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Application of the Local Approach to Cleavage Fracture to Failure Predictions of Heat Affected Zones

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Abstract. With the increased capabilities of elastic-plastic finite element analyses and hence the possibilities to determine accurately the stress distribution ahead of sharp cracks the use of fracture risk predictions based on a local fracture parameter has recently attracted much interest. To date most investigations in this area concentrated on homogeneous materials avoiding the complications related to the complex situation of welded joints.

In this paper results are presented where the Local Approach to cleavage fracture has been applied to the heat affected zone of two structural steel welds. Local cleavage fracture parameters were determined from tests and finite element modelling of notched tensile specimens. In all cases the properties of the weld metal, the parent material and the heat affected zone (HAZ) were determined. A thermal simulation technique was used to produce large enough areas of HAZ microstructures for tensile and notched tensile testing. Subsequent application of the Local Approach to the crack tip situation for the prediction of the dependence of fracture toughness on temperature and the scatter in fracture toughness only produced satisfactory results for a limited number of the situations modelled. Discrepancies between predictions and actual results are thought to be due partly to the differences in FE mesh and stress distribution between notched tensile and pre-cracked bend specimens.

1. INTRODUCTION

Welded structures such as pressure vessels or offshore platforms require safety analyses and structural integrity assessments in order to provide evidence of satisfactorily low risk of failure due to brittle fracture in the presence of defects resulting either from the initial fabrication, corrosion or fatigue loading. Fracture mechanics approaches are commonly used for such assessments but their predictive capability is limited since fracture toughness data determined on highly constraint deep pre-cracked specimens are always intended to be conservative compared to the structural component, in which the stress state is, in general, less severe [1]. In addition, due to the scatter inherent to the fracture toughness of steels, weld metals and their heat affected zones (HAZs), a statistical treatment of the data is required for reliability analysis as well as for lower bound estimations [2]. The Local Approach to cleavage fracture, as introduced by Beremin [3], accounts for both of these effects by correlating fracture probabilities with stress distributions ahead of the crack tip. Since it is based on a local stress criterion, directly reflecting microstructural features of the material assessed, it can also be used to investigate the influence of microstructural changes on the fracture resistance of steels [4,5]. Hence it could be used to derive microstructural requirements for improved toughness at the steel development stage or to provide guidelines for welding procedures in order to guarantee minimum toughness levels [2].

The aim of the present work was to investigate the applicability of the Local Approach to cleavage fracture for fracture toughness predictions of two structural steels and their welded joints. This involved the use of thermal simulation to determine the strength, deformation and fracture properties of the HAZ broadly based on the methodology first employed by Sainte Catherine et al [2]. The individual steps involved in the determination of the Local Approach parameters, i.e. the cleavage fracture stress $\sigma_c$ and
the Weibull exponent \( m \), and the subsequent application to the crack tip situation have been reported elsewhere \([6,7]\) and are therefore not repeated here. Some specific details and assumptions made in relation to the present work are mentioned in the appropriate sections throughout the paper.

2. MATERIALS, TESTING PROCEDURES AND FINITE ELEMENT ANALYSIS

2.1 Base Materials and Welded Joints

The parent materials investigated were two 50 mm thick offshore plates produced to BS 7191:1989 \([8]\) requirements. The first steel, called Steel A throughout this paper, was a Grade 355EMZ steel produced via the thermomechanically controlled rolled (TMCR) route resulting in a ferrite-pearlite microstructure, Figure 1a. The second, Steel B, was a Grade 450EMZ steel produced via the quenching and tempering route resulting in a tempered bainite microstructure, Figure 1b. The simulated grain coarsened heat affected zone (GCHAZ) of Steel A is shown for comparison in Figure 1c. The respective chemical compositions are listed in Table 1.

