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CALCULATION WITH CHABOCHE'S ELASTIC-VISCOPLASTIC MODEL: STATUS AND FUTURE DEVELOPMENTS

B. Riou[1], O. Faure[1], A. Turbat[1], N. Waeckel[2] and B. Autrusson[3]

[1]NOVATOME, a division of FRAMATOME, Lyon, France
[2]EDF/SEPTEN, Villeurbanne, France, [3]CEA/DMT, Saclay, France

ABSTRACT

Several calculations have been performed by NOVATOME, a division of FRAMATOME, with the CHABOCHE's elastic-viscoplastic model in order to validate its use. They concern mainly the behaviour of mock-ups or specimens subjected to cyclic loads (fatigue, creep-fatigue, ratchetting) for which experimental results are available. The aim of this paper is to make a synthesis on the experience gained from these calculations.

The paper presents the calculations carried out and compares the results with experiments. The status of this type of elastic-viscoplastic model as well as future developments in inelastic analyses is thereafter discussed.

1 - INTRODUCTION

NOVATOME designs and manufactures Liquid Metal Fast Reactors (LMFRs). The structures of these reactors are subjected to high temperatures and their design requires in some cases to take into account the non linear behaviour of the materials. For this type of calculations, complex constitutive laws associated with Finite Element codes have to be used.

NOVATOME was led to perform inelastic analyses with elastic-viscoplastic model proposed by J.L. CHABOCHE from O.N.E.R.A. (Office National d'Etudes et de Recherches Aérospatiales). This was made possible after the following stages :

* Implementation of the constitutive equations into SYSTUS computer code [1].
* Identification of the parameters of the elastic-viscoplastic model for the 316 L(N) SS.

The logical step forward was to validate this model on experiments.

This paper presents a synthesis on the calculations performed with the elastic-viscoplastic model and draws conclusions as regards future developments.

2 - PRESENTATION OF THE ELASTIC-VISCOPLASTIC MODEL

The elastic-viscoplastic model proposed by J.L. CHABOCHE is a unified model based on the concept of viscous stress, with non linear kinematic hardening, isotropic hardening, plastic strain memorization and time recovery on kinematic and isotropic hardening. Table 1 summarizes the link between the state variables and the material properties.

25 parameters are needed to define this model. These parameters have to be identified on the basis of material data resulting from monotonic and cyclic tests, creep-relaxation tests and creep-fatigue tests.

The identification was performed for the 316 L(N) SS at temperatures going from 20 °C to 600 °C [2]. The corresponding parameters are listed in table 2.

Table 1. Link between state variables and material properties

Material properties	State variables
Elasticity	-
Isotropic hardening Kinematic hardening	R $X = X_1 + X_2$
Cyclic hardening or softening plastic strain memorization	Q
Creep-relaxation	K
Time recovery on isotropic and kinematic variables	R X

Table 2. Viscoplastic identification for the 316 L (N) SS

Material Parameters		20 °C	200 °C	400 °C	600 °C
E	(MPa)	192 000	178 000	161 000	145 000
ν		0.3	0.3	0.3	0.3
k	(MPa)	200	135	95	35
α_R		1	1	1	1
b		20	12	12	12
Q_o	(MPa)	- 30	40	70	40
Q_M	(MPa)	390	460	495	460
μ		19	19	19	19
η		0.04	0.04	0.04	0.04
γ_r	(MPa^{-mr} s^{-1})	0	0	0	2.10^{-7}
Q_r^*	(MPa)	200	200	200	200
m_r		2	2	2	2
c_1	(MPa)	65 000	65 000	65 000	65 000
γ_1^0		1 300	1 300	1 300	1 300
c_2	(MPa)	1 950	1 950	1 950	1 950
γ_2^0		50	50	50	50
a_∞		0.5	0.5	0.5	0.5
γ_{x1}	(MPa^{-m1} s^{-1})	0	0	0	10^{-12}
m_1		4	4	4	4
γ_{x2}	(MPa^{-m2} s^{-1})	0	0	0	2.10^{-13}
m_2		4	4	4	4
k_o	(MPa $s^{1/n}$)	10	10	10	70
α_k		0	0	0	1
n		24	24	24	24
α		0	0	0	0

3 - DESCRIPTION OF THE CALCULATIONS PERFORMED WITH THE VISCOPLASTIC MODEL

The following sections present a few calculations carried out with the elastic-viscoplastic model on mock-ups and specimens for which experimental results were available. The comparison with experiments is mainly based on the number of cycles to failure. This requires a life assessment to be performed and, for this purpose, the inelastic route of the RCC-MR [3] and the continuum damage model also proposed by J.L. CHABOCHE for creep and fatigue damages [2, 4] are used.

