Study on Fracture Behaviour in Clad Cruciform Specimens under Biaxial Loading

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ABSTRACT

This paper describes results of post-test analysis of NESC-IV tests conducted on the cruciform clad specimens of type A533 Grade B steel. A total of six clad cruciform specimens containing shallow surface flaws were tested in the temperature interval –55 up to -33 within the transition region of the material. Detailed 3-D elastic-plastic finite element calculations are used to evaluate the outcomes of the test program. Crack driving forces expressed in the $J$-integral and crack-tip constraint expressed in the $Q$-parameter are calculated along the whole crack front in the cruciform tests under biaxial loading. The “Master Curve” methodology is used to predict the experimental outcomes of these experiments. It is observed that the fracture initiated in a region close to the cladding HAZ, where a combination of the crack driving force and the crack-tip constraint is critical. Size-corrected Master Curves predicted reasonably well the fracture events in these experiments.

KEYWORDS: clad cruciform specimen, biaxial loading, finite element calculation, transferability, A533 steel, $Q$-parameter, master curve

1. INTRODUCTION

Evaluation of fracture toughness of materials is normally conducted by testing on laboratory specimens subjected to uniaxial loading. Pressure vessels are subject to biaxial loading. 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 co-ordinated experimental/analytical program that draws from major elements of the biaxial cruciform testing program conducted by the Heavy Section Steel Technology (HSST) Program.

A major objective of the NESC-IV project is to address the transferability of fracture toughness data from laboratory specimens to applications that assess the integrity of RPVs subjected to upset and normal loading transients. 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. The NESC-IV test program covers tests on standard SEN(B) specimens and clad beams under uniaxial and biaxial loading. A total of six clad cruciform specimens containing shallow surface flaws were tested in the temperature interval –55 up to -33 within the transition region of the material. The test material was reactor steel of type A533 Grade B with a single-layer stainless-steel clad overlay on it, Nilsson and Bass [1].

This report is aimed to give post-test assessments of some of the cruciform experiments performed within NESC-IV. These tests were intended to challenge applications of Master Curve procedures to predict the behaviour of shallow flaws in RPV clad materials subjected to biaxial loading conditions in the transition region. Three-dimensional elastic-plastic finite element calculations, considering the crack-tip constraint (stress triaxiality), are employed in assessments of the experimental results. Detailed information of this study is given by Sattari-Far [2].

2. THE MASTER CURVE METHODOLOGY

The micromechanism of cleavage fracture exhibits a strong sensitivity to random inhomogeneities in material along the crack front. Thus, cleavage toughness data should be treated statistically rather than deterministically. It means 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.

* Participation of DNV in this research project is sponsored by the Swedish Nuclear Power Inspection (SKI) under contracts: SKI-14.42-010726/01138.
embrittlement studies. To meet these desires, the ASTM E 1921-02 standard [3] 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 toughness through a fracture toughness Master Curve approach developed by Wallin [4]. The temperature dependence of the fracture toughness can be determined by performing a certain amount of fracture toughness test at a given temperature. 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 \( K_{Jc} \) 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 \( K_{Jc} \). 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:

\[
K_{Jc(50\%)} = 30 + 70 \exp(0.019(T-T_0)) .
\]  

(1)

For test program conducted on other than 1T specimens, the measured toughness data should be size-corrected according to:

\[
K_{Jc(x)} = 20 + \left[ K_{Jc(1T)} - 20 \right] \left( \frac{B_1}{B_x} \right)^{1/4} ,
\]

(2)

where \( B_1 \) is the 1T specimen size (25 mm) and \( B_x \) the corresponding crack front length (cfl) 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. One important question arising here is “How does the master curve methodology account for the crack-tip constraint effects? Ruggieri et al [5] found that constraint loss leads to decrease in the \( T_0 \) temperature. Questions such as how quantitatively consider effects of in-plane constraint (shallow cracks) and out-of-plane constraint (biaxial loading) are still open issues in the master curve methodology. Despite this, application of this methodology in predictions of experimental results has shown promising results, see for instance Bass et al [6] and Sattari-Far [7].

