STUDY OF DUCTILE FRACTURE OF AUSTENITIC STAINLESS STEELS BY LOCAL APPROACH

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The safety of nuclear power plants requires good knowledge of the fracture behaviour of materials. For austenitic stainless steels, the usual methods of elastic-plastic fracture mechanics cannot be applied. This study aims to test the application of local approach methods to this kind of materials. The Rice-Tracey and Gurson-Tvergaard models were applied to two austenitic stainless steels, at room temperature and at 280°C. Tensile tests on axisymmetric round notched specimens were used to calibrate the model's parameters.

The results show that local approach can be successfully applied to very ductile materials.

INTRODUCTION

The safety of nuclear power plants requires good knowledge of the fracture behaviour of structural materials. Safety analyses of such installations consist in making sure that a defect with known dimensions will not involve the fracture in the structure. So it is important to have reliable fracture models for structural materials.

The austenitic stainless steels used for certain parts of naval power plants exhibit a highly ductile behaviour, such that a global approach by elastic-plastic fracture mechanics (J_{IC} ,$CTOD_c$) cannot be applied.

The present work studies the validity of the use of local approach methods of ductile fracture to this kind of materials.

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LOCAL APPROACH MODELS STUDIED

The ductile fracture of austenitic stainless steels is a result of nucleation, growth and coalescence of cavities. Thus, Rice-Tracey (1) and Gurson-Tvergaard (2, 3) models are used.

The Rice-Tracey model expresses the fracture in terms of critical growth rate of cavities, defined by :

$$\mathrm{Ln}\left(\frac{R}{R_0}\right)_c = \int_1^2 0,283 \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon^p_{eq} \quad \ldots\ldots(1)$$

The Gurson-Tvergaard model uses a plastic dissipation potential, which depends on the volume fraction of cavities. This potential is defined by :

$$\phi = \frac{\sigma_{eq}^2}{\sigma_y^2} + 3f\cosh\left(\frac{3\sigma_m}{2\sigma_y}\right) - 1 - (1.5f)^2 = 0 \quad \ldots\ldots(2)$$

where the cavity rate f is defined as the sum of a growth term and a nucleation term $df = df_c + df_g$ with :

$$df_c = (1-f)\ d\varepsilon^p_{eq} \quad \ldots\ldots(3)$$

$$df_g = \frac{f_N}{S_N\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\varepsilon^p_{eq} - \varepsilon_N}{S_N}\right)^2\right) d\varepsilon^p_{eq} \quad \ldots\ldots(4)$$

One parameter $(\mathrm{Ln}(R/R_0)_c)$ must be identified for the Rice-Tracey model, and four parameters (f_0, f_N, ε^p_{eq}, S_N) for the Gurson-Tvergaard model.

EXPERIMENTAL CONDITIONS

Two austenitic stainless steels were studied : a Z2CND17-12 steel (steel A) and a Z8CNDNb 18-12-2.5 steel (steel B). Both steels have been initially solution-treated and then water-quenched. Steel A is essentially a solid solution while steel B still contains niobium carbonitrides. Table 1 gives monotonous tensile properties.

TABLE 1 - Monotonous tensile properties

Mat.	T°	E (GPa)	$\sigma_{y0.2}$ (MPa)	σ_{UTS} (MPa)	A (%)	Z (%)
A	R.T.	184	220	537	65	87
A	280°C	160	168	416	43	85
B	R.T.	164	278	612	54	69
B	280°C	157	192	456	35	67

The Rice-Tracey and Gurson-Tvergaard model parameters were identified using monotonous tensile tests performed on axisymmetric round notched specimens, at room temperature and 280°C. The specimens, noted AE2, AE4 and AE10, have notched radii of 2, 4 and 10 mm respectively, and a common minimum diameter of 10 mm.

The initiation of a crack is identified by a sudden change of the slope of the load versus diameter reduction curve.

Tests were performed at imposed displacement, at a rate of 0.5 mm/minute. Values of load and diameter reduction, measured by a load cell and a specific diametral extensometer respectively, were recorded with a frequency of 5 Hz.

NUMERICAL MODELLING

The numerical modelling of tensile tests on axisymmetric notched specimens was performed with the finite element code ABAQUS.

Only a half specimen was modelled, in 2D axisymmetric using 8 nodes biquadratic, reduced integration elements. Calculations were carried out with a large strain hypothesis.

The first step was an elastic-plastic simulation in order to obtain stress and strain fields in the centre of the specimen and to identify the Rice-Tracey parameter.

Test results show that the strain undergone by the specimen can be very large, up to 180% at fracture for the steel A. So the monotonous stress-strain curve of the materials must be defined up to 180%. A first simulation showed that a simple extrapolation of the monotonous stress-strain law ($\sigma=K\varepsilon_p^n$) defined from a tensile test on a smooth specimen does not allow satisfactory results to be obtained. Thus, the stress-strain curve was determined by invert resolution with SIDOLO software coupled with ABAQUS, using experimental data given by axisymmetric tensile tests, before crack initiation.

The stress and strain fields obtained were used to calculate the Rice-Tracey parameter by post treatment.

The Gurson-Tvergaard model parameters, f_0, f_N, ε_N et S_N, were obtained by invert resolution, using all experimental data of tests on axysimmetric specimens.

RESULTS

The Rice-Tracey parameters obtained are given in Table 2 and the Gurson-Tvergaard parameters in Table 3.

