E 2/5

Prediction of Creep-Fatigue Damage for Fast Breeder Reactors: Sensitiveness to Material Behaviour Laws

B. Daron
Stein Industrie, Département Nucléaire, B.P. No. 74, F-78140 Vélizy-Villacoublay, France
A. Millard
C.E.A., CEN Saclay, DEMT, F-91191 Gif-sur-Yvette Cedex, France

Abstract

The purpose of our studies is to appraise influence of both hardening and creep laws used, on the creep damage predicted by an inelastic analysis.

The estimation was carried out for two different geometrical models, one very simple and the other representative of a real F.B.R. component, subjected to various types of loading cycles, each one being calculated using different plasticity and creep laws.

This paper presents a study achieved and enlights general principle of choice of visco-plastic laws which will guarantee a conservative creep fatigue damage appraisal.

I. Introduction

The demonstration of admissible creep-fatigue damage, according to the French RCC-MR Code, chapter RB 3200, often fails due to a very conservative estimate of the level of stresses σ_k responsible for the usage factor and the creep strain used in the fatigue calculation.

Indeed, this estimate assumes that creep occurs at high temperature, under the maximum stresses reached during the cycle, and that no relaxation happens during the hold period. In most cases, for complex structures like reactor components, this is not true because of stress relaxation and redistribution.

Therefore, when there is no more geometrical improvement or technological modification to be done in order to reduce the damage to an allowable value, it is necessary to turn to an elasto-viscoplastic analysis of the component. However, one of the main difficulties consists in choosing a material behaviour law which leads to a realistic and conservative estimation of the structural behaviour. For structures working at low temperature, the damage is due to fatigue only, and therefore it is sufficient to adopt a plasticity model with the lowest values for the yield stress and the hardening parameter. But for structures working at high temperatures, the creep damage may not be neglected and must be calculated on the basis of an accurate level of stresses. Thus, for a hold period at the maximum stress over a cycle, higher yield stress and hardening parameter will lead to a more important creep damage. For a hold period at some intermediate stress value during the cycle, the choice is not so clear, as shown on figure 1.

The purpose of the present paper is to appraise the influence of various material behaviour laws on the creep fatigue damage as predicted according to the classical inelastic analysis.

The estimation was carried out first on a very simple structure in order to gain a better understanding of the phenomena, and then the results were generalized by the study of a more complex axisymetrical structure representative of a real component of the fast breeder reactor Superphenix. This paper gives the main results and draws some conclusions, which enlight some general principle of choice of viscoplastic material behaviour laws which will lead to a conservative creep fatigue damage. However, it must be kept in mind that these conclusions are relevant to similar structures and loading cycles, and more studies should be performed in case of very different conditions.

II. Description of the studies

II.1 - Basic loading cycle

A typical loading cycle for a fast breeder reactor component has been defined from a real case. It is shown on figure 2. It is repeated 1010 times for a total time life of 200,000 hours at high temperature.

II.2 - Geometrical models

A first very simple model termed "beam model" has been defined (see figure 3). It can be represented as a portion of a straight beam ; one side is subjected to a parabolic displacement profile, which corresponds to a thermal gradient accross the section of the beam due to a thermal shock during a thermal transient. Thus, the 1st degree term corresponds to the linearized bending (secondary) stress, and the 2nd degree one, to the non-linearized (peak) stress. The other side is loaded by a prescribed primary force and must remain plane, which corresponds to the permanent primary loads of the structure.

It may be noticed that with such a model, the only degree of freedom is the axial AB cross-section displacement and thus the increase of displacement due to plasticity will be uniformly distributed over the cross-section.

Therefore, a second model, more complex, has been defined in order to take into account the effects of strain concentrations and the redistributions which happen in a real structure (internal elastic following). In fact it represents a junction between a plate and a cylindrical shell, loaded by an internal pressure and axial force (primary loading) and a rotation imposed by the plate (secondary loading) (see figure 4).

