Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997 **LW/4**

Benchmark on a thermal ratchetting test. Comparison of different constitutive models

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ABSTRACT: An experimental program has been performed to study ratchetting on axisymmetrical cylinders with geometrical discontinuities submitted to permanent internal pressure and to cyclic thermal loading. One of these test has been selected to carry on a benchmark in order to compare the ability of different constitutive models to describe the ratchetting behaviour A specific program for material characterization has been realised allowing to fit properly the parameters of the different models. After a description of the test, of the experimental results and of the characterization program, the main results obtained are presented.

INTRODUCTION

Structures of PWR (Pressurised Water Reactors) have to be designed relatively to ratchetting. In the French design code (RCC-M) analysis rules based on elastic evaluation of stresses are proposed. They generally appear to be very conservative. An alternative consists in performing inelastic analyses to justify the design of the structures. For that purpose it is necessary to have validated constitutive models, able to describe accurately the ratchetting behavior. In order to check the conservatism of the design rules and to evaluate the possibilities of different constitutive models an experimental program, named COTHAA, has been carried out.

In a first part, a short description of the test is proposed, and a few experimental results are given. Then the different constitutive models used are described and their identification, based on a specific material characterization program, is presented. Finally the main results obtained through this benchmark are discussed.

COTHAA EXPERIMENTAL PROGRAM

The purpose of this program was to test the behavior of pipes near geometrical discontinuities (parts with different thicknesses) when they are submitted to internal pressure and to cyclic thermal loading inducing difference of mean temperature on both sides of the discontinuity. Different geometries were tested. One of them is presented in Figure 1.

An internal pressure is kept constant all along the test. Thermal transients are realized by heating the mock-up by Joule effect. Due to the geometry, temperature in the thin part increases very rapidly (up to a fixed temperature varying between 250 to 550°C according to the tests) while temperature in the thick part doesn't exceed 100°C. This difference of mean temperature induces high thermal stresses near the discontinuity. The heating time lasts 18seconds, then the mock-up is cooled by natural convection down to 50°C. When this temperature is obtained in the whole structure a new thermal cycle begins.

A profilometry of the mock-up is performed in order to visualize the shape evolution. An increase of the diameter is observed in the thin part, near the geometrical discontinuity. An evolution of the diameter in this area is observed from one cycle to another.

Measurements are made at room temperature and after depressurisation of the sample. These records are performed at the end of cycles number 1, 2 5, 10 and then every 10 cycles up to stabilization is obtained. For all the tests performed, stabilization was obtained within 30 to 60 cycles. An example of experimental results obtained on one mock-up is presented in Figure 2.

About 30 tests have been carried out. A description of these tests is presented in reference [7].

CONSTITUTIVE MODELS

Different constitutive models have been used in this benchmark with this aim of checking their abilities to describe the progressive deformation of the sample.

Three of the models tested are models derived from a Chaboche model, with a modification of the kinematic variable law evolution in order to improve the ratchetting description. The corresponding models are:

- *Chaboche model* [1]: $\dot{X}_i = 2/3\, C_i\, \dot{\varepsilon}_p - \gamma_i\, \varphi(p)\, X_i\, \dot{p}$ (1)

with: $\dot{p} = |\,\dot{\varepsilon}_p\,|$ $\quad \dot{\varepsilon}_p$ = plastic strain rate $\quad \varphi(p) = \phi_s + (1-\phi_s)e^{-bp}$ (2)

The function $\varphi(p)$ is introduced to take account of the evolution of the tangent modulus:

- *Chaboche model coupled with Burlet-Cailletaud proposition* [2] (this model will be named Burlet model from now on):

$$\dot{X}_i = 2/3\, C_i\, \dot{\varepsilon}_p - \gamma_i\, \varphi(p)\, [\, \delta_i\, X_i + (1-\delta_i)(X_i : n)n]\, \dot{p} \qquad (3)$$

with: n = normal to the yield surface $\quad \delta_i$ is a new parameter

This model is a combination through parameter δ of the Chaboche model and of the Burlet-Cailletaud model which introduces a radial evanescence of the dynamic recovery. For the benchmark two kinematic variables are considered and the model is used in an elastic-plastic formulation.

