

Assessment of the Creep-Fatigue Damage by the Elastic Route of the RCC-MR Some Lessons Drawn from in Sodium Test

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1. INTRODUCTION

One of the major problems encountered in fast breeder reactor internal structures design is the creep-fatigue problem. In its first edition in 1985, the French design code RCC-MR produced by EDF, NOVATOME and CEA proposed rules for evaluating creep-fatigue damage. These rules were largely based on ASME methods and code case N47, and on some developments of French R and D programs. New experimental programs carried out to study some special points for structures operating at high temperature have been completed, and have led to revision to existing codes. These modifications are dealt with in the first addendum to RCC-MR, published in 1987.

This communication summarizes the various modifications to the creep-fatigue rules as a result of specific tests.

2. CREEP-FATIGUE ANALYSIS METHOD - 1985 EDITION

Our intention here is not to describe the complete analysis method, but simply to set down the main concepts. Figure 1 diagrammatically shows the procedure to be followed.

- We refer only to elastically calculated local stress values.
- Deformation increases due to plasticity are obtained by means of coefficients K_ϵ and K_ν the first to take account of plastic redistribution, and the second to take account of variations of Poisson's ratio.
- The fatigue damage evaluation procedure is identical, regardless of whether or not creep is significant. One corrective term only ϵ_f is involved for creep-fatigue interaction cases increasing the strain range.
- The fatigue usage rate is evaluated by using continuous fatigue curves (without hold time).
- Fatigue and creep damage are evaluated independently and then combined using the interaction diagram.

The application of this method to industrial cases often gives very conservative creep-fatigue damages estimates, for various reasons. Some reasons for excess conservatism are :

- The combination of primary and secondary stresses. The proposed method, the scalar addition of two types of stresses, is very severe in some cases. It is also necessary to be able to correctly identify primary stresses without excessively overestimating them.
- Neglecting stress relaxation during hold times. In the 1985 edition, the stress σ_k is assumed to be constant during the entire hold time period.
- Multi-axial creep criterion. The Von Mises criterion, used to evaluate creep damage, does not consider the less damaging effects of compressive stresses in creep.

3. TESTS CARRIED OUT

Special tests were carried out at the CEA to study all these problems on representative structures. These tests are :

- EVASION (references 1-2) : thermal shocks on a plate to shell junction mock-up. This model can be used to study the following problems : elastic follow up, stress relaxation, multi-axial creep.
- THERMINA (reference 3) : thermal shocks on a plate to shell junction mock-up in the presence of primary stresses. Problems encountered are : the classification of stresses, combination of primary and secondary stresses and stress relaxation during the hold times.
- MARINA (reference 4) : creep study in the presence of a biaxial compressive stress condition. This model is a thick cylinder subjected to a cyclic radial thermal gradient : the hot skin subjected to

creep, is in a biaxial compressive stress state whereas the cold skin which is below the creep range is in a biaxial tensile stress state.

4. INFORMATION DERIVED FROM THE TESTS

4.1 Stress classification

4.1.1 Primary stresses

The THERMINA tests were designed to study creep-fatigue interaction in the presence of primary stresses. Two types of samples were tested (see figure 2). An axial force produces membrane stresses only on sample 1, whereas it produces significant bending stresses on sample 2. The primary loads applied to the two samples were defined as a function of elastic calculations to produce :

(P_m + P_b) sample 2 = 1.5 (P_m) sample 1

Tests were carried out for the following values :

Loading case	I	II	III
Sample 1 (P _m) MPa	50	100	140
Sample 2 (P _m + P _b) MPa	75	150	210

Designing the samples using the 1985 RCC-MR requirements and using best fit curves gives a very small number of cycles N_R to initiate cracks.

Case 0 corresponds to a loading case without primary stresses.

Loading case	0	I	II	III
N _R sample 1	75	14	2	< 1
N _R sample 2	75	6	< 1	< 1

The first experimental results have shown that this analysis was much too conservative (crack initiation detected after about 100 cycles for loading case III), and also that damage was lower on type 2 samples than on type 1 samples, contrary to predictions.

Due to these results, we tried to determine the nature of the stress (primary or not) generated by the axial force on sample type 2. Various calculations were carried out for this purpose :

- Elastoplastic calculations with various constitutive equations using either the monotonic curve or the reduced cyclic curve for the material behaviour.
- Creep calculations.
- Use of a method developed by NOVATOME consisting of gradually reducing the elastic limit of the material using a dummy thermal load, while constantly checking the total energy. The variation is stopped when this latter has doubled. In the presence of a primary load, the system energy increases as the elastic limit reduces. This is not the case for a purely secondary load.

All these calculations demonstrate that bending stresses due to an axial force redistribute themselves throughout the section and therefore do not have a primary nature (figure 3).

