A Review of Creep-Fatigue Life Prediction Methods

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Abstract: A review of ten creep-fatigue life prediction methods is made. An application to continuous fatigue and cyclic relaxation data on an austenitic stainless steel is shown, then the models are used to evaluate the number of cycles to failure in hypothetical tests involving very long hold times (until $10^5$ m), Such an exercise allows to point out the similarities (and the differences) between the different methods, to discuss their general trends and finally to characterize two main classes of models, the one taking the plastic strain, the other the integrated actual stress as the critical variable to represent hold time influence: this opposite choice may lead to opposite responses if very long hold times are considered.
Introduction: Several comparative evaluations of creep-fatigue failure models have been made in the past [1] [2] [3] [4]. But the present review shows specific aspects:

- the study is a collaborative research, so that a lot of models have been identified, most of them being determined by their authors themselves: such a methodology avoids misinterpretations and allows to obtain the best results in each case,

- the comparison of the methods is first made on a set of continuous fatigue and cyclic relaxation tests and then extended to extrapolated conditions by predicting the life of hypothetical tests involving very long tensile holds (until $10^5$ mm). The results obtained in such conditions allow to reveal the true nature of each model and to point out the respective influence of creep and fatigue. From an industrial point of view, this evaluation gives an idea of the scatterband and the reliability of long term predictions.

All the models used have been previously exposed in the literature by their authors, and they need no complete explanation in the framework of our study: the main references are given in each case. In the following text, the series of tests are presented together with the chosen stress-strain extrapolations for the extrapolated long dwell tests (Part 1), then the results obtained are shown in each case using the different methods (Part 2). The third part is devoted to the general discussion of the nature of the models, the attention being focused on the respective representation of fatigue and time influence, so that several classes of models are finally characterized. Some remarks are also added on the ability of each method for modeling more complex loading cases.

1. The experimental data and their extrapolation
1.1. The tests results: The experimental results used were previously obtained in a study of G.T.M.\textsuperscript{+} on an austenitic stainless steel type 18 Cr, 12 Ni No, with low carbon ($< 0.03$), AFNOR Z2 CN 18-12, (cast T 7426 supplied by Creusot Loire), the material being solution annealed before testing [5]. In this paper, we only are interested in the tests conducted at 600°C under strain control, with or without tensile hold time. The strain rate $\dot{\varepsilon}$ was $1.5 \times 10^{-3}$ s$^{-1}$ or $4.10^{-3}$ s$^{-1}$ and the hold time $t_h$ is varying from 1 to 300 mm. Two strain range $\Delta \varepsilon$ are used 0.7 % and 1.2 %.

The stress response is summarized on fig. 1 where the maximum tensile stress $\sigma_{t\text{max}}$ and the minimum tensile stress after relaxation $\sigma_{t\text{min}}$ are plotted vs hold time. The highest $\sigma_{t\text{max}}$ is obtained in the 3 minutes hold test, but the relaxed stress amplitude continuously increases with hold time. Figure 2 shows the reduction of life due to hold time: the smaller the strain range, the larger the life reduction.

1.2. Representation of stresses during relaxation: All the results shown in the previous part are very classical, and we also use very classical methods to represent the stress evolution during relaxation.

- a power function derived from primary creep type law is used in the model noted CEA-N [6]

$$\left( \frac{\sigma_{t\text{max}}}{\sigma} \right)^{n-1} = 1 + \frac{\dot{\varepsilon}_{t\text{max}}^{n-1}}{A E \dot{t}^{n-1}}$$

\textsuperscript{+}G.T.M., "Groupe de Travail Matériaux" is a french working Group on Materials involving Commissariat à l'Énergie Atomique and Electricité de France; four Laboratories have been concerned with the present experimental work: Commissariat à l'Énergie Atomique - SNEA-CEH Saclay; Creusot Loire - Centre de Recherches d'Unieux; Electricité de France - EMA - Les Renardières; École des Mines de Paris - Centre des Matériaux - Corbeil.
(\(\sigma\) is the current stress at time \(t\) during the relaxation period, \(E\) the Young's modulus; \(n = 5.12, p = 0.33, A = 1.7310^{-16}\) are constants adjusted for \(\Delta\varepsilon_e = 1.2\%\); units: MPa, hours);

