COMPARISON OF DIFFERENT DAMAGE LAWS FOR CREEP FATIGUE LIFE ASSESSMENT

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1 INTRODUCTION

The structures of fast breeder reactors are submitted to cyclic loading at high temperature. Consequently, they must be designed relatively to creep fatigue. Creep fatigue damage models already exist in the design codes, ASME and RCCMR propose models which provide separate estimation of fatigue damage and creep damage and then recombine them by means of an interaction diagram, with creep damage being assessed as a function of the stresses. The LASG procedure developed in Great Britain is similar in its principle but different as concerns the manner of assessing creep damage which is, in this case, based on the exhausting of the material's ductility.

These models have already been widely used for the design of structures and have already formed the subject of benchmark allowing their comparison with experimental results (reference 1). Other damage models have been developed, in France in particular, by ONERA and EMP (Ecole des Mines de Paris). These models are based on different considerations than those mentioned above. After presentation of the equations and principles of these models, the results of validations with respect to uniaxial fatigue relaxation tests are shown. Their utilization is then extended to the prediction of multiaxial tests on mock-ups tested in sodium.

2 DESCRIPTION OF MODELS

2.1 ONERA Model (Reference 2)

This model draws the hypothesis of additivity of fatigue and creep damage on one cycle, with a single damage variable, D being used.

Creep damage is assessed according to a Kachanov Rabotnov law:

$$dD_{\text{creep}} = \left(\frac{X(v)}{A}\right)^t (1 - D)^k$$

uniaxial law

The fatigue damage law is a nonlinear law based on the concept of effective stress \(\sigma_{1 - D}\) and taking the effect of mean stress into account. Its uniaxial expression is as follows:

$$dD = [1 - (1 - D)^\beta + 1] \alpha(\sigma M, \bar{\sigma})(\frac{\sigma M - \bar{\sigma}}{M(\bar{\sigma})(1 - D)})^\beta dN$$
With:

\[ \sigma (\tilde{\sigma}, \bar{\sigma}) = 1 - a \frac{\sigma_M - \bar{\sigma}_1 (\sigma)}{\sigma_U - \sigma_M} \]

\[ \sigma_1 (\tilde{\sigma}) = \tilde{\sigma} + \sigma_{10} (1 - b \tilde{\sigma}) \]

\[ M(\sigma) = M_0 (1 - b \tilde{\sigma}) \]

\( \sigma_M \) being the maximum stress obtained during the cycle and \( \tilde{\sigma} \) being the mean stress.

\( \sigma_U \) is the rupture stress.

\( \sigma_{10} \) is the fatigue limit stress at null mean stress.

\( A, k, r, a, \beta, b, M_0 \) are characteristic parameters of the material.

In situations of creep fatigue interaction, we can write:

\[ dD = dD_{\text{creep}} + dD_{\text{fatigue}} \]

or

\[ dD = \frac{(1-D)^k}{(k+1)N_C} + \frac{[1 - (1-D)^{\beta+1}] \alpha (\sigma_M, \sigma)}{(\beta + 1)N_C - [1 - \alpha (\sigma_M, \sigma)](1 - D)^{\beta}} \] \( dN \)

with:

\( N_C \) = number of rupture cycles if only creep damage is considered.

\( N_C \) = number of rupture cycles if only fatigue damage is considered.

The number of rupture cycles under creep fatigue \( N_R \) is obtained by integrating the previous equation with \( D \) varying between 0 and 1.

These equations were extended to the multiaxial case.

An identification of this model was carried out for various temperatures for material 316SPH (Reference 3). This identification corresponds to cast SP.

2.2 EMP MODEL (Reference 4)

This model is a creep damage model based on physical observations. It was adjusted on the basis of tests on smooth specimens and notched specimens. It is written in incremental form:

\[ dD = A <\sigma> \alpha_\epsilon \beta_\epsilon d\epsilon_{\epsilon q} \]

\(<\sigma> \) is the greatest principal tensile stress. It is considered that the creep damage is null if all the stresses are compressive.

\( \epsilon_{\epsilon q} \) is the equivalent creep deformation.

\( A, \alpha, \beta \) are characteristic parameters of the material.

\( D \) is the damage variable.

