CONSTRAT BASED FRACTURE ASSESSMENT OF EMBEDDED-FLAW BEAMS IN THE NESC-IV TESTS*

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ABSTRACT

To study the transferability of fracture toughness data from laboratory specimens in the integrity assessment of reactor pressure vessels, the test program NESC IV was conducted within Network for Evaluation of Structural Components (NESC). One part of the test program covered tests on bend specimens containing embedded flaws. Four beam specimens having test-section thickness of 102 mm fabricated from an A533 B pressure vessel steel were tested under uniaxial loading at temperatures that resulted in cleavage fracture events. Two of the test sections included the clad layer, while the remaining two without cladding.

Detailed elastic-plastic finite element calculations are used to evaluate the crack driving force and crack-tip constraint. The Master Curve methodology is used to predict the experimental outcome of these tests. Also study is the application of the constraint-based R6 method in prediction of the fracture events in these tests. It is observed that the size- and constraint-adjusted master curves yield good predictions of the fracture events in these tests. The constraint-based R6 improves prediction of test results of these tests.

Keywords: embedded flaws, fracture assessment, master curve, constraint, R6-method

1. INTRODUCTION

Evaluation of fracture toughness of materials is normally conducted by testing on relatively small laboratory specimens. To study the transferability of fracture toughness data from laboratory specimens to applications that assess the integrity of reactor pressure vessels, the test program NESC-IV was conducted within Network for Evaluation of Structural Components (NESC). The NESC IV project is a coordinated experimental/analytical program that has focused on modelling of postulated shallow flaws in heavy-section nuclear RPVs that are subjected to realistic loading states. The test program was divided in biaxial and uniaxial loading. The analysis of the cruciform tests under biaxial loading has been published by, among others, Sattari-Far (2003). In the uniaxial test program, four tests on extended sub-clad defects in RPV plate material were conducted.

The project has exploited the availability of an A533 B pressure vessel steel (PVRUF material) with a single-layer stainless-steel strip-clad overlay on the inner surface. The fabrication of the test pieces, the testing procedure and the preliminary results were reported by Bass et al (2002). In parallel to these, the European NESC partners performed an extensive characterization of the mechanical and fracture properties of the RPV source material.

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residual stress measurements, design and fabrication work on the embedded flaw specimens and pre-test fracture mechanics analyses. This information is presented by Bass et al. (2002).

The "Master Curve" concept incorporated into ASTM E-1921 provides standardized testing and data analysis techniques for characterizing fracture toughness of RPV steels in the ductile-to-brittle transition region. Specifically, it provides the median fracture toughness for a 1T specimen under small-scale yielding conditions as a function of temperature in the transition region. However, the deep-notch compact tension or bend specimens typically used to generate those data may provide a sharp contrast to crack-tip conditions potentially encountered in RPV assessments. The feature experiments were intended to challenge applications of Master Curve procedures to predict the behaviour of shallow flaws in RPV clad materials.

This paper concerns the post-test assessments of the beam tests containing embedded flaws performed within NESC-IV. Three-dimensional elastic-plastic finite element calculations, considering the crack-tip constraint (stress triaxiality), are employed in assessments of the experimental results. The analysis also covers the application of the constraint-based R6-methodology.

2. EXPERIMENTAL RESULTS

The NESC-IV tests were divided into cruciform specimens under biaxial loading and beam specimens under uniaxial loading. The project has exploited the availability of an A533 B pressure vessel steel with a single-layer stainless-steel strip-clad overlay on the inner surface. Here, only tests of uniaxial loading are considered. Four embedded-flaw beams were fabricated from PVRUF material blocks provided by ORNL. Two of the test sections included the inner-surface clad layer, while the remaining two were without cladding. The test section for these beams contained only plate material below the clad layer. The flaw was a two-dimensional notch extending the entire specimen width, with a ligament size of 14 mm and a notch depth of 21 mm, as shown in Figure 1. The overall length of the beam was 508 mm, with depth and width of 102 mm in the cross section.

The RPVUF material was from an A533 B pressure vessel with a single-layer stainless-steel strip-clad overlay on the inner surface. The shell had a nominal inner radius of 2210 mm and a thickness of 232 mm, which includes the ~5 mm clad overlay. Tensile, Charpy, drop weight (DWT), single-edge notched bend (SEN(B)), and compact tension (C(T)) tests were conducted to characterize the material behaviour. A summary of characterization tensile data of the main materials is given in Table 1. The master curve \( T_0 \) value of the base material is obtained from testing of standard specimens, giving a \( T_0 \) value of -96.7 °C. This value was then size- and constraint-adjusted for the post-test analysis of the tests.