- the model labelled CEA-T introduces the Gittus equation [7]

\[
\log \frac{\sigma_{\text{max}}}{\sigma} = E A t^p
\]

(with \(p = 0.24\) and \(A = 1.26.10^{-6}\) for 1.2 % strain range, \(p = 0.164\) and \(A = 6.88.10^{-7}\) for 0.7 % strain range; units: MPa, hours);

- in the other cases, the Gittus formula is slightly modified, by the introduction of a limit stress \(\sigma_{\text{lim}}\) representing the residual stress for very long hold times:

\[
\sigma = (\sigma_{\text{max}} - \sigma_{\text{lim}}) \exp(-A t^p) + \sigma_{\text{lim}}
\]

(\(\sigma_{\text{lim}}\) is taken equal to 30 MPa for \(\Delta\varepsilon_e = 0.7\%\) and 50 MPa for \(\Delta\varepsilon_e = 1.2\%\), \(p\) to 0.245;

\(A = 0.05\) for \(\Delta\varepsilon_e = 0.7\%\) and \(A = 0.08\) for \(\Delta\varepsilon_e = 1.2\%\); \(t\) in seconds).

1.3. Stress extrapolation for very long hold times: Extrapolations are intended as long as \(10^5\) mm, this hold time corresponding to a working cycle of about two months: considering the experimental data, that is a two-decade extrapolation for \(\Delta\varepsilon_e = 1.2\%\) and a three-decade extrapolation for \(\Delta\varepsilon_e = 0.7\%\).

The application of eq. (1), (2) or (3) furnishes the stress during relaxation for any hold time provided the initial stress \(\sigma_{\text{max}}\) is known: several hypotheses were considered and we show here a mean solution, inspired by an additional experimental point corresponding to 24 hours hold time, obtained in a two-level test after 30 cycles [5]. The expressions (1) and (3) lead to the lines of the fig. 1; it is worth noting that the absence of \(\sigma_{\text{lim}}\) in the expression (2) makes \(\sigma_{\text{lim}}\) significantly smaller for \(\Delta\varepsilon_e = 1.2\%\) that for \(\Delta\varepsilon_e = 0.7\%\) (89 MPa vs 149 MPa for \(t_H = 10^5\) mm).

2. Identification and application of the models

2.1. The expressions used: We give here some brief indications on the form of the equations and on the identification methods.

- the most popular model proposed for creep-fatigue life prediction is the linear cumulation of creep and fatigue damage, the number of cycles to failure being obtained as a combination of the number of cycles to failure in continuous fatigue \(N_F\) and in creep alone \(N_C\):

\[
\frac{1}{N_R} = \frac{1}{N_F} + \frac{1}{N_C} \quad \text{with} \quad \frac{1}{N_C} = \int \frac{d t}{\varepsilon \sigma(t)}
\]

(4)

The determination of the coefficients of the creep failure law (chosen as a power function of the stress) must be made carefully with the stainless steels, because large strains are involved in creep tests: the experimental creep failure points must be fitted by

\[
1 = \int_{\varepsilon_c}^{\varepsilon} (\sigma/V) d \varepsilon
\]

\(\sigma\) being the true actual stress in the creep test deduced from the engineering stress by a section correction due to strain [8].

As for the fatigue part, we use two extreme hypothesis assuming that \(N_F\) is stress dependent (linear cumulation in term of stress, LCS)

\[
N_F = \left(\frac{\sigma_{\text{max}}}{A}\right)^{-\frac{1}{p}}
\]

(5)

or that \(N_F\) depends on plastic strain range (linear cumulation in term of strain, LCE)

\[
N_F = C_1 \Delta\varepsilon_F^{-\frac{1}{2}} (\tau - \tau_H)^{-\delta}
\]

