FRACTURE MECHANICS IN CREEP SITUATION: INTERPRETATION OF RESULTS ON A TEST SPECIMEN

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ABSTRACT

Fracture mechanics in creep situation is required in LMFR safety studies. Experimental data are already rare and theoretical models to predict initiation and propagation of cracks are in progress. This situation leads today to overconservative analyses for LMFR's structures operating at high temperatures. In France, CEA Saclay has led experimental tests on CT specimens at 650 °C and 600 °C under creep, fatigue and creep-fatigue situations. The constitutive material is the 316 SPH austenitic stainless steel used for most LMFR's structures.

Simplified methods were investigated to predict crack initiation on one of the tests (CT specimen at 650 °C under constant load). Numerical simulation has been performed to evaluate global behaviour and σ_d parameter, using the elastoviscoplastic CHABOCHE's model in SYSTUS code.

From C* parameter, incubation time obtained with the R5 rule was conservative. Incubation time obtained by σ_d method was very pessimistic.

The σ_d values calculated by finite element method was upper (25 per cent) than σ_d obtained by simplified method. CASTEM 2000 computation under plane stress and plane strain conditions gave comparable σ_d values (difference less than 10 per cent). Due to geometrical characteristic such as thickness (B = 25 mm), the behaviour of the specimen appeared to be intermediate between plane strain and plane stress conditions.

1 - INTRODUCTION

Experimental tests on Compact Tension (CT) specimens under creep situation (incubation) have been performed at CEA Saclay. The constitutive material is the 316 SPH austenitic stainless steel used for most LMFR's structures. One of these tests (CT specimen at 650 °C under constant load) is the subject of the present study.

The variation of the notch opening versus time and the time corresponding to the crack initiation have been measured. The purpose of this study is to compare these results with those obtained with theoretical approaches.

The analytical investigations are broadly classified under two categories :

- * Application of simplified methods :

CEA simplified method noted σ_d [1] and method based on the evaluation of the so-called C* parameter by simplified route (R5 rule [2]) are investigated to predict crack initiation.

- * Numerical simulation :

Inelastic computations using SYSTUS and CASTEM 2000 codes have been performed to evaluate global behaviour and σ_d parameter.

2 - EXPERIMENTAL TEST

An experimental test was led at CEA Saclay on a CT specimen at 650 °C [3]. The figure 1 shows geometrical details of the specimen tested. All dimensions are standard :

thickness $B = 25$ mm
 notch depth $a = 27.5$ mm
 notch to width ratio $a/w = 0.55$.

The initial defect is realized by machining ($r = 0.1$ mm).

A tensile test on a smooth specimen was performed in order to obtain the true stress-strain curve of the constitutive material 316 SPH.

The test was conducted with a loading monotonically increasing from $P = 0$ to $P_{\max} = 13\,500$ N (see figure 1) and maintained during the hold time ($t_h = 143$ h) [3]. This situation is that of a CT-specimen with rather severe loading conditions so that the plasticity effects were sufficiently important before the specimen was allowed to creep.

Experimental results such as the variation of the notch opening versus time and the time corresponding to the crack initiation have been measured. The initiation was detected by an electric potential drop method. Creep crack initiation time has thus been conventionally defined as the time, T_i , needed for the initial defect to propagate over a critical distance $X_c = 0.05$ mm. The initiation time measured experimentally was $T_i = 49$ h [3].

3 - INVESTIGATION BY ANALYTICAL SIMPLIFIED METHODS

Theoretical studies based on simplified methods were performed to determine the incubation time and a comparison with test results was conducted. The CEA simplified method noted σ_d [1] and the method based on the evaluation of the so-called C^* parameter by simplified route (R5 rule) were investigated to predict the incubation time before crack initiation.

Time to failure :

The continuum damage failure mechanism for creep rupture involves widespread and significant creep damage in the ligament ahead of the crack. The time T_{cd} (required for creep rupture of ligament) can be assessed from a reference stress concept based on a limit load analysis, and may be estimated as [4] :

$T_{cd} = T_r(\sigma_{ref})$, where $T_r(\sigma_{ref})$ is the rupture time from uniaxial creep rupture data at a stress level equal to the reference stress. One finds that the time T_{cd} is greater than the experimental incubation time.

Estimation of σ_{ref} :

The reference stress is defined as : $\sigma_{ref} = \sigma_y \frac{P}{P_L}$

where P is the applied load, while P_L is the limit load of the cracked specimen for a material of yield stress σ_y . For CT specimen, the reference stress is calculated as :

$$\sigma_{ref} = \frac{P}{m (a/w) B W}$$

where w is the specimen width and B the specimen thickness. The factor m is given by [5] :

$$m = \left[\left(1 + \frac{a/w}{b-1} \right)^2 + \frac{(1-a/w)^2}{b-1} \right]^{1/2} - \left(1 + \frac{a/w}{b-1} \right)$$

with $b = 1.5876$ in plane strain and $b = 2$ in plane stress.

Estimation of the stress-intensity-factor :

$$\text{From [6] : } K = \frac{P\sqrt{a}}{BW} \left[29.6 - 185.5 \frac{a}{W} + 655.7 \left(\frac{a}{W} \right)^2 - 1017 \left(\frac{a}{W} \right)^3 + 638.9 \left(\frac{a}{W} \right)^4 \right]$$

This expression is used for the evaluation of σ_d and C^* parameters in simplified methods.