3. THE MASTER CURVE METHODOLOGY

Cleavage toughness data should be treated statistically rather than deterministically. This implies that a given steel does not have a single value of cleavage fracture toughness at a particular temperature in the transition region; rather, it has a toughness distribution. Testing numerous specimens to obtain a statistical distribution of toughness can be expensive and time-consuming. In addition, there has been the interest to utilize small fracture specimens, e.g. Charpy size, to obtain fracture toughness data when severe limitations exist on material availability, for instance in nuclear irradiation embrittlement studies. To meet these desires, the ASTM E 1921-02 standard (2002) has been developed that greatly simplifies the process of determination of fracture toughness in the transition region. The ASTM standard accounts for temperature dependence of fracture toughness through a fracture toughness Master Curve approach developed by Wallin (1991). The standard covers the determination of a reference temperature \( T_0 \), which characterizes the fracture toughness of ferritic steels that experience onset of cleavage cracking. By definition, \( T_0 \) is a temperature at which the median of the \( K_{\text{JC}} \) distribution from 1T size specimens will equal 100 MPa√m. Statically elastic-plastic fracture tests are performed on standard SEN(B) or C(T) specimens having deep notches \((a/W \sim 0.5)\) to evaluate the cleavage fracture toughness \( K_{\text{JC}} \). The Master Curve is defined as the median (50% probability) toughness for the 1T specimen over the transition range for the material, and is given by the following expression:

\[
K_{\text{JC}(50\%)} = 30 + 70 \exp[0.019(T-T_0)]
\]
For test program conducted on other than 1T specimens, the measured toughness data should be size-corrected according to:

\[
K_{\text{JC}(x)} = 20 + \left[ K_{\text{JC}(1T)} - 20 \right] \left( \frac{B_{1T}}{B_x} \right)^{1/4}
\] (2)

Where, \(B_{1T}\) is the 1T specimen size (25 mm) and \(B_x\) the corresponding crack front length in the actual test specimen.

In Equation (2), 20 MPa/√m represents the minimum (threshold) fracture toughness adopted for ferritic steels addressed by the standard.

The master curve methodology proposes to describe the cleavage fracture of the material under high constraint conditions for which the single parameter characterization of material toughness \((K_{Jc})\) holds. Ruggieri et al (1998) found that constraint loss leads to decrease in the \(T_0\) temperature. Consideration of the constraint effects within the context of the Master Curve methodology is described below.

### 3.1. Consideration of the crack-tip constraint

The \(T\)-stress and the \(Q\)-stress are the most cited constraint parameters in the literature. These two parameters are briefly described below.

For a crack in an isotropic elastic material subject to plane strain Mode I loading at a load level that is sufficiently small that crack-tip plasticity is well-contained, the crack-tip field can be characterized by the two-term Williams (1957) solution as:

\[
\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) + T\delta_{ij}\delta_{ij}
\]

Where, \(T\) is the \(T\)-stress, and is a function of geometry and loading conditions. Using different combination of the two loading parameters, \(K_I\) and \(T\), different near crack-tip fields can be generated.

O’Dowd and Shih (1991, 1992) suggested that the crack-tip stress field in a cracked body of elastic-plastic material can be approximated by:

\[
\sigma_{ij} \approx \sigma_{ij}^{\text{Ref}} + Q\sigma_\gamma \delta_{ij}
\]

Here, \(\sigma_{ij}^{\text{Ref}}\) is a reference field with high stress triaxiality, which can be the HRR solution or the SSY solution assuming plane strain conditions. Thus, the parameter \(Q\) corresponds to a uniform hydrostatic shift in the stress field.

A definition of \(Q\) using the opening stress component \(\sigma_{\theta\theta}\) at the head of the crack tip is proposed as:

\[
Q = \frac{\sigma_{\theta\theta}^{\text{SSY}} - \sigma_{\theta\theta}^{\text{Ref}}}{\sigma_\gamma}
\]

Where, \(\sigma_{\theta\theta}^{\text{SSY}}\) is the opening stress from the SSY analysis (with zero \(T\)-stress), and \(\sigma_\gamma\) the yield strength.

For the SSY condition, one may develop a one-to-one correspondence between \(Q\) and \(T\), for instance according to the presented results of O’Dowd and Shih (1993), which are shown in Figure 2. Factors influencing the crack-tip constraint include specimen thickness, crack depth relative to the specimen thickness, loading type (tension or bending) and loading level. Specimen thickness and crack geometry influences in-plane crack-tip constraint, while biaxial loading influences out-of-plane crack-tip constraint. Most of the studies reported in the literature consider in-plane constraint effects (for instance shallow-crack effects) and the beneficial effects of the loss of in-
plane constraint \((T\text{ or } Q < 0)\) in elevating cleavage fracture toughness, see for instance Towers and Garwood (1986), Theiss et al (1992), Kirk et al (1993) and Sattari-Far (1995). However, there is still no generally validated constraint parameter which can cover effects due to in-plane and out-of-plane constraint in both the cleavage and ductile regimes.