2.1. Crack-Tip Constraint Parameters

O’Dowd and Shih [8, 9] suggested that the crack-tip stress field in cracked body can be approximated by:

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

(3)

Here, \( \sigma_{ij}^{Ref} \) 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 \( Q \) in elastic-plastic materials using the opening stress component \( \sigma_{00} \) is proposed as:

\[
Q = \frac{\sigma_{00} - \sigma_{00}^{SSY}}{\sigma_y} \quad \text{at} \quad \theta = 0 \quad \text{and} \quad \frac{r}{(J/\sigma_y)} = 2 ,
\]

(4)

where, \( \sigma_{00} \) is the opening stress taken from the analysis of the actual geometry, \( \sigma_{00}^{SSY} \) the opening stress from the SSY analysis (with zero \( T \)-stress), and \( \sigma_y \) the yield strength. Among the different proposals on constraint parameters, the parameter \( Q \) has received the most attention in the literature. The \( J-Q \) theory in combination with a micromechanical model has been successfully applied in description of cleavage fracture in different crack configurations.
3. EXPERIMENTAL STUDIES

The NESC-IV project consists of two parts, A and B, that are focused on fracture toughness testing and model development for shallow surface flaws and for embedded flaws, respectively. In this report, only part A of the test program is considered. A total of six clad cruciform specimens containing shallow surface flaws in welds were tested in Part A of the project. The specimens were fabricated by Oak Ridge National Laboratory (ORNL/USA) using source material removed from RPV shell segments available from a pressurized-water RPV that was never in service, Figure 1. The specimen design was the same as that employed previously in the HSST program, i.e., the intermediate-scale cruciform specimen with a test-section thickness of 102 mm.

3.1 Materials Characterisation

The RPV material is an A533 B pressure vessel steel with a single-layer stainless-steel strip-clad overlay on the inner surface. The longitudinal weld geometry is of the double-J configuration requiring that the weld be essentially symmetric about the mid-plane of the vessel wall. The welds were submerged-arc welds (SAWs) with A533 B Class 1 filler metal. The shell had a nominal inner radius of 2210 mm and a thickness of 232 mm, which includes the ~5 mm clad overlay. The different materials characterized in NESC-IV include: A533 B plate, longitudinal weld, clad overlay and cladding HAZ.

Tensile, Charpy, drop weight (DWT), single-edge notched bend (SEN(B)), and compact tension (C(T)) tests were performed. The HAZ regions were much too small for Charpy and DWT specimens. A summary of characterization tensile data of the main materials fitted to the Ramberg-Osgood model is given in Table 1. The master curve $T_o$ values of the base and weld materials obtained from testing of standard specimens and size-corrected to the actual crack front are given in Table 2. Detailed material data are presented in Ref. [1].

3.2. Fracture Specimen Configurations and Tests

A basic functional requirement for configuration of test specimen was that the stress conditions in the ligament would be in the same condition, which exists in the reactor beltline region. Six clad cruciform specimens were fabricated by ORNL using source material removed from the RPV shell segments, depicted in Figure 1. The specimens are cut from the inner (clad) surface of the shell in the longitudinal welds. Note that the longitudinal weld, which is approximately 25.4 mm wide, is at the mid-length of and perpendicular to the blank. This procedure assured that the blank was aligned properly; i.e., the weld was at the centre of the specimen and perpendicular to the longitudinal axis of the final specimen. Due to the curvature of the specimen, the clad layer is full thickness only at the centre of the specimen. Therefore, great care was used to assure proper blank alignment. The final specimen configuration, after machining, is shown in Figure 1.

