CREEP DAMAGE PROCESSES IN CYCLICALLY LOADED STRUCTURAL MEMBERS

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Abstract. The paper contains the description of the cyclic creep damage law that allows to estimate the long-term strength of metallic materials in wide range of frequencies of loading and heating. Asymptotic methods and procedures of averaging in a period were used for deriving the damage laws.

1. Introduction

Traditionally the deformation of structural members is studied separately for static and varying loading, especially in the cases of the loading frequencies which take place in the processes of forced oscillations and exceed 1-3Hz. However, for high-temperature creep processes, which flow in different engines, power turbine etc, such separation is impossible due to non-linear character of the phenomena. The important contribution of the dynamic stresses, which occur following to fast load or temperature varying, can essentially change the rate of creep strain and damage accumulation as well as the place of macro crack initiation. From the other hand, the real loading presents the combination of the cycles with large (hours or days, caused by loading, operating and unloading, heating and cooling (etc) and small (fractions of a second, caused by forced oscillations) periods.

The aim of a paper is introducing the unified approach to the description of different creep damage phenomena, which occur due to joint action of static and varying loading. The case of initially elastic stress-strain state, which has to be realized in different industrial applications, where creep strain growth and damage accumulation are started from the stress level which is less then yield limit, is considered.

2. Cyclic creep damage averaged laws

Let us regard the mostly common case. The long-term strength of the structure is determined by the action of the temperature $\overline{T}(t)$ and stress fields $\overline{\sigma}(t)$. It is well

known, that mechanical behaviour of structural element subjected by cyclic loading, is significantly depends upon its frequency. The cyclic creep-damage processes in a solid which are originated by the action of temperature fields, can be divided by the action of low or high cycle loading or heating.
In the case of high cycle loading, when the frequencies of oscillations correspond to the phenomenon of forced vibrations, the processes of 'dynamic creep' [1] as well as the creep-high cycle fatigue interaction can occurred [2]. These processes are divided by the value of so-called critical stress cycle asymmetry coefficient $A_{cr} = \sigma^a / \sigma$ where σ^a and σ are amplitude and mean stress correspondingly. The big values of A_{cr}, which are arisen when the significant values of varying stresses are acted, characterize the high cycle high temperature fatigue damage accumulation which is coupled with creep one. The low values of A_{cr} caused to substantial acceleration of pure creep damage accumulation. This process was called the 'dynamic creep' and the damage occurs here by creep mechanism [1].
Otherwise, the loading of structures at elevated temperatures very often corresponds to low-cycle with the frequency is less than 1Hz. The values of period can be hours or days, for example in power turbines, where one cycle contains the time from starting to transition into the operating mode, some peak loading and finishing.
In real working conditions the low and high cycle creep processes are coupled. The main idea of the presented theory is subsequent studying of both processes. The approach of asymptotic methods [3] will be used. Due to the real situation in a structure, where the forced oscillations occur on the background of processes, caused by static or quasi-static loading, firstly let us regard the low cycle creep damage accumulation processes. The growth of creep strain c and scalar damage parameter ω can occur here due to the varying of loading as well as due to the varying of temperature.
Let us use the the Rabotnov-Kachanov kinetic law with scalar damage parameter ω

$$\dot{\omega} = D \frac{(\sigma)^r}{(1-\omega)^l} \tag{1}$$

The process of low-cycle loading will be described by the period T_σ and stress $\bar{\sigma} = \sigma + \sigma^1$, where σ and σ^1 are its constant and varying parts:

$$\bar{\sigma} = \sigma + \sigma^1 = \sigma \left[1 + \sum_{k=1}^{\infty} M_k \sin\left(\frac{2\pi k}{T_\sigma} t + \beta_k \right) \right] \tag{2}$$

Let us expand the damage parameter into asymptotic series on the small parameter μ [3] and limit by two terms of series:

$$\omega \cong \omega^0(t) + \mu\omega^1(\xi), \quad \dot{\omega} \cong \dot{\omega}^0(t) + \frac{1}{\mu}\frac{\partial \omega^1}{\partial \xi} \tag{3}$$

where $\omega^0(t)$, $\omega^1(\xi)$ are the functions which depends upon low t and fast time ξ , $(0 \le \xi \le 1)$ [4]. After the substitution of the Eq.(3) into Eq.(1) and further averaging the damage law on the time interval $(0 \le \xi \le 1)$:

$$\left\langle \omega^0(\xi) \right\rangle = \int_0^1 \omega^0(t)\, d\xi \cong \omega^0(t), \quad \left\langle \omega^1(\xi) \right\rangle = \int_0^1 \omega^1(\xi) d\xi \cong 0, \tag{4}$$

we obtain [4]:

$$\dot{\omega} = D g_r(M_k) \frac{(\sigma)^r}{(1-\omega)^l} \quad \omega(0) = \omega_0, \ \omega(t_*) = \omega_*, \tag{5}$$

$$g_r(M_k) = \int_0^1 \left[1 + \sum_{k=1}^{\infty} M_k \sin(2\pi k\xi) \right]^r d\xi, \quad M_k = \sigma^{ak} / \sigma .$$