The relation between the Master Curve \(T_0\) and constraint is studied by Wallin (2001). He has suggested the following relationship between \(T_0\) and \(T_{\text{stress}}\):

\[
T_0 \approx T_{0\text{deep}} + \frac{T_{\text{stress}}}{10 \text{ MPa} / ^\circ C} : \text{for } T_{\text{stress}} < 0 \tag{6}
\]

Where, \(T_{0\text{deep}}\) is the \(T_0\) obtained from standard specimens (having \(T_{\text{stress}} \approx 0\)). This relation provides a simple tool for the application of the Master Curve technology also to low constraint geometries. The present relationship can also be transformed into a simple approximate constraint correction directly for \(K_{JC}\) as:

\[
K_{JC} \approx 20 + \left( K_{JC\text{deep}} - 20 \right) \cdot \exp \left( 0.019 \cdot \left[ -\frac{T_{\text{stress}}}{10} \right] \right) \text{ for } T_{\text{stress}} < 0 \tag{7}
\]

Where, \(K_{JC}\) is in MPa\(\sqrt{m}\) and \(T_{\text{stress}}\) in MPa.

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

The general purposed finite element method (FEM) program ABAQUS (1998) is used for the computations reported in this study. The base and cladding materials are assumed to be elastic-plastic of type Ramberg-Osgood model fitted to the hardening behaviour of the uniaxial test results. It is assumed that the materials obeyed the von Mises flow criterion with its associated flow rule and isotropic hardening behaviour. For the analysis of the beam specimens, due to symmetry in geometry and load, only one half of the specimens needs to be modelled. The finite element model used for this analysis is shown in Figure 2. The model consists of 3135 eight-noded plane strain elements, fine enough around the crack tips to resolve the crack-tip fields at the load level of interest. Contact elements are used between the specimen and the loading platen. No specific modelling of the cladding HAZ is considered in this analysis.

To calculate the crack-tip constraint parameter in Equations (5), the near-tip fields in the beam specimens are compared with a reference field representing a high level of stress triaxiality. Here, the SSY solution is chosen as the reference field. To resolve the SSY field, one needs to perform a FE analysis with high degree of refinement. The solution is obtained by imposing a \(K\)-field on the remote boundary of a standard boundary-layer model (a semicracked annulus). In practice, the radius of the boundary layer model needs to be about 100 times the plastic zone size developed due to the imposed \(K\)-field. The FE model used for evaluation of the SSY solution consisted of 640 eight-noded plane strain elements comprised in 40 rings focused toward the crack tip. The reference value and the \(Q\) values in the beam tests are evaluated at the distance \(r/H(\sigma_Y) = 2\) ahead of the crack tip. Because the cladding residual stresses are negligible in the base material, no such stresses are considered in the FEM analysis. The FEM analysis is only conducted for two tests; test 4.1.2 with no cladding, and test 4.2.1 with cladding.

Figure 4 shows the load-CMOD (Crack-Mouth-Opening-Displacement) response of test 4.2.1 compared with the FEM results. It is observed that the FEM responses are in general more compliant than the experimental responses. One explanation to these deviations is the fact that the cladding HAZ is not specifically model in the FEM analysis, and the tensile test data have shown superior strength properties in the HAZ material compared with the base materials [1].

Cleavage fracture toughness data for the beam specimens under uniaxial loading were determined by the finite element analysis using the CMOD data from the tests. Variations of crack driving force \(K_I\) at the two crack tips of test 4.2.1 under the loading are shown in Figure 5. Here, it is assumed that the fracture events have occurred simultaneously at the two crack tips.
Variation of the constraint parameter $Q$ evaluated in different crack configurations at a load level of $K = 100$ MPa/m are given in Table 2. Here, the $Q$ values at the surface and deep tips are compared with the corresponding values in a shallow $(a/W = 0.10)$ and a deep $(a/W = 0.50)$ SEN(B) specimen. It is observed that the constraint levels in the beam tests are substantially lower than the SSY yielding level. The constraint level at the deep tip is similar to the constraint level in the shallow SEN(B) specimens of $a/W = 0.10$.

The $J$-values at the two crack tips at the failure events in tests 4.1.2 and 4.2.1 are calculated from the FEM analysis, and are converted to elastic plastic stress-intensity factors $K_J$. These results together with fracture toughness results obtained from master curve methodology are presented in Figure 6. The master curves (5%, 50% and 95% fracture probability) are size-corrected according to Equation (2) for a crack front length ($cfl$) of 101 mm in the base material. It is observed that the master curves give conservative predictions of fracture events for these two tests.