(\(\tau\) is the period of one cycle), the usual hypothesis \(N_F (\Delta\varepsilon_e)\) lying between the two.
we also use the Code Case N 47, which introduces a non-linear cumulation with the double linear limit of the admissible damage domain in the plane $D_{\text{creep}} - D_{\text{fatigue}}$, but also some corrective coefficients for safety, making the prediction generally very conservative;

the same double linear damage limit is involved in the rules from CEA [9], the fatigue part is evaluated with a Manson-Coffin law:

$$\Delta F_T^T = AN_{\text{T}}^{-\alpha} + BN_{\text{T}}^{-\beta}$$

and the creep part from the creep curve (but without section correction) using a power function:

$$t_c = (\sigma/M)^p$$

(7bis)

for the method CEA-M or a Larson-Miller parameter for the method CEA-T:

$$P = a + b \log g + c (\log g)^2$$

with

$$P = C (\log t_c + c)$$

The evaluation of creep damage during the relaxation period is made using eq. (1) or (2).

- the model proposed by E.M.P. is metallurgically supported [10]; it is assumed that the crack propagation rate in cyclic relaxation $(dN/dN_{\text{F}})$ is accelerated by the intergranular damage $D_c$ with regard to the continuous fatigue rate $(dN/dN_{\text{F}})_C$, $D_c$ being measured by the fraction (in terms of length) of cracked grain boundaries. Some correlations between the life reduction due to the hold time and intergranular damage are established, and it is shown that the relaxed stress amplitude $\sigma_{RT} = \sigma_{\text{max}} - \sigma_{\text{min}}$ is a good critical parameter in cyclic relaxation tests able to characterize the life reduction. The authors distinguish between an initiation and a propagation phase in fatigue, they use a Manson-Coffin type law (eq. 7) for fatigue representation and obtain the number of cycles for propagation $N_p$ through:

$$N_p = aN_{\text{T}}^{-\alpha} + bN_{\text{T}}^{-\beta} + c$$

In presence of a relaxation period, the initiation period is neglected and the number of cycles to failure $N_p$ in this case is deduced from the number of cycles for propagation in continuous fatigue by:

$$\frac{1}{N_p} = \frac{1}{N_p} + \frac{1}{N_{\text{R}}} \sigma_{RT}$$

(10)

- the EMP model finally presents some similarities with strain range partitioning method (SRP) [11] because the quantity $\sigma_{RT}$ is proportional to $\Delta E_p$ during relaxation; the failure under a cyclic tensile relaxation loading is given in this last case by:

$$\frac{1}{N_p} = \frac{F_{pp}}{N_{pp}} + \frac{F_{ep}}{N_{ep}}$$

(11)

with:

$$F_{ij} = \frac{\Delta E_{ij}}{\Delta E_p} \quad N_{ij} = \frac{\Delta E_{ij}}{\Delta E_p} \alpha_{ij}$$

In the present study, we used no ductility correction [12] in the method so that the results obtained for very long hold times are optimistic with regard to the other models.

- the Oertgoren's model [13] introduces both maximum stress $\sigma_{\text{max}}$ and strain range $\Delta E_p$, and takes also into account the time under positive stress to, under maximum load $t_T$ and minimum load $t_c$, so that:

$$\sigma_{\text{max}} \cdot \Delta E_p \cdot t_c^{\alpha} \cdot N_{\text{T}}^{\beta} = C$$

(12)

with:

$$\frac{1}{g} = \max \left( \frac{1}{t_c}, \frac{1}{t_T + t_T - t_c} \right)$$

- the expression of the model developed at ANL by Majumdar and Maiga [14] is much more complex, the variable $c$ describing the creep damage and a the fatigue damage
\[
\frac{1}{V} \frac{d \varepsilon}{d t} = \left\{ \begin{array}{l}
G \text{ or } G \end{array} \right\} |\varepsilon_p|^{m} |\dot{\varepsilon}_p|^{k}c
\]
\[
\frac{1}{\alpha} \frac{d \varepsilon}{d t} = \left\{ \begin{array}{l}
T \text{ or } C \end{array} \right\} \left( 1 - \alpha \log \frac{\dot{\varepsilon}_p}{\varepsilon_0} \right) |\varepsilon_p|^{m} |\dot{\varepsilon}_p|^{k}
\]
(13a) (13b)

The constants are different in tension (T) or compression (C) and the failure is obtained as critical values of \( a \) or \( c \) are reached (resp. \( a_g \) and \( c_f \)). As long as the integration result during the compression path is equal or larger than during the tension path for eq. (13a), \( c \) is equal to \( c_0 \) and no creep-interaction occurs.