![Figure 1 Parent material and simulated GCHAZ microstructures](image)

**Table 1: Chemical composition**

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>S</th>
<th>P</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Cu</th>
<th>Nb</th>
<th>Ti</th>
<th>Al</th>
<th>CEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.06</td>
<td>&lt;0.002</td>
<td>0.008</td>
<td>0.36</td>
<td>1.45</td>
<td>0.48</td>
<td>0.03</td>
<td>0.008</td>
<td>&lt;0.005</td>
<td>0.03</td>
<td>0.23</td>
<td>0.01</td>
<td>0.037</td>
<td>0.34</td>
</tr>
<tr>
<td>B</td>
<td>0.10</td>
<td>0.002</td>
<td>0.011</td>
<td>0.28</td>
<td>1.20</td>
<td>0.47</td>
<td>0.02</td>
<td>0.14</td>
<td>0.05</td>
<td>0.01</td>
<td>&lt;0.002</td>
<td>&lt;0.002</td>
<td>0.032</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Multipass submerged arc welds were produced on both plates using a procedure with controlled weld bead placement and \( \frac{1}{2} K \) preparation to produce a high proportion of grain coarsened HAZ (GCHAZ) and to facilitate the placement of the crack tip in fracture mechanics specimens. Steel A was welded with two heat inputs, 3.5 kJ/mm and 4.5 kJ/mm, denoted weld A1 and A2 respectively, and Steel B was welded with the lower heat input of 3.5 kJ/mm only (weld B1). The weld metals were strength over-matched by approximately 20%. This matrix of welds allowed the investigation of the influence of heat input and of chemical composition on HAZ properties.

GCHAZ microstructures were simulated using a Gleeble 1500 simulator applying thermal cycles with a peak temperature of 1350°C, a hold time at peak temperature of 0.35 s and a cooling time of 24 s.
and 32 s for heat inputs of 3.5 kJ/mm and 4.5 kJ/mm respectively. HAZ microstructures other than the 
grain coarsened zone were not considered in this work.

2.2 Fracture Toughness Tests

Fracture toughness tests were carried out using full scale 50 x 50 mm SENB (Single Edge Notch Bend) 
specimens loaded in three point bending and tested at temperatures between -196°C and 0°C in order to 
produce lower shelf fracture toughness values. All specimens were taken transverse to the rolling and 
welding direction and in HAZ specimens the notch was entered from the surface of the plate. All testing 
was in accordance with BS 7448:Part 1[9] with the exception of the crack depth ratio a/W in some HAZ 
surface notched specimens which had to be reduced to approximately a/W = 0.3 in order to sample only 
GCHAZ. Post test sectioning confirmed that fracture in the HAZ notched specimens initiated in all cases 
from GCHAZ microstructures. Two additional sets of small scale 10 x 10 mm SENB specimens on the 
real weld and simulated GCHAZ A1 were carried out in order to investigate the potential of the Local 
Approach to account for volume and constraint effects. All fracture toughness results have been used for 
comparison with Local Approach toughness predictions and are therefore presented in combination with 
these at a later stage.

2.3 Tensile Testing

Tensile tests were performed for both parent materials, all three weld metal conditions and on the three 
thermally simulated GCHAZ microstructures over a temperature range from +20°C to -196°C. Yield 
strength versus temperature results are shown in Figure 2a for the three constituents of the weld condition 
A1 as example.

![Figure 2a](Image)

**Figure 2a**: Yield strength versus temperature for weld condition A1

![Figure 2b](Image)

**Figure 2b**: True stress-true strain curves for Steel A

True stress-true strain properties were determined from all tensile tests for input in the elastic plastic 
finite element calculations. An example for these curves is shown in Figure 2b for Steel A where the 
curves at temperatures other than the actual test temperatures were obtained by inter- and extrapolation of 
existing curves on the basis of the yield strength versus temperature curves as shown in Figure 2a.