- *Chaboche model modified by Ohno-Wang* [3] (this model will be named Ohno):

$$\dot{X}_i = 2/3\, C_i\, \dot{\varepsilon}_p - \gamma_i\, \varphi(p) \left(\frac{\overline{X_i}}{r_i} \right)^{m_i} < \dot{\varepsilon}_p : \frac{X_i}{\overline{X_i}} > X_i \qquad (4)$$

with: $\overline{X_i} = \sqrt{(3/2) X_i : X_i}$ and $r_i = C_i / \gamma_i \phi(p)$ $\quad m_i$ is a new parameter

$< >$ are the Mac Cauley bracket: $< u > = u$ if $u>0$ and $< u > = 0$ if $u<0$

The modification introduced by Ohno and Wang considers that the dynamic recovery of the variable Xi is fully activated only when its magnitude reaches a critical value r_i. Dynamic recovery is activated non linearly, depending of the parameter m_i, when its magnitude is lower than r_i. For the benchmark two kinematic variables are considered and the model is used in an elastic-viscoplastic formulation including strain memory effect.

- *Guionnet model* [4]:

The main idea of the Guionnet model is the use of an Armstrong Frederick equation (as in Chaboche models) with non constant coefficients C_i and γ_i.

$$\dot{X}_i = m\alpha_1 \left\{ \left[2/3 A\alpha_2 + A_1(\varepsilon_p : n) - (C - C_1\alpha_4)(X_i : n) \right] \dot{\varepsilon}_p - \left[C_0\alpha_3 + C_1\alpha_4 \right] X_i \dot{p} \right\} \qquad (5)$$

α_1, α_2, α_3 and α_4 are functions of two semi discrete variables p_l and p_{lM} which correspond respectively to the cumulated plastic strain from the last loading reversal and between the last two loading reversals (see figure 3). The radial evanescence of variable X_i is also considered. That leads to 11 coefficients for the kinematic variable. Only one kinematic variable is considered and the model is used in an elastic-viscoplastic formulation.

- The fourth model is a *"micro-macro model"* developped at Ecole des Mines de Paris [5]. This model is also presented in [6]. Micromechanical approaches take into account some microstructural informations to describe elementary mechanisms of inelastic deformations. In this approach only cristallographic slip is considered. Two microstructural levels are represented in the model. The constitutive equations are defined on a microscale. They allow to obtain the local slip rate, which is summed up to give the macroscopic plastic strain rate. Due to the modelization, a large number of variables are introduced, but only a low number of material parameters are needed.

The formulation of this model elastic-viscoplastic.

In addition, calculations were also performed with more classical constitutive models such as:

- *elastoplastic isotropic model*
- *elastoplastic linear kinematic model*
- *elastoplastic Chaboche model* derived from the Burlet model by considering δ_i=1. Identification of other parameters is identical.
- *elastoviscoplastic Chaboche model* equivalent to the Ohno model by suppressing the modification introduced. Other parameters have the same value in the two models.

MATERIAL CHARACTERIZATION AND MODELS IDENTIFICATION

A specific material characterization program was undertaken to obtain a good data bank to fit the models parameters. This program included:

- monotonic tensile tests
- cyclic strain controlled tension compression tests for increasing strain ranges: ($\Delta\varepsilon/2$ = 0.15,0.3,0.45,0.6,0.8 and 1%)
- traction-torsion tests for 2 values of tensile stress (80MPa and 100MPa) and increasing shear amplitudes varying between 0.2% to 1.5%.

All these tests were conducted at 20°C, 250°C and 450°C.

Parameters were fitted for the four models presented previously. Identifications were performed for the three temperatures mentionned before. For the numerical calculations, parameters will be interpolated between these values for intermediate temperatures.

The Guionnet and the "micro-macro" models did not consider monotonic tensile tests for the identification. That explains the results presented in figure 4 which shows a comparison of monotonic tensile curve simulations at 450°C. A large overestimation of the monotonic behaviour is predicted with the Guionnet and the "micro-macro" models.

The experimental curve is also represented. The quasi bilinear behaviour of the experimental curve is due to the fact that the mock-ups are annealed after machining. Consequently, characterization tests are also performed on annealed specimens.

Cyclic behaviour is well represented by the four models as shown on figure 5.

Ratchetting simulations on traction-torsion tests are also in relatively good agreement with experimental results (figure 6). Comparisons have been made with the corresponding Chaboche models for Burlet and Ohno models (see figure 7) and it can be pointed out that the modifications introduced in the kinematic variable law evolution (for Burlet and Ohno models) improve considerably the ratchetting prediction.

It must be specified that no main differences are observed between the simulations of the elastoplastic Chaboche model and of the corresponding elastoplastic Burlet model on one hand, and the simulations of the viscoplastic Chaboche model and of the equivalent Ohno model on another hand, for the radial loadings (monotonic or cyclic behaviour).