- the model proposed by ONERA [8] [15] [16] also uses a differential form but the critical parameter is the stress for creep, the maximum and mean stresses \( \bar{\sigma} \) for fatigue. The damage increment for one cycle is:
\[
dD = \left( \frac{1}{A} \right) \left( 1 - D \right)^{k} dt + \left( \frac{\sigma_{t \text{max}} - \bar{\sigma}}{M(\bar{\sigma})(1 - D)} \right) \left( 1 - (1 - D)^{3+1} \right) \frac{\dot{\sigma}}{\bar{\sigma}} dN
\]
(14a)

with
\[
1 - D = a \left( \frac{\sigma_{t \text{max}} - \bar{\sigma}}{\sigma_u - \sigma_{t \text{max}}} \right)
\]
\[
\langle H \rangle = M \left( \bar{\sigma} \right) \left( 1 + b \bar{\sigma} \right)
\]
and
\[
M(\bar{\sigma}) = M_0 \left( 1 + b_0 \bar{\sigma} \right); \quad \sigma_{t \text{max}}(\bar{\sigma}) = \bar{\sigma} + \sigma_0 \left( 1 + b \bar{\sigma} \right)
\]
(14b) (14c)

\( D \) is the so-called "damage" variable representing the actual degradation of the material; the integration of eq. (14a) between \( D = 0 \) and \( D = 1 \) allows to obtain the number of cycles to failure for any type of loading, from pure creep to pure fatigue. If only the time (number of cycles) dependent part is integrated, one obtains the creep (fatigue) reference \( N_c \) (resp. \( N_f \)). The model predicts non-linear creep fatigue cumulation between these two references. Let us note that \( N_f \) is the same as in the linear cumulation method.

- Some other rules have been tested in our study [17], time-temperature equivalence or direct extrapolation using \( \sigma_{t \text{max}}(\bar{\sigma}) \) as a critical parameter [6]. Some more recent propositions [18] [19] could be also tried. But in the following, we restrict our comparison to the ten evaluation methods previously exposed.

2.2. Comparison of calculated lives: The figure 3 shows the comparison between predictions and experimental results for the different experimental hold times: the predictions are within a factor of two for most cases; linear cumulation and SRP methods tend to become unconservative, CEA-T rule leads to conservative results; as long as initiation period is neglected, the EMP prediction is conservative for the short dwell. But the general agreement is good, the difference being due to the choice of smoothing in the determination of the coefficients.

Three examples of application to hypothetical cases with larger hold times are plotted on fig. 4: we use in each case the values of the coefficients indicated on fig. 3 and the extrapolations from the part 1.3. It can be noted that the SRP method is unconservative with regard to the other predictions. If we except this method, all the results are within a factor of 2 (150 - 300 cycles) for \( \Delta E_b = 1.2 \% \) and \( t_R = 24 \text{ h} \); the uncertainty is larger for the same strain range and \( 10^5 \text{ mm} \) hold time, the maximum differences arising when we consider a 0.7 \% strain range (the extrapolation runs on more than three decades in this last case).

As discussed in the next part, this shows that the strain range effect remains important even for long hold times in the models where the time influence comes (directly or not) from plastic strain but on the contrary, the failure tends to become independent of strain range if a Taira's type summation is used for creep (LCE, LCS, ONERA, the effect being reduced in CEA model).
3. Discussion

3.1. Fatigue and creep: All the models discussed here are based on the existence of two types of mechanisms during cyclic relaxation: the first one, number of cycles dependent and related to microcracks propagation characterizes continuous fatigue, the second one representing hold time corresponding to microvoids.

