Cumulative Damage Concepts with Interaction Effect Consideration for Fatigue or Creep: A Perspective

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ABSTRACT

In this paper, an interaction effect consideration is introduced in the damage concepts already proposed in order to explain the strong deviation of the sum of life-fractions. This effect is analyzed separately for two-level loading under fatigue tests or under creep tests. The potential of the approach is outlined for a combination of creep-fatigue loading. Some published experimental data is presented which supports the results of the present analysis.

1. Introduction

The aim of the paper is to discuss an approach developed for predicting the remaining life of a material subjected to cumulative damage in either fatigue, creep or a combination of both. The particular situation emphasized is that in which two different levels of loading are involved.

The essential feature of the approach is the resulting stress or strain-dependent damage functions with the introduction of an interaction effect between the two different loading conditions. With this consideration, the behavior of the material at the second level of a two-step loading condition when, say, the stress is changed from σ_1 to σ_2 is such that the damage evolution is not the same as if the stress σ_2 had been applied in the first place.

2. Fatigue damage

a. Damage function

The following parameters are defined either in terms of the applied stress σ (for stress-controlled conditions) or as a function of the imposed strain range $\Delta\varepsilon$ (for strain-controlled conditions)[1,2]:

$$\gamma = \sigma/\sigma_o \quad \text{or} \quad 1 + \ln(\Delta\varepsilon/\Delta\varepsilon_o)$$

$$\gamma_e = \sigma_e/\sigma_o \quad \text{or} \quad 1 + \ln(\Delta\varepsilon_e/\Delta\varepsilon_o)$$

where σ_u: ultimate tensile stress; σ_o and $\Delta\varepsilon_o$: are the stress and the strain range, respectively, corresponding to the endurance limit of the original material; σ_e and $\Delta\varepsilon_e$ are the instantaneous strengths associated with the endurance limit.

An expression of the decrease of the strength γ_e during a fatigue loading has been suggested in [1]. The damage D is defined in terms of the above parameters as ($\gamma_u = \sigma_u/\sigma_o$)

$$D = \frac{1 - \gamma_e}{1 - (\gamma/\gamma_u)^8} \tag{1}$$

The development, already outlined in detail in [3], leads to the damage function expressed in terms of the life fraction $\beta = n/N$ (where n is the number of applied cycles and N is the cycles at failure at the same level)

$$D = \frac{\beta}{\beta + (1-\beta)\,\dfrac{\gamma-(\gamma/\gamma_u)^8}{\gamma - 1}} \tag{2}$$

Using this damage function specified by eq. (2), the order effect of loading under a two-stress (or two-strain) sequence is taken into consideration. The procedure for calculating the remaining life is illustrated in Fig. 1 for a sequence of two increasing levels. The estimated remaining cycle-ratio in terms of the damaging one is shown in Fig. 2 in comparison with some experimental data for En-3A mild steel. It is seen that the theoretical order effect is "qualitatively" valid; it is, however, far less pronounced than that obtained experimentally for some materials [4,5]. This observation suggests that there is an interaction effect between the levels considered and that, due to this effect, the course of damage accumulation is modified with respect to that corresponding to the single level.

b. Interaction effect consideration in two-level sequence

Due to the interaction effect, after a loading specified by a cycle-ratio β_1 at γ_1, the damage evolution at the second level will be governed by a fictitious level γ_2', instead of the actual value γ_2, as illustrated in Fig. 3. In this figure, β_2' and β_2 are the remaining cycle ratios with and without the interaction effect consideration respectively.

A parameter, denoted by Y, has been defined in terms of γ_2' and has been used in the following model for a multiple regression analysis:

$$Y = 1 + A_1 \, (\Delta\gamma/\Delta\gamma^*)^{A_2} \, \beta_1^{A_3} \tag{3}$$

where the definition of parameter $\Delta\gamma^*$ will depend on whether the loading sequence is increasing or decreasing and A_1, A_2, and A_3 are material constants. With the results of a few selected two-step tests, these constants may be obtained; the correlation may then be used to estimate the remaining life for other conditions of testing.

