Validation of a New Multiaxial Criteria for Creep-Fatigue Damage Evaluation

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1. INTRODUCTION

For many years, design codes (code case N47 and more recently RCCMR) evaluated creep damage using the Von Mises criterion to take account of multiaxiality of stresses.
However, recent studies have confirmed that the Von Mises criterion is overconservative for nonuniaxial stress state.
Various criteria have been put forward to take account of the real stress state.
This paper describes a criterion which was introduced in the new version of RCCMR in 1987 and the various studies which led to its adoption.

2. REVIEW OF VARIOUS CRITERIA

Reference 1 contains a review of various multiaxial creep criteria. The present paper is restricted to a small number of criteria which will be compared with Von Mises criterion.

2.1 ORNL model (ref. 2)

This model combines the Von Mises stress $\bar{\sigma}$, the hydrostatic stress $J_1/3$ and the maximum principal stress. Introduction of the hydrostatic stress allows to take account of the less damaging effect of compressive stresses.

$$\sigma_e = \frac{3}{2} S1 \left[\frac{2\bar{\sigma}}{3 S_1} \right]^a \exp \left[b \left(\frac{J1}{S_s} - 1\right)\right]$$

With : $J_1 = \sigma_1 + \sigma_2 + \sigma_3$

$$S_s = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$$

$$S_1 = \sigma_1 - J_1/3$$

Parameters a and b are material dependent parameters. Tests have been carried out on various materials leading authors to adopt values a = 1.0, b = 0.4 for 304 and 316 austenitic steels and for inconel.

The criteria then simplifies to :

$$\sigma_e = \bar{\sigma} \exp \left[b \left(\frac{J1}{S_s} - 1\right)\right]$$

Figure 1 compares this criterion with the Von Mises criterion.

2.2 "Ecole des Mines de Paris" proposal (ref. 3)

The authors have proposed a criterion which is a linear combination of the Von Mises stress and the hydrostatic stress.

$\sigma_{eq} = (1 - c)\,\sigma_{VM} + C\,Tr\sigma$

This criterion is actually a special case of the Hayhurst criterion which is a combination of the three stress invariants.
The authors had initially chosen a value $c = 0.25$ for use with 316 steel but had concluded that this value was too high.

2.3 Restoration of elastic energy criterion (ref. 4)

$$\sigma_{eq} = \sigma_{VM} \left[\frac{2}{3} (1 + \nu) + 3 (1 - 2\nu) \left(\frac{\sigma_H}{\sigma_{VM}} \right)^2 \right]^{1/2}$$

The triaxial stress condition appears in the term σ_H/σ_{VM}. However this criterion does not distinguish between tensile and compressive conditions.

2.4 New proposal

Von Mises plasticity criterion only refers to shear energy, shearing being the main mechanism acting in plastic strains. Creep damage is sensitive to shear strain energy but also to volume dilatation energy, because increases in cavities and cracks are sensitive to hydrostatic stress and strains.
A creep criterion could therefore be written as follows in the linear elastic range :

$$\sigma_{eq} = E\,(\varepsilon_{VM} + \varepsilon_H)$$

With : $\varepsilon_{VM} = \frac{2\,(1 + \nu)}{3} \frac{\sigma_{VM}}{E}$

And : $\varepsilon_H = \frac{1 - 2\nu}{E} \sigma_H = \frac{1 - 2\nu}{E} \frac{tr\sigma}{3}$

Then : $\sigma_{eq} = \frac{2\,(1 + \nu)}{3} \sigma_{VM} + \frac{1 - 2\nu}{3} tr\sigma \quad (1)$

For $\nu = 0.3 \rightarrow \sigma_{eq} = 0.867\,\sigma_{VM} + 0.133\,tr\sigma$

For uniaxial tension, this gives : $\sigma_{eq} = \sigma$
It can also be noted that this criterion is equivalent to that proposed in 2.2 with $c = 1(- 2\nu)/3$. This value is lower than the value of 0.25 and therefore is closest to experimental results.
This new criterion as expressed in (1), and generalized for creep was introduced in addenda to RCCMR in 1987, under the name of $\hat{\sigma}$.
Figures 1, 2 and 3 compare the various criteria. It will be noted that the ORNL criterion and $\hat{\sigma}$ are quantitatively similar, $\hat{\sigma}$ being slightly more severe.
The σ_{VM} and elastic energy restoration criteria cannot distinguish between tensile and compressive stresses.