2.4 Notched Tensile Testing

Notched tensile tests were done on specimens with three different notch geometries. The outer and inner 
specimen diameter were kept as 11 and 6 mm but three different notch radii (1.25, 2.5 and 6.4 mm) were 
used in order to produce different levels of constraint. With the exception of Steel A, where only 
specimens with a notch radius of 2.5 mm (NT2.5) were used, ten specimens of each notch geometry were
tested. The test temperatures were chosen such that the true strain at failure was between 3 and 30% although it could not be avoided that some results fell outside this range. From these tests the true strain at failure was determined by measurements of the final diameter of the specimen in the plane of the fracture surface. GCHAZ tests for weld A1 and B1 were carried out on thermally simulated microstructures as for the tensile tests, whereas the tests on the GCHAZ A2 were carried out on the actual HAZ of the weld. Great care was taken in marking the specimens prior to notching in order to ensure that the fusion line coincided with the notch root and post test sectioning confirmed that all specimens fractured in the GCHAZ along the fusion line.

2.5 Finite Element Modelling and Determination of Local Approach Parameters

Large strain, elastic-plastic finite element stress analyses were undertaken of the notched tensile and SENB specimens. ABAQUS versions 5.4 and 5.5 were used for all calculations. The analyses were carried out using the elastic and strain hardening properties of the relevant material for each of the various test temperatures.

The notched tensile specimens were modelled by axisymmetric meshes using ABAQUS element type CAX8R, a second order element employing reduced integration. The SENB specimens were modelled by two-dimensional meshes using element type CPE8R, a second order plane strain element using reduced integration. Either the full SENB specimen or one half was modelled, according to whether the specimen consisted of an actual weld or homogenous material. The models of SENB specimens of real welds contained a layer of GCHAZ material of width 0.2 mm.

A program was developed to post-process the results of the finite element analyses. The value of the Weibull stress was determined at each of the (approximately 50) load increments taken to conduct a typical analysis. The Weibull stress was determined as follows:

$$\sigma_w = \sqrt[1/\sigma_{\text{max}}]{\frac{1}{V_o} \sum \sigma_{\text{max}}^{m} V_j}$$

In Equation 1 the summation is carried out over all the finite element integration stations within the plastic zone, $V_j$ is the volume associated with the integration station, $\sigma_{\text{max}}$ is the maximum principal stress acting at the station and $m$ is the Weibull exponent. $V_o$ is a reference volume taken to be $(100 \, \mu m)^3$.

The Local Approach parameters of the various materials were determined using the notched tensile test results, and also some of the SENB results. The Weibull stress at the point of failure of each specimen was determined by linking an experimental parameter to the same one monitored in the appropriate finite element analysis. The reduction of diameter was used for the notched tensile specimens, and the CTOD measured according to BS 7448 for the SENB specimens.

For each set of notched tensile test results on a particular material combination, the Weibull parameters were determined using the maximum likelihood method together with an iterative procedure which uses the statistical sample of Weibull stresses at failure to find the theoretical Weibull stress distribution that best matches the probability distribution of the experimental results. The mean value of these distributions gives the cleavage fracture stress, $\sigma_c$, and the gradient of the regression line the Weibull exponent, $m$, which characterises the scatter in the fracture stress results. $\sigma_c$ and $m$ are the so-called Local Approach parameters which for the purpose of the later presented fracture toughness predictions were assumed to be temperature independent.

This procedure was also applied to the test results for some of the SENB specimens as an alternative method of calculating the Weibull parameters for the GCHAZ of weld A1.
2.6 Estimation of Failure Probabilities for SENB Specimens

The theoretical CTOD transition curves were determined for each SENB specimen using the Local Approach parameters determined from the notched tensile tests together with the results of Weibull stress versus CTOD and:

\[ P_f = 1 - \exp \left[ - \left( \frac{\sigma_w}{\sigma_c} \right)^m \right] \]  

(2)

where \( \sigma_w \) is calculated over the whole of the plastic zone in homogenous specimens and over the GCHAZ in welded specimens. The values of CTOD required to cause cleavage failure at the 10, 50 and 90% levels of probability were subsequently calculated by interpolation.

3. RESULTS

3.1 Fracture Parameter Determination from Notched Tensile and Fracture Mechanics Specimens

The Weibull stress distributions determined from notched tensile tests for the different weld regions investigated are shown in Figure 3.

