A Simplified Model for Cumulative Damage with Interaction Effect for Creep Loading

Reha Gomuc, Thang Bui-Quoc, Andre Biron
Ecole Polytechnique, Montreal, Canada

INTRODUCTION

The basic creep-rupture behavior of a material at high temperature is, in general, obtained with constant stresses under isothermal conditions. Structural components operating at high temperature are, however, usually subjected to fluctuations of stresses and/or temperatures. Experimental conditions cannot cover all possible combinations of these parameters and, in addition, systematic investigations on cumulative creep damage are very limited due to long-term testing. There is, therefore, a need to establish a reliable procedure for evaluating the cumulative creep damage effect under non-steady stresses and temperatures.

There is experimental evidence on the order effect of creep loading involving several stresses (Kelly et al, 1984; Ohnami et al, 1988; Goldhoff et al, 1972). This effect is interpreted through the sum of time ratios under different stress sequences. For example, a decrease in stresses generally produce lower creep rates than in the case where the latter stress is applied alone, while an increase in stress produce the reverse trend (Swindeman et al, 1981); as a consequence, the experimental sum of life-fractions is greater than unity for two decreasing stresses and the reverse is also true for two increasing stresses (Kelly et al, 1984). The linear damage rule (Robinson, 1952) is not, therefore, adequate to characterize the material behavior in many situations and several alternative procedures have been suggested in the literature for evaluating cumulative creep damage (Kelly et al, 1984; Goldhoff et al., 1972; Gittus, 1971; Rice, 1970; Ponter al, 1971; Lagneborg, 1972; Bui-Quoc, 1979; Bui-Quoc et al, 1980).

The cumulative damage method recently suggested (Bui-Quoc, 1979; Bui-Quoc et al, 1980) has been derived from a phenomenological continuous damage approach which takes into consideration the order effect of loading. The theoretical order effect in creep loading considered by the concept is not, however, as pronounced as that observed experimentally for some materials. This phenomenon is usually attributed to the material memory effect between stress levels.

In this paper, a further development on the interaction effect is made in order to account for a modification in the material behavior due to a previous creep loading history. Empirical relations have been established for this purpose, using published test results obtained from three different materials at high temperatures.

A particular feature of the present concept is that the continuous damage associated with creep may be combined to that associated with fatigue for the study of the creep-fatigue interaction problems (Bui-Quoc et al, 1982; Gomuc et al, 1986; Gomuc et al, 1987).

THE CONTINUOUS CREEP DAMAGE APPROACH

The damage accumulation during creep loading has been considered as a continuous process of the deterioration of the "creep strength" (as defined in Bui-Quoc, 1979) and a formulation has been suggested to describe the decrease of this strength. The development led to an equation for expressing the basic isothermal creep-rupture data, i.e. applied stress σ versus time to rupture T (Bui-Quoc et al, 1982).

In pure creep, the damage state has been defined in terms of the instantaneous creep strength and the normalized damage function D is expressed in terms of the life-fraction β ($\beta = t/T$ where t is the exposure time) with the dimensionless stress Θ as a parameter:

$$D = \frac{\beta}{\beta + (1 - \beta)\left[\dfrac{\Theta - \Theta_p}{\Theta^{0.5} - \Theta_p}\right]} \tag{1}$$

In the above equation, $\Theta = \sigma/\sigma_u$ and $\Theta_p = \sigma_p/\sigma_u$, in which σ_u is the ultimate tensile strength at the considered temperature whereas σ_p is the creep limit stress. For most materials, it has been found that Θ_p is close to 0.05 and this value is used in the present investigation (Bui-Quoc, 1979). The creep damage function is represented schematically in Fig. 1 with two different stress levels Θ_1 and Θ_2. The dotted curve identified by D' will be explained in a latter section.

It is noted that as the stress approaches the ultimate tensile strength (i.e. $\Theta = 1$), the damage function tends to be linear with the life-fraction (this is usually identified as the linear damage rule), a concept generally adopted in cumulative damage studies under creep loading in the high stress region. For a given creep loading condition, the exposure time has a direct effect on the creep strength and, to an extent, on the static properties of the material determined subsequently. For example, as this exposure time increases, the ultimate strength and yield strength of an exposed material are considerably reduced with respect to those obtained from the unexposed material (Van Leeuwen et al, 1973/74); furthermore, the damage accumulation rate decreases as the exposure time increases (Goldhoff et al, 1972). The theoretical trend of the model suggested in (Bui-Quoc et al, 1980) correctly reflects these essential features.

