FINITE ELEMENT SIMULATIONS OF CHARPY-V AND SUB-SIZE CHARPY TESTS FOR A LOW ALLOY RPV FERRITIC STEEL

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ABSTRACT

Charpy-V is largely used for the surveillance program of RPV (Reactor Pressure Vessel) embrittlement by neutron irradiation. Service life prolongation of nuclear power plants and more stringent safety requirements are increasing the request for small test specimens such as Sub-Size Charpy. Furthermore, the empirical correlation formulas between conventional Charpy-V and fracture toughness are sometimes questionable. But, before using reduced specimen size, we have to validate different hypotheses and this can only be achieved by combining tests and finite element simulations.

In a first step, the aim of finite element simulations is to get a clear description of the global mechanical behaviour of the specimens. It was demonstrated that the complete description of dynamic impact is not required for fracture mechanics purposes even for the Sub-Size geometry. A quasi-static simulation taking into account the effect of the strain rate on the elastic plastic material constitutive equation is sufficient. But, a 3D mesh is required in order to get a good description even for tests with cleavage failure mode.

The second objective is related to the transferability of fracture criteria. We began this task at low temperature (-90°C) by using the Beremin (1983) cleavage model [1]. The same material parameters were used for CT 25, Charpy-V and Sub-Size Charpy at this temperature and the finite element results are compared to the experimental one. These first results are showing good transferability potential, but further studies are required on this point and in particular have to be extended to ductile and transition range.

INTRODUCTION

Miniaturisation of mechanical testing specimens is particularly important in case of irradiated materials (volume reduction of activated material, number of tests for a given volume). If this size reduction is nearly without any problem for some specimens such as tensile tests, it is not the same for Charpy tests. The results obtained on reduced specimens must be comparable to those on standard size and compact tension (CT) specimens. In fracture mechanics, it is called a transferability problem and is always a matter of discussions and research even for more conventional geometry.

In nuclear industry, the conventional Charpy test is commonly used for the surveillance program of reactor pressure vessel steel neutron embrittlement. The material used for these tests has been cut from the pressure vessel. It is put in surveillance capsules which are introduced in the reactor and are highly irradiated. It can be interesting to use reduced specimens size either to re-use some already tested samples or to perform more tests for the same volume. For this purpose, the Sub-Size Charpy geometry (3x4x27 mm) developed in the frame of ESIS TC 5 [2] is of high interest. But, of course, before using another test than the well know conventional Charpy-V test, it is required to get large validation for the new test and also to establish strong connections with the usual ones (Charpy-V and CT 25). In order to go further than empirical correlations, the only mean is to develop a realistic finite element modelisation of this test and of the corresponding fracture mechanisms. Main connected studies in the literature are the Ph. D. from A. Rossoll [3], 5 articles from Needleman and Tvergaard [4] and one for ductile tearing from Schmitt et al. [5].
In this article, we will first detail the modelisation of the global mechanical behaviour of the specimens (i.e. Sub-Size Charpy, Charpy-V and CT 25). The second step will concern the fracture mechanisms. It will be reduced to low temperature range and in particular to -90°C. This was done in order to remain in small deformation and in pure cleavage ranges. With this range reduction, the simulation will be more simple because it does not require finite strain formulation and coupled damage formulation. Furthermore, adiabatic heating is not important in this range. But, as we will show, 3D modelisation and strain rate effects have to be taken into account. This article is linked to another one [6] devoted to experimental results.

FINITE ELEMENT SIMULATION OF GLOBAL MECHANICAL BEHAVIOUR

Finite Element Code

The finite element code used is CASTEM 2000. It is developed at CEA Saclay in DRN/ DMT/ SEMT. The particularity of this finite element code is that it makes use of an object oriented meta-language called "GIBIANE". An overall description can be found on the web site at http:/ / www.castem.org:8001.

