FRACTURE TOUGHNESS DETERMINATION OF A NUCLEAR PRESSURE VESSEL STEEL BY INSTRUMENTED CHARPY IMPACT TEST

N. VERDIERE(1), A. PARROT (1), P. FORGET (2), J.M. FRUND (1)

(1) EDF - R&D - Département EMA, Les Renardières, 77818 Moret-sur-Loing Cedex, France
E-mail : nicolas.verdiere@edf.fr

(2) CEA - SRMA - CEA/SACLAY - 91190 Gif-sur-Yvette Cedex, France

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ABSTRACT
Charpy V-notch (CVN) impact testing is widely used to characterise the resistance of a material, by measuring the energy consumed by a specimen during the impact. Notably, materials undergoing a ductile-to-brittle transition, e.g. ferritic steels, are quality controlled by means of CVN testing, and their ductile-to-brittle transition temperature can be determined. Charpy testing is also widely used in the toughness assessment of large forged components, e.g. pressure vessels for pressurised water reactor (PWR). However, to justify the integrity of components, a fracture toughness versus temperature curve is needed and no satisfactory link exists between the Charpy impact energy and the fracture toughness.

A study has been engaged in order to establish a non-empirical relationship between the Charpy impact energy and the fracture toughness of a A508 Cl. 3 steel. The methodology is based on the local approach of fracture.

INTRODUCTION
The innocuity of the defects located in the base metal of RPV has to be demonstrated at every moment of the "life" of nuclear plants. Theses structural integrity assessments are usually performed with elastic or elasto-plastic analyses. The stress intensity factor is calculated in different accidental situations and is compared to the fracture toughness of the material.

But usually, for simplicity reasons, materials are characterised using Charpy specimens, because theses tests are easy to perform and the specimen sizes are not as big as the Compact Tension specimen needed for toughness tests. The fracture toughness of the material is then calculated using the Charpy transition curve through empirical relationships (Barsom, 1970, and many others). These relationships are quite simple and efficient but they have drawbacks and lead for instance to excessive margins.
The aim of our study is to predict directly the fracture toughness from CVN testing results. This is made using the modelization of the Charpy test and the local approach of fracture.

For the future, the final objective is to calculate directly the toughness of embrittled materials after irradiation from the Charpy specimens of the irradiation surveillance program.

FROM CHARPY TO TOUGHNESS

Methodology

The suggested methodology can be broken down in three main steps, as indicated in the following diagram:

1/ Simulation of the Charpy test using F.E.M.
2/ Evaluation of a critical fracture stress through comparison with KCV experimental results. The Beremin model is used for this step.
3/ Simulation of the toughness using F.E.M.

The transition from Charpy to toughness will be demonstrated at low temperatures where fracture occurs by cleavage in the brittle mode. That demonstration is made with a A508 Cl.3 steel, taken from a real nozzle of the shell of a RPV. The chemical and mechanical properties (chemical composition, Charpy transition curve and fracture toughness) of this material are presented on the figures 1 to 3 (Renevey, 1997).
Numerous works have been published on the simulation of this test (Rossol, 1999; Tahar, 1998). At low temperature, where the fracture occurs with no ductility, the impact test can be simulated with a 2D mesh under plain strain conditions. The viscosity of the material has to be taken into account, but the inertial effects of the impact test can be neglected. However, at higher temperature, in the transition, the simulation is more complex and some other hypothesis have to be done.

The 2D-mesh is presented on figure 4. Due to symmetry, only one half of the specimen is represented with QUA8 elements. The mesh size at the crack tip is (50 microns)^2.

**Simulation of the Charpy test using F.E.M.**
The material behaviour is simulated with a LEMAITRE viscoplastic law:

$$\sigma = K \varepsilon^{1/M} (d\varepsilon/dt)^{1/N}$$

with

- \(K = 1207.9\)
- \(1/N = 0.02057\)
- \(1/M = 0.10997\)

The value of \(K\), \(M\) and \(N\) have been identified on tests performed at various strain rates, from \(10^{-4}\) \(\text{s}^{-1}\), up to \(1000\) \(\text{s}^{-1}\) (the last were compression tests made with Hopkinson bar).