Alternatively, eq. (1) may be rearranged in the following form:

$$\beta = \frac{D\left[\dfrac{\Theta - \Theta_p}{\Theta^{0.5} - \Theta_p}\right]}{1 - D\left[\dfrac{\Theta^{0.5} - \Theta}{\Theta^{0.5} - \Theta_p}\right]} \tag{2}$$

MULTILEVEL CREEP LOADING

a) The procedure. - For a multilevel isothermal creep loading, when the stress is changed from one level to another, the damage state is assumed to remain unchanged. Fig. 1 also shows the procedure for calculating the remaining life-fraction β_r in creep loading involving two decreasing stresses. The damage state D_1 at the end of the first loading is calculated from eq. (1) with $\theta = \theta_1$ and $\beta = \beta_1$; then, the equivalent life-fraction β_2 necessary for generating this damage state during the second loading is calculated from eq. (2) with $D = D_1$ and $\theta = \theta_2$. Finally, the remaining life-fraction is given by:

$$\beta_r = 1 - \beta_2 \tag{3}$$

The procedure may be extended for creep loading involving several stresses. The theoretical sequence effect of loading in multistep tests given by the method is consistent with the experimental trend generally reported in the literature. Experimental results obtained from some materials (Kelly et al, 1984; Ohnami et al, 1988) have shown, however, that the sequence effect is far more important than what is obtained theoretically. This means that the creep damage evolution at the latter stress level is influenced by the previous loading history and the damage accumulation process during the latter stress would not coincide with the original curve (Swindeman et al, 1981). The interaction between stresses at different levels of loading is therefore proposed.

b) The interaction effect. - The concept of consideration of the interaction effect between stresses under cumulative damage loading has been suggested, in a manner similar to what was done for cumulative fatigue (Bui-Quoc, 1982; Bernard-Connolly, 1983), by introducing an interaction parameter v_i in the damage function, as follows:

$$D' = \frac{\beta^{v_i}}{\beta^{v_i} + (1 - \beta^{v_i})\left[\dfrac{\theta_i - \theta_p}{\theta_i^{0.5} - \theta_p}\right]} \tag{4}$$

where θ_i is stress corresponding to i^{th} level. The interaction parameter characterizes the cumulative sequence effect by taking into account the previous loading history. After a preloading, the damage accumulation during the i^{th} level will be governed by this modified damage curve, instead of the damage curve given by eq. (1). The concept for two-level creep loading is also shown schematically in Fig. 1.

c) Evaluation of the interaction parameter. - The value of v_i associated with the i^{th} level is suggested as follows:

$$v_i = v_1' \times v_2' \,.........\times v_{i-1}' \times v_i' \tag{5}$$

where v_i' is the interaction parameter between two successive stress levels $i-1$ and i with $v_1' = 1$. In particular, v_i' is a function of the difference between two consecutive stress levels $\Delta\theta_i = \theta_i - \theta_{i-1}$ and is given by:

$$v_i' = \left[1 - \left[\frac{|\Delta\theta_i|}{1-\theta_p}\right]^{\alpha}\right]^{-\,\mathrm{sign}\,(\Delta\theta_i)} \tag{6}$$

When the loading pattern is specified, the interaction parameter at each level may be computed by means of eqs. (6) and (5). For example, under a two-level creep loading, $v_2 = v_2'$ and Fig. 2 shows the correlation of eq. (6) with a limited number of experimental data on Cr-Mo-V steel (Goldhoff et al, 1972). It appears that $\alpha = 0.1$ may be representative for this particular material.

APPLICATION OF THE CONCEPT

a) Two-step isothermal creep loading. - Typical remaining life-fractions β_r' with the interaction effect consideration in terms of β_1 (life-fraction corresponding to the first level) are shown in Fig. 3a for two-step creep with constant temperature on the Cr-Mo-V steel. Also included in this figure is the remaining life-fraction β_r obtained from the procedure without interaction effect consideration ($v_2 = 1.0$). It is seen that the calculated remaining life-fractions with interaction are closer to the experimental results, as expected.
An attempt has been made to apply the procedure to the data obtained from two stainless steels and the results are shown in Fig. 3b for SS 316 (Kelly et al, 1984) and in Fig. 3c for SS 304 (Ohnami et al, 1988).
It is noted that for the materials studied, the linear life-fraction rule (represented by the 45° - line) gives estimates far different from the experimental data.

b) Non-isothermal multilevel creep loading. - A particular feature of the present technique is that the concept can handle the case involving a temperature change in creep loading. This advantage is due to the fact that the dimensionless stress, instead of its absolute value, is used in the damage function.