Physical Phenomena to be Taken into account

Before beginning the Finite Element (FE) simulation task, it is important to list the different physical phenomena that can play a role. Then, we will have to evaluate the importance for each of them and then to conclude if we need to take it into account or not. The first step was achieved by listing the following questions :

- <u>Dynamic effects :</u> What are the influence of striker impact, imposed specimen bending vibrations and wave propagation on global (but also at notch root) mechanical behaviour of the specimen ?
- <u>Friction :</u> What is the importance of friction between specimen and anvils ?
- <u>2D or 3D FE simulations :</u> Are 2D plane strain or plane stress sufficient or is 3D required ?
- <u>Strain Rate :</u> Is dynamic hardening of the material an important parameter ?
- <u>Adiabatic Heating :</u> Do we must take it into account at notch root ?
- <u>Failure Mode :</u>
  - <u>Brittle :</u> What about the applicability of existing criterion and of their transferability potential between different specimens ?
  - <u>Ductile :</u> Does tearing can be properly described by damage coupled models ?
  - <u>Transition :</u> Is not yet well described by FE simulations and so will be more difficult to take into account for Charpy.

When all these items will get appropriate answers and validations, we will be able to properly correlate the different test types between them and to use only one for checking purpose.

2D and 3D meshes and boundary conditions

Only 3D meshes are represented in Figure 1 but either 2D or 3D meshes have been used.
For 2D simulations, due to plane symmetry in the centre, only half of the specimen is used. The specimen is elastic plastic and is composed of quadratic elements with 8 nodes and 9 Gauss points. The striker and the anvil are considered to be perfectly elastic with a Young's modulus equal to 200 GPa and composed of the same type of elements. Contact conditions without any inter-penetration nor friction are imposed to specimen, anvil and striker. The anvil is fixed on the back in the vertical direction and at one point in horizontal direction. An imposed displacement is imposed at the back face of the striker.
For 3D simulations, due to symmetry planes only 1/ 4 of the specimen is represented. For the specimen and striker, CUB20 elements are used. The striker is elastic and the anvil is perfectly rigid. This was done in order to simplify the contact formulation. The corresponding meshes are represented, on the same scale, in Figure 1 in order to have a view of the differences in size. Note also that the 3D meshes are coarser than the corresponding 2D ones due to size limitation in the FE simulations.