![Figure 3: Weibull stress distributions for the determination of the Local Approach parameters](image)

The values of the cleavage fracture stress, \( \sigma_u \), and the Weibull exponent, \( m \), are listed in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Steel A</th>
<th>GCHAZ A1</th>
<th>WM A1</th>
<th>GCHAZ A2</th>
<th>WM A2</th>
<th>Steel B</th>
<th>GCHAZ B1</th>
<th>WM B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_u ), MPa</td>
<td>2579</td>
<td>2894</td>
<td>3657</td>
<td>3532</td>
<td>2760</td>
<td>4143</td>
<td>3694</td>
<td>3902</td>
</tr>
<tr>
<td>( m )</td>
<td>17</td>
<td>14</td>
<td>14</td>
<td>10</td>
<td>17</td>
<td>12</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

As mentioned before, another, additional approach as previously used by Minami et al [10] has been applied for the determination of the Local Approach parameters of the GCHAZ of Weld A1 from SENB
specimens. The determination of the local fracture parameters by this new analysis are shown in Figure 4
where the test results of the thermally simulated 10 x 10 mm SENB specimens were used.

![Figure 4: Local approach parameters determined from pre-cracked SENB specimens of thermally simulated GCHAZ A1](image1)

The new value of $\sigma_s$ for the GCHAZ A1 is 2509 MPa compared to 2894 in the previous
determination (Table 2) and the value of m has decreased from 14 to 13. It must, however, be pointed out
that the results of the new distribution are subject to uncertainties due to the very limited number of
results available. It has been shown that the value of the Weibull exponent, m, strongly depends on the
number of tests available and only converges to a constant value when the number of tests is 20 or more
[13].

### 3.2 Fracture Toughness Predictions

The increase of lower shelf fracture toughness with temperature has been predicted for Steel A and the
HAZ of Welds A1, A2 and B1 where for Weld A1 both the local approach fracture parameters determined
on notched tensile and on pre-cracked SENB specimens were used.

The predictions obtained using the $\sigma_s$ and m values from notched tensile specimens are compared
with the actual test results in Figure 5 for 50 x 50 mm SENB specimens.

![CTOD (mm) vs Temperature (°C) for a) Steel A and b) GCHAZ A1](image2)
Figure 5: Fracture toughness predictions for 50 x 50 mm SENB specimens using local approach fracture parameters determined on notched tensile specimens.

Figure 5 shows that the predicted increase in toughness with temperature in the transition region is in broad agreement with the experimental results. However, the lower bound predictions for $P_f = 0.1$ seem to be too conservative in comparison with the actual test results. Also the predicted scatter band is very wide for some of the weld conditions. Furthermore, the steep increase in fracture toughness is not normally predicted by the Local Approach to cleavage fracture.

A comparison of actual results with predictions for small scale 10 x 10 mm specimens is provided in Figure 6.

In comparison with the results for the full scale 50 x 50 mm SENB specimens, Figure 5b, the transition is predicted, as expected, to occur at lower temperatures for the smaller specimens due to reduction in constraint and smaller material volumes sampled by the plastic zone. Comparison of Figure 6a and b highlights how slightly different stress states, due to the different assumed stress-strain properties in the two models and, probably more significantly, how the larger volume of GCHAZ sampled by the plastic zone in the simulated specimens shifts the predictions towards lower toughness. The discrepancy between predictions and actual results, as also observed in Figure 5, points towards a limited transferability of the Local Approach parameters obtained on the notched tensile specimens to the crack tip situations.

Fracture toughness predictions for the GCHAZ A1 obtained using the Local Approach parameters determined on the simulated pre-cracked SENB specimens are presented in Figure 7.
As would be expected, good agreement between test results and predictions is obtained for the simulated GCHAZ situation, Figure 7a, since the pure cleavage fracture test results of this series were used to determine the values of $\sigma_u$ and $m$. The lower bound toughness of the real weld GCHAZ A1 is overestimated for the small scale specimens, Figure 7b, and underestimated for the full scale specimens, Figure 7c, using the new values of $\sigma_u$ and $m$.