It is considered that rupture occurs when the variable \( D \) reaches the critical value \( D_C \), which is a characteristic of the material.

This model was identified by EMP on the basis of creep tests for material 316SPH (Reference 4).

Developments were required in order to be able to use it in the cases of creep fatigue interaction. Two different approaches were tested:

- The first approach, called EMP1, consists in assuming that the law described above allows the influence of fatigue to be taken into account owing to the fact that the stresses are restored at each cycle. It is shown, in this case, that if \( D_1 \) is the damage on the first cycle, the damage for \( N \) cycles will be equal to:

\[ D_N = N^{\beta+1} D_1 \] and the number of rupture cycles is then obtained by:

\[ N_R = \left( \frac{D_C}{D_1} \right)^{\frac{\beta+1}{\beta+1}} \]
- the second approach, called EMP2, consists in considering that the incremental law proposed allows only creep damage to be calculated. It is, therefore, coupled with a fatigue damage, assessed elsewhere, by means of an interaction diagram (as in the case of the RCCMR and LASG approaches). In the study described here, the RCCMR procedure was used to assess fatigue damage. The interaction diagram adopted is similar to the RCCMR diagram but the following differences should be noted:

1. as the axes must be normed at 1, we take the values \( \frac{D_{\text{creep}}}{D_c} \) and \( D_f \);
2. unlike the RCCMR damage model, this procedure results in a nonlinear accumulation of damage according to the number of cycles. The representative point according to the number of cycles moves on a curve with the equation:

\[
y = ax^{\beta + 1} \quad \text{with} \quad a = \frac{D^1_c}{D_f^{\beta + 1}} \quad D_f \text{being the fatigue damage per cycle.}
\]

3. **VALIDATION WITH RESPECT TO UNIAXIAL FATIGUE RELAXATION TESTS**

Reference 1 gives the results of the benchmark aimed at testing the LASG and RCCMR damage models in comparison with uniaxial fatigue relaxation tests. Among all these tests, those performed in FRANCE by CEA and EDF were selected to test the models specified in the previous paragraph.

The description of these tests is given in Table 1. There were tests carried out at 600°C with imposed deformations (\( \Delta \varepsilon = 0.7 \% \) and 1.2 \%), with holding times varying between 10 min and 5 hours under either tensile or compressive state. The stresses at the stabilized cycle are known. We thus use the experimental results directly to apply the damage models.

The tests were carried out on two different casts: SP and SQ. Different creep rupture data are available for these two casts:

- for the ONERA model, this was taken into account by proceeding with two different identifications of the creep damage parameters: the identification described in Reference 3 corresponds to cast SP. For cast SQ, we adopted the following values for the parameters of the creep damage law: \( A = 2337 \) MPa, \( r = 7.3 \) and \( k = 5 \). In addition, the following expression was considered for the function \( \chi(\sigma) \):

\[
\chi(\sigma) = (1-c)\sigma V M + c \sigma r \sigma \quad \text{with} \quad c = 0.133 \quad \text{(RCCMR, 1987 edition), which allows for the fact that compressive stresses are less damaging in creep.}
\]
- for the EMP model, a single identification was retained for both casts. The identification was, however, modified from one approach to the other. On the basis of reference 4, different tests allowed us to propose the following values:

\[
\begin{align*}
\text{EMP1:} & \quad A = 4.6 \times 10^{-5}, \quad \alpha = 2, \quad \beta = 0.5, \quad D_c = 3 \% \\
\text{EMP2:} & \quad A = 2.10^{-5}, \quad \end{align*}
\]

with the other values remaining unchanged.

In these models, \( D \) is expressed as \% and \( \epsilon \) as a true magnitude.

Finally, all these identifications are made with the aim of providing a "best-fit" assessment. The results obtained are shown in the following table for the ONERA model and the EMP1 model in terms of (Number of experimental cycles/Number of cycles provided for by the models).