For example, the damage accumulation in two individual creep tests involving a change of the stresses and/or of the temperatures will be represented, in general, by two different damage curves (since $\Theta_1 = \Theta_2$). An attempt has been made to include in the analysis (Fig. 2) a few experimental data available with different combinations of stresses and temperatures. The results shown in Fig. 2 suggest that parameter v_i is dependent mainly upon $\Delta\Theta$ (the dimensionless stress difference) and less sensitive to absolute values of the temperature and the stress level. Fig. 4 presents the correlation between the remaining lives for the case involving a simultaneous change of stress and temperature together with the experimental results. The agreement between theoretical value and data is reasonably satisfactory.

DISCUSSION

The present approach is based on a continuous damage where the influence of the previous loading history is interpreted by an interaction parameter v_i'. Typical values of α used in the present analysis for two-level creep loadings are 0.1 for Cr-Mo-V steel, 0.22 for 316 SS and 0.5 for 304 SS. For increasing stress levels, v_i' is larger than unity, while the reverse is true for decreasing stress levels; in the case where there is no stress change, ($\Delta\Theta=0$) v_i' is equal to unity. It is also noted that the interaction effect is very significant when the difference between stress levels becomes large.

It is reasonable to assume that the material constant α in eq. (6) depends upon material characteristics. For the materials which exhibit a strong interaction effect, such as Cr-Mo-V steel, the value of α is close to zero; on the other hand, for materials with a negligible memory effect, the value of α is large, and v_i' approaches unity; in this case, the theoretical sums of life-fractions are closer to unity. The values of α used in the present analysis were obtained using a relatively small number of experimental data. For each material, this parameter could be evaluated with confidence only when a reasonable number of two-step test results is available.

CONCLUSION

Experimental observations have shown that, under two-step creep loadings, the sums of life-fractions are different from unity, depending upon the stress and/or temperature sequence. Therefore, the linear damage rule is not adequate for evaluating the cumulative creep damage in those circumstances. An interaction effect consideration has been introduced in the cumulative creep damage concept previously suggested; this permits to take into account the strong sequence effect of loading reported for some materials. The procedure, using the dimensionless stress, may be extended to cases involving a change of stresses and/or of temperatures. The agreement between experimental results and predictions is reasonably good in view of the scatter normally observed in experimental work on cumulative creep damage.

REFERENCES

BERNARD-CONNOLLY, M., BUI-QUOC, T. and BIRON, A. (1983). Jl. of Eng. Mat. Techn. (ASME), Vol. 105, pp. 188-194.

BUI-QUOC, T. (1979). Jl. of Eng. Mat. Techn. (ASME), Vol. 101, pp. 337-343.

BUI-QUOC, T. and BIRON, A. (1980). Proc. Int. Conf. on Engng. Aspects of Creep, Vol. 1, pp. 121-126.

BUI-QUOC, T. and BIRON, A. (1982). Nucl. Eng. Design, Vol. 70, pp. 89-102.

BUI-QUOC, T. (1982). Proc. Joint Conf. on Exp. Mech., SESA/JSME, pp. 144-149.

GITTUS, J. (1971). Phil. Mag., Vol. 24, pp. 1423-1440.

GOLDHOFF, R.M. and WOODFORD, D.A. (1972). ASTM STP 515, pp. 89-106.

GOMUC, R. and BUI-QUOC, T. (1986). Jl. of Press. Vess. Tech. (ASME), Vol. 108, pp. 280-288.

GOMUC, R., BUI-QUOC, T. and BIRON, A. (1987). Res Mechanica, Vol. 21, pp. 135-154.

KELLY, D.A. and SINGH, G.(1984). Fatigue of Engng. Mater. Struct., Vol. 7, pp. 75-83.

LAGNEBORG, R. (1972). Met. Sci. Jl., Vol. 6, pp. 127-133.

OHNAMI, M., SAKANE, M. and NISHINO, S. (1988). in High Temperature Creeep-Fatigue, Elsevier Applied Science, London, pp. 165-181.

PONTER, A.R.S. and LECKIE, F.A. (1971). Jl. of Eng. Mat. Techn. (ASME), Vol. 98, pp. 1423-1440.

RICE, J.R. (1976). Jl. Appl. Mech., Vol. 37, pp. 728-737.

ROBINSON, E.L. (1952). Trans. ASME, Vol. 74, pp. 777-780.

SWINDEMAN, R.W. and KLUEH, R.L. (1981). Res Mechanica, Vol. 3, pp. 245-270.

VAN LEEUWEN, H.L. and SCHRA, L. (1073/74). Proc. Int. Conf. on Creep/Fatigue in Elevated Temps. Appl., pp. 134.1-134.9.