The specimens were machined with four load-diffusion control slots (LDCS) in each side of the test section. These slots are machined through the complete thickness of the specimen using the wire-EDM process. The purpose of the LDCS is to provide lateral flexibility in the interface between test section and beam arm. This design assures that the central region of test section is loaded uniformly with only small transverse edge effects. The length orientation of the flaw is parallel to the longitudinal weld. The flaw depth extends in the weld through-thickness direction. The specimens are fatigue pre-cracked in the longitudinal beam configuration. The final dimensions of the flaw are, nominally, 53.3 mm long and 19.1 mm deep. Transverse beam arms are then electron-beam (EB) welded onto the longitudinal beam, giving the completed clad cruciform specimen with the relevant dimensions shown in Figure 1.

The cruciform beam tests were executed at the ORNL biaxial cruciform testing facilities. The instrumentation plan developed to assure monitoring of all critical parameters for testing of the cruciform beam specimens. The clad cruciform specimens in this series were all tested under 1:1 biaxial loading, an eight-point bending configuration with equal loads applied to each beam arm. The support lines for the beam are at the edge of the test section, 50.8 mm from the specimen centre. The moment arm is 285.8 mm long. The test temperatures, varied in the range of –55 to –33.4 °C, were based on the test program objective, reference temperature $T_o$ values for the material, pre-test analyses, and initial test results. The specimens were cooled to the appropriate test temperature and loaded monotonically to failure. Relevant failure conditions are summarized in Table 3. Due to a software problem, no data were recorded for test PVR-4. Detailed information on the testing data is given in Ref. [10].

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

The general purposed finite element method (FEM) program ABAQUS [11] is used for the computations reported in this study. The pre-processor of the FEM program ANSYS [12] is used for development of the three-dimensional FEM models. The materials (weld, base and cladding) 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 clad cruciform specimens under biaxial loading, due to symmetry in geometry and load, only one forth of the specimen needs to be modelled. The finite element model used for this analysis is shown in Figure 2. The model consists of 3610 twenty-noded solid elements, fine enough around the crack front 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, Equations (3), the near-tip fields in the cruciform 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 stress parameters were computed for all three materials; base, cladding and weld materials. These reference values are evaluated at the distance $r/\sqrt{\sigma_y} = 2$ ahead of the crack tip.

To consider the cladding residual stresses in the FEM analysis, the FEM model is assumed to be stress free at 399 °C, experiencing cooling down to ambient temperature, at which the crack is inserted in the model. After that, the model is cooled down to the test temperature (around -40 °C).

Figure 3 shows the load-CMOD response of the tests and 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. Some preliminary tensile test data show superior strength properties in the HAZ material compared with the weld and base materials [10]. Preparation of tensile data of the cladding HAZ is under progressing, and is not ready at preparation of this manuscript. For this reason, only tests PVR-5 and 6, for those FEM load-CMOD responses are in good agreement with the experimental results, are studied in this report.

Cleavage fracture toughness data for the clad cruciform specimens under biaxial loading were determined by 3-D finite element analysis using the CMOD data from the tests. Variations of the $J$-integral and the constraint parameter $Q$ along the crack front in test PVR-1 at the CMOD-value of the failure are shown in Figure 4. The $Q$ values are evaluated from Equation (4). It is observed that, for this crack configuration, the most critical location for crack growth is likely to be in the cladding HAZ, considering both $J$ and $Q$ values.

Variation of the constraint parameter $Q$ evaluated in different crack configurations at a load level of $K = 100$ MPa√m are given in Table 4. Here, the $Q$ values at the deepest point and in the cladding HAZ in the cruciform specimen under biaxial loading 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 cruciform test are above the SSY yielding level. It may be stated that the constraint conditions are effectively similar in the cruciform test and in the deep SEN(B) specimen at the cleavage fracture loads.

The $J$-values at the deepest point and in the cladding HAZ at the failure events in tests PVR-5 and 6 are calculated from the FEM analysis, and are converted to elastic plastic stress-intensity factors $K_p$. These results together with fracture toughness results obtained from master curve methodology are presented in Figure 5. The master curves (5%, 50% and 95% fracture probability) are size-corrected according to Equation (2) for a crack front length (cfl) of 63 mm in the weld material. It is observed that the master curve with 50% fracture probability gives a good prediction of fracture toughness of these two tests.