<table>
<thead>
<tr>
<th>Test</th>
<th>SQC3</th>
<th>SQC71</th>
<th>181.6</th>
<th>181.5</th>
<th>181.1</th>
<th>181.4</th>
<th>SPJ4</th>
<th>SPJ1</th>
<th>195</th>
<th>132</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONERA</td>
<td>1.94</td>
<td>1.56</td>
<td>1.17</td>
<td>1.56</td>
<td>1.44</td>
<td>1.84</td>
<td>1.72</td>
<td>1.54</td>
<td>1.31</td>
<td>1.57</td>
</tr>
<tr>
<td>EMP1</td>
<td>1.04</td>
<td>/</td>
<td>0.50</td>
<td>/</td>
<td>0.72</td>
<td>/</td>
<td>1.72</td>
<td>1.16</td>
<td>0.88</td>
<td>1.17</td>
</tr>
</tbody>
</table>

It is noted that the ONERA model gives extremely good results as the \( N_{\text{exp}}/N_{\text{calc}} \) ratio is always between 1 and 2. This model is thus always conservative but never excessively.

With the EMP1 model, it is not possible to analyze the test with compressive holding time as this then predicts null damage. For tests with tensile holding times, the results are considered to be satisfactory in so far as this is a "best-fit" evaluation.
For the EMP2 model, the results are shown in Figure 1. It is noted that the tests with tensile holding time are well placed in the diagram of the RCCMR type without being excessively conservative. The tests with compressive holding time, however, are located inside the diagram. It appears that the hypothesis drawn, i.e. null creep damage under compressive stresses, is not verified. In these conditions, creep damage should not be null but lower than is the case for tensile stresses. The model should be modified to take this into account.

4 APPLICATION TO TESTS ON STRUCTURES

The above-mentioned models were used to predict the test results on mock-ups subjected to thermal shocks in sodium : THERMINA tests. These tests have been described in various publications (References 5 and 6). Specimens representing a plate-shell junction were subjected to thermal shocks in sodium (see Figure 2). They were filled with sodium maintained at 600°C by means of an electrical heater. The thermal shocks were realised by sending cold sodium at 300°C onto the outer face of the specimen for 20 s. The temperature then increased to 600°C and was maintained for two hours before the next shock. In addition, a constant axial force was applied throughout the duration of the test. Eight different specimens were tested for primary stress value P and were subjected to the following number of cycles:

<table>
<thead>
<tr>
<th>SPECIMEN REFERENCE</th>
<th>D1</th>
<th>D3</th>
<th>E1</th>
<th>E3</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P MPa</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>N Cycles</td>
<td>589</td>
<td>645</td>
<td>302</td>
<td>452</td>
<td>600</td>
<td>600</td>
<td>2035</td>
<td>2035</td>
</tr>
</tbody>
</table>

After these tests, the specimens were cut up and metallographic observations were made to evaluate the damage sustained. It was noted on an experimental basis that the upper junctions were generally less damaged than the lower junctions.

The results obtained can be summarized as follows:
- under primary stress P = 50 MPa:
  . at 2,000 cycles, there was a through crack on the lower section (shell thickness = 2 mm) and cracks of 800 to 900 μm depth on the upper section (or about half the thickness). All these cracks were of the intergranular type,
  . at 600 cycles, there were through cracks on the lower section and cracks with a mean length of 500 μm on the upper section,
  . at 450 cycles, the cracks were propagated over approximately 500 μm on the lower section,
  . at 300 cycles, the cracks were approximately 300 μm long on the upper section.

The interpretative calculations were performed using a 5-parameter Chaboche elastoplastic model, identified so as to directly represent the stabilized cycle, coupled to a classic creep model. The calculations were made for the two junctions (for which a different thermal loading was identified) and for the two primary stress levels.

These results were then used for the application of the three damage models previously described. The identification used is the same as for the interpretation of the uniaxial tests. The results obtained, in number of rupture cycles predicted by the different models, are shown in the following table.
<table>
<thead>
<tr>
<th>CASE</th>
<th>MODEL</th>
<th>ONERA</th>
<th>EMP1</th>
<th>EMP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P = 50 MPa</td>
<td>Upper junction</td>
<td>139</td>
<td>135</td>
<td>272</td>
</tr>
<tr>
<td>P = 50 MPa</td>
<td>Lower junction</td>
<td>107</td>
<td>92</td>
<td>173</td>
</tr>
<tr>
<td>P = 100 MPa</td>
<td>Upper junction</td>
<td>112</td>
<td>90</td>
<td>200</td>
</tr>
<tr>
<td>P = 100 MPa</td>
<td>Lower junction</td>
<td>89</td>
<td>65</td>
<td>131</td>
</tr>
</tbody>
</table>

It will be noted that the three models clearly show that damage is greater on the lower section than on the upper section.
In addition, the numbers of cycles predicted by the three damage models are fairly close one to the other and consistent with the experimental observations.