3.1 - EVASION mock-ups

3.1.1 - Geometry

The geometry of the EVASION mock-ups is shown in figure 1. Tests were carried out at CEA CADARACHE on two mock-ups : one fully machined and the other one with welded plate-to-shell junction and rolled and welded shell.

3.1.2 - Loading

Both mock-ups have been subjected to 2 500 cycles divided as follows :

* 1 500 cold shocks from 600 °C to 350 °C followed by reheating up to 600 °C and 6-hour hold period (first load history),

* 1 000 additional cold shocks from 600 °C to 200 °C followed by reheating up to 600 °C and 1-hour hold period (second load history).

3.1.3 - Mesh

The mesh of the structure is shown in figure 2. It is a 2D axisymmetric mesh which consists of 194 8-noded and 6-noded quadratic elements.

3.1.4 - Results of the viscoplastic calculation

12 cycles have been computed for the first load history and 15 for the second one.

The most loaded parts of the mock-ups are the groove ring (under compression during the hold period) and the smooth part at the plate level (under tension during the hold period). Figure 3 shows the map of equivalent cumulated plastic strain after the 15 computed cycles of the second load history.

3.1.5 - Results of the life assessment and comparison with experiments

The life assessment is carried out using bestfit data. This means for the RCC-MR analysis that calculations are performed :

* without coefficient 2 and 20 on fatigue curves,
* without coefficient 0.9 on the equivalent stress,
* using the average S_r curve.

Two calculations are performed : one with the parent metal data and the other one with the welded metal data.

The damage due to the first load history is almost negligible.

The results of the life assessment for the second load history are summarized in table 3 and compared with experimental results.

The conclusions of these calculations are the following :

* Both inelastic analyses (continuum damage model and RCC-MR inelastic route) predict the failure of the mock-ups in the groove ring where the presence of cracks is confirmed by destructive tests.

* For the fully machined mock-up, failure is foreseen at around 2 000 cycles whereas no damage is shown by destructive tests at 1 000 cycles of the second load history.

* For the welded mock-up, the RCC-MR alone would predict the failure in the longitudinal weld. The margin is however relatively small and it may be wondered if creep properties of this weld were not close to the minimum values.

Results are therefore very satisfactory when considering that, for design purposes, safety coefficients would be used.

Table 3.EVASION results of the life assessment and comparison with experiments

<table>
<tr><th rowspan="2"></th><th colspan="2">Groove ring</th><th colspan="2">Smooth part</th></tr>
<tr><th>Calculation</th><th>Experiment</th><th>Calculation</th><th>Experiment</th></tr>
<tr><td rowspan="2">Full machined mock-up</td><td>Continuum damage model
(1) N_r = 99
(2) N_r = 260
(3) N_r = 464</td><td rowspan="2">Transgranular cracks Maximum depth is 600 μm after the 1 000 cycles of the 2nd load history</td><td>Continuum damage model
N_r = 2 373</td><td rowspan="2">No damage shown by destructive tests after the 1 000 cycles of the second load history</td></tr>
<tr><td>RCC-MR
(1) N_r = 11
(2) N_r = 134
(3) N_r = 2 380</td><td>RCC-MR
N_r = 2 054</td></tr>
<tr><td rowspan="2">Welded mock-up</td><td>Continuum damage model
(1) N_r = 23
(2) N_r = 104
(3) N_r = 464</td><td rowspan="2">Transgranular cracks Maximum depth is 750 μm after the 1 000 cycles of the 2nd load history</td><td>Continuum damage model
N_r = 1 682</td><td rowspan="2">Macrocospic crack in the longitudinal weld in the outer skin of the shell. Creep mechanism</td></tr>
<tr><td>RCC-MR
(1) N_r = 0
(2) N_r = 11
(3) N_r = 2 380</td><td>RCC-MR
N_r = 964</td></tr>
</table>

N_r Number of cycles to failure in creep-fatigue interaction.

