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Evaluation of thermal ratchetting on axisymmetric thin shells at the sodium free level

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ABSTRACT : The ratchetting behaviour of thin-walled cylinders of 316 stainless steel submitted to cyclic thermal loading at the free level of sodium was experimentally studied. Mock-ups were designed in order to obtain stress states similar to those of reactor structures.

After a rapid presentation of the test facility and of the experimental program performed, the main experimental results are summarized.

Then the paper proposes a comparison of the predictions of different simplified elastic methods commonly used in design codes or recently developped to solve this particular situation of ratchetting.

In addition, a few results obtained with complete inelastic analyses using either classic inelastic models or more complex ones are given.

1 INTRODUCTION

Start-up and load variations on FBR type reactors cause level variations in the hot header which load shells emerging in the free level area. Shell loadings are mainly due to the axial thermal gradient, since primary type stress loadings are generally low or insignificant, as are wall thermal gradients.

Repeated cycling (start-up/shutdown, load variations) may cause different types of damage: ratchetting , creep-fatigue, buckling.

Concerning ratchetting , simplified analysis rules used during EFR (European Fast Reactor) project design studies did not allow to justifiy the behaviour of such structures submitted to axial thermal gradients which are both variable in time and mobile in space.

Furthermore, constitutive equation models were very ill adapted for correct modelling of ratchetting. At the time, development studies were under way but had not yet been validated and were not even available. It was therefore not possible to justify the design of the structures through an inelastic analysis.

Bearing these various questions in mind, programmes were initiated in order to study the behaviour of large shells in the vicinity of the sodium free level. The experimental programme VINIL was one of these.

2 EXPERIMENTAL PROGRAMME

2.1 *Experimental layout*

These tests were dimensioned using the enveloppe cycle defined for EFR large shells design studies. Geometrical similarity is obtained by using parameter β (parameter characteristic of shells $\beta = \sqrt[4]{3(1-\nu^2)/R^2e^2}$ with R=radius, e=shell thickness and ν=Poisson coefficient of the material).

Representativity of the different types of damage: ratchetting, buckling and creep-fatigue is obtained by defining an operating cycle such that elastically calculated stress levels are identical on the mock-up and the reactor structure. In order to be representative in terms of creep damage, the maximum temperature value was raised to 620 °C, which causes damage similar to that of reference cycles with much shorter hold times.

The test facility is illustrated in Figure 1. The test mock-up (cylindrical shell) is placed in a sodium filled annular chamber. The chamber is filled by an electromagnetic pump operating permanently at a low flow rate. The sodium level is maintained by means of an overflow system. Level variations are therefore simulated by moving the mock-up vertically with a motorised device. Sodium heating is ensured by 3 pyrothenax type heating elements.

Three different mock-ups were used during the tests. They all had identical geometrical characteristics: diameter=800 mm, thickness=1.2 mm but differed in length and attachment mode. The mock-ups used were as follows:

- "long mock-up", embedded at the top, and on which the length between the free level position and the restraint exceeds the shell decay length,
- "short slotted mock-up", with a free upper end and an emerging length which is lower than the shell decay length. Four 35 mm long slots have been made in the upper part in order to limit the emerging area's rigidity whilst keeping a sufficient length for significant thermal loading,
- "short slotless mock-up", similar to the previous one but without slots. This mock-up is very interesting since its' upper part is free and its emergent area is shorter than the shell decay length.

This last mock-up is the most representative of real reactor conditions.

Very extensive thermocouple instrumentation permits precise measurement of thermal fields to which the mock-up is submitted.

A specific metrology bench was developed in order to monitor structure deformation. This device measures 200 points per circumference with an axial pitch of 2 mm in the studied area.

2.2 *Loading*

The operating cycle must simulate temperature and sodium level variations of a real reactor operating cycle. The sodium temperature passes from 200 °C at the beginning of the cycle to 620 °C. It is maintained at this temperature for 50 mn, then cooled down to 200 °C.

The test shell must simultaneously be moved vertically in order to simulate sodium level variations (see Figure 2). When the sodium temperature reaches 620 °C, the shell is pushed down in order to simulate the increase in sodium volume. This position is maintained throughout the 620 °C temperature hold. The shell is then raised during the sodium cooling phase. A time interval is added when the cold·temperature is reached in order to thoroughly cool the whole mock-up.

3 EXPERIMENTAL RESULTS

Results concerning the long shell have already been described (Ref. 1 and 2). The following paragraphs will therefore describe results obtained for the two short mock-ups. These tests were spread over several campaigns. At the end of each campaign, a series of measurements were performed.

