A Comparison Between Japanese and French A16 Defect Assessment Procedures for Creep-Fatigue Crack Growth

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ABSTRACT

This paper presents the results of a benchmark on creep-fatigue crack growth evaluation for a plate subjected to cyclic bending loads with a one hour dwell. The simplified creep-fatigue crack growth evaluation methods of JNC in Japan and A16 procedures proposed by CEA in France that are used for the benchmark are presented. These methods, based on the reference stress approach, are compared with each other. They are found to differ in the expression used for the reference stress solution. It is also pointed out that in contrast to the A16 procedures, the JNC method accounts for an heterogeneous creep strain distribution for small scale yielding condition. The predictions obtained by the methods are also compared to the experimental data. It is found that the methods exhibit conservatism which are significantly reduced when using an alternative model to integrate the creep law.

INTRODUCTION

Benchmark problems on creep-fatigue crack growth have been exchanged between JNC and CEA. The overall objective is to contribute in developing a good understanding of the simplified crack growth evaluation methods applicable to the structural integrity assessment of fast breeder reactor components. In both the JNC and A16 procedures, the interaction between fatigue and creep damages is not accounted for. The creep-fatigue crack growth rate da/dN is calculated as a linear summation of the fatigue and creep contributions as follows :

$$\frac{da}{dN} = \left(\frac{da}{dN} \right)_f + \left(\frac{da}{dN} \right)_c \quad (1)$$

In this paper, emphasis is given to the calculation of the creep contribution. The calculation of the fatigue contribution is detailed and discussed in [1].

DESCRIPTION OF BENCHMARK PROBLEM

The benchmark consists of an austenitic stainless steel 316L(N) plate containing a semi-elliptical surface notch subjected to cyclic bending loads at 650°C [2]. The load controlled creep-fatigue loading cycle consists of a trapezoidal wave form with a 1 hour dwell at the maximum load of the cycle. The experimental setup is shown in Fig. 1. The loading

conditions, the geometry of the plate and the dimensions of the initial notch after fatigue pre-cracking are given in Table 1. The membrane stress σ_m and the bending stress σ_b can be calculated elastically. The mechanical properties and the cyclic curve available in the RCC-MR [3] are given in Table 2 together with the creep curve, the Paris law and the creep crack growth characteristics [4].

JNC SIMPLIFIED CREEP CRACK GROWTH EVALUATION METHOD

Using the Newman and Raju solution [5] for a plate containing a semi-elliptical notch, the stress intensity factor K is calculated using the influence function method based on the principle of superposition. In the calculation, plasticity is accounted for. The elastic J-integral J_{el} is estimated at the maximum load of the cycle :

$$J_{el} = \frac{K_{max}^2}{E^*} \quad (2)$$

where K_{max} is the stress intensity factor at the maximum load of the cycle, $E^*=E$ for plane stress conditions and $E^*=E/(1-\nu^2)$ for plane strain conditions. JNC assumes that the time dependent creep J-integral $J_c(t)$ is obtained using a creep correction parameter f_c defined by :

$$J_c(t) = f_c \cdot J_{el} = \frac{E \cdot \dot{\varepsilon}_{c-ref}(t)}{\sigma_{c-ref}} \cdot J_{el} \quad (3)$$

where $\dot{\varepsilon}_{c-ref}(t)$ is the time dependent reference creep strain rate and σ_{c-ref} is the reference stress at the beginning of the dwell. The creep strain rate is estimated accounting for stress relaxation, but the reference stress at the beginning of the dwell is used in the creep correction procedure. The equivalent creep J-integral range ΔJ_c , equivalent to the C^* parameter (Table 2), has to be integrated over the dwell t_c as follows :

