to be an outlier. Figure 3 shows that a better fit to the experimental is obtained from STEP 2. STEP 2 provides a 20th percentile K_{mat} of 194MPam$^{0.5}$, which is close to but 11% higher than the BS procedure. This is consistent with the SINTAP procedure which recommends halting the analysis at STEP 2 when more than 9 results are available.

Nevertheless, Fig.4-6 show the particular strength of the mml procedure when dealing with small data sets, in that, in comparison with the MOTE procedure, it minimises the likelihood of overestimating fracture toughness. Furthermore, the results do illustrate the potential problems of relying on the results from data sets as small as three. For safety critical components reliance on three test results is unacceptable, unless high safety factors are included in other input parameters to the flaw assessment.

6. CONCLUSIONS

APPLICATION AND VERIFICATION OF THE SINTAP FRACTURE TOUGHNESS ESTIMATION PROCEDURE FOR WELDS AND PARENT MATERIALS

The SINTAP mml procedure for inhomogeneous materials tested at a single temperature has been described and the results assessed using experimental data from weld metal, HAZ and parent plate. The results have been compared against existing data and assessed using the procedure described in BSI PD6493:1991 and the draft BS 7910. The following conclusions are drawn:

1. For small data sets (less than about 12 results), the mml procedure provides more consistent estimates of K_{mat} compared with the MOTE procedure described in the BSI documents. In particular, in comparison with the MOTE procedure, the mml procedure minimises the risk of overestimating the 'true' fracture toughness of the material.
2. For large data sets (>15), the procedures given in the BSI documents, which are based on characteristic value taken from a fitted statistical distribution, give similar results to the mml procedure, although the latter generally result in lower estimates of K_{mat}.
3. As the mml procedure is biased towards the lower tail of the fracture toughness distribution, care is required in discriminating between K_{mat} estimates made from the lowest value in the data set (STEP 3 mml) and the lower tail (STEP 2 mml), since underestimates of fracture toughness are possible. However, such 'errors' are likely to be on the conservative side.

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Table 1 K_o estimates (reference 25mm thick) from mml procedure

Data set	K_o, MPam$^{0.5}$			Step with lowest K_o
	STEP 1	STEP 2	STEP 3	
Weld metal	449.5	374.3	389.3	STEP 2
HAZ	286.6	246.7	294.8	STEP 2
Parent plate	336.5	272.5	181.2	STEP 3

Table 2 Log$_e$-normal distribution parameters for experimental data

Data set	N	Mean*	Std. dev.*	20th % K_{mat}**	Mean – 1 std. dev K_{mat}**	K_{mat} 20th % mml**
Weld metal	27	5.8472	0.5048	266	245	264
HAZ	39	0.3276	0.3173	184	173	176
Parent plate	108	5.4284	0.4738	177	165	131^{+}

* for actual test thickness, ** values (units MPam$^{0.5}$) corrected to 25mm thickness,
$^{+}$ K_{mat}=194MPam$^{0.5}$ for STEP 2

$^{+}$

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