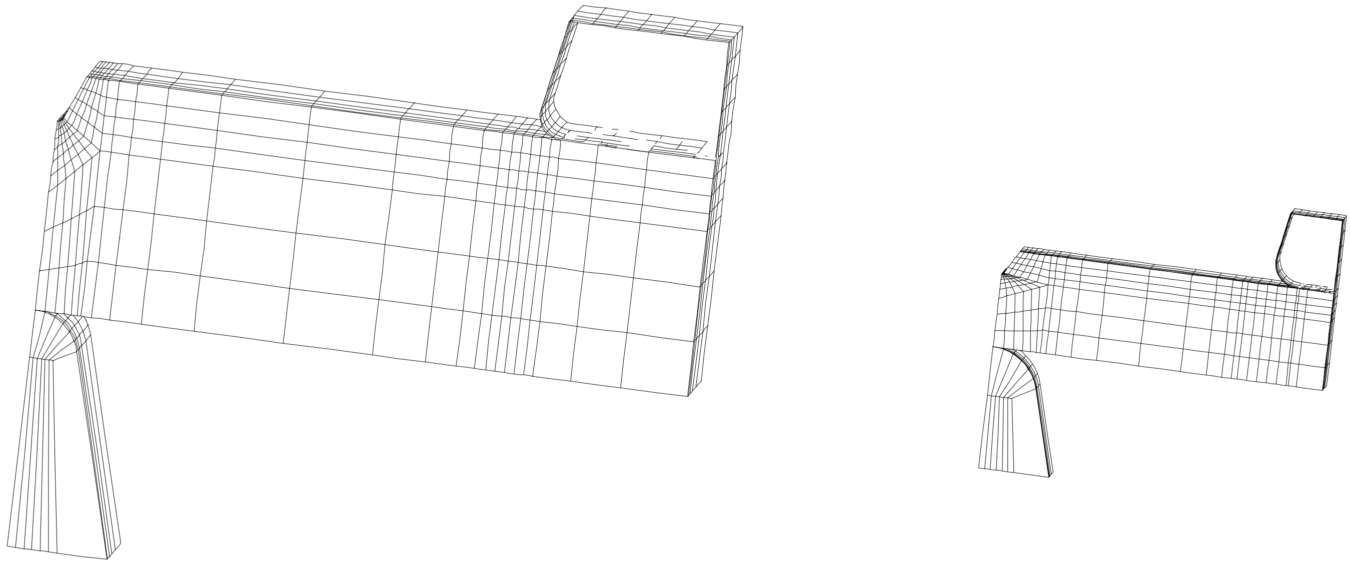
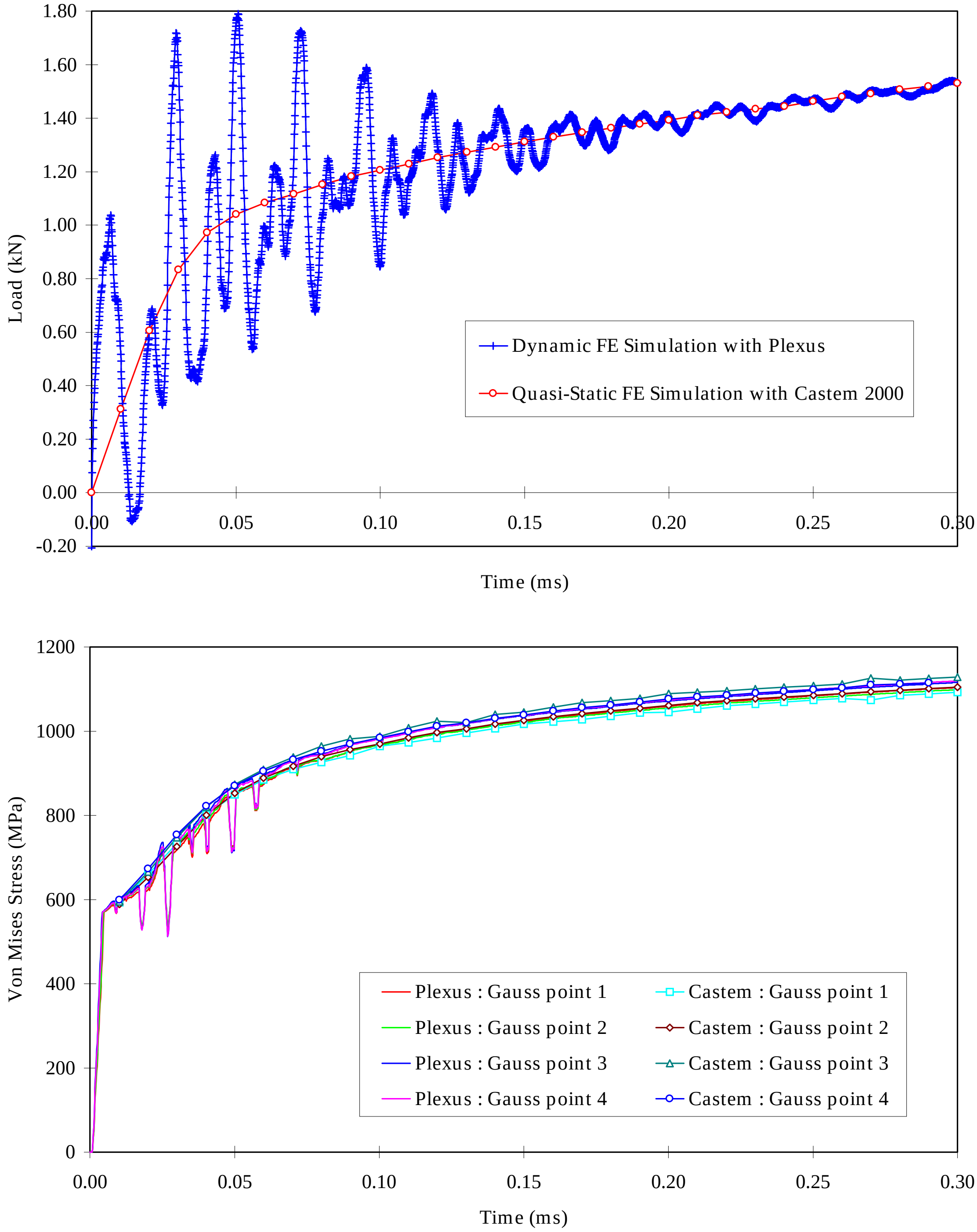