(1) With creep under tension and compression leading to the same damages.
(2) With creep under compression according to RCC-MR addendum November 1987.
(3) With creep under compression non damageable.

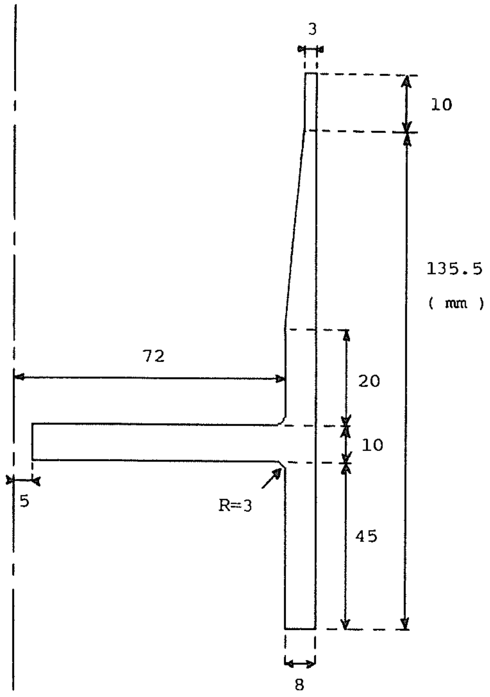

Figure 1 : GEOMETRY OF EVASION MOCK-UPS

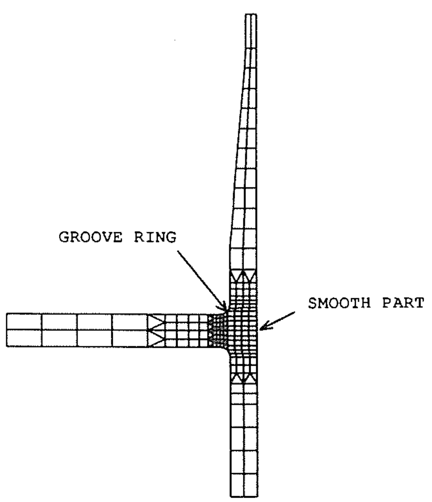

Figure 2 : MESH OF THE STRUCTURE

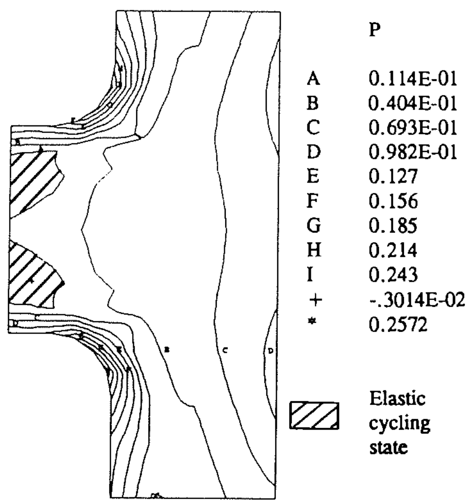

Figure 3 : EQUIVALENT CUMULATED PLASTIC STRAIN MAP (P) (2nd LOAD HISTORY)

3.2 - U-Bend specimens at 600 °C

3.2.1 - Geometry

The geometry of the U-bend specimens is shown in figure 4. Tests were carried out at CEA SACLAY on 15 specimens at 600 °C subjected either to pure fatigue or to fatigue-relaxation loadings.

3.2.2 - Loading

During tests, one extremity of the specimen is fixed whereas a displacement u(t) is imposed at the other one (see figure 4).

Two types of tests will be modelized : tests under pure fatigue at 0.03 Hz (tests 1b, 2b and 3b) and tests under fatigue-relaxation with 30-minute hold period at one extremity of the cycle (tests 5b, 7b, 8b and 9b). In both cases, the value of Δu is 7.24 mm.

3.2.3 - Mesh

The mesh of the specimen is shown in figure 5. It is a 2D plane mesh which consists of 152 8-noded quadratic elements.