The fatigue influence is introduced with opposite points of view: for the EMP or CEA models, the fatigue reference is related to strain range and does not change when the hold time increases for a given $\Delta \varepsilon_{pl}$. For LCS or ONERA models, the fatigue reference, which is stress dependent, increases with hold time but it decreases for SRP or LCE models where it depends on $\Delta \varepsilon_{pl}$ and for ANL model where it is also time dependent. The same type of comparison can be made for the "creep" part. The understanding of $N_C^*$ is clear for LCS, LCE or ONERA model, but it is easy to exhibit some equivalent terms $N_C^*$ with the other models. For instance, in the case of EMP model, the analogy between eq. (10) and (4) allows to write:

$$N_C^*(EMP) = \frac{1}{R} \sigma_{RT}^{-q}$$

In a similar way, it is possible to obtain for the SRP model:

$$\frac{1}{N_R} = \frac{1}{N_{pp}} + F_{cp} \left( \frac{1}{N_{cp}} - \frac{1}{N_{pp}} \right)$$

so that:

$$N_C^*(SRP) = \frac{N_{pp}}{N_{pp} - N_{cp}} \frac{1}{F_{cp}} \sim N_{cp}^{-q}$$

this expression being proportional to the inverse of $\sigma_{RT}^{-q}$ (and not to $\sigma_{RT}$ as in eq. (15): it explains the unsatisfactory evaluations).

For the ANL model, $N_C$ is obtained by integrating eq. (13 a) alone. One can show that $N_C^*$ typically depends on $\sigma_{RT}$ and $t_h$.

It is clear in such conditions that if we change the chosen extrapolations, the responses of the models will be opposite: decreasing $\sigma_{RT}$ for a fixed $\Delta \varepsilon_{pl}$ and $t_h$ produces a decrease of number of cycles to failure for the models integrating a creep law (linear cumulation, CEA, ONERA) and an increase for the other.

Finally, fig. 5 summarizes these similarities (or differences) in fatigue and creep for a strain range of 1.2 %.

3.2. Creep-fatigue interactions: Some fundamental differences also occur for the introduction of interaction and coupling. Several cases may be considered:

- it could be assumed that even in simultaneous presence of creep and fatigue, the failure is produced by creep or fatigue alone: in that case, there is no interaction and no coupling; but no one model uses this hypothesis;

- if each mechanism contributes to failure the sum of damage being equal to 1 (Linear Cumulation, SRP), we have linear interaction but no coupling.

- it is possible to obtain non-linear interaction without coupling with the CEA or Code Case rules;

- a "one way" coupling appears in ANL or EMP models where the accumulated creep damage increases fatigue damage rate;

- a complete coupling is found in ONERA model where creep (fatigue) damage increases fatigue (creep) damage rate.
Conclusion: Finally, this study shows positive aspects: although the basic assumptions are different from one model to the other, the predictions realized are fairly good in the experimental domain and are not drastically different for long term calculations, the maximum discrepancy being about a factor of 4 for most cases with two months hold time. Some of the methods investigated here are very specific, and can be used only for cyclic relaxation (EMP for instance), on the contrary, some others, introducing differentials equations (ANL, ONERA), are more general and can be applied to more complex loading paths. In fact, the two approaches are complementary to each other, the identification being easier in the first case, the possibilities larger in the second one.

In such conditions, working out some calculations for long life components seems to be realistic, but more accurate information is needed about stress-strain evolution for very long operating time: microstructural instabilities (if existent) are to be pointed out and additional tests must be carried out. Clearly, long term tests with larger hold times and smaller strain ranges are needed to investigate the actual stress-strain response and the microstructural evolution during cyclic relaxation.

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References


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Fig. 1 - Number of cycles to failure vs. hold time.

Fig. 2 - Variation of maximum and minimum stresses vs hold time - (316 L. - 600° C).

Fig. 3 - Evolution of \( N_{RF} \) (PRE/EXP) vs. hold time (mm) in each case.

Fig. 4 - Long-term predictions; 
\[ \Delta E_L = 1.2\% \], \( t_H = 24\) h (\( \square \));
\[ t_H = 0.5\) mm (\( \circ \)). \[ \Delta E_C = 0.7\% \],
\( t_H = 105\) mm (\( \triangle \)).

Fig. 5 - Comparison of fatigue (a) and creep (b) influence from each model for 1.2% strain range.