As the constraint level at the deep tip is substantially higher than at the surface tip, it is more likely that the cleavage fracture event would initiate at the deep tip. The constraint effects in the Master Curve assessments of the test results are considered by using Equation (6) and (7). Taking the constraint value at the deep tip, $Q = -0.37$, and using Figure 2 and equation (6) yields the constraint-adjusted $T_0$ to be -105 °C. The corresponding Master Curve assessment is shown in Figure 7. This indicates obvious improvement in the prediction of the test results, when the crack-tip constraint is also considered.

4.1. Assessments using the constraint-based R6 method

Fracture assessments of cracked components considering the constraint effects can be conducted using the new version of the R6-method (2002). In this version of R6, the failure assessment diagram (FAD) can be modified using the constraint parameter $T$ or $Q$. The modified Option 1 of FAD using $Q$ as the constraint parameter has the following form:

$$K_r = (1 + 0.5L_r)^2 \left[0.3 + 0.7 \exp(-0.6L_r^6) \left[1 + \alpha\left(-\frac{Q}{L_r}\right)^m\right]\right]$$

(8)

Where, $\alpha$ and $m$ are material fracture parameters, which are determined from fracture toughness tests on specimens having different levels of constraint. For the actual base material, $\alpha = 1.1$ and $m = 2.7$ are reported by Smith (2004).

The R6 assessment of the two beam tests considering the constraint effects are shown in Figure 8. The size-adjusted Master Curve toughness for a crack length of 101 mm is used in calculation of $K_r$. The SACC program, Andersson et al. (1996), with its procedure based on the R6-method is used for calculations of $K_r$ and $L_r$. It is observed that both tests failed close to $L_r = 1$, in a region where large constraint effects are predicted. The R6 assessments suggest that the failure is more likely to initiate at the deep crack tip. It is observed that using the constraint-based FAD improves the prediction possibility of the R6-method for this type of problems.

5. SUMMARY AND CONCLUSIONS

The major motivation of this study was to investigate application of the Master Curve methodology in prediction of cleavage fracture events in beam specimens containing embedded flaws. A test program consisted of experiments on standard SEN(B) specimens and beam specimens containing embedded flaws under uniaxial loading was conducted within the framework of the NESC-IV project. The structural analysis of the test program supports the following conclusions:

1. Load-CMOD responses of all tests are predicted well by FE analysis.
2. The size-corrected master curves yield good predictions of fracture events in the beam specimens with and without cladding.
(3) Considering the constraint effects in the Master Curve methodology improves the prediction results of the embedded flaw tests.

(4) The constraint-based R6 successfully predicts the outcome of the tests.

REFERENCES


**Table 1: Mechanical properties of the base and cladding materials.**

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Base</th>
<th>Cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E$</td>
<td>$\sigma_y$</td>
</tr>
<tr>
<td>-100</td>
<td>213</td>
<td>596</td>
</tr>
<tr>
<td>0</td>
<td>207</td>
<td>480</td>
</tr>
<tr>
<td>250</td>
<td>193</td>
<td>435</td>
</tr>
<tr>
<td>400</td>
<td>184</td>
<td>420</td>
</tr>
</tbody>
</table>

**Table 2: Crack-tip constraint values in different crack geometries at a load level of $K = 100 \text{ MPa} \sqrt{\text{m}}$ ($J = 43 \text{ kN/m}$).**

<table>
<thead>
<tr>
<th>Crack geometry</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEN(B)</td>
<td></td>
</tr>
<tr>
<td>$a/W = 0.10$</td>
<td>-0.45</td>
</tr>
<tr>
<td>$a/W = 0.50$</td>
<td>-0.05</td>
</tr>
<tr>
<td>Beams with embedded flaws</td>
<td></td>
</tr>
<tr>
<td><em>Surface tip, Tip-S</em></td>
<td>-0.80</td>
</tr>
<tr>
<td><em>Deep tip, Tip-D</em></td>
<td>-0.37</td>
</tr>
</tbody>
</table>
Fig. 1: Clad beam containing an embedded flaw prepared from a reactor pressure vessel.

Fig. 2: Variations of the constraint parameters $T$ and $Q$ for different hardening exponents according to O'Dowd and Shih (1993).
Fig. 3: Finite element model used for analysis of the cruciform specimens.

Fig. 4: Load-CMOD responses of the tests and the FEM analysis.
**Fig. 5:** Variation of $K_I$ at the two crack tips in the clad beam test during loading.

**Fig. 6:** Fracture toughness in the embedded flaw tests for simultaneous initiation at both crack-tips compared with size-corrected master curves.
Fig. 7: Fracture toughness in the embedded flaw tests for simultaneous initiation at both crack-tips compared with size- and constraint-adjusted master curves.

Fig. 8: R6-constraint based assessment of embedded tests 4.1.1 and 4.2.1.