Figure 1 : *3D meshes for Charpy-V and Sub-size Charpy specimens.*

Dynamic effects

Comparative simulations of Sub-Size Charpy were performed with Castem and Plexus finite element packages. Plexus is the dynamic explicit code developed in parallel with Castem. The basic idea adopted here was to compare the two FE simulations for the global mechanical behaviour point of view and also to look at the local stress evolution at the notch root.
In Figure 2, the graph on the left shows that the quasi-static load evolution versus time is corresponding to the mean value of the dynamic curve. On the right, the stress evolution in the notch root element are identical for the two simulations. Except that, in the dynamic simulation, some very brief unloading can occur.
It means that a quasi-static simulation is able to properly represent the mean loading of the specimen. Furthermore, the stress fields developing at the notch root are well described in quasi-static simulation. This last point is due to the fact that, as soon as yielding occurs, the elastic waves are completely smoothed. Furthermore, it is this yielding which is the governing mechanisms for failure initiation even at low temperatures.
So, all other simulations will be performed with Castem 2000 under quasi-static hypothesis.



<u>Figure 2 :</u> *Comparison between dynamic and quasi-Static 2D plane strain FE simulations of Sub-Size Charpy at -90°C.*

Strain Rate Effects

As Charpy test is dynamic, some dynamic strain hardening effects can occur in steel depending on strain rate fields. A. Rossoll [3] has shown that strain rate is a very important parameter for Charpy-V for this RPV steel even at low temperature such as -90°C. He has performed static and dynamic (with Hopkinson bars) compression tests in order to identify Cowper and Symonds relation at different temperatures. The two parameters used here are $p_0 = 12$ and $\dot{\varepsilon}_0 = 10^8\ s^{-1}$.

$$\sigma_{DYN} = \sigma_{STAT} \cdot \left[1 + \left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right)^{1/p_0} \right] \qquad (1)$$

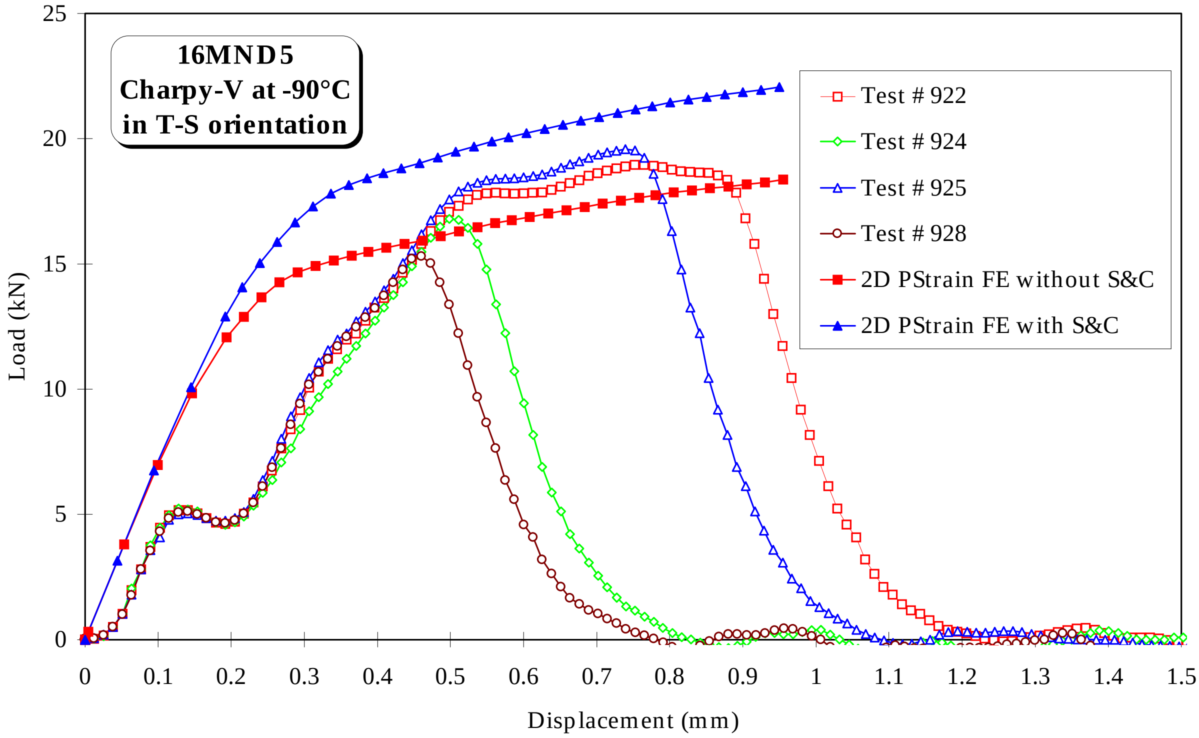


Figure 3 : *Influence of strain rate on the global mechanical response for Charpy-V at -90°C.*

On this curve, there are four experimental tests performed on instrumented Charpy-V at -90°C. These curves do not exhibit the correct slope for the elastic part due to an insufficient band pass in the acquisition system. The two other curves are FE simulations without, or with, strain rate hardening effect taken into account. It clearly shows that strain rate has a very important effect and so it will be taken into account in the next parts.