For torsion loading on En-3A mild steel, typical results of the analysis are given below [6] :

(i) For two increasing strains, with

$$Y = \frac{\gamma_u^{8/7} - \gamma_2}{\gamma_u^{8/7} - \gamma_2'} \quad \text{and} \quad \Delta\gamma^* = \gamma_u^{8/7} - \gamma_1 \tag{4}$$

the numerical values of the three constants are: $A_1 = 12.0$, $A_2 = 1.50$ and $A_3 = -1.53$.

(ii) For two decreasing strains, with

$$Y = \frac{\gamma_2 - 1}{\gamma_2' - 1} \quad \text{and} \quad \Delta\gamma^* = \gamma_1 - 1 \tag{5}$$

one obtains: $A_1 = 0.95$, $A_2 = 0.31$ and $A_3 = 0.76$.

Fig. 4 shows the predicted cycle ratio with the interaction effect consideration on the same material using the results of the above analysis. The procedure, applied for two other materials with the same numerical values of constants (A_1, A_2, A_3) gives a satisfactory improvement in correlation [7] .

3. Creep damage

a. Formulation

A material characteristic, defined as the creep strength σ_s (dimensionless creep strength $\theta_s = \sigma_s/\sigma_u$ where σ_u should be obtained in a short-term tensile test at the temperature considered), has been considered for describing the creep damage process [8] . Under constant stress loading specified by the stress $\sigma(\theta = \sigma/\sigma_u)$, this strength decreases from an original value to a value equal to the applied stress at the onset of failure. The creep endurance limit σ_p ($\theta_p = \sigma_p/\sigma_u$) has also been noted as the stress under which there is no damage incurred by the material for whatever duration of exposure. This may be related to the stress opposing the movement of dislocations which has been included in the relation governing the steady creep strain rate [9] .

Using a formulation similar to that for fatigue, a normalized damage function has been defined as:

$$D = \frac{\theta^d - \theta_s^d}{\theta^d - \theta} \tag{6}$$

where d = 0.5 (arbitrarily set) and the development leads to [8] :

$$D = \frac{\beta}{\beta + (1 - \beta)\dfrac{\theta - \theta_p}{\theta_d - \theta}} \tag{7}$$

where $\beta = t/T$ (ratio between the exposure time and the time to rupture at the same level).

Fig. 5 shows the variation of D in terms of β with θ as a parameter. It is seen that, when the stress increases, the damage curve tends to be more linear with β, thus approaching in the high-stress region the linear damage rule commonly used in the assessment of the creep damage. The concavity of the damage curves is directed downwards, reflecting the experimental observations concerning the strength-loss rate [10] and in conformity with the concept schematically suggested by Goldhoff and Woodford [11] .

Comparison with a limited number of experimental data obtained on a Cr-Mo-V steel at 538^{0}C suggests that there is some interaction between two levels for creep cumulative damage.

b. Interaction effect consideration

An analysis has been carried out in a manner similar to that for fatigue. With the Z-parameter defined as ($\theta_2{}'$: fictitious second stress level):

$$Z = \frac{\theta_2{}' - \theta_2}{\theta_2 - \theta_p} \tag{8}$$

the following model has been used for a multiple regression analysis.

$$f(Z) = 1 + B_1 \, (\Delta\theta/\Delta\theta^*)^{B_2} \, \beta_1^{B_3} \tag{9}$$

The analysis has been made on the basis of a limited number of tests results on a Cr-Mo-V steel at 538^{0}C and the following results have been obtained [12] :

(i) for two increasing stresses, $f(Z) = Z$, $\Delta\theta^* = 1 - \theta_1$ and $B_1 = 35.5$, $B_2 = 1.29$, $B_3 = -1.23$

(ii) for two decreasing levels, $f(Z) = 1/Z$, $\Delta\theta^* = \theta_1 - \theta_p$ and $B_1 = 195$, $B_2 = 2.57$, $B_3 = 0.85$

Fig. 6 shows some typical results.