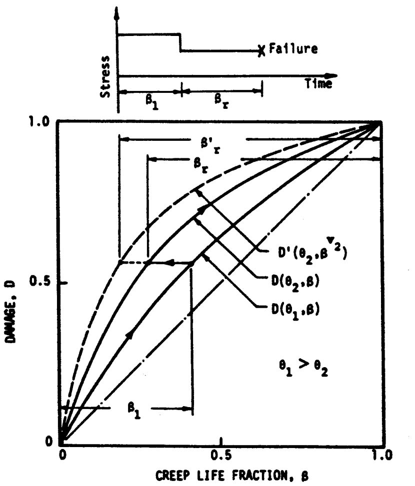

Fig. 1. Creep damage function and application of the cumulative damage concept, with and without interaction effect, for two dereasing stresses.

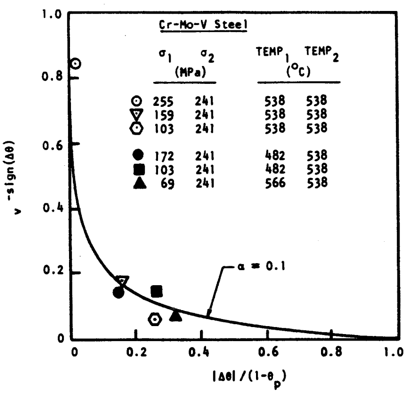

Fig. 2. Correlation between interaction parameter and difference of dimensionless stress levels.

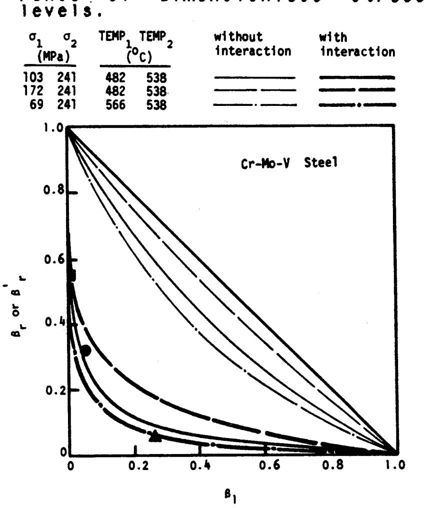

Fig. 4. Correlation between experimental results and estimated remaining time-fractions for two-step tests with stress and/or temperature changes.

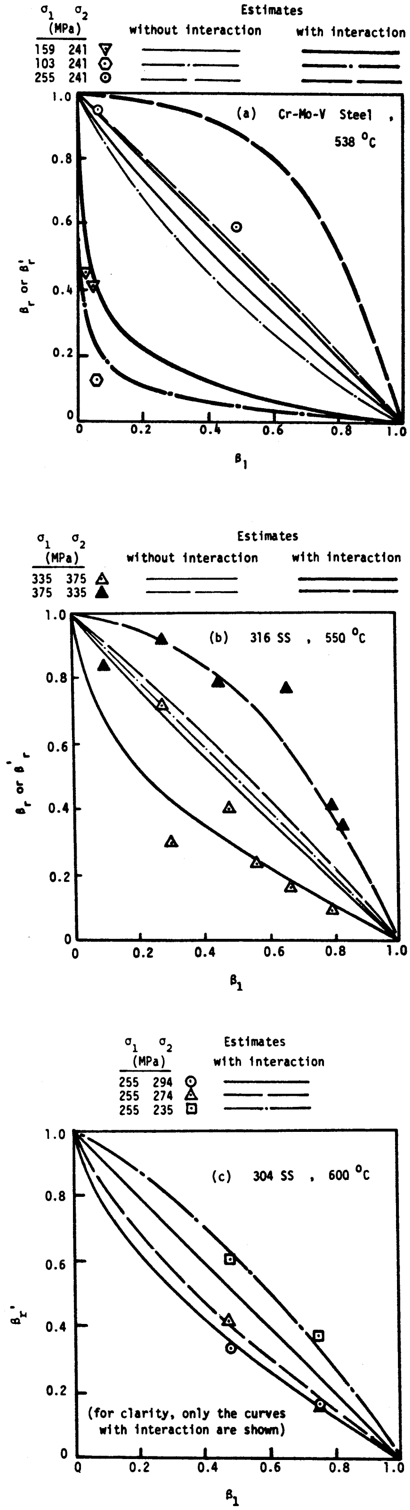

Fig. 3. Correlation between experimental results under isothermal two-step creep and estimated remaining time-fractions.