BENCHMARK RESULTS

Finite element simulations

Calculations were conducted on a mock-up submitted to an internal pressure of 45bars and a threshold temperature of 450°C. Due to the geometry and the loading, axisymmetrical calculations were performed. The mesh used was the same for all the participants and the description of the mechanical and thermal loadings also.

The temperature fields, obtained experimentally by Joule effect, are simulated using a thermo-electric analogy. A good correlation between experimental and calculated temperatures is observed (see reference [7]).

Inelastic calculations have been conducted on a minimum of 5 cycles in order to estimate the progressive deformation predicted by the different models. With the Burlet model and the Guionnet model, 10 cycles have been calculated.

Radial displacement evolution

One of the main objectives of these calculations was to evaluate the radius increase in the thin part of the mock-up and more precisely its evolution with the number of cycles and to compare it with the experimental results.

The figure 8 presents a comparison of the evolution of the radial displacement with the number of cycles in the point of the structure where it is maximal. On this figure are shown the results obtained with the four models described previously: Burlet, Ohno, Guionnet and "micro-macro" models and the experimental results.

It can be seen that the Ohno, Guionnet and "micro-macro" models give a very good estimation of the radial displacement at the end of the first cycle while the Burlet model underestimates it.

The ratchetting rate predicted by the Burlet and the "micro-macro" models is too low.

The results obtained by the Ohno and the Guionnet models on 5 cycles are reasonnably good.

Evaluation at 40 cycles

These different results were used to evaluate the radius increase predicted at 40 cycles. Experimentally the test was stopped at 40 cycles because radial displacement stabilization was obtained.

The extrapolation method used is the rule proposed in RCC-MR [8](French Design code for Fast Reactors).

Calculations being performed on n cycles (with n≥4), strains (or displacements) at N cycles will be evaluated as follows:

$$\varepsilon_N = \varepsilon_n + \frac{n\delta\varepsilon_n}{m-1}[1-4^{1-m}] + \frac{\delta\varepsilon_n}{4^m}[N-4n] \qquad \text{if } N \geq 4n \qquad (6)$$

$\delta\varepsilon_n$ being the strain (or displacement) increment for cycle n and m a coefficient which is evaluated as a function of $\delta\varepsilon_n$ and n.

Using this rule, results presented on the figure 9 were obtained.

Tendencies are the same as before: the Burlet and the "micro-macro" models underestimate considerably the experimental results, while the Ohno and the Guionnet models give very good estimations at 40 cycles. Nevertheless we can observe that the ratchetting rate obtained with these last two models is too large. This overestimation is the fact partly of the constitutive models, which have a tendency to predict a permanent ratchetting, and partly to the extrapolation rule, which can not predict a stabilization of the strains (or of the displacements).

Cyclic behaviour comparisons

Many other comparisons have been made between the different models tested.

Globally they give similar results for stress and strain evolution in a point with the time, or for stress and strain distribution in the structure. General evolutions are similar, but some differences are obtained on the absolute values.

Stress and strain evolutions are found to be very complex near the geometrical discontinuity. Redistribution can occur in the different sections and stress evolutions are no longer radial. So this situation is far from an uniaxial test or even from the traction-torsion sollicitation.

Comparison with other constitutive models

It is also interesting to compare the results obtained with the more classical models. These comparisons are shown on figures 10 and 11. The main conclusions are as follows:

- the linear kinematic model underestimates the results since the first cycle and predicts no ratchetting
- the isotropic model gives rather good results on 5 cycles
- the Chaboche elastoplastic model gives also good results on 20 cycles, but the ratchetting rate is too high. On the first 5 cycles results are almost similar to those obtained with the isotropic model.
- the Chaboche viscoplastic model overestimates considerably the experimental results, since the first cycle. Here again the ratchetting rate is too high.

The results obtained with the viscoplastic Chaboche model and the Ohno model on the Cothaa experiment are coherent with the results obtained with these two models on traction-torsion tests (simulated during the model identification phase).

On the opposite, concerning the elastoplastic Chaboche model and the Burlet model, results are somewhat surprising: on traction-torsion tests, the Burlet model was able to predict very precisely the experimental results, while the elastoplastic Chaboche model always overestimated them. On Cothaa experiments, results are quite different: the Chaboche model is very correct on the first 20 cycles while the Burlet model underestimates the results.