4. Fatigue/Creep Combination

The combined effect of damage due to creep and fatigue may be investigated by carrying out tests with a specific pattern of loading. Fig. 7 illustrates some typical patterns where the creep and fatigue damages may be activated sequentially or in a interspersed manner. The remaining life of the material under these testing conditions may be computed by using the damage functions previously developed for fatigue and creep.

With the approach used, Fig. 8 shows some experimental results for IN-100 in a fatigue-creep sequence (Fig. 7a) together with the predicted curve without interaction. With the interaction effect introduced in the concept, it is conceivable that an improved correlation can be obtained, such as shown by the dotted line in the figure. The parameters involved in the concept are presently examined on the basis of the data available on some other materials.

5. Conclusion

An approach of cumulative damage has been formulated separately for fatigue or for creep loading. It gives the expression for describing the basic curve, i.e. data corresponding to one-level loading, as well as the damage functions for evaluating the remaining life in multi-level loading.

The method of life prediction under a combined fatigue/creep sequence has then been outlined. Some typical combinations of fatigue-creep loading patterns have been considered. The predictions depend upon, among several parameters, the pattern involved.

An interaction effect between imposed levels in each process has been considered. This resulting development may be used to explain the strong deviation from unity of the sum of life fractions obtained in tests with two levels. An interaction effect between the two processes, i.e. fatigue and creep, may possibly exist for certain types of materials. The potential of the method has been discussed in the light of some available test results.

Acknowledgments

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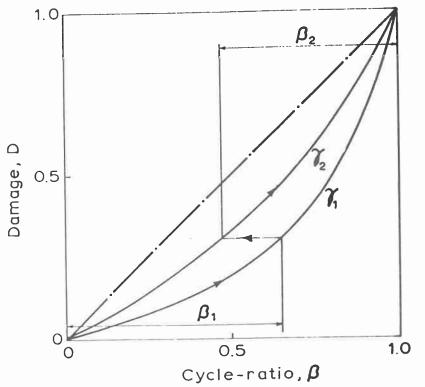

Fig. 1 Procedure for estimating the remaining life-fraction under fatigue loadings with two increasing levels (without interaction effect consideration).

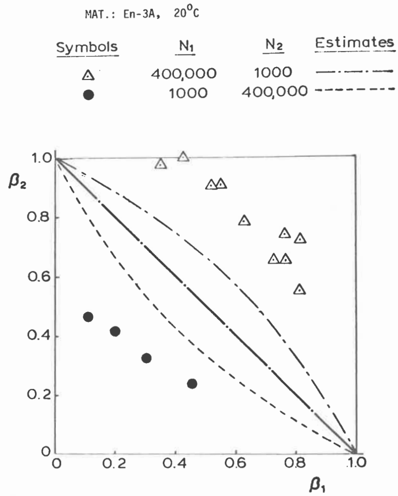

Fig. 2 Correlation between experimental results and estimated life-fraction, without interaction effect consideration, (from Ref. 7).

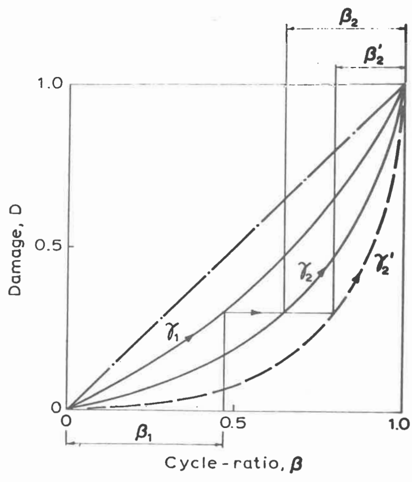

Fig. 3 Interaction effect consideration in the present damage concept (for fatigue loading).