In fact two models have been considered, with different stress concentration factor K_σ :

$$K_\sigma = \frac{P + Q + F}{P + Q}$$

where P + Q + F stands for the total stress and P + Q stands for the membrane and linearized bending stress. The values adopted for the two models are respectively 1.26 and 1.92.

II.3 - Inelastic material behaviour laws

Four behaviour laws have been investigated for the present studies. The material is a 316L-SPH stainless steel (which corresponds to the 316 SS in Code Case N47). The various models are listed in the table 1.

III. Studies performed and results

Table 2 displays the various combinations of material laws and geometrical models used for the evaluation of creep-fatigue damage, on the basis of the inelastic analysis.

Moreover, the damage has also been calculated using classical elastic analysis according to Code Case N47 and RCC-MR Code for comparison (see table 3).

IV. Comments on the results

IV.1 - Fatigue damage

The fatigue damages calculated are very similar between the various models, which can be explained by the fact that the primary stresses are low in front of the secondary stresses, since the structure is more in a displacement controlled situation.

Besides, the calculations show clearly the breakdown of the fatigue damage between the elastic analysis according to Code Case N47 and the inelastic one. This is due to the difference between the "pure" fatigue curves used in inelastic analysis or elastic analysis according to RCC-MR Code, and the "time dependent" fatigue curves used in elastic analysis according to Code Case N47, which account implicitly for some creep effects (strain increase, creep damage due to peak stress, etc...)

IV.2 - Creep damage

The creep damage is essentially influenced by the plasticity model, while the influence of the creep law is unsignificant.

Indeed, the level of the stress is determined by the plasticity model together with the tensile strength curve used, whereas the shape of the basic loading cycle explains the lack of influence of the creep law : In fact, the consequences of the creep during the hold-period (stress relaxation, creep strain) are obliterated by the addition of plasticity caused by the transient period which follows the hold period and which leads to one of the cycle extrema.

IV.3 - Comments on the beam model

It has been noticed that despite a different overall mechanical behaviour, the stress levels observed at the most loaded point of the beam model represent fairly well the stress levels observed at the most loaded point of the axisymmetrical model. Therefore, it justifies a posteriori the representativeness of the beam model for the study of the stresses evolution at the most loaded point of the complex model.

IV.4 - Influence of the creep law on the damage

It has been observed that for large amplitude cycles (i.e. the elastically calculated range of the stresses overstep the elastic limit), a loading which generates cyclic plasticity at the most loaded point obliterates the creep effects caused by the hold period.

Therefore it is possible to appraise the effects of the creep law on the creep damage only in the case of structure which shakes down. Then the loading cycle does not modify the creep process.

As a consequence, in order to enlight the influence of the creep law on the creep damage, some additional studies have been performed on the same geometrical models but with a modified basic loading cycle, where the transient period following the hold period has been suppressed (The cycle on figure 2 becomes ABCE). The three creep laws (slow, mean, fast) were used in conjunction with the above mentioned tensile strength curves.

The following conclusions can be drawn :

. The creep damage seem to be more dependent on the creep law used in the inelastic analysis (they diminish when the creep rate increases) than on the hardening law which supplies the initial stress level at the most loaded point, before relaxation. However, they are lower when the tensile strength curve leads to a smaller initial stress.

The preponderence of the creep law on the hardening law is more marked when the creep law is faster. The reason for this is that the creep partially obliterates the differences of stress levels due to different hardening laws over a period which is short in comparison with the 200,000 hours (see figure 7).

. The damage estimated by means of an elastic analysis are very important and completely different from the inelastic analysis.

This overprediction is attributable not to a bad estimate of the initial stress before relaxation, but to the lack of account for the stress decrease at the most loaded point. This decrease happens principaly during the first thousands hours, leading to a relatively low stress during the major running period at high temperature.

Table 4 shows the various creep damages calculated.

V. Conclusion

. In case of plastic shakedown, the stress level will be due to the plasticity model, since the creep effects will be obliterated at each cycle.

