

The Damage Operator Approach: Fatigue, Creep and Viscoplasticity Modeling in Thermo-Mechanical Fatigue

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ABSTRACT

In the last decades the development time of vehicles has been drastically reduced due to the application of advanced numerical and experimental methods. Specifications concerning durability and other functional attributes for every new model improve for every vehicle.

In particular, for machines and components under variable multiaxial loading, fatigue evaluation is one of the most important steps in the design process. Appropriate material testing and simulation is the key to efficient life prediction.

However, the life of automotive components, power plants and other high-temperature facilities depends mostly on thermo-mechanical fatigue (TMF). This is due to the normally variable service conditions, which contain the phases of startup, full load, partial load and shut-down.

Within this context, there are several requirements for making accurate life predictions: a proper material model with material parameters derived from testing, modeling of stress-strain response during cyclic loading, a multiaxial fatigue criterion, a proper damage accumulation model and component testing to evaluate the correlation between life prediction models and experiments.

For high temperatures the influence of creep, creep fatigue and viscoplastic stress relaxation have to be considered both in an accurate way and efficiently.

The present paper presents the damage operator approach enabling online continuous damage calculation for isothermal and non-isothermal loading with mean stress correction. The cycle closure point, cycle equivalent temperature, threshold temperature and separate rainflow counting (mandatory for the equivalent temperature approach) are not necessary any more for the damage operator approach. In fact, for constant temperature, both approaches are equivalent for the second run of block loading. It also highlights an extension of the strain-life approach to take into account viscoplastic effects and creep.

INTRODUCTION

The failure mechanisms associated with TMF are mechanical fatigue, oxidation and creep. The damages due to fatigue, oxidation and creep can be treated separately or together. In the latter case, fatigue damage prediction is often based on the isothermal strain controlled low cycle fatigue (LCF) tests performed at various temperatures, strains and strain rates.

In TMF evaluations, the thermal and mechanical loadings acting on the specified structure has to be considered. In order to obtain the temperature fields that are later applied together with the mechanical loads in the structural analyses, an assumption has to be made regarding the uncoupling of the thermal and structural analyses. Transient thermal analyses are performed in order to obtain the desired temperature fields for all load cases. The computed temperature fields are then applied in combination with the mechanical loading in the stress-strain finite element analysis (FEA).

The second uncoupling regards the separation of the stress-strain response from the damage calculation. The stress-strain response together with the temperature fields are used for the final damage evaluation by the LMS Virtual.Lab Durability module.

This non-unified approach has been widely and successfully used for TMF calculations in the automotive industry.

For many cases in this latter industry, the durability is no longer mainly determined by mechanical loads only, but by a combined effect of thermal and mechanical loading of the component or system under normal design working conditions. Both kinds of loading result in TMF.

In order to address this difficult balance exercise, the development engineer needs a reliable numerical and experimental tool that allows him to tune his task into the increased pace of (virtual) development processes of the OEM's.

Structures that are subject to varying mechanical loads under varying temperatures exhibit different fatigue behaviors at different temperatures, different stress-strain behavior at different temperatures and creep at high temperatures. This is mainly due to temperature induced stresses.

The aim of this paper is to give an overview on the recently developed methodology for stress-life and strain-life finite-element based approaches to TMF. In depth the analysis and description are found in [1, 2, 3].

DAMAGE OPERATOR APPROACH

The damage operator approach for all cases of stress-life and strain-life under varying temperatures is presented. It is based on the pseudo-elastic stresses that are converted into elastoplastic stress-strain states by using approximate notch analysis formulas for strain-life approach or directly on the elastoplastic stress-strain FEA states. Cyclic hardening and cyclic softening can frequently be assumed to contribute negligibly to the damage. By applying half-life stabilized cyclic stress-strain response the requested FEAs can be shortened drastically.

Traditional fatigue damage accumulation uses rainflow counting and linear Miner damage accumulation rule. In the case of TMF one experiences that due to the changes in the environment (like temperature) the fatigue behavior is changing over time. For variable amplitude loading it is very typical that the largest load cycles - that contribute most to the damage - take a very long time to complete, due to the many nested cycles inside. In this case the approach to only consider cycles when they are completed