3. APPLICATION TO UNIAXIAL FATIGUE RELAXATION TESTS

Uniaxial fatigue relaxation tests were undertaken by CEA and EDF in the frame of a material working group in order to evaluate the reduction in life due to relaxation during the dwell time and the influence of the stress condition (tension or compression) during this dwell time. These tests were carried out on 316 SPH steel, SQ plate, at 600°C and for two values of strain ranges : $\Delta\varepsilon_t = 0.7$ % and $\Delta\varepsilon_t = 1.2$ %.
The main conclusions of the study were as follows :

- The nature of the stress during dwell time (tension or compression) does not affect cyclic consolidation or stress relaxation.
- The nature of the stress during dwell time influences the reduction of life (see figure 4). The selected criteria is the factor :

$$F_{R25}\,(T_M) = \frac{N_{25}\,(T_M)}{N_{25}\,(T_M = 0)}$$

where T_M is the dwell time,

and N_{25} is the number of cycles leading to a reduction of 25 % of the initial stress at the start of the dwell time, compared with the stabilized value.
Observation of the rupture surfaces with an electronic scanning microscope shows mainly intergranular ruptures for tensile hold time specimens and transgranular ruptures with marked striation for specimens under compression. It would therefore appear that the damage and rupture mechanisms are different in the two cases.
Starting from experimental datas, creep-fatigue lives were evaluated using the various criteria for creep damage calculation. The different criteria tested are :

1) σ_{VM}

2) ORNL criterion

3) $\sigma_{eq} = (1 - C)\,\sigma_{VM} + C\,\mathrm{tr}\sigma$ with $C = 0.25$

4) $\hat{\sigma} = \frac{2\,(1 + \nu)}{3}\,\sigma_{VM} + \frac{1 - 2\,\nu}{3}\,\mathrm{tr}\sigma$

The RCCMR cumulative method is used to evaluate creep fatigue lives, allowing for the following :
- It is considered that the allowable number of cycles in fatigue is the number of experimental continuous fatigue cycles obtained in the same laboratory.
- The stress at the start of the dwell time is the experimental stress.
- Stress relaxation during the dwell time is allowed for. This relaxation is evaluated using a creep law identified by E.D.F. on cycled material. This law compares well with experimental results (see figures 5 and 6). Comparatively, the relaxation calculated by the RCCMR creep law is markedly too rapid.
- Creep rupture times are evaluated based on mean creep rupture curves of RCCMR.

This procedure produces the results shown on figure 7.
It will be noted that :
1) For tests with tensile hold times, all criteria give the same results, which are conservative compared with experimental results.
2) Criteria 2, 3 and 4 give two sets of results : one for tensile hold times and one for compressive hold times.
   Criterion 3, with $c = 0.25$ give results which remain within the scatter of experimental datas. Nevertheless it tends to underestimate slightly these experimental results for long dwell times, which are of industrial interest. It seems that the value $c = 0.25$ is slightly high.
3) The Von Mises criterion predicts prevailing creep damage in all cases, regardless of whether the dwell time is in tension or compression.

The other 3 criteria give prevailing creep damage for tests with tensile dwell times, but prevailing fatigue damage for tests with compressive dwell times. This agrees with experimental results.

4. MARINA TESTS

Up to now, no experimental results have been available for compressive biaxial stresses. This is the case for which there is the biggest difference between the criteria (figures 1 to 3).
Therefore an experimental program (ref. 5) was undertaken in which the mock-up which is a thick cylinder was subjected to a cyclic radial thermal gradient (figure 8). The internal surface which is at high temperature (600°c) is then in a state of biaxial compression, whereas the external surface is in a state of biaxial tension, but at a temperature below the creep range : 370°C.
Two different mock ups were tested : the first one is entirely machined, and the second one presents an axial weld and a circumferencial weld in the area subjected to the thermal gradient.
Periodic checks were carried out to detect crack initiations.
Estimates of life durations were made using the various criteria mentioned before. These criteria make use of the stress tensor components and can only be used after an inelastic analysis for the precise determination of the stress field.
Plastic calculations were carried out using two different constitutive equation models :
- a linear kinematic model,
- a Chaboche model with 5 parameters (2 kinematic variables, R constant).

