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Continuous damage parameter calculation under thermo-mechanical random loading

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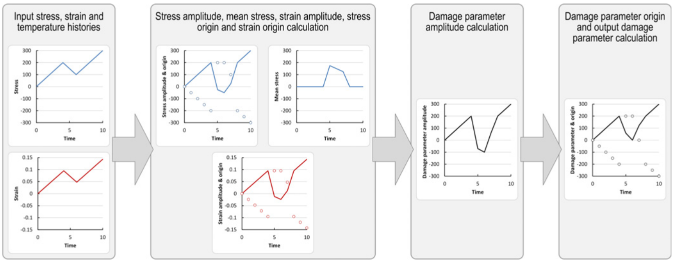
GRAPHICAL ABSTRACT



ABSTRACT

The paper presents a method on how the mean stress effect on fatigue damage can be taken into account under an arbitrary low cycle thermo-mechanical loading. From known stress, elastoplastic strain and temperature histories the cycle amplitudes and cycle mean values are extracted and the damage parameter is computed. In contrast to the existing methods the proposed method enables continuous damage parameter computation without the need of waiting for the cycles to close. The limitations of the standardized damage parameters are thus surpassed. The damage parameters derived initially for closed and isothermal cycles assuming that the elastoplastic stress–strain response follows the Masing and memory rules can now be used to take the mean stress effect into account under an arbitrary low cycle thermo-mechanical loading. The method includes:

- stress and elastoplastic strain history transformation into the corresponding amplitude and mean values;
- stress and elastoplastic strain amplitude and mean value transformation into the damage parameter amplitude history;
- damage parameter amplitude history transformation into the damage parameter history.

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Method details

Introduction

It is well known that mean stress affects fatigue life significantly and can therefore not be neglected under low cycle isothermal mechanical loading [1–4]. The mean stress correction formulae [5–7] are applied to transfer the extracted closed cycles with known stress amplitudes σ_a, mean stresses σ_m and elastoplastic strain amplitudes ε_a^{ep} into the closed cycles with equivalent damage parameter amplitudes P_a. Moreover, closed cycles can be extracted by, e.g., the rainflow counting method [8].

However, under low cycle non-isothermal mechanical loading a cycle closure problem may appear due to variable temperature or strain rate or both, which results in a more difficult determination of the stress and strain amplitudes and mean stresses [3]. The cycle closure problem leads to a more difficult determination of σ_a, σ_m and ε_a^{ep} because the cycle counting methods [8] cannot count the cycles before they close. This is particularly important if damage is calculated continuously (at any moment without the need of 'waiting' for the cycle to finish), which is the case in the damage operator approach (DOA) [4].

The aim of the method is to extend the usage of damage parameters derived initially for closed cycles and isothermal mechanical loading to arbitrary cycles and non-isothermal mechanical loading.

Requirements

The stress and strain tensor histories are gained by elastoplastic models from structural finite element analyses (FEA) and are converted into equivalent uniaxial stress $\sigma(t_i)$ and equivalent uniaxial elastoplastic strain $\varepsilon^{ep}(t_i)$ histories for $i=1,\ldots,n$. Thermal FEA are required to assess the corresponding temperature history $T(t_i)$. Test stand tests can replace FEA. Temperature history $T(t_i)$ influences the elastoplastic stress–strain response and material parameters, e.g., Young modulus $E(t_i)=E(T_i)$, where $T_i=T(t_i)$ but does not appear in the algorithm directly.

Counter j counts the strain reversal points including the first $\varepsilon^{ep}(t_1)$ and the last $\varepsilon^{ep}(t_n)$ point in the elastoplastic strain history. The strain reversal points constitute strain residuum $\varepsilon_j^{ep,res}$ for $j=1, \ldots, \leq n$. Current $\varepsilon^{ep}(t_i)$ and the latest three strain reversal points $\varepsilon_j^{ep,res}$, $\varepsilon_{j-1}^{ep,res}$, and $\varepsilon_{j-2}^{ep,res}$ are checked for a closed cycle successively. Residuum stresses σ_j^{res} and residuum damage parameters P_j^{res} coincide in time domain with residuum strains $\varepsilon_j^{ep,res}$.

Logical operator s enables the identification of rainflow cycles that hold nested rainflow cycles. It is set to true if the rainflow cycle is identified and $j>2$. Otherwise it is false.

Algorithm flow

The procedure of working out the damage parameter is given in Fig. 1. Here an overview of the pseudo code is provided. In line 1, counters i, j and maximum absolute strain $\varepsilon_{\max}^{ep}$ are initiated. Superscript *ep* stands for elastoplastic. Next, the outer loop begins. Index i runs over n available times t_i. If the number of strain reversal points in the residuum $j>2$, the algorithm in line 3 first checks if residuum strains $\varepsilon_{j-2}^{ep,res}$, $\varepsilon_{j-1}^{ep,res}$, $\varepsilon_j^{ep,res}$ and strain $\varepsilon^{ep}(t_i)$ form a rainflow [8] cycle.

The three residuum strains representing strain reversal points as well as $\varepsilon^{ep}(t_i)$ are required for the standardized four point rainflow counting algorithm [8]. The Clormann–Seeger [9] cycle is searched for in line 11. If $j\leq 2$ or neither rainflow nor Clormann–Seeger cycle is found, the algorithm in line 15 checks if $\varepsilon^{ep}(t_i)$ is on the cyclic stress–strain curve. Else, strain origin $\varepsilon_o^{ep}(t_i)$, stress origin $\sigma_o(t_i)$ and damage parameter origin $P_o(t_i)$ are set to the j-th residuum values and logical operator s is set to false in line 18. Origins are required to make the amplitude and mean values calculation possible. They are