Moreover an important difference is registered between the Chaboche elastoplastic and the Chaboche viscoplastic models. On traction-torsion tests they give similar results while on the Cothaa experiment simulations the results are very different.

In traction-torsion tests stress state is uniform in the sample. This is a situation of "material ratchetting". On the contrary in a structure, like in Cothha mock-ups, loading paths are complex and stress or strain redistributions occur. This is a situation of "structural ratchetting".

Considering these results it can be assumed that:

- there is an influence of the formulation choosen for each model: plasticity or viscoplasticity. Moreover in the viscoplastic model strain memory effect was taken into account and not in the plastic one. Maybe this effect is not negligible.
- traction-torsion tests are not representative of local loadings supported by the structure (which are very complex as found in the calculations) and are not relevant to discriminate the different models. It would be interesting to confront the different models with complex loading

paths as proposed in [9]. In this reference, tests were performed including diagonal paths (with positive or negative slope), bowtie paths (direct or reverse) and hourglass path.

This exercise has been performed and it clearly shows that the Chaboche models (elastoplastic or viscoplastic formulation), the Ohno model and the "micro-macro" model are able to describe all the complex loadings. The Burlet and the Guionnet models predict negative ratchetting for the reverse bowtie path and large overprediction for the direct bowtie path. Some results are presented in [10].

These difficulties to describe complex loading paths can explain some differences obtained on the structure tested.

CONCLUSIONS

Four constitutive models, developped to improve the ratchetting strain prediction, have been used to simulate a ratchetting test on a structure submitted to internal pressure and to thermal transients. The Ohno and the Guionnet models allow to obtain a satisfactory estimation of the radial displacement evolution with the number of cycles though the ratchetting rate is too high. On the opposite the Burlet and the "micro-macro" models underestimate the results.

Some surprising results are observed between the elastoplastic and the viscoplastic Chaboche models. The viscoplastic formulation gives results which are of the same order between the traction-torsion tests and the Cothaa experiment. It is not the case for the elastoplastic formulation.

Moreover it appears that traction-torsion tests, which characterize "material ratchetting"', are not representative of "structural ratchetting" situations. Simulations of complex loading paths point out that the Burlet and the Guionnet models have difficulties to describe the bowtie paths.

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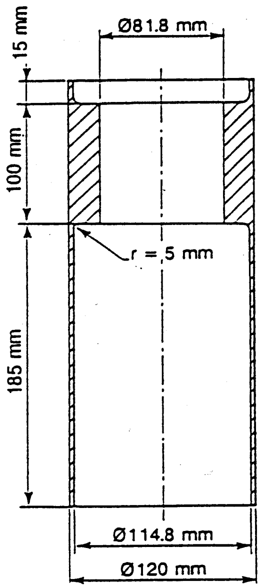