The short slotted mock-up was submitted to 2 campaigns of 12 and 73 cycles, i.e. a total number of 85 cycles.

The short slotless mock-up was submitted to one single 56 cycles campaign.

Measurements underlined, for both mock-ups, a preferential deformation on a O mode, i.e. radius reduction in the free level area. Figure 3 illustrates the profilometry on the short slotless mock-up's generating line at the end of the test. The following was observed:

- a reduction of radius ΔR of approximately 0.3 to 0.4 mm (i.e.circumferencial strain ε_θ approximately 0.075 % to 0.1 %) with a stabilisation of the deformations in less than 12 cycles for the short slotted mock-up.
- A Fourier series analysis was performed for measurements made before and after the tests, on both mock-ups, in order to evidence possible shell buckling. Results were identical for both shells and no buckling was observed.

4 INTERPRETATION

The results of these tests were used in order to evaluate available ratchetting analysis methods. In a first step simplified elastic or elasto-plastic analysis methods were tested, then complete inelastic calculations over several loading cycles were performed with different constitutive models, in order to assess their abilities to describe ratchetting behaviour.

4.1 Simplified elastic or elasto-plastic analyses

The thermal calculations, which take into account conduction and convection exchanges with sodium and argon, as well as sodium temperature variations and level variations, evidence an excellent correlation with temperatures recorded during tests.

Elastic mechanical calculations were conducted on the basis of this thermal data using A3-1S RCC-MR material data. Concerning the short slotted mock-up, the presence of slots is taken into account by considering a material with zero circumferential rigidity in the corresponding area.

Axial and circumferential stresses evolve in the free level variation area throughout the cycle. Axial stresses are mainly bending stresses whereas membrane is preponderant for circumferencial stresses. For both mock-ups, maximum stress variations are obtained on the shell's outer skin, slightly below the upper sodium level. Figures 4 and 5 show the evolution of axial and circumferential stresses on the outer skin for the slotless mock-up at the 2 transient moments considered as dimensioning cases.

Elastic stress results are then used in order to assess the risk of ratchetting by means of various existing methods. The following conclusions were drawn:

- The efficiency diagram method (RCC-MR, edition 1987) and the Bree diagram based method (Case Code) are not applicable in the absence of primary stress loading.
- The lower bound shakedown method is not applicable since the whole thickness of the shell yields.
- The upper bound shakedown method (Ref. 3) uses specific diagrams for shells submitted to an axial thermal gradient which is variable in time and mobile in space. This method defines the boundary between plastic shakedown and ratchetting, as a function of a parameter F which measures the severity of the thermal gradient variation.
  The point (C,T) corresponding to the structure's maximum loading is then placed on the diagram in order to locate the area in which it is found. C and T represent standardised (Tresca) mechanical and thermal stresses, respectively.
  This method foresees thermal ratchetting (see Figure 6) which seems far too conservative in the light of experimental results.

- The RCC-MR "3 Sm" alternative rule is observed for both mock-ups, but is only theoretically applicable in the absence of significant creep. It therefore cannot be used for hot header shell design.
- "Japanese method"
  References 4 and 5 proposed a method to evaluate progressive deformation increment per cycle, and final stabilised deformation. Applied to the "long mock up" (Ref. 1), final circumferencial deformation was overestimated by far: ε_θ of approximately 1.8 %, whereas the experimental value was lower than 0.45 %.
  New contributions have been made to this method (Ref. 8).
  The progressive deformation increment per cycle is given by

  $$|\varepsilon_R| = (\phi + 1)\gamma_0^{N-1}\left(|\sigma_{\theta,el}| - \sigma_y\right)/E$$

  ϕ and γ depend on the length on which axial gradient moves, and N represents the number of cycles.
  Applied to the two short mock-ups, this method gives very satisfactory results. Final circumferencial deformation was evaluated at 0.146 % and 0.259 % for the slotted mock-up and the slotless mock-up, respectively, with stabilisation in approximately 20 cycles (experimental value ~ 0.1 %).