$$\begin{aligned} \Delta J_c &= \int_0^{t_c} J_c(t) \cdot dt \\ &= \frac{E \cdot K_{max}^2}{E^* \cdot \sigma_{c-ref}} \cdot \int_0^{t_c} \dot{\varepsilon}_{c-ref}(t) \cdot dt \\ &= \frac{E \cdot K_{max}^2 \cdot \varepsilon_{c-ref}(t_c)}{E^* \cdot \sigma_{c-ref}} \end{aligned} \quad (4)$$

where $\varepsilon_{c-ref}(t_c)$ is the reference creep strain at $t = t_c$, that is at the end of the dwell and can be calculated by time integration of the creep strain rate from 0 to t_c . In the calculation $\varepsilon_{c-ref}(t_c)$, stress relaxation is considered using a parameter q_C defined in Fig. 2. $\varepsilon_{c-ref}(t_c)$ is calculated using the creep law of the material, reinitialised at each cycle. The time dependent reference creep strain rate $\dot{\varepsilon}_{c-ref}$ is determined from the reference stress σ_{c-ref} . JNC determines σ_{ref} using the net section shape function F_{net} [1] :

$$\sigma_{ref} = F_{net} \cdot (p_m \cdot \sigma_m + p_b \cdot \sigma_b) \quad (5)$$

For a plate subjected to bending loads, F_{net} is determined assuming that the crack shape is rectangular and accounts for the displacement of the neutral axis. For a plate subjected to bending loads, JNC recommends that $p_m = p_b = 1.0$. However, for small scale yielding

condition, JNC observed that such an assumption gives too small creep J-integral values. Therefore, JNC assumes that the reference stress at the beginning of the dwell σ_{c-ref} depends upon the yielding conditions :

$$\begin{aligned} \text{for } \sigma_{ref} < \sigma_y &\rightarrow \text{Small scale yielding condition : } \sigma_{c-ref} = \sigma_{ref} \cdot \left(\sigma_y / \sigma_{ref} \right)^p \\ \text{for } \sigma_{ref} \geq \sigma_y &\rightarrow \text{Large scale yielding condition : } \sigma_{c-ref} = \sigma_{ref} \end{aligned}$$

where σ_y is the 0.2% proof stress derived from the cyclic stress-strain curve of the material and p is a parameter that accounts for the heterogeneous stress distribution in the ligament under small scale yielding condition. JNC proposes the following expression for p :

$$p = p_1 + p_2 \cdot (a/t) \quad (6)$$

and recommends a value of 0.2 for p_1 and p_2 . This is based on the results obtained from creep finite element analyses for plates containing a through wall notch subjected to uniaxial tension. Since such an heterogeneous stress distribution will disappear immediately with strain redistribution, the stress is allowed to relax from σ_{c-ref} to the value of σ_{ref} given by Eq. (5). This is illustrated in Fig. 2. The stress relaxes during the dwell in accordance with the following expression :

$$d\sigma_{relax} = \frac{E \cdot d\epsilon_c}{q_c} \quad (7)$$

where $d\epsilon_c$ is the creep strain increment calculated by time integration of the creep strain rate $\dot{\epsilon}_c(t)$ from t to $t+dt$ as follows :

$$d\epsilon_c = \int_t^{t+dt} \dot{\epsilon}_c(t) \cdot dt \quad (8)$$

In the stress relaxation process, JNC assumes a strain hardening rule for the calculation of the creep strain rate.

In the original JNC method, the creep crack growth rate per load cycle is evaluated using the equivalent creep J-integral range ΔJ_c formulation. However, in this benchmark, the creep crack growth rate per hour is related to the C^* parameter. Since the creep J-integral $J_c(t)$ given in Eq. (3) is equivalent to the C^* parameter and the duration of the dwell equals to unit time, the A coefficient and the q exponent given in Table 2 can be adopted for the creep crack growth calculations.