TABLE 2 - Rice-Tracey parameters

Mat.	T°	AE2	AE4	AE10
A	R.T.	1.45	1.48	1.42
A	280°C	1.08	1.06	.97
B	R.T.	0.875	0.97	0.965
B	280°C	0.59	0.675	0.67

TABLE 3 - Gurson-Tvergaard parameters.

Mat.	T°	f_0	f_N	ε_N	S_N
A	R.T.	$5.3\ 10^{-5}$	$1.15\ 10^{-3}$	0.535	0.1
A	280°C	$5.3\ 10^{-5}$	$1,19\ 10^{-3}$	0.109	0.047
B	R.T.	$1.59\ 10^{-3}$	$9.79\ 10^{-3}$	1.08	0.141
B	280°C	$1.59\ 10^{-3}$	$9.79\ 10^{-3}$	0.5	.143

Load versus diameter curves obtained by Gurson-Tvergaard model are compared with experimental curves in Figure 1 for steel A and Figure 2 for steel B, at room temperature (Fig 1-a and 2-a) and 280°C (Fig 1-b and 2-b).

DISCUSSION

The results obtained for the Rice-Tracey model parameter are satisfactory. Nevertheless, it is noticeable that the value for steel B at room temperature on the AE2 geometry is lower than the other values, due to an uncertain measurement of diameter. The values obtained at 280°C are about 30% lower than those at room temperature ; this can be related to the reduction of elongation in monotonous tensile tests.

For the Gurson-Tvergaard model, results are relatively good for both temperatures, except for steel B at room temperature, probably due to the same difficulty in measuring the diameter reduction. Indeed, the diameter measure is very sensitive to the position of the diameter extensometer. Moreover, steel B exhibits a strong evolution of the initially smooth surface during the test, and the resulting roughness prevents the displacement of the extensometer to minimum diameter.

For steel A, the f_0 parameter is very low, as expected with its low inclusion content. In steel B, the f_0 parameter is higher (about 30 times), due to the presence of niobium carbonitrides. For the same reason, f_N is 10 times higher for steel B than for steel A.

For each steel, the same value of f_0 was used at room temperature and 280°C. The main difference obtained for the nucleation parameters at each temperature is found for the values of ε_N.

CONCLUSION

Rice-Tracey and Gurson-Tvergaard models were used in local approach of ductile fracture for two austenitic stainless steels. Both models enabled satisfactory results to be obtained. The next aim of our work is to apply these models to the simulation of propagation of a pre-existing crack in a structure, in order to validate the application of fracture local approach for these materials.

SYMBOLS USED

f = volume fraction of cavities

f_0 = initial volume fraction of cavities

f_N = volume fraction of nucleating cavities

R = cavity radius

R_0 = initial cavity radius

S_N = standard deviation of the nucleation-strain normal distribution

$\varepsilon^p{}_{eq}$ = Von Mises equivalent plastic strain

ε_N = mean value of the nucleation-strain normal distribution

σ_{eq} = Von Mises equivalent stress

σ_m = mean stress

σ_y = flow stress of the fully dense matrix material

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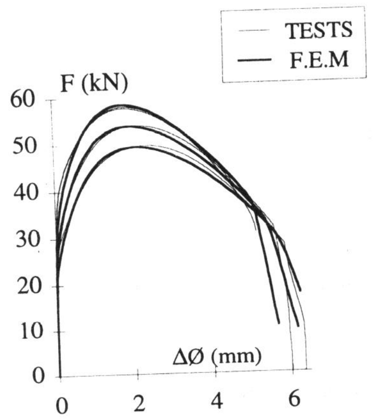

Figure 1-a : Gurson-Tvergaard model
Steel A, Room temperature

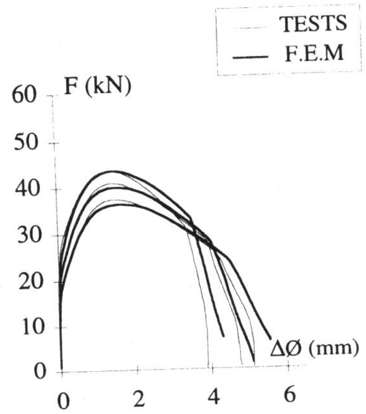

Figure 1-b : Gurson-Tvergaard model
Steel A, 280°C

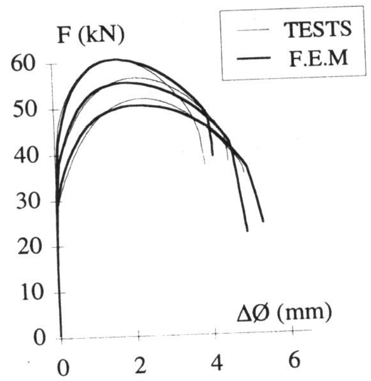

Figure 2-a : Gurson-Tvergaard model
Steel B, Room temperature

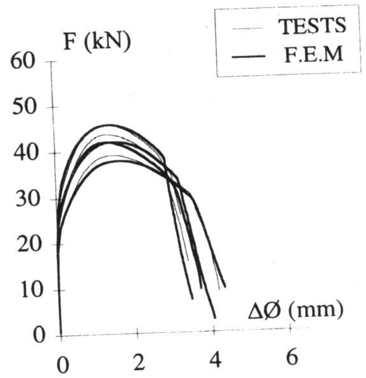

Figure 2-b : Gurson-Tvergaard model
Steel B, 280°C