2D Plain Strain or Plain Stress and 3D Finite Element Simulations

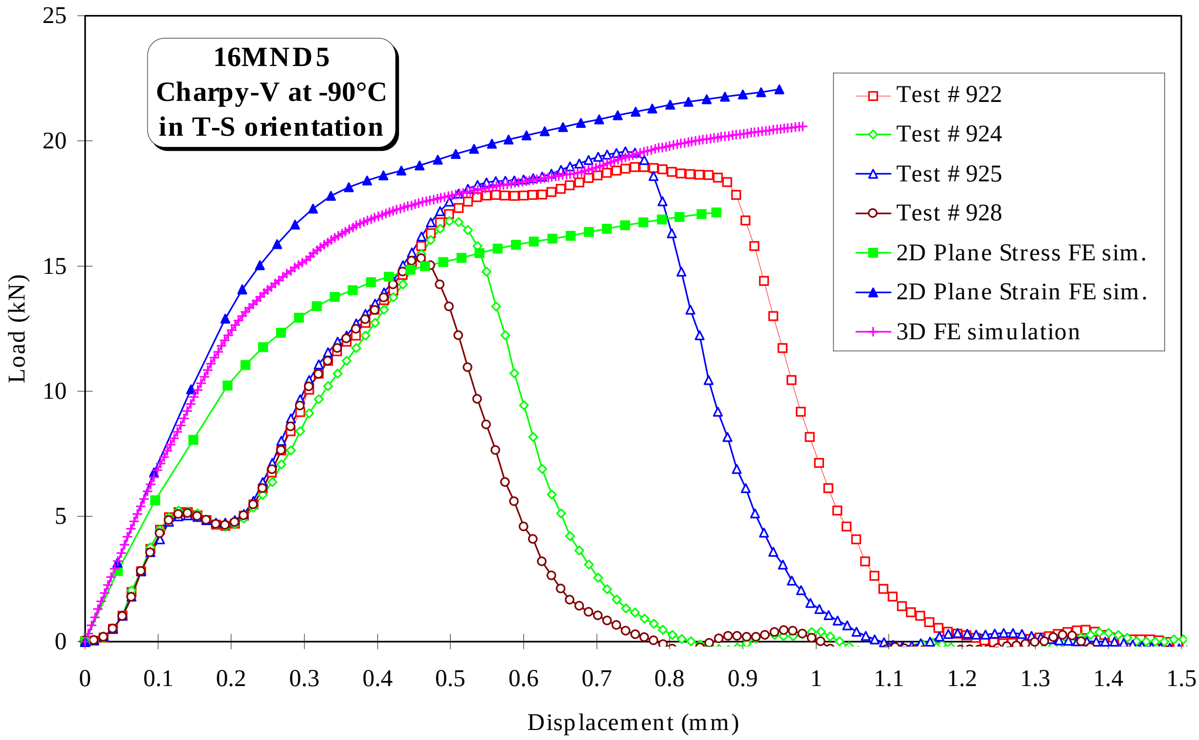


Figure 4 : *Comparison of experimental and simulated (2D and 3D) load versus displacement curves for Charpy-V specimen at -90°C.*

As noted in the preceding part, 2D FE simulations under plain strain conditions are over estimating the experimental load versus displacement curves. We also performed plain stress FE simulation and got a curve under the experimental results (figure 4). So, a 3D FE simulation was also carried out and gave a result included between the two 2D simulations and in quite good agreement with the experimental curves. So, 3D FE simulations are required for an adequate description of the global mechanical behaviour even at low temperature such as -90°C.