Figure 1
MOCK-UP GEOMETRY

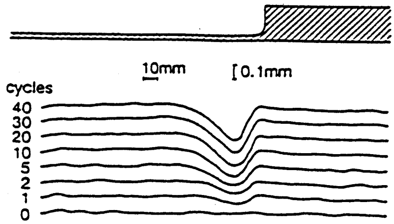

Figure 2 : TEST 8 - PROFILOMETRY

$$P1 = \int_{l(k)}^{M} dp$$

$$P1_M = \int_{l(k-1)}^{l(k)} dp$$

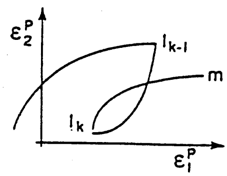

Figure 3 : GUIONNET MODEL

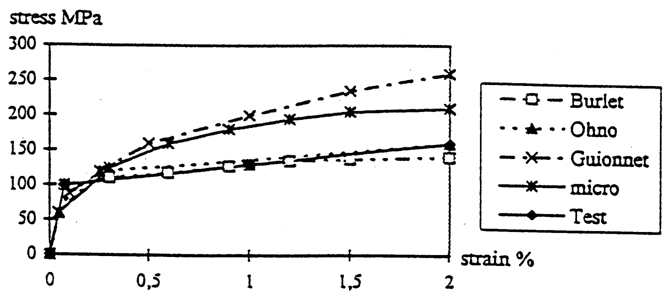

Figure 4: monotonic tensile curve 450C

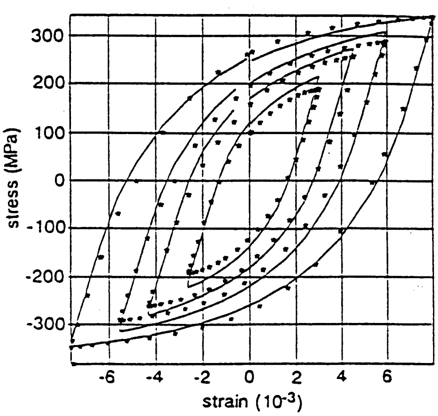

Figure 5
CYCLIC BEHAVIOUR - 450° C
"MICRO-MACRO" MODEL

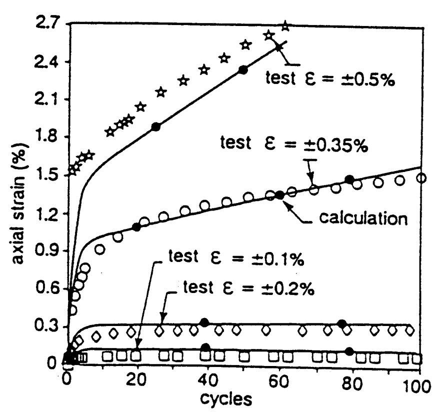

Figure 6
BURLET MODEL
TRACTION-TORSION TEST AT 20°C

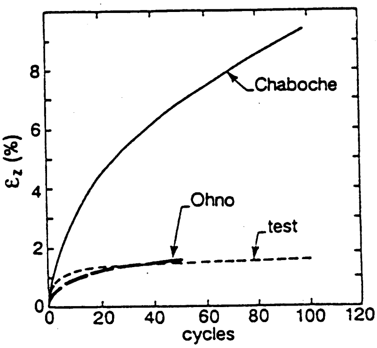

Figure 7
TRACTION-TORSION TEST
AT 450°C - $\varepsilon = \pm 0.2\%$

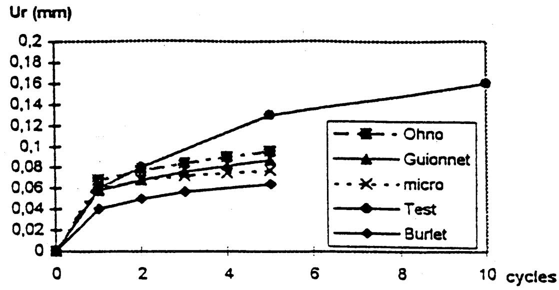

Figure 8: Ur end of cycles

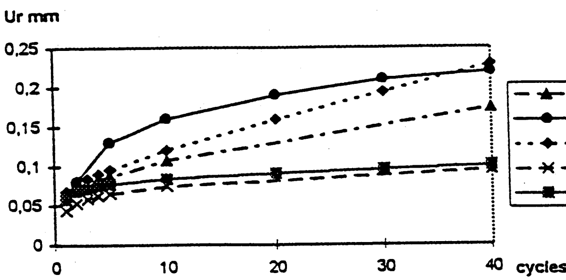

Figure 9: Ur extrapolation at 40 cycles

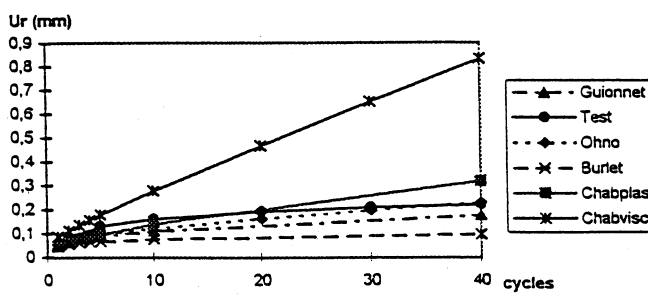

Figure 10:Ur extrapolation 40 cycles

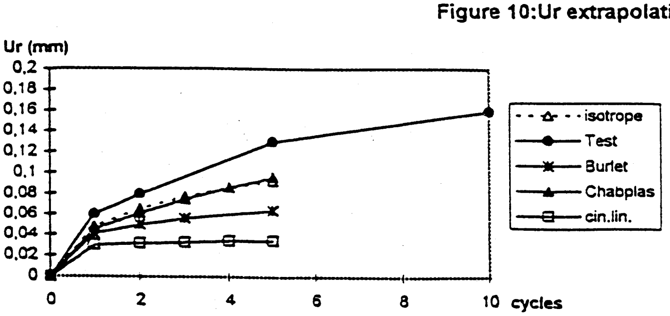

Figure 11: Ur end of cycles