3.2.4 - Results of the viscoplastic calculations

20 cycles have been computed for the fatigue loading and 25 cycles for the fatigue-relaxation loading.

The most loaded parts of the structure are point I (at the intrados) and point E (at the extrados).

Figure 6 illustrates the stress distribution at the end of the hold period for the fatigue-relaxation loading.

It is to be noticed that the intrados zone is under compressive stresses during the hold period.

Table 4 summarizes the viscoplastic calculations for both loadings.

It is to be mentioned that during the fatigue tests, a measure of strain variations was made. Experimental values were much larger than calculated ones but the differences were attributed to errors of measurement at such a high level of temperature.

Measurements of variations of forces were also performed during tests. In opposition to previous results, these latter were very close to the calculated values.

3.2.5 - Results of the life assessment and comparison with experiments

The life assessment is carried out, as for the EVASION mock-ups, using bestfit data.

The results of the life assessment are summarized in table 5 and compared with experimental results.

Table 4. Summary of the viscoplastic calculations with the U-bend specimens

	Point I	Point E
Fatigue	$\overline{\Delta\varepsilon}$ = 0,66 %	$\overline{\Delta\varepsilon}$ = 0,62 %
	$(\sigma_{yy})_{max}$ = 291 MPa	$(\sigma_{yy})_{max}$ = 278 MPa
Fatigue-relaxation T = 30 min.	$\overline{\Delta\varepsilon}$ = 0,68 %	$\overline{\Delta\varepsilon}$ = 0,64 %
	$(\sigma_{yy})_{max}$ = 286 MPa	$(\sigma_{yy})_{max}$ = 272 MPa

Table 5. U-Bend specimen - Results of the life assessment and comparison with experiments

	Calculation		Experiments
	Point I	Point E	
Fatigue	Continuum damage model N_f = 2 699	Continuum damage model N_f = 3 794	Tests 1b N_{final} = 4 225 3b N_{final} = 4 649
	RCC-MR N_f = 4 611	RCC-MR N_f = 5 978	
Fatigue-relaxation T = 30 min.	Continuum damage model (1) N_r = 648 (2) N_r = 1 063 (3) N_r = 3 106	Continuum damage model N_r = 803	Test 5b N_{final} = 2 820 Estimation of the number of cycles necessary to reach a crack depth of 0.4 mm is : Intrados : 1 190 Extrados : 1 730
	RCC-MR (1) N_r = 582 (2) N_r = 1 243 (3) N_r = 4 240	RCC-MR N_r = 781	

N_{final} Final number of cycles of the experiment.
N_f Number of cycles to failure in pure fatigue.
N_r Number of cycles to failure in creep-fatigue interaction.

(1) With creep under tension and compression leading to the same damages.
(2) With creep under compression according to RCC-MR addendum November 1987.
(3) With creep under compression non damageable.

Table 6. U-bend specimen - Elastic analyses according to the RCC-MR code

	Point I	Point E
Fatigue	N_f = 1 280	N_f = 1 556
Fatigue-relaxation T = 30 min.	N_r = 241	N_r = 292