Figure 5 indicates that the same type of result is also valid for Sub-Size Charpy geometry. 3D FE simulation is required for Sub-Size Charpy tests at -90°C. For this test, the experimental elastic slope is in agreement with the calculated one. This is mainly due to the fact that for the Sub-Size Charpy Zwick device, the band pass for the signal acquisition is equal to 1 MHz. In order to smooth the highly oscillating raw signal, a centred mobile mean on 20 µs was used. Further comparisons with the FE simulated curves show that yielding is predicted earlier than it occurs in the experience. Then, this is partly compensated by the fact that strain hardening seems to be overestimated. It did not seem to be the case for Charpy-V. Nevertheless, these results are not purely comparable with those obtained on conventional Charpy-V because the global deformation is comparatively higher for a given deflection in the Sub-Size specimen. At -90°C, the final fracture of Sub-Size specimens occurs for a deflection which is larger than those observed for Charpy-V. This is mainly due to the fact that, due to constraint loss, -90°C is located in the beginning of the brittle-ductile transition for Sub-Size Charpy specimen.

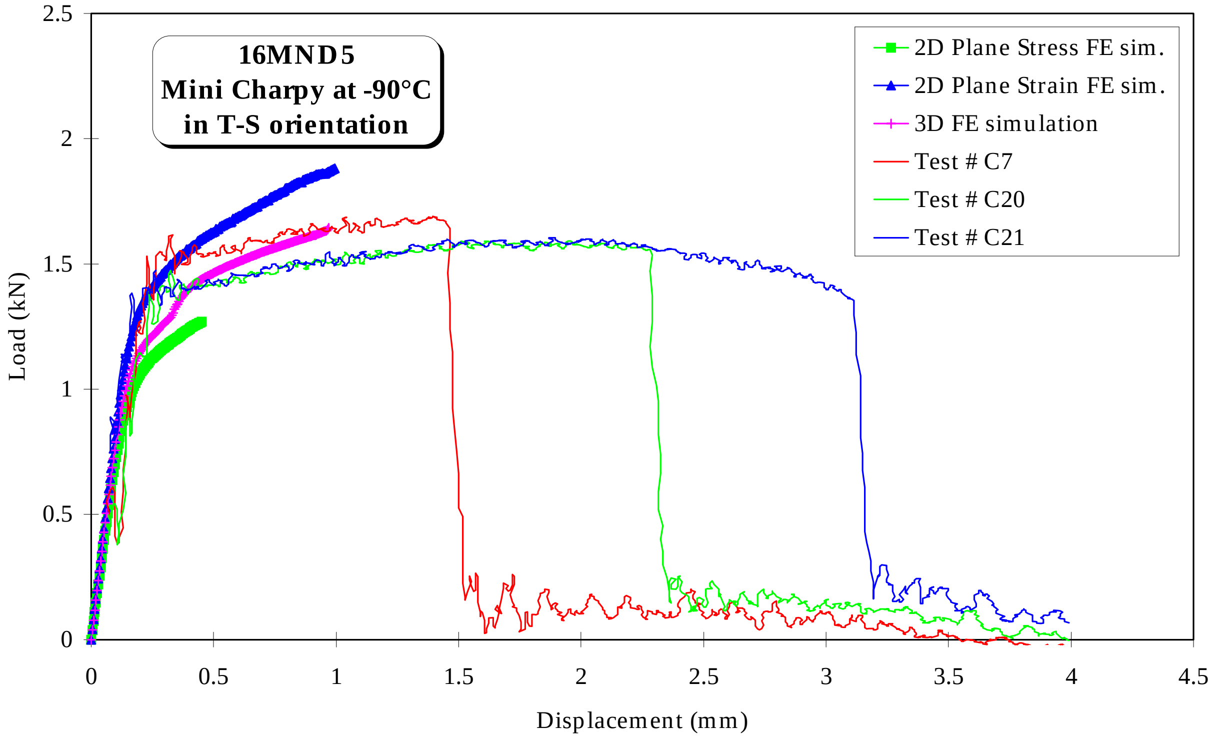


Figure 5 : *Comparison of experimental and simulated (2D and 3D) load versus displacement curves for Sub-Size Charpy specimen at -90°C.*

CLEAVAGE AT LOW TEMPERATURES

Beremin Cleavage Model

Statistical Beremin (1981) model [1] is now largely used for the prediction of cleavage failure cumulative probability (P_F). The corresponding equations are as follows :

$$P_F = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right] \qquad \text{with} \qquad \sigma_W = \left[\int_{V_p} \sigma_I^m . \frac{dV}{V}\right]^{1/m} \tag{2}$$

where σ_w is called the Weibull stress and is only computed on the yielded volume under tension. σ_u and m are two material parameters. For the steel of interest, these parameters have been identified in earlier work [3] and are respectively equal to 3015 MPa and 20 for $V_0=(50\ \mu m)^3$. These material parameters are considered here as temperature independent.