A new evaluation using the results of these calculations as primary stresses gives the following :

Loading case	I	II	III
N _R sample 2	19	4	1

This gives results which are still too conservative, but which are consistent between the two types of samples.

4.1.2 Secondary stresses

Elastic calculations were carried out on the EVASION and THERMINA mock-ups, in the absence of primary stresses. The only loading case considered was thermal shock, and the stress relaxation was evaluated during hold times.

It was noted (figures 4 and 5), that although the loading is purely thermal, and is therefore considered to be secondary, the relaxation rate obtained by the finite element calculation is lower than that obtained in the case of a purely uniaxial relaxation evaluated under the same conditions. This is typical of the elastic follow up effect and must be considered in the elastic design of the structure.

4.2 Combination of primary and secondary stresses

Creep damage, and additional creep strain ε_f, are calculated as a function of a stress σ_k obtained by the scalar addition of primary and secondary stresses.

$$\sigma_k = \text{Mean } P + K_s \Delta\sigma^*$$

Since creep rupture times decrease very quickly as the stress increases, the primary stress in this combination has a very high effect on the creep-fatigue life.

Plastic calculations on the THERMINA samples were used to evaluate the stress value at the beginning of the hold time for the various loading cases considered. Two different constitutive equation models were used :

- linear kinematic model,
- Chaboche's non-linear kinematic model.

These values were compared with the σ_K values obtained by the scalar addition of primary and secondary elastic stresses. Figure 8 shows the results obtained. It will be noted that values of σ_K calculated from the elastic analysis are much higher than those obtained from plastic calculations. This leads to estimations of creep rupture time which are much too severe.

A large difference is observed between the two plastic models for low levels of primary load. If there are no primary stresses, the hold time corresponds to a residual stress condition close to $\epsilon = 0$. In this case, the linear kinematic model significantly underestimates the stresses, whereas Chaboche's non-linear model allows symmetrisation of stresses and therefore produces a higher stress during the hold time. This difference reduces as the primary stress is increased (see figure 9).

4.3 Effect of multi-axial conditions on creep

Creep damage is evaluated as a function of the Von Mises stress.

The application of this criterion to MARINA (reference 6) and EVASION models gives excessively conservative predictions when the hold time stresses are compressive stresses.

On MARINA, the elastic analysis carried out using RCC-MR 1985 requirements predicts crack initiation at 95 cycles using the best fit curve and after 4 cycles using the design curves, whereas experimental results showed that no crack initiation had occurred after 1600 cycles (conservativeness factors of 17 and 400 respectively).

On EVASION, the analysis predicts much higher damage in the groove ring (figure 11). Experiments show that there is actually obvious damage in the external part. In the groove ring a detailed destructive analysis would be necessary to draw any conclusions. In any case, the comparative conditions of the two zones should be interpreted in multiaxial terms since the stress sensor tends to be compressive in the groove ring and tensile in the outer skin.

4.4 Conclusions of the experimental program

Performing specific tests and interpretation calculations has allowed us to identify various reasons for the excessively conservative nature of analysis based on the RCC-MR :

- Stress classification problem.
- Stress relaxation during hold time is neglected ; this problem brings up the problem of evaluating the elastic follow up effect.
- Combination of primary and secondary stresses.
- Consideration of multi-axial conditions in evaluating creep damage.

Various modifications have been suggested and introduced in RCC-MR (1987 Addendum) to reduce this excess conservatism.

5. ADDENDA OF THE RCC-MR

5.1 Stress relaxation

The new version of RCC-MR allows evaluation of secondary stress relaxation. The initial value of these stress is $\sigma_r = K_s \Delta\sigma^*$ and the relaxation rate is : $\dot{\sigma}_r(t) = -E \dot{\epsilon}_c / C_r$

where C_r is a coefficient for the elastic follow-up effect and triaxial conditions. This coefficient is taken to be 3.

$\dot{\epsilon}_c$ is the creep deformation rate for stress σ_r .

Figures 4 and 5 compare the values of σ_r thus obtained with those derived using inelastic calculations (for EVASION and THERMINA tests respectively).

It is observed that this method gives a conservative estimate of the stress with time.

5.2 Combination of primary and secondary stresses

A new method of combining primary and secondary stresses was introduced in the RCC-MR : the stress σ_K is the stress on the reduced cyclic curve corresponding to the sum of the strain ϵ_p due to the primary stress Mean P and ϵ_s due to the secondary stress $K_s \Delta\sigma^*$ respectively (see figure 6).

This proposal was tested :

- Firstly, on tension-torsion tests : the stress σ_K thus obtained is compared with the equivalent stress σ_{VM} determined from experimental results (see figure 7).
- Secondly, on THERMINA tests. The stress σ_K obtained using this method is compared with the stress σ_{VM} obtained at the beginning of the hold time by the plastic calculations described in section 4.2 (see figure 8).