If we consider more general low cycle process when not only stress but the temperature T varies throw a cycle

$$\overline{T} = T + T^1 = T\left[1 + \sum_{i=1}^{\infty} M_i^T \sin\left(\frac{2\pi i}{T_T} t + \beta_i^T \right) \right] \quad M_i^T = T_i^a / T, \tag{6}$$

the creep-damage law can be written in the following form:

$$\dot{\omega} = D \frac{\sigma^r}{(1-\omega)^l} \exp\left[-\frac{\overline{Q}}{T} \right] = D(T) \frac{\sigma^r}{(1-\omega)^l}$$

(7)

Now we can use the similar suggestions and reasoning, regarding the averaged damage parameter law Eq. (5) as an initial one. Finally we have

$$\dot{\omega} = g_r(M_k) g_T^{\omega}(T) \frac{\sigma^r}{(1-\omega)^l}, \omega(0) = \omega_0, \omega(t_*) = \omega_* .$$

(8)

where $$g_T^{\omega}(T) = d \int_0^1 \exp\left[\frac{-\overline{Q}}{T} \left[1 + \sum_{i=1}^{\infty} M_i^T \sin(2\pi i\xi) \right]^{-1} \right] d\xi .$$

Now let us consider the case of mono-harmonic loading with sine law, when frequencies of forced oscillations are more than 1 Hz. If the stress cycle asymmetry coefficient $A>A_{cr}$, the essential fatigue damage appears. We'll use the Yokobori suppose [2] that in this case the total damage increment contains from creep and high-temperature high cycle fatigue parts

$$d\omega = d\omega_c + d\omega_f = F_c(\sigma, \sigma^a, \overline{T}, \omega)dt + F_f(\sigma, \sigma^a, \overline{T}, \omega)dt$$

(9)

The creep damage law (1) and auto-model fatigue damage law

$$d\omega_F = \frac{F\left(\sigma^a + b\sigma\right)^p}{\left(1-\omega_F\right)^q} dN = \frac{F(\sigma^a + b\sigma)^p}{\left(1-\omega_F\right)^q} dt, \qquad N = \frac{t}{T_F}$$

(10)

can be used. In the case of $A<A_{cr}$ the influence of fatigue damage is marginal, but damage acceleration happens due to 'dynamic creep' mechanism [1, 5]. If we regard the slow varying of the loading with big period by law like Eq. (2), we have to slightly change the law Eq.(5) in order to account the multiplying on the coefficient A:

$$\dot{\omega} = Dg_r(1+K_r)\frac{(\sigma)^r}{(1-\omega)^l} \quad K_r = \int_0^1 \left(1 + A_r \sin(2\pi\xi)\right)^r d\xi - 1,$$

$$A = \frac{\sigma^a}{\sigma} \quad (11)$$

$$g_r = \int_0^1 \left[1 + \sum_{k=1}^{\infty} M_k \sin(2\pi k\xi)\right]^r d\xi \quad A_r = \frac{A}{g_r^{1/r}}$$

Here K_r is dynamic creep influence function had been obtained by asymptotic expansion and averaging procedure in [6]. Now we have to construct the universal damage law, which reflects above mentioned physical laws. Let us use the influence functions, which reflect the acceleration or retardation of appropriate damage processes. These functions have to operate with stress asymmetry coefficient A_{cr} and can be selected in the following form [5]:

$$\beta_f(A) = 1 - \exp(\pi\frac{A^2}{A_{kp}^2}); \quad \nu_f(A) = \exp(\pi\frac{A^2}{A_{kp}^2});$$

(12)

Finally the damage law takes the following form:

$$\dot{\omega} = g_T g_r \alpha_f(A) D\frac{\sigma^r}{(1-\omega)^l} + \beta_f(A) F\frac{\left(\sigma^a + b\sigma\right)^p}{(1-\omega)^q} \qquad (13)$$

$$\omega(0) = \omega_0, \ \omega(t_*) = \omega_*, \qquad \alpha_f(A) = 1 + K_r(A)\nu_f(A)$$

Constructed general damage law Eq.(13) have to be generalized for the case of complex stress state. Here the three invariants criterion for creep long term strength description as well as Sines criterion [7] for fatigue were used [4, 5].

3 Conclusions

The paper contains the creep damage law, which had been formulated for the wide range of cyclic loading and heating frequencies. By use of the same asymptotic procedures the flow rule for cyclic creep with different frequencies of loading and heating were obtained and averaged creep-damage law was added to the general system of equation of motion of the creeping solid [4-6].

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