4. DISCUSSION

Given the level of complexity required to predict HAZ toughness in multipass joints, the Local Approach predictions gave in general a fair level of agreement with the actual test results. The remaining differences suggest that the values of $\sigma_u$ and $m$ did not reflect appropriately the materials' cleavage resistance and inherent scatter. The potential of the methodology to account for volume and constraint effects in fracture toughness has been shown by the comparison of predictions for small scale and full scale fracture toughness specimens. However, further work is required regarding the transferability of the Local Approach parameters between different specimen configurations. One general problem is the transfer of Local Approach parameters determined on notched tensile specimens to the crack tip situation. This may be related to the use of very different meshes in the models of the two different types of specimens (Moinereau and Gilles [12] have shown that the Weibull stress can be dependent on the mesh size at the crack tip of fracture toughness specimen models), but the main reason for the problems encountered in the applicability of $\sigma_u$ and $m$ determined on notched tensile specimens to the crack tip situation is thought to be related to microstructural features as discussed in the following section.
5. MICROSTRUCTURAL OBSERVATIONS

A number of the broken notched tensile specimens were examined by optical microscopy and scanning microscopy, resulting in the following main observations: (i) None of the specimens appeared to have fractured from a surface irregularity, even at strains below 3%, which justified the decision not to exclude strain results below 3% from the Weibull stress distributions. (ii) The majority of the specimens examined contained long subsidiary cracks in the centre of the specimen formed by linkage of individual microcracks of the size of the grain or packet diameter. Examples for such secondary linked-up cracks are shown in Figure 8.

(iii) Furthermore, in two of the notched tensile specimens with simulated GCHAZ microstructures, inclusions or particles were found in the centre of the initiation site despite a high concentration of secondary microcracks on the fracture surfaces. (iv) One specimen contained small areas of intergranular fracture in the vicinity of the initiation point; and (v) some ductility was observed on weld metal specimens which failed at strains less than 30%.

A number of parent material SENB specimen fracture surfaces were also examined on the SEM but no particular features were found in the initiation area and secondary cracks were generally limited to individual cracks of the size of a grain or packet diameter.

These observations highlight aspects which were not considered in the determination of the Local Approach parameters and the subsequent fracture toughness predictions. All notched tensile test results were included in the Weibull distribution without any selection but the microstructural observation shows that this can result in a combination of results which are micro-mechanistically not identical. This implies that fractographic examination of every single specimen would be required before the establishment of a Weibull stress distribution. Imposing limits such as 3% strain may exclude appropriate results from the distribution; on the other hand, an upper limit such as 30% does not automatically exclude the presence of ductility on the fracture surface.

Of concern is the fact that many of the notched tensile specimens were found to contain long connected secondary cracks, implying that most of the failures initiated from such a crack. On the actual fracture toughness specimens secondary cracks were also present but they were not found to have linked up to form longer cracks. This means that in the steep stress gradient ahead of a sharp crack, the fracture event occurred from smaller, grain sized cracks, before the linkage to larger cracks could take place. These differences in failure mechanism may have caused the problems of using $\sigma_s$ and m values determined on notched tensile specimens for the prediction of fracture toughness in sharply cracked specimens.
6. CONCLUDING REMARKS

Local Approach parameters $\sigma_c$ and $m$ have been determined for two structural steels, their GCHAZs and weld metals using notched tensile specimens. Subsequent predictions of the change in lower shelf fracture toughness with temperature for heat affected zones resulted in a fair level of agreement between predictions and actual test results given the complexity of the joints under consideration. Discrepancies between the test results and predictions were caused by (i) the inclusion of all notched tensile test results in the Weibull stress distributions, without fractographic based selection of test results and (ii) possible differences in the fracture mechanisms in notched tensile and pre-cracked fracture toughness specimens.

While the potential of the Local Approach in quantifying size and constraint effects has been shown to be also applicable to HAZ microstructures, this work has made clear that future investigations will have to concentrate in more detail on microstructural aspects and the possibility of using pre-cracked specimens for the determination of the Local Approach parameters.

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