In both cases, it is noted that this stress combination method provides a conservative value of σ_K , either compared with experimental results, or compared with numeric results, but the excessive conservatism obtained using scalar addition is reduced.

5.3 Multi-axial creep criterion

A new criterion was adopted in the RCC-MR to take account of the less damaging effect of compressive stresses in creep. This criterion is a combination of the Von Mises stress and the hydrostatic stress :

$$\sigma_{eq} = \frac{2(1+\nu)}{3} \sigma_{VM} + \frac{1-2\nu}{3} \text{tr}(\sigma)$$

It can be noted (figure 10) that it gives results which are very close to the Huddleston criterion (reference 5).

Studies carried out to justify the use of this criterion are described in another SMIRT communication (reference 6).

6. APPLICATION OF THESE RULES TO TESTS

The life of THERMINA samples has been re-estimated using the new requirements described in 5.1 and 5.2 ; in other words, considering stress relaxation during hold times and the new combination of primary and secondary stresses.

This leads to the following results (using the best fit curves) :

Loading case	0	I	II	III
N _R Edition 1985	75	14	2	1
N _R Edition 1987	310	212	115	62

Experimentally, cracks of about 150 μm are observed after 107 cycles for case III, 300 to 400 μm after 350 cycles for case II, and 200 μm after 530 cycles for case I.

It is difficult to determine the number of cycles at initiation experimentally. This could be carried out by more precise metallographic examinations. However, it appears that the accuracy obtained using the new requirements are more in accordance with experimental results.

Similarly, the use of a multi-axial creep criterion for the MARINA model reduces the excess of conservatism of the Von Mises criterion, and is closer to experimental results. An application is planned on the EVASION model during 89, which should have the same tendency.

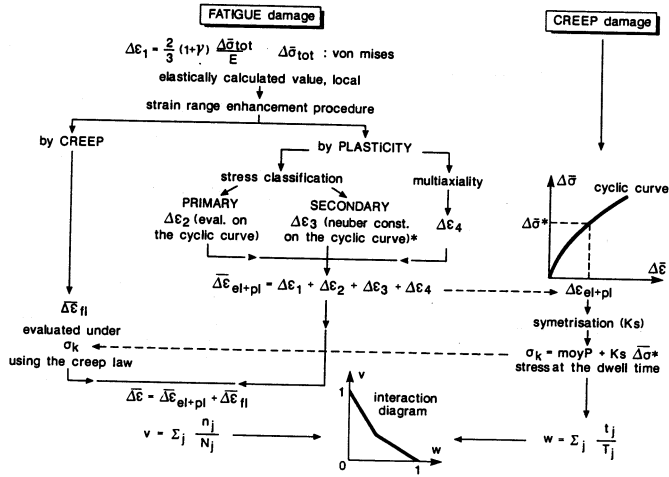
7. CONCLUSIONS

The 1985 version of the RCC-MR gave practical rules for the evaluation of creep-fatigue damage. Specific tests were carried out to reduce the excessive conservatism of some rules. Interpretation calculations were carried out in parallel. This resulted in the proposal for new rules which provide a better estimate of creep-fatigue damage.

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- [6] M.T. CABRILLAT - Ph. MARTIN
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RCC-MR (JUNE 1985) CREEP FATIGUE
ELASTIC ROUTE



* non mandatory for that part of $\Delta\epsilon_1$ which is strictly determined by kinematics