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 test specimens having the stress conditions similar to those existing in the reactor beltline region. A test program consisted of experiments on standard SEN(B) specimens and clad cruciform specimens under biaxial loading was conducted within the framework of the NESC-IV project. The structural analysis of the test program supports the following conclusions:

- FEM load-CMOD responses of the cruciform tests are sensitive to material data (mechanical properties).
- Considering $J$ and $Q$ values along the crack front in the cruciform tests, it is more likely that crack growth initiated in the cladding HAZ.
- Size-corrected master curves satisfactorily predict crack growth in cruciform specimens under biaxial loading.
- Application of the master curve methodology still needs more investigation, in particular with respect to quantifying crack-tip constraint effects and size adjustment of crack geometry.
REFERENCES


Table 1. Mechanical properties of different materials based on the Ramberg-Osgood model [1].

<table>
<thead>
<tr>
<th>Temp. [°C]</th>
<th>Base</th>
<th>Weld</th>
<th>Cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E$</td>
<td>$\sigma_0$</td>
<td>$n$</td>
</tr>
<tr>
<td>-100</td>
<td>213</td>
<td>596</td>
<td>6.39</td>
</tr>
<tr>
<td>0</td>
<td>207</td>
<td>480</td>
<td>6.39</td>
</tr>
<tr>
<td>250</td>
<td>193</td>
<td>435</td>
<td>6.4</td>
</tr>
<tr>
<td>400</td>
<td>184</td>
<td>420</td>
<td>7.67</td>
</tr>
</tbody>
</table>

Table 2. Reference Temperature $T_0$ for different materials in the test specimens [1].

<table>
<thead>
<tr>
<th>$a/W = 0.50$</th>
<th>Size-corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld</td>
<td>-88.3</td>
</tr>
<tr>
<td>Base</td>
<td>-96.7</td>
</tr>
</tbody>
</table>

Weld (Crack front = 63 mm) |
Base (Crack front = 100 mm) |
Table 3: Failure conditions in the clad cruciform specimens under 1:1 biaxial loading.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test temperature [°C]</th>
<th>Failure moment [KN-m]</th>
<th>CMOD [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVR-1</td>
<td>-40.2</td>
<td>112.2</td>
<td>0.22</td>
</tr>
<tr>
<td>PVR-2</td>
<td>-38.3</td>
<td>140.2</td>
<td>0.51</td>
</tr>
<tr>
<td>PVR-3</td>
<td>40.6</td>
<td>97.6</td>
<td>0.18</td>
</tr>
<tr>
<td>PVR-4</td>
<td>-55.0</td>
<td>70.0</td>
<td>N.A.</td>
</tr>
<tr>
<td>PVR-5</td>
<td>-33.4</td>
<td>147.5</td>
<td>0.87</td>
</tr>
<tr>
<td>PVR-6</td>
<td>-35.3</td>
<td>150.7</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 4: Crack-tip constraint values in different crack geometries at a load level of $K = 100$ MPa/$\sqrt{m}$ ($J = 43$ 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>Cruciform tests</td>
<td></td>
</tr>
<tr>
<td>At deepest point</td>
<td>+0.10</td>
</tr>
<tr>
<td>In the cladding HAZ</td>
<td>+0.25</td>
</tr>
</tbody>
</table>

Fig. 1: Clad cruciform specimen prepared from welds in a reactor pressure vessel.
Fig. 2: Finite element model used for analysis of the cruciform specimens.

Fig. 3: Load-CMOD responses of the tests and the FEM analysis.

Fig. 4: Distributions of $J$ and $Q$ along the crack front in test PVR-1.
Fig. 5: $K_J$ at the deepest points and in the cladding HAZ of two cruciform tests compared with the size-corrected master curves.