5 CONCLUSION
Creep fatigue damage models were developed at ONERA and EMP. These models allow the satisfactory description of uniaxial fatigue relaxation tests, and they also allow the prediction of the results of test performed on structures.

REFERENCES
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Creep fatigue analysis for LMFB’s structures : Identification of Chaboche’s models for stainless steel 316 SPH. SMIRT 11, TOKYO - August 1991. Paper L 07/1
Quantitative study of intergranular damage in an austenitic stainless steel on smooth and notched bars. Proceedings of MECAMAT, Dourdan - FRANCE October 1987
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Creep fatigue interaction on Thermin samples - Experimental and numerical results. SMIRT 10 - LOS ANGELES August 1989 - Session L.
<table>
<thead>
<tr>
<th>Test by</th>
<th>Test no</th>
<th>Material (part)</th>
<th>Speed</th>
<th>Tempa °C</th>
<th>$\Delta E_t$ (m/s$^2$)</th>
<th>Hold time (h)</th>
<th>Cycles to failure</th>
<th>Time to failure (h)</th>
<th>For the stabilized (MPa)</th>
<th>Onset crack pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO03</td>
<td>316L SPH</td>
<td>C.L. SPH</td>
<td>C.Y.C</td>
<td>600°C</td>
<td>0.7</td>
<td>0.1567 T</td>
<td>1740</td>
<td>204</td>
<td>201</td>
<td>242</td>
</tr>
<tr>
<td>SO04</td>
<td>G</td>
<td>C.Y.C</td>
<td>0.7</td>
<td>650°C</td>
<td>1.5 x 10$^{-2}$</td>
<td>0.1567 C</td>
<td>2100</td>
<td>355</td>
<td>260</td>
<td>-270</td>
</tr>
<tr>
<td>G</td>
<td>156</td>
<td>C.Y.C</td>
<td>0.7</td>
<td>500°C</td>
<td>0.50 T</td>
<td>1003</td>
<td>523</td>
<td>215</td>
<td>222</td>
<td>-265</td>
</tr>
<tr>
<td>E</td>
<td>181-5</td>
<td>C.Y.C</td>
<td>0.7</td>
<td>600°C</td>
<td>1.5 x 10$^{-3}$</td>
<td>0.50 C</td>
<td>1178</td>
<td>683</td>
<td>282</td>
<td>-270</td>
</tr>
<tr>
<td>A</td>
<td>181-1</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 T</td>
<td>212</td>
<td>319</td>
<td>317</td>
<td>224</td>
<td>-316</td>
</tr>
<tr>
<td>F</td>
<td>181-4</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 x 10$^{-2}$</td>
<td>605</td>
<td>967</td>
<td>320</td>
<td>-326</td>
<td>-260</td>
</tr>
<tr>
<td>E</td>
<td>SPJ-2</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 T</td>
<td>396</td>
<td>365</td>
<td>329</td>
<td>258</td>
<td>322</td>
</tr>
<tr>
<td>D</td>
<td>SPJ-1</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 T</td>
<td>315</td>
<td>315</td>
<td>311</td>
<td>224</td>
<td>306</td>
</tr>
<tr>
<td>F</td>
<td>105</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 T</td>
<td>314</td>
<td>1571</td>
<td>296</td>
<td>215</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>152</td>
<td>C.Y.C</td>
<td>1.2</td>
<td>600°C</td>
<td>1.5 x 10$^{-2}$</td>
<td>1516</td>
<td>212</td>
<td>257</td>
<td>235</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 1:**
- Data point
- Test with tensile hold time
- Test with compressive hold time

**Figure 2:**
- Sample
- Electrode
- Press

**Table 1:**
- Table with various test conditions and results.
- Columns include Test by, Test no, Material (part), Speed, Tempa °C, $\Delta E_t$ (m/s$^2$), Hold time (h), Cycles to failure, Time to failure (h), For the stabilized (MPa), and Onset crack pattern.