With instrumented Charpy impact tests, the load and the hammer displacement are recorded. The comparison between the experimental results and the numerical simulation gives a reasonable agreement (figure 5).

A numerical experiment with the BEREMIN model

The fracture is described with the Beremin model (1983). This model predicts the statistic brittle fracture by cleavage through 3 parameters: \(V_0\) (characteristic volume, in
this study \( V_0 = (50 \text{ microns})^3 \), \( m \) : the dispersion parameter, and \( \sigma_u \) : the normalisation stress. The dispersion parameter \( m \) is directly linked to the distribution of micro-defects over which cleavage can initiate. The failure probability is determined by:

\[
Pr = 1 - \exp \left\{ -\left( \frac{\sigma_w}{\sigma_u} \right)^m \right\} \quad \text{where} \quad \sigma_w^m = \int \sigma_1^m \text{d}V / V^o.
\]

The Beremin model has been widely used to simulate the brittle fracture of the A508 Cl. 3 steel. Many different sets of parameters \((m, \sigma_u)\) have been published (Renevey, 1997; Rossol, 1999; and many others). Usual values vary from 18 to 30 for \( m \), and from 2400 to 3500 MPa for \( \sigma_u \).

In a first step, we made a numerical study to see the influence of various sets of \((m, \sigma_u)\) on the calculated KCV failure energy probability curve for a Charpy test, and on the calculated \( K_{ic} \) fracture toughness probability curve for a CT test.

The \((m, \sigma_u)\) sets tested are shown below:

<table>
<thead>
<tr>
<th>set number</th>
<th>( m )</th>
<th>( \sigma_u )</th>
<th>( \sigma_u V^o )^{1/m}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>2800</td>
<td>1707</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>2700</td>
<td>1721</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>2600</td>
<td>1721</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>2500</td>
<td>1708</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>2450</td>
<td>1720</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>3015</td>
<td>1838</td>
</tr>
<tr>
<td>7</td>
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<td>1853</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>3225</td>
<td>1966</td>
</tr>
<tr>
<td>9</td>
<td>22</td>
<td>3085</td>
<td>1967</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>2970</td>
<td>1966</td>
</tr>
<tr>
<td>11</td>
<td>26</td>
<td>2880</td>
<td>1968</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>2800</td>
<td>1966</td>
</tr>
</tbody>
</table>

Sets of \((m, \sigma_u)\) tested in Charpy and toughness simulation

The sets # 1 to # 5 (respectively the sets # 8 to # 12), have approximately the same value of \( \sigma_u V^o \)^{1/m}, which is the most influential parameter. The sets #6 and #7 are usual values for this material.

The results of the predicted failure probability with the different sets are presented on figures 6 (for Charpy tests) and 7 (for toughness tests).

The predicted failure curves for set #1 to set #5 (respectively for set #8 to #12) are quite identical: the two parameters \( m \) and \( \sigma_u \) are not so independent. For the identification of \((m, \sigma_u)\) from a set of statistical fracture results, \( m \) can be fixed and only \( \sigma_u \) have to be optimised in order to fit the results. Of course, it is necessary to choose a realistic value for \( m \) (between 20 and 30 for example). Renevey (1997) had also proposed a model of fracture with a single parameter (the critical stress).

The choice to fix \( m \) is justified by the fact that the distribution of micro-defects is quite the same for all materials of the type of A508 Cl.3.
This result is very encouraging. Usually, it is necessary to have a set of 25 or 30 experiments to determine correctly the values of m and \( \sigma_u \). With this alternative method of fixing m, it will become possible to identify the value of \( \sigma_u \) with less experiments and a relative good confidence. A study is in progress on this subject (Forget, 2000). 