Figure 1

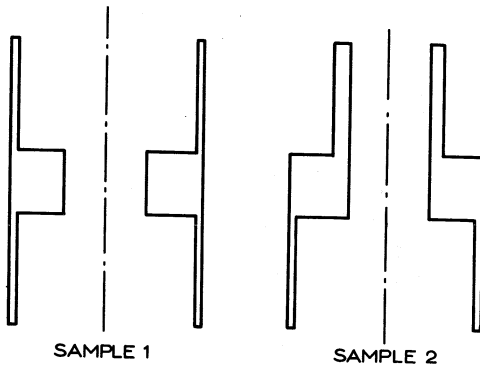


figure 2

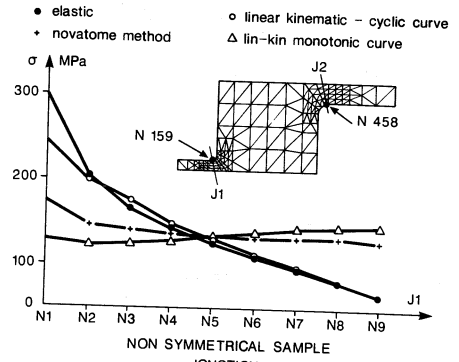


Figure 3

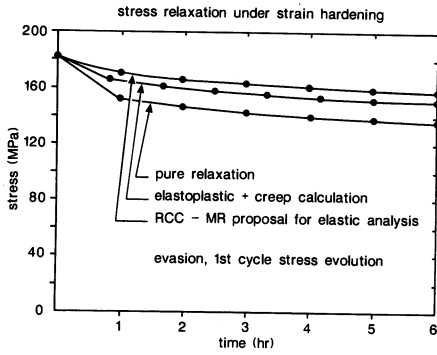


Figure 4

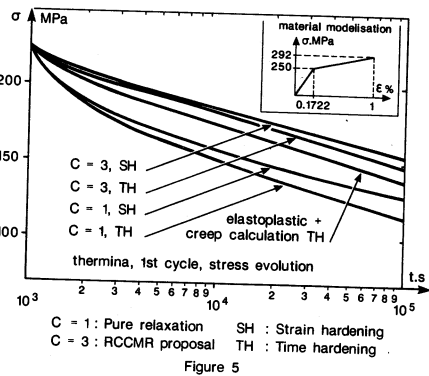
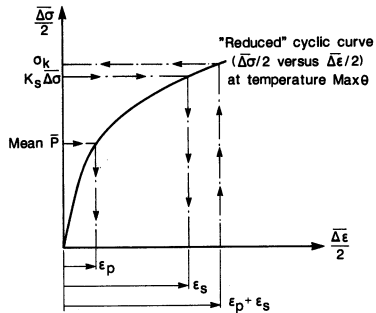
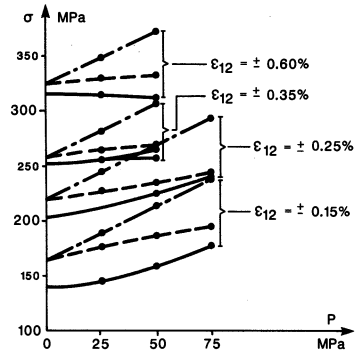


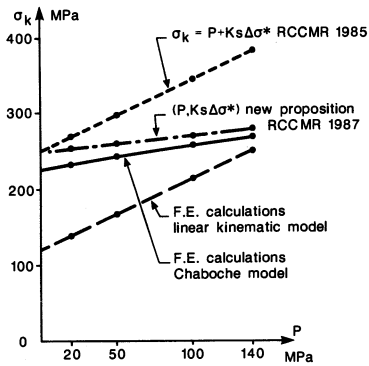
Figure 5



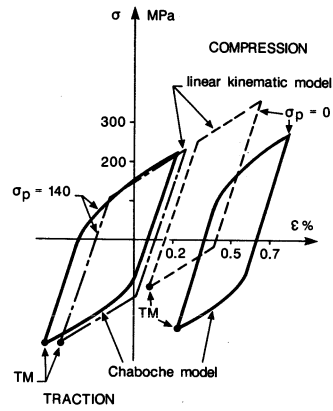
NEW DETERMINATION OF σ_k
 (RCC-MR, First addenda, Nov.1987)
 Figure 6



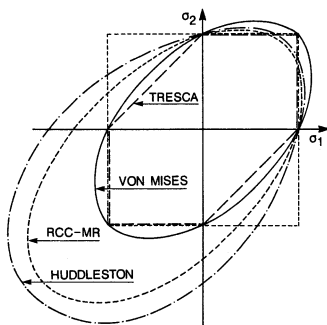
— experimental values
 - - - σ_k RCC MR 1987
 - - - σ_k RCC MR 1985
 TRACTION-TORSION TESTS
 Figure 7



THERMINA
 Figure 8



TM : hold time position
 Figure 9



TRESCA : $\bar{\sigma}_{TR} = \text{Max} [|\sigma_2 - \sigma_1|, |\sigma_1 - \sigma_3|, |\sigma_3 - \sigma_2|]$

VON MISES : $\bar{\sigma}_{VM} = (1/2) \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$

RCC-MR, addenda Nov. 87 : $\bar{\sigma}_{RCC} = 0.867 \sigma_{VM} + 0.133 (\sigma_1 + \sigma_2 + \sigma_3)$
 (Austenitic steels)

HUDDLESTON : $\bar{\sigma}_{HU} = \bar{\sigma}_{VM} \exp [0.24 \left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}} - 1 \right)]$
 (Austenitic steels)

COMPARISON OF SOME STRESS CRITERIA ($\sigma_3 = 0$)

Figure 10

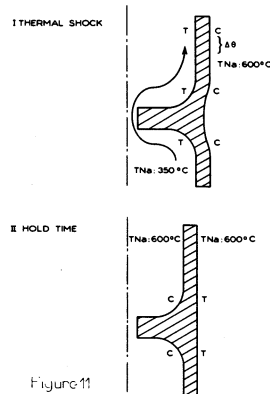


Figure 11