❒ Extension of the efficiency diagram method.
The efficiency diagram method developed in RCC-MR, Edition 1987 cannot be used for this type of problem. Recent work has however permitted the generalisation of this approach (Ref. 2 and 7). The main idea consists in considering the true mean stress working during the first cycle as primary stress P* for the application of the efficiency diagram. The classic efficiency diagram rule is then applied.
This evaluation is based either on an elastic calculation using an elastic follow up coefficient to assess real stress, or on a first cycle elasto-plastic calculation. The second approach was chosen for the interpretation of Vinil test results.
The following results were obtained:
- for both shells, the limitation of efficient primary stress to 1.2 S_m or to 1.8 S_m was observed. The same is observed for the limitation of the creep usage rate.

Considering experimental results obtained, this conclusion seems satisfactory.

4.2 *Inelastic analyses*

Inelastic calculations were performed on the short slotless mock-up using 2 constitutive equation models:

- isotropic plastic model + strain hardening creep law (from RCC-MR-A3-1S)
- Chaboche's visco-plastic model.

With the first model, stabilisation is achieved in 3 cycles. With Chaboche's model, 6 cycles were calculated, however, strain stabilisation is not always achieved.
The following conclusions were drawn:

❒ The 2 models effectively forecast the radius reduction in the free level variation area, in compliance with experimental results.

❒ The isotropic model cannot be used to model the progressive deformation phenomenon. Stabilisation is achieved as soon as the 2nd cycle (Figure 7) and for far too low strain values. The radius reduction obtained equals 0.035 mm at stabilisation (experimental value: 0.3 mm).

❒ The influence of creep in uncoupled models is insignificant, for this particular case of structure and of loading.

❒ Chaboche's model gives a qualitative representation of the ratchetting phenomenon (Figure 8). However, it cannot be envisaged to continue calculations up to stabilisation.
By coupling this model with the RCC-MR extrapolation method, it is possible to assess cumulated strains for N cycles using results from the inelastic calculation over n cycles ($n \geq 4$).
This approach produces very good results. The ε_{final} is evaluated at 0.082 %.
The experimental value for this mock-up was $\varepsilon_{final} = 0.075$ %.
In this specific structure and loading configuration, the approach which consists in coupling Chaboche's visco-plastic model with the RCC-MR extrapolation method produces very satisfactory results.
Other constitutive models will be tested as soon as they are available in finite element codes.

5 CONCLUSION

Tests performed on VINIL mock-ups evidence a major deformation corresponding to the reduction of the radius in the free level variation area.

Considering elastic analysis methods, both the "Japanese method" and "modified efficiency diagram method" provide satisfactory results.

Concerning inelastic analyses, Chaboche's model is the only one which allows to describe the ratchetting phenomenon in a satisfactory way. Other models will be tested as soon as they are available in finite element code.

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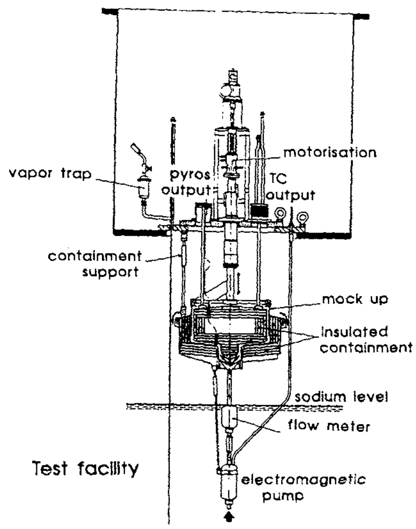