**Evaluation of the critical stress from Charpy results**

Around 30 Charpy tests have been performed at -90°C. Following to the former "numerical exercise" on the Beremin model, four identifications have been done: three with an imposed value of m (m=20 ; m=24 ; m=28), and one "classical" identification with both m and \( \sigma_u \) free to vary. The different steps of the "classical" identification have already been presented many times (Beremin, 1983). For the identification with m fixed, only one F.E. calculation is necessary. The optimum value of \( \sigma_u \) is the mean value of the various values of \( \sigma_u \) calculated for each numerical result.
Identification number | m | $\sigma_u$ identified | $\sigma_u V_0^{1/m}$
--- | --- | --- | ---
1 | 20 | 3162 | 1927
2 | 24 | 2884 | 1909
3 | 28 | 2705 | 1900
4 | 37.35 | 2472 | 1896

Identification of m and $\sigma_u$ on Charpy tests at -90°C

The experimental and calculated fracture energy probability curves are presented on figure 8. The 4 identifications led more or less to the same results. This is not surprising since the values of $\sigma_u V_0^{1/m}$ don't vary so much (from 1896 up to 1927) between the 4 identifications.

![Figure 8: Fracture Energy (KCV) probability: experimental and calculated curves](image)

Simulation of the fracture toughness using F.E.M.

The last step of the method is the simulation of the fracture toughness. This simulation is not so difficult when fracture occurs with no ductility. Around 25 tests have been made at -90°C, with 1T-CT side-grooved specimen (25 mm thickness).

The calculation is made with a 2D - mesh (presented on figure 9) in plane strain condition. The mesh size at the crack tip is (50 microns)$^2$.

![Figure 9: 2D-Mesh for the fracture toughness simulation](image)
The total load is calculated with the net section of the specimen (20 mm thickness). The calculated and experimental loads are presented on figure 10.

The fracture is predicted with the Beremin model, using the four sets of \((m, \sigma_u)\) identified in the former step. The experimental and calculated failure probability curves are shown on figure 11. The experimental curve is well represented, and the difference between the results given by the 4 sets of Weibull parameters is very low.

![Figure 10: Experimental and calculated load curves for the toughness experiment](image)

**Figure 10**: Experimental and calculated load curves for the toughness experiment

![Figure 11: Fracture toughness \((K_{1c})\) probability: experimental and calculated curves](image)

**Figure 11**: Fracture toughness \((K_{1c})\) probability: experimental and calculated curves

**THE CENTENAIRE® SOFTWARE**:

A software has been developed to make automatically the different steps presented in this paper. The user has to enter the values of fracture energy \(K_{CV}\); and the software identifies the critical stress and calculates the associated probability curve of toughness (as presented on figure 11).

**PERSPECTIVES**:

The same method will be applied in order to evaluate the fracture toughness in the transition at higher temperatures. However, the simulations will have to describe the ductile tearing before fracture which is observed on specimens. This simulation of
ductile tearing requires the use of a damage model like the Rousselier model (Rousselier, 1986). This work is in progress.

In the next stage, irradiation embrittlement will be taken into account by changing the tensile curve of the material, and increasing the yield stress.

CONCLUSION:

Charpy V-notch (CVN) impact testing is widely used to characterise the resistance of a material, by measuring the energy consumed by a specimen during the impact. However, to justify the integrity of components, we need fracture toughness versus temperature curve and no satisfactory link exists between the Charpy impact energy and the fracture toughness.

It is possible to calculate directly the toughness from the Charpy impact tests. This can be done with the use of F.E.M. calculations and the local approach to fracture.

The Beremin model which describes the brittle fracture by cleavage can be used in an alternative way, with an imposed value of the dispersion parameter m. The results of Charpy energy and fracture toughness with different suitable sets of (m, σu) parameters are quite similar.

In this demonstration at low temperature where fracture is brittle, the fracture toughness of the material has been determined from Charpy Impact tests results. This demonstration gave encouraging results, and the toughness is predicted with a good confidence.

REFERENCES


Forget P. & al., 2000. Determination of toughness value of a PWR steel in brittle fracture by analysing a limited set of Charpy specimen with "local approach" of fracture. This conference.