Stress relaxation during dwell time was taken into account. In fact, uniaxial relaxation was used with the creep law identified on cycled material as explained in section 2.
Graphs in figure 3 show the results obtained with each of these calculations using the following three criteria : σ_{VM}, ORNL, $\hat{\sigma}$.
It will be noted that the Von Mises criterion is much too conservative, even using the best fit curves. There is a ratio of more than 5 to 1 between the results of mock-up 1 which does not have any crack initiation at 1600 cycles ($D < 1$) and the highest estimate obtained using the Von Mises criterion.
The other two criteria give highest estimates between 1400 cycles and 3600 cycles.

Experimental results above 1600 c are not yet available. Tests will be carried on up to 3600 cycles on both mock-ups if no crack initiations are observed earlier.
The influence of the constitutive equation model may be emphasized. Since the dwell time in this case was at the maximum of the cycle, the linear kinematic models tends to overestimate the stresses, whereas the Chaboche model tends to symmetrize the cycles and therefore to reduce the stresses (figure 10).

5. CONCLUSION

A creep damage criterion has been defined which takes account of the multiaxiality of stresses. This criterion predicts less damage in compression than in tension.
The use of this criterion to interpret uniaxial fatigue/relaxation tests gives results which are qualitatively and quantitatively satisfactory.
A specific test has been undertaken to study the case of biaxial compression : the MARINA tests. The first experimental results show that the Von Mises criterion is much too conservative in this case. It is still too early to judge the conservativeness of the other criteria. Finally, this criterion has been added into the RCCMR addenda in 1987.

6. ACKNOWLEDGEMENTS

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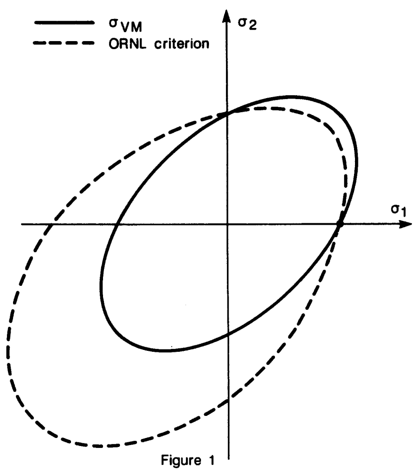