Comparison between Predicted and Experimental Failure Probabilities

If enough tests are performed at the same temperature, an experimental failure probability diagram can be derived. For that, the N experimental results are ranked (i) by increasing order of absorbed energy and then the experimental failure probability is obtained by using :

$$P_F = \frac{i - 0.5}{N} \tag{3}$$

This was applied for Charpy-V and for Sub-Size Charpy at -90°C (figure 6). For Charpy-V, the predicted failure probability is a little bit overestimating the observed experimental one, but this type of result can be considered as slightly conservative. For Sub-Size geometry at -90°C, the prediction is more largely overestimating the failure probability. This is due to the fact that this temperature is in the onset of the transition. So, a FE simulation was also performed for -120°C and the results are in very good agreement with the experience. The ratio between the two LSE at P_F=50% is equal to 7.9 which can be compared to 6.3 experimentally reported value [6].

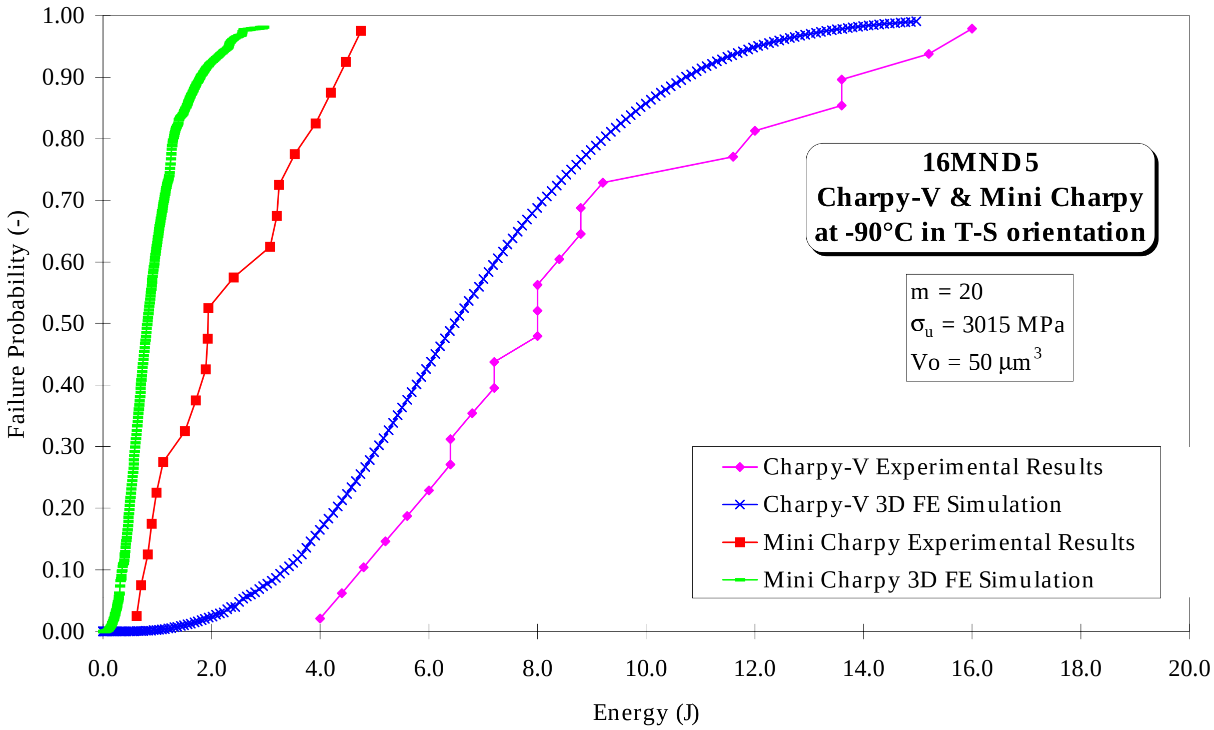


Figure 6 : *Experimental and calculated cleavage failure probability for Charpy-V and Sub-Size Charpy.*

Position of Simulations within the Master Curve

With the same material parameters, 2D plain strain FE simulations of CT 25 can be carried out with the same elastic plastic material behaviour. Then, Beremin model can be applied and give thus the failure probability for a given toughness level. This kind of result can be transposed in the transition curve. For 16MND5 French forging RPV steel, the Master Curve [7] has been established on the base of more than 75 toughness tests. The corresponding T_0 temperature is equal to -100°C. FE simulations at 3 low temperatures (-150°C, -120°C and -90°C) have been reported in this diagram and are in excellent agreement with the Master Curve.