CEA SIMPLIFIED CREEP CRACK GROWTH EVALUATION METHOD

The CEA crack growth methods are gathered together in the A16 document [6]. This document proposes the C_{A16}^* method to calculate the creep crack growth rate. Similarly to the JNC method, the C_{A16}^* method is derived from an elastic J-integral value. It is expressed by :

$$C_{A16}^* = J_{el} \cdot k_{IA16} \cdot k_c \quad (9)$$

where

$$k_{IA16} = \left(\frac{\sigma_{mor}}{\sigma_{no}} \right)^2 \quad \text{and} \quad k_c = \frac{\dot{\epsilon}_{ref}}{\sigma_{ref} / E}$$

where $\dot{\epsilon}_{ref}$ is the reference creep strain rate corresponding to the reference stress σ_{ref} . J_{el} is the elastic J-integral calculated from Eq. (2) without considering plasticity. Similarly to the

JNC method, the A16 procedure uses the Newman and Raju solution [5] to calculate the SIF. The determination of σ_{no} , σ_{nor} and σ_{ref} is illustrated in Fig.3. $\dot{\epsilon}_{ref}$ is calculated using the creep law of the material, reinitialised at the beginning of each cycle. The reference stress at the beginning of the dwell is given by :

$$\sigma_{ref} = \frac{\sigma_{ref}^A + \sigma_{ref}^B}{2} + \frac{\Delta\sigma_{ref}}{2} \quad (10)$$

where $\Delta\sigma_{ref}$ is the reference stress range and σ_{ref}^A and σ_{ref}^B are the reference stresses calculated at the extreme load points A and B. For a load ratio $R=-1.0$, Eq. (10) reduces to $\sigma_{ref} = \Delta\sigma_{ref} = 2.\sigma_{ref}^A$. The creep crack growth rate per loading cycle $(da/dN)_c$ is calculated by :

$$\left(\frac{da}{dN}\right)_c = \int_0^{t_c} C.(C_{SA16}^*)^q .dt \quad (11)$$

In contrast to the JNC method, the A16 method does not account for stress redistribution under load controlled conditions.

DISCUSSION

The crack dimensions as a function of number of cycles are compared with the experimental data in Fig. 4. The two methods lead to significantly different predictions. In the benchmarks on fatigue crack growth [1], discrepancies caused by the determination of the reference stress and consideration of crack closure effects have been reported. For this benchmark, these are still responsible for differences in the predictions. However, both methods predict that the creep damage is predominant in comparison to the fatigue one. It is found that the two methods use different values of the reference stress at the beginning of the dwell. Figure 5 shows the reference stress during the first dwell. At the beginning of the dwell, the value used in the A16 procedure is approximately 1.4 times larger than that in the JNC method. In addition, stress relaxation is assumed in the JNC method which results in reducing the creep crack growth rate per cycle. Therefore, the A16 prediction is significantly larger than the JNC one.

Figure 4 also shows that the two methods exhibit some conservatism when predicting crack growth. There is an evidence that reinitialising the creep curve of the material at each cycle is too conservative [7]. This figure shows the predictions using an alternative model to integrate the creep law of the material. This model, proposed by Polvora et al. [4], consists in integrating the creep curve continuously during the experiment. The predictions obtained according to this model are also shown in Fig. 4 (solid lines). The A16 predictions are much closer to the experimental data than assuming creep reinitialising. However, when accounting for stress relaxation like in the JNC method, this model is found to underestimate the creep crack growth behavior.

In the determination of the reference stress, JNC accounts for the creep strain intensity due to an heterogeneous stress distribution in the ligament under small scale yielding condition. However, the recommended values of p_1 and p_2 in Eq. (6) are based on creep finite element analyses for plates containing a through wall notch subjected to uniaxial tension. The applicability to the semi-elliptical surface crack has not been verified yet. In fact, in this work, the JNC predictions are too conservative. Although not fully verified yet, some calculations using $p_1 = p_2 = 0$ in Eq. 6 were performed, that is substituting σ_{ref} for

σ_{c-ref} . The calculation results are shown in Fig. 6. Better agreement with the experimental data is obtained.