Figure 1

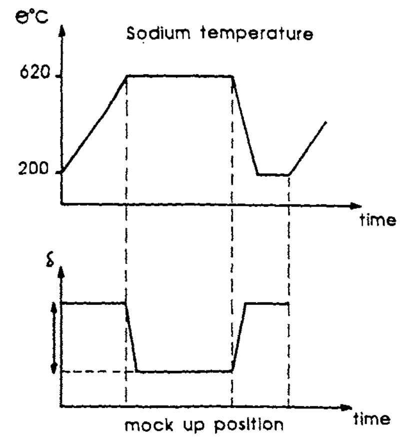

Figure 2

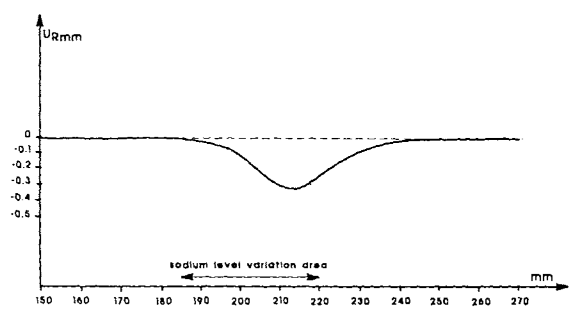

Figure 3 Deformed shape after test

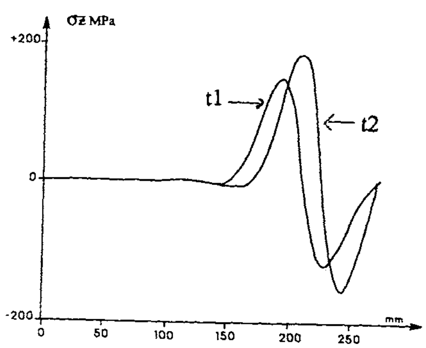

Figure 4 Axial stress on outer skin

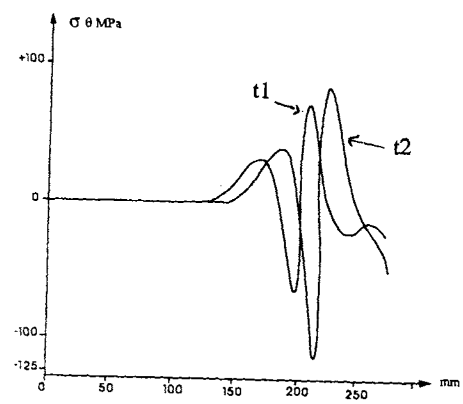

Figure 5 Circumferencial stress on outer skin

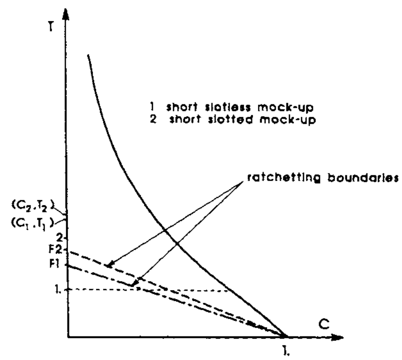

Figure 6 SHAKEDOWN METHOD - UPPER BOUND

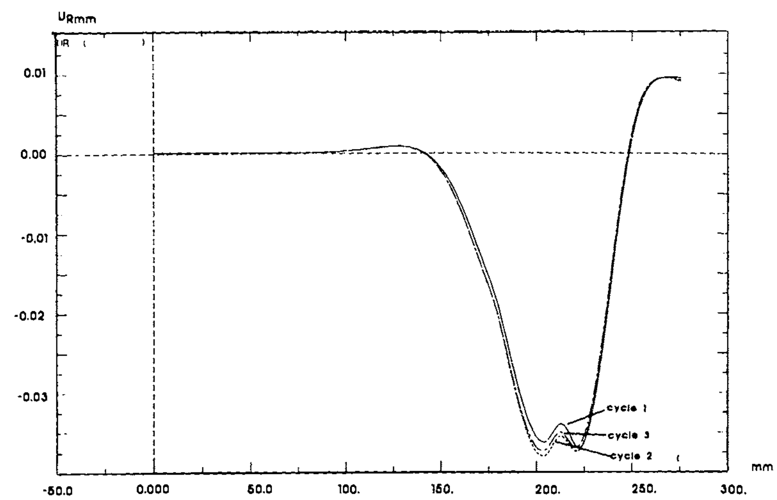

Figure 7 ISOTROPIC MODEL Radial displacement at the end of each cycle

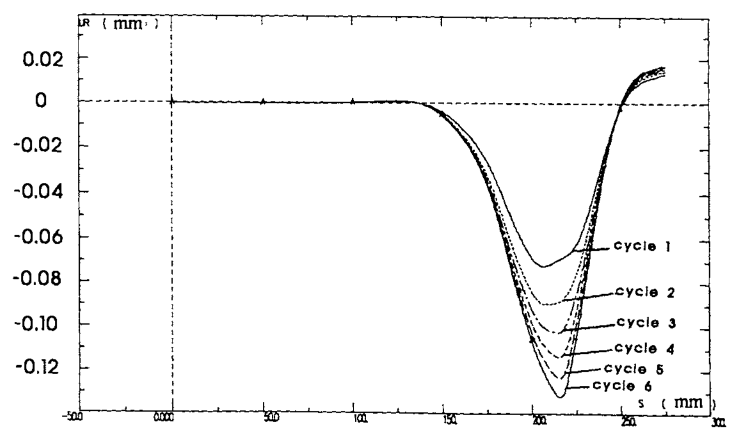

Figure 8 CHABOCHE VISCOPLASTIC MODEL
Radial displacement at the end of each cycle