Evaluation of the incubation time from σ_d route :

This method [1] assumes that initiation by creep occurs when the real stress σ_d at a small distance d ($d = 0.05$ mm) from the crack front is equal to the stress that causes rupture in a smooth specimen.

The value of σ_d obtained by a simplified estimation [1] is 372 MPa and then the incubation time is $T_i = 2.5$ h.

Evaluation of the incubation time from C* parameter :

Method based on the evaluation of the so-called C* parameter by simplified route (R5 rule) was investigated to predict the incubation time T_i using an experimental correlation [7]. The approach is based on reference stress, and reference length concepts.

CEGB procedure (R5 rule) : the primary creep law used was given by RCC-MR [8]. The C* parameter may be estimated from R5 rule [2] as,

$$C^* = \sigma_{ref} \dot{\epsilon}_c (\sigma_{ref}, \epsilon_c) R$$

where, $\dot{\epsilon}_c (\sigma_{ref}, \epsilon_c)$ is the creep strain rate at the reference stress and the creep strain accumulated under the reference stress history. The reference length R is estimated from :

$$R = \left(\frac{K}{\sigma_{ref}} \right)^2$$

The incubation time values obtained from these methods were compared with the experimental result ($T_i = 49$ h). Results obtained both using the σ_d method ($T_i = 2.5$ h) and CEGB rule ($T_i \approx 13$ h) were conservative.

4 - NUMERICAL SIMULATION OF THE INCREASING LOAD UP TO P_{max}

A finite element analysis of the CT specimen has been performed using SYSTUS [10] where the material constitutive law was represented by the elasto-viscoplastic CHABOCHE's model, with values of parameters identified by NOVATOME at 650 °C. Another computation [9] has been performed at CEA Saclay using CASTEM 2000. The investigation of hold time will be realized in a later stage.

The values of σ_d parameter and notch opening obtained through the different approaches were compared and discussed.

Modelisation of the structure and loading :

Due to symmetry, only one half of the standard CT specimen (see figure 2) was modelled using 2D plane 6 and 8 node elements.

The mesh was generated using SYSTUS pre-processor. It consists of 350 quadratic isoparametric elements and 1 120 nodes.

The mesh construction was radial near the crack tip enabling the radial variation of field quantities to be easily discerned. The elements near the crack tip comprise triangles whose radial size is 0.016 mm.

The load was applied as a local load at the 9 nodes located upper to the centre of the pinhole.

Boundary conditions : The boundary conditions were imposed in order to respect the symmetry conditions. Moreover, one node was completely restrained to eliminate rigid body motion during loading. Nodes localized on the lips of the crack were free and the nodes along the uncracked ligament were not allowed to move vertically.

Material characteristics : The analysis was conducted at 650 °C. The true stress-strain curve of the material and the corresponding RCC-MR curve (type 1S) at this temperature are shown on figure 3 compared with its simulation by CHABOCHE's model. The main constants are recalled below :

Young's modulus	E	=	141 000 MPa
Yield stress	σ_y	=	108 MPa
Poisson's ratio	ν	=	0.3

Computation : The computation was carried out using the large deformation formulation of SYSTUS, i.e. taking into account the geometrical non-linearities. The specimen was loaded step by step up to a maximum load $P_{max} = 13\,500$ N, under plane stress conditions. The beginning of the calculation was also run using plane strain conditions. Another study was realized by CEA [9] using CASTEM 2000. Figure 4 shows the experimental load-displacement curve as compared to numerical results issued from SYSTUS calculations.

Due to geometrical characteristic such as thickness $B = 25$ mm, the plane stress conditions did not seem to be perfectly verified. The true situation is likely intermediate between plane stress and plane strain conditions. Similar conclusions were observed both with CASTEM 2000 and EPRI [11] results.

Figure 5 describes the principal stress variations through the uncracked ligament and figure 6 shows the principal stress isovalues at maximum load obtained with SYSTUS.

The σ_d values calculated by finite element method with plane stress conditions (490 MPa and 460 MPa for SYSTUS and CASTEM 2000 codes respectively) were upper than σ_d obtained by simplified method (372 MPa). Computations realized by CEA [9] under plane stress and plane strain conditions using CASTEM 2000 gave comparable σ_d values (difference less than 10 per cent).

5 - CONCLUSION

Simplified methods were investigated to predict incubation time before crack initiation on a CT specimen. In addition, numerical simulation of the increasing load up to P_{max} has been performed to evaluate global behaviour and σ_d parameter.

From C^* parameter, incubation time obtained with the R5 rule was conservative. When compared with experimental results, incubation time obtained by σ_d method was more conservative.

The σ_d values calculated by finite element method were upper (25 per cent) than σ_d obtained by simplified method. Concerning global behaviour (load-displacement curve), due to geometrical characteristic such as thickness ($B = 25$ mm), the situation of CT specimen was likely intermediate between plane stress and plane strain assumptions.

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Figure 1 : GEOMETRY OF CT SPECIMEN

Figure 2 : FINITE-ELEMENT MESH

Figure 3 : TRUE STRESS-STRAIN CURVE

Figure 4 : LOAD-DISPLACEMENT CURVE

Figure 5 : PRINCIPAL STRESS ALONG UNCRACKED LIGAMENT

Figure 6 : ISO PRINCIPAL STRESS LIGAMENT CURVE AT MAXIMUM LOAD