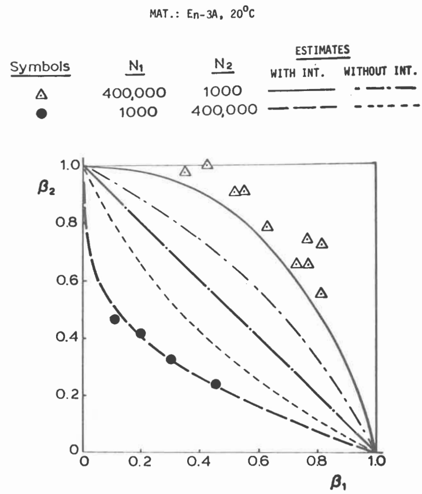

Fig. 4 Correlation between experimental results and estimated remaining life-fraction, with and without interaction effect consideration, (from Ref. 7).

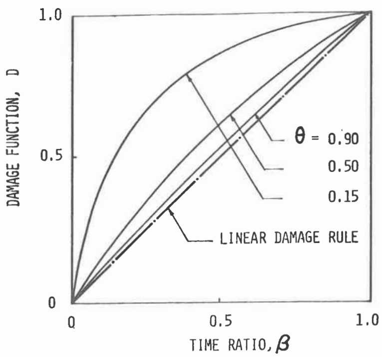

Fig. 5 Representation of stress-dependent damage function in terms of β (for creep loading)

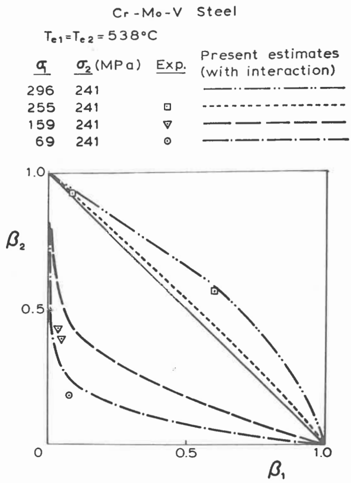

Fig. 6 Correlation between experimental results under isothermal conditions and estimated life-fractions with interaction effect consideration (from Ref. 13).

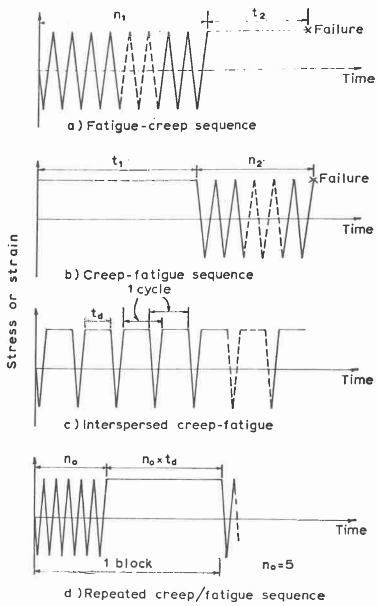

Fig. 7 Some typical loading patterns for studying the combined damage effect due to creep and fatigue.

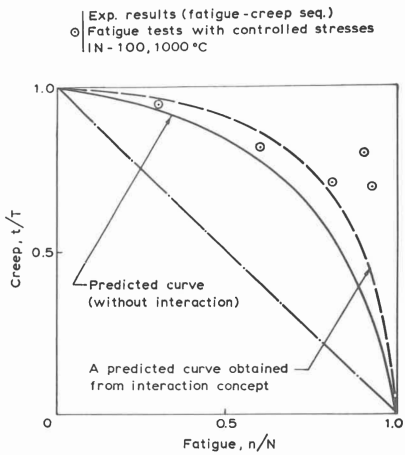

Fig. 8 Interaction effect consideration under fatigue-creep sequence loading for IN-100 at 1000°C (Data from Ref. 14).