The crack closure effect has a minor influence when the creep curve is reinitialised at each cycle, as shown in Fig. 7. This is to be expected since the creep damage is predominant in comparison to the fatigue one. However, when assuming that the creep curve is not reinitialised at each cycle, the influence of crack closure becomes more important since the fatigue damage becomes more pronounced.

CONCLUSIONS

A benchmark problem consisting in predicting creep-fatigue crack growth in 316L(N) cracked plates subjected to a cyclic bending moment has been solved. The predictions according to the JNC and A16 procedures have been compared with each other. Differences are found between the predictions and the causes of those have been discussed. Comparing to the experimental data, it is found that the simplified methods exhibit conservatism which are significantly reduced when using alternative models to integrate the creep law of the material.

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TABLES

Table 1 Description of the benchmark problem [2, 7]

TESTING CONDITIONS					PLATE GEOMETRY			INITIAL NOTCH	
Temperature T °C	Load ratio R	Min. Load F_{min} kN	Max. Load F_{max} kN	Dwell t_c hour	Thickness t mm	Width $2w$ mm	Bending arm L mm	Depth a_0 mm	Length $2c_0$ mm
650	-1.0	-14.0	14.0	1.0	24.5	350.0	350.0	7.9	87.2

Table 2 Material properties of the 316L(N) at 650°C

MECHANICAL PROPERTIES [3]	CREEP LAW [4]
<ul style="list-style-type: none">Young's modulus $E=140600$ MPaPoisson's ratio $\nu=0.3$0.2% proof stress $\sigma_y=125$ MPa	<ul style="list-style-type: none">Primary creep law ($t < t_{fp}$) : $\epsilon_c = C_1 t^{C_2} \sigma^n$Secondary creep law ($t \geq t_{fp}$) : $\epsilon_c = C_1 t^{C_2} \sigma^n + 100 \cdot C \cdot \sigma^n \cdot (t - t_{fp})$
CYCLIC STRESS STRAIN CURVE [3]	
$\Delta \epsilon = 100 \cdot \frac{2 \cdot (1 + \nu)}{3 \cdot E} \cdot \Delta \sigma + \left(\frac{\Delta \sigma}{K} \right)^{1/m}$ <p>$K=718$, $m=0.319$ $\Delta \epsilon$ (%), $\Delta \sigma$ (MPa)</p>	<ul style="list-style-type: none">Transition time : $t_{fp} = \left(\frac{C}{C_1 \cdot C_2} \cdot \sigma^{n-n_1} \right)^{\frac{1}{C_2-1}}$ $C_1=6.78 \times 10^{-14}$, $C_2=0.4845$, $n_1=5.469$, $C=1.7 \times 10^{-20}$, $n=6.999$ ϵ_c (%), σ (MPa), t_{fp} (hour)
FATIGUE CRACK GROWTH LAW [4]	CREEP CRACK GROWTH LAW [4]
$\frac{da}{dN} = C_f \cdot \Delta K_{eff}^n$ <p>$C_f=3.2 \times 10^{-7}$, $n=2.46$ da/dN (mm/cycle), ΔK_{eff} (MPa√m)</p>	$\frac{da}{dt} = A \cdot (C^*)^q$ <p>$A=7.1 \times 10^{-3}$, $q=0.73$ da/dt (mm/hour), C^* (N/mm h)</p>

FIGURES

Figure 1 Experimental setup

(a) load controlled condition

(b) displacement or strain controlled condition

(c) generalised condition

Figure 2 Stress relaxation considered in the JNC method

(a) Nominal stresses

(b) Stresses in the ligament

Figure 3 Determination of σ_{no} , σ_{nor} and σ_{ref} in the AI6 method

Figure 4 Influence of creep strain integration on crack growth behavior

Figure 5 Reference stress during the 1st dwell

Figure 6 Influence of the reference stress on the JNC crack growth predictions

Figure 7 Influence of the crack closure factor on the A16 crack growth predictions