. In case of elastic shakedown, the creep occurs without disturbance due to cyclic plasticity thus the creep damage is strongly dependent on the speed of the creep law since the relaxation reduces the initial stress level.

. In all cases, the use of a simplified model which reproduces the stress distribution in the most loaded section enables to appraise the influence of the material laws on the damages, provided that plasticity remains confined in small regions which do not generate large stress redistributions.

Table 1 - Material behaviour laws -

Model	Plasticity	Creep
A	- linear kinematic hardening - stress strain curve obtained by bilinearisation of mean monotonous uniaxial tensile strength curve, for plastic strains ranging from 0.01 % to 1 %. - yield stress σ_{po} - hardening modulus h_o	Mean creep law with strain hardening hypothesis $\frac{d\varepsilon_c}{dt} = f\ (\sigma,\ \varepsilon_c)$
B	Similar to A, with high monotonous uniaxial tensile strength curve. - yield stress $\sigma_p = 1.2\ \sigma_{po}$ - hardening modulus $h_p = 1.2\ h_o$	Fast creep law with strain hardening hypothesis $\frac{d\varepsilon_c}{dt} = f\ (1.2\ \sigma,\ \varepsilon_c)$
C	Identical to B	Slow creep law with strain hardening hypothesis $\frac{d\varepsilon_c}{dt} = f\ (\frac{\sigma}{1.2},\ \varepsilon_c)$
D	- non linear kinematic hardening with cyclic consolidation (CHABOCHE's model) - yield stress σ_{Po} - hardening rule : CHABOCHE's model $d\bar{X} = c(\frac{2}{3}\ a\ d\tilde{\varepsilon}_p - \bar{X}\ d\varepsilon^*)$ where $\bar{X}$ = tensor of kinematic internal variables ε^* = equivalent plastic strain	Identical to A

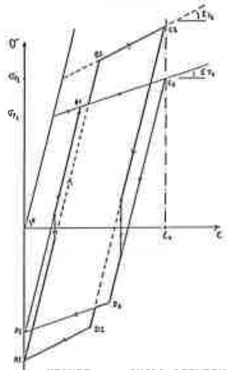

FIGURE 1 : CYCLE BETWEEN O AND ε_o CALCULATED IN KINEMATIC HARDENING WITH TWO PLASTICITT LAWS : On "low" (σ_{P_1}, E_{T_1} ⟶), the other "right" (σ_{P_2}, E_{T_2} ⟶). The strong line corresponds to the plasticity law which leads to the most important stress level at each point of the cycle.

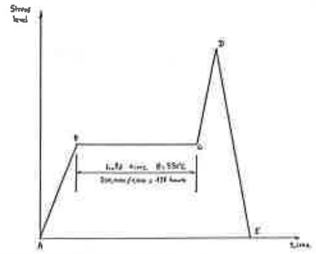

FIGURE 2 : BASIC LOADING CYCLE

Points A and E : "Stop state" : No load $\theta = 250°C$
Point D : "Transient state" $\theta = 550°C$
B to C : "Steady state" $\theta = 550°C$

Table 2 - Studies performed - Inelastic analysis results -

Dc = creep damage
Df = fatigue damage

Material behaviour law / geometrical model	A	B	C	D
Beam model	Dc = 0.123	0.163	0.225	0.124
	Df = 0.059	0.058	0.055	0.056
Axisymmetrical model $K_\sigma = 1.26$	Dc = 0.269	-	0.224	-
	Df = 0.066	-	0.042	-
Axisymmetrical model $K_\sigma = 1.92$	Dc = -	-	3.32	-
	Df = -	-	0.680	-