Figure 1

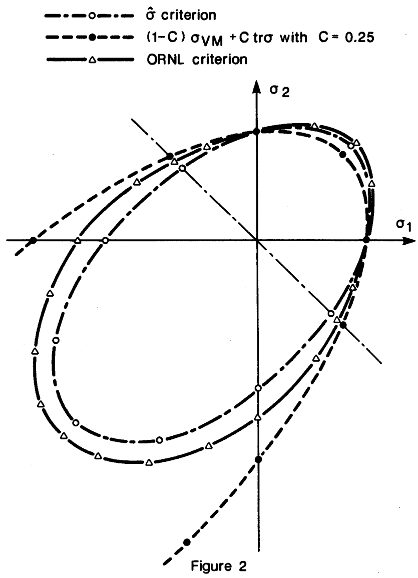


Figure 2

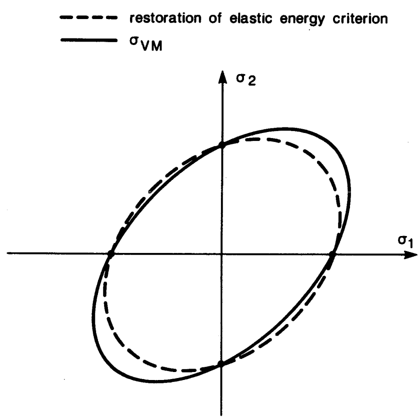


Figure 3

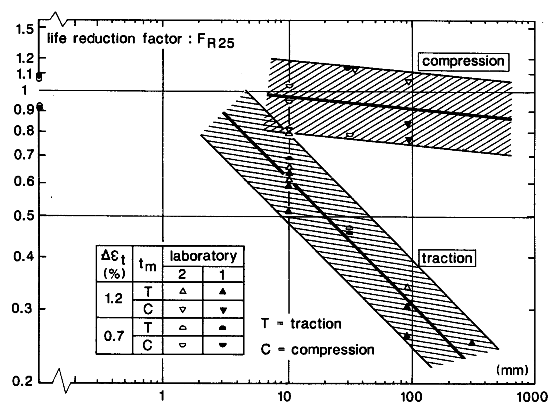


Figure 4

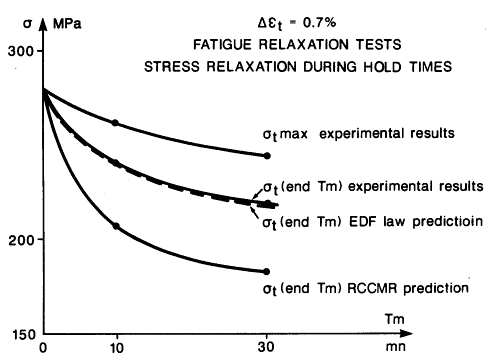


Figure 5

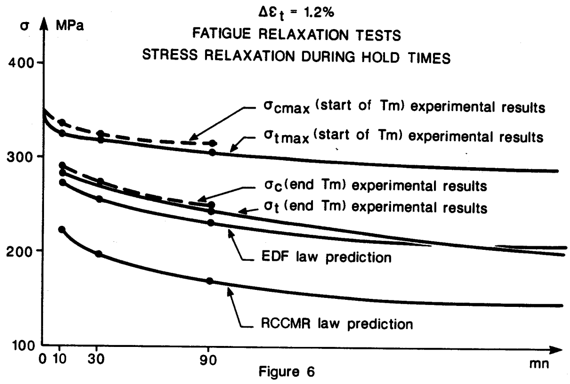
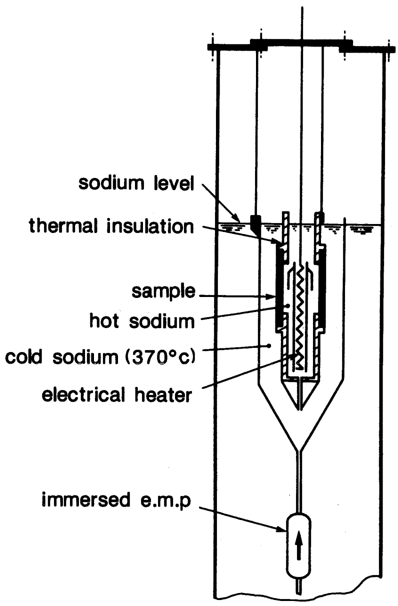


Figure 6



MARINA TEST FACILITY
Figure 8

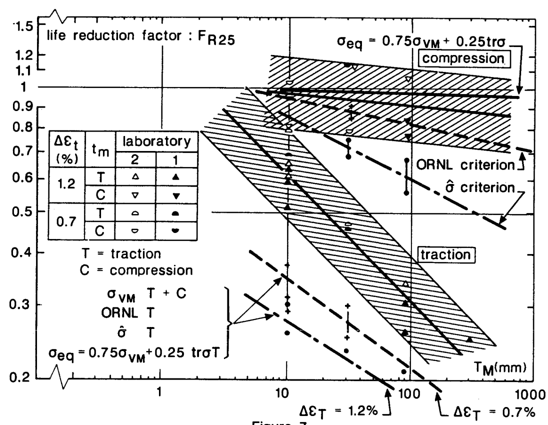


Figure 7

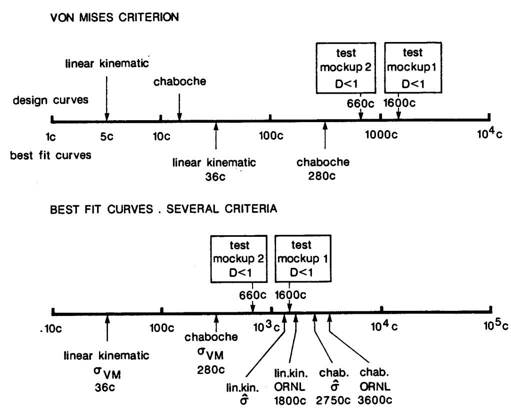


Figure 9