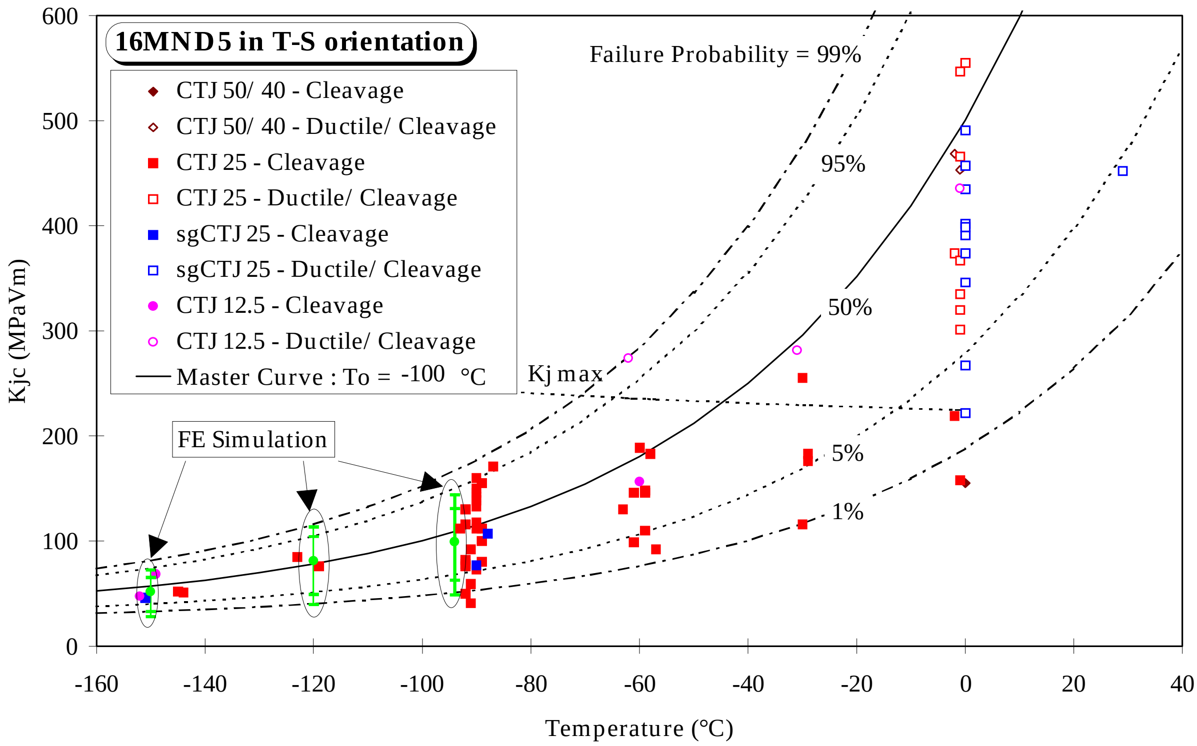


Figure 7 : *Master curve and position of CT 25 finite element simulations.*

CONCLUSIONS AND FUTURE PROSPECTS

3D finite element simulations are required for both Sub-Size and full size Charpy even in the brittle region in order to get the correct load versus displacement curve. Quasi-static finite element simulations are correct if the effect of strain rate on the true stress-strain curve is taken into account with a relation such as Symonds & Cowper's. Stress triaxiality ratio is higher for the Charpy-V (1.6) than for Sub-Size Charpy (1.3) at a given imposed deflection of 1 mm. This can partly explain the observed transition shift between the two geometries.
Transferability of Beremin cleavage criterion from Sub-Size Charpy to CT 25 was investigated at low temperatures and gives encouraging results, but needs again some improvements.
Finite element simulation of ductile tearing is now on going with additional difficulties such as coupled damage, large strain and possibly adiabatic heating at the notch root.

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