Table 3 - Studies performed - Elastic analysis results -

Code / Geometric. model	Code Case N47	RCC-MR
Beam model	Dc = 6.24 Df = 4.93	Dc = 14.52 Df = 0.23
Axisymmetrical model $K_\sigma = 1.26$	Dc = 6.24 Df = 6.92	Dc = 14.37 Df = 0.26
Axisymmetrical model $K_\sigma = 1.92$	Dc = 6.24 Df =32.58	Dc = 63.11 Df = 1.41

Table 4

Geometrical model		INELASTIC			ELASTIC	
	Creep law / Tensile strength curve	low	mean	fast	CCN47 *	RCC-MR
Beam model	Mean	0.0794	0.0369	0.0131	6.477	2.984
	High	0.1408	0.0654	0.0177		
Axisymmetrical model	Mean	0.1550	0.0829	0.0330	2.780	2.485
	High	0.2649	0.1251	0.0446		

* as pure fatigue damage, is very small for such a cycle, the CCN47's creep damage indicated here is the sum of the fatigue and creep damages.

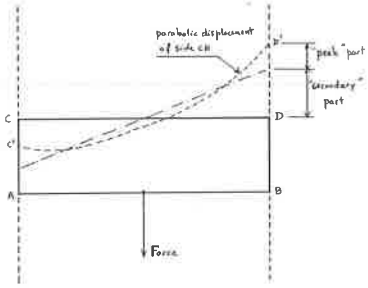

FIGURE 3 : BEAM MODEL

The side AD must remain parallel to its initial position

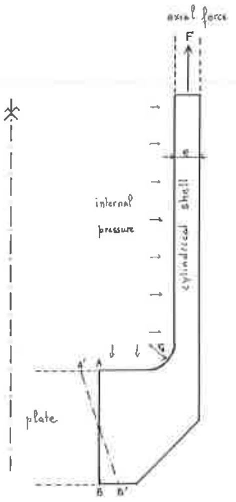

FIGURE 4 : AXISYMMETRICAL MODELS

For the model with $K_\sigma = 1.26$, the ratio $r_o/e = 0.78$

For the model with $K_\sigma = 1.92$, the ratio $r_o/e = 0.17$

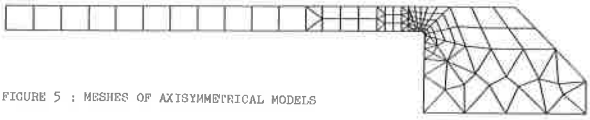

FIGURE 5 : MESHES OF AXISYMMETRICAL MODELS

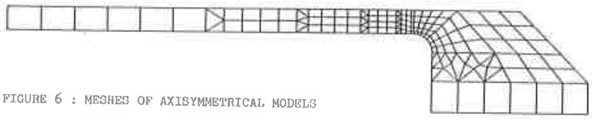

FIGURE 6 : MESHES OF AXISYMMETRICAL MODELS

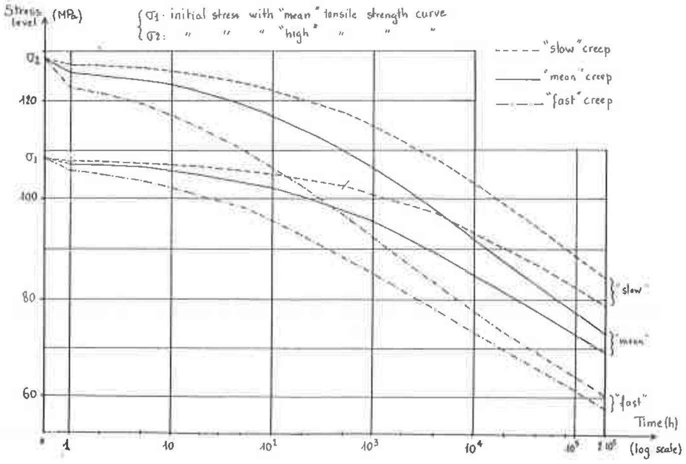

FIGURE 7 : EVOLUTION VERSUS TIME OF THE STRESS LEVEL OF THE MOST LOADED POINT OF THE "BEAM MODEL"