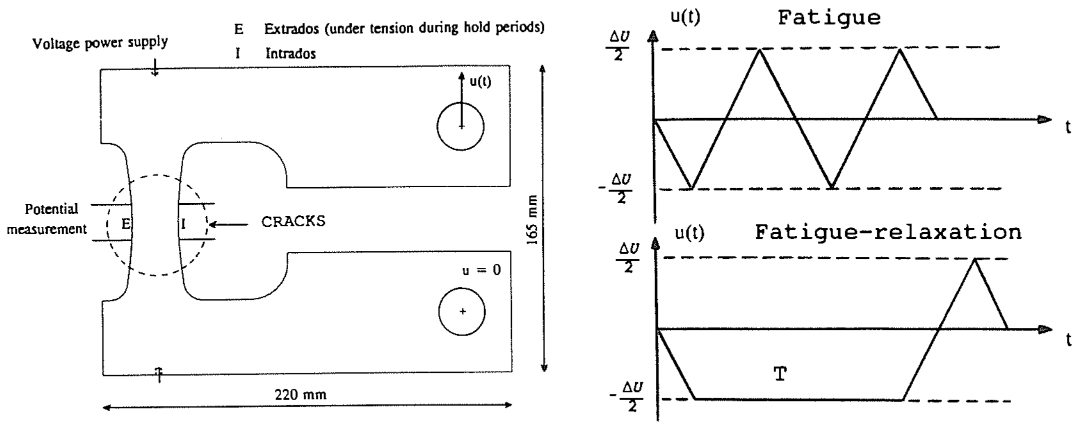

Figure 4 : GEOMETRY OF THE U-BEND SPECIMEN AND LOADING HISTORY

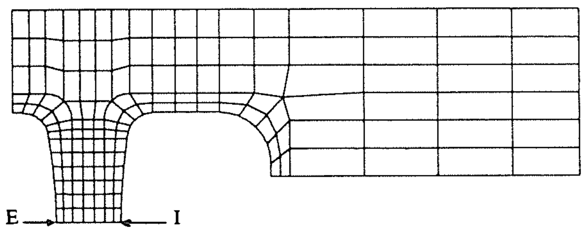

Figure 5 : MESH OF THE SPECIMEN

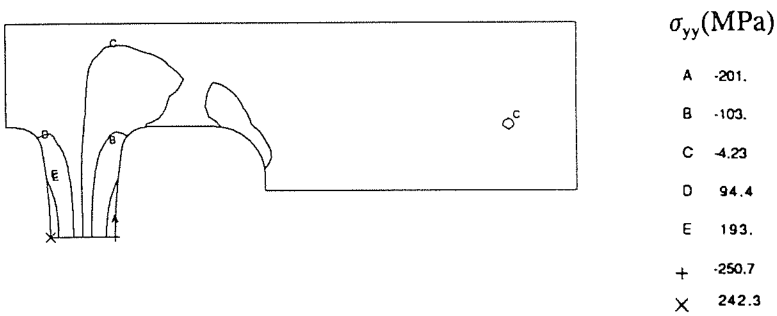

Figure 6 : σ_{yy} STRESS MAP AT THE END OF THE HOLD PERIOD (FATIGUE-RELAXATION TEST)

The conclusions are the following :

* Both inelastic analyses (continuum damage model and RCC-MR inelastic route) give a conservative estimate of the life duration under fatigue and fatigue-relaxation loadings.

* The fatigue-relaxation test confirms the less damaging effect of creep under compression and the necessity to take it into account.

Table 6 shows in addition the result of the corresponding elastic analyses according to the RCC-MR code (bestfit analysis).

The benefit brought by inelastic analysis when compared to traditional elastic analysis is shown to be non negligible.

3.3 - Ratchetting tests

Ratchetting tests have been usually modelized with the elastoplastic model proposed by J.L. CHABOCHE even when the structure was in conditions of significant creep.

The general conclusions as regards the ability of the elastoplastic model to deal with ratchetting is that it gives a good description of the behaviour of the structure but usually overestimates the progressive deformation.

Some works are however presently under way using the viscoplastic model for the modelization of ratchetting tests. This is the case at INSA LYON for the BITUBE mock-up [5] and at NOVATOME for the ECHO tests (carried out at CEA SACLAY), where these tests are aimed to represent ratchetting phenomena with respectively axial thermal gradients and axial thermal moving gradients.

The conclusions concerning the ability of the viscoplastic model to deal with such types of problem should therefore appear more clearly.

4 - STATUS OF THE ELASTIC-VISCOPLASTIC MODEL

Inelastic analyses are likely to be used when dealing with fatigue, creep or creep-fatigue loadings as well as ratchetting phenomena. Examples of application of paragraphs 3.1 to 3.3 show that the viscoplastic model associated with a life assessment route gives good results for fatigue and creep-fatigue problems. This is expected to be less true for ratchetting problems where the progressive deformation is likely to be overestimated.

This means that, for creep-fatigue analyses, the viscoplastic model can significantly help the designer.

This type of calculation presents however two drawbacks.

The first one is that viscoplastic calculations are expensive on the one hand because the number of cycles which is to be computed is usually large and on the other hand because these calculations need a particular attention to convergency problems which is often time-consuming for the designer.

The second drawback is that the viscoplastic model uses 25 parameters which have to be identified with accuracy. This can only be done when sufficient material data are available. This limits of course the generalization of the inelastic calculations with this model.

It is however to be noted that, for material in the non significant creep regime, the elastoplastic model can be used. This means a reduction of the parameters (only 12 parameters are needed) and a simplification of the identification procedure.

As far as ratchetting problems are concerned, the present version of the viscoplastic model is not adapted for design purposes and should only be used for R & D applications.

The designer should therefore use rules for the prevention of ratchetting based on elastic calculations. It may also be possible to use simplified inelastic calculations such as the shakedown method developed in the UK or the ZARKA's method developed in France. However, these approaches have still to be validated for design purposes and should therefore be used with cautions.

5 - FUTURE DEVELOPMENTS

The former paragraphs have outlined that a significant limitation of the present version of the viscoplastic model concerns the ability to deal with ratchetting.

Many persons have been working on how to modify constitutive equations in order to improve the ratchetting calculations. Everyone agrees that the overestimation of the progressive deformation comes from the use of the Armstrong-Frederick equation in the evaluation of the kinematic hardening variables :

$$\dot{X}_i = \frac{2}{3} C_i \dot{\varepsilon}_p - \gamma_i X_i \dot{p}$$

Different approaches have been proposed for the modification of this equation but all of them concern the dynamic recovery term (second term of the equation).

J.L. CHABOCHE proposes [6] to use in addition to the two traditional non linear kinematic variables, one linear kinematic variable and one kinematic variable with a threshold on the dynamic recovery term :

$$\dot{X}_3 = \frac{2}{3} C_3 \dot{\varepsilon}_p$$

$$\dot{X}_4 = \frac{2}{3} C_4 \dot{\varepsilon}_p - \gamma_4 \langle 1 - \frac{X\ell}{J\ (X_4)} \rangle X_4 \dot{p}$$

where <> is the Mac Cauley bracket and J () is the second invariant of the tensor.

This approach is not really different from that proposed by N. OHNO [7] where a critical value of dynamic recovery is introduced :

$$\dot{X}_i = \frac{2}{3} C_i \dot{\varepsilon}_p - \gamma_i H\ (J^2\ (X_i) - r_i^2) \langle \dot{\varepsilon}_p : \frac{X_i}{J\ (X_i)} \rangle X_i$$

where H () is the Heaviside function.

This last equation may be written under the form :

$$\dot{X}_i = \frac{2}{3} C_i \dot{\varepsilon}_p - \gamma_i \langle 1 - \frac{r_i}{J\ (X_i)} \rangle X_i \frac{\langle \dot{\varepsilon}_p : X_i \rangle}{\left| 1 - \frac{r_i}{J\ (X_i)} \right|}$$

which shows that the main difference between these approaches is that, in the OHNO's model, the accumulated inelastic strain rate $\dot{p}$ is replace by

$$\frac{\langle \dot{\varepsilon}_p : X_i \rangle}{\left| 1 - \frac{r_i}{J\ (X_i)} \right|}.$$

NOVATOME will investigate in the following months the possibility to incorporate the modifications proposed by J.L. CHABOCHE in the viscoplastic model implemented in SYSTUS code.

This action should be linked with the implementation in SYSTUS of a procedure of automatic adjustment of time steps in order to facilitate the designer's work.

In addition, NOVATOME will also study the need for using softwares such as COMPVP developed at ONERA or SIDOLO developed by the EMP (Ecole des Mines de Paris) which enable quick identifications of parameters of constitutive laws as well as sensitivity studies of these parameters on uniaxial tests.

6 - CONCLUSIONS

The paper has presented several calculations performed with the elastic-viscoplastic model proposed by J.L. CHABOCHE.

The conclusions of these calculations are that, for creep-fatigue problems, this viscoplastic model coupled with a life assessment route gives good results when compared to experiments and gives a significant benefit when compared with traditional elastic analyses. This model can therefore be used for design applications for this type of problems.

A significant drawback of this model is its unability to deal with ratchetting phenomena. However modifications are proposed by J.L. CHABOCHE in order to improve this point. These modifications listed in the paper should be implemented in SYSTUS code.

In the meantime, for ratchetting problems, the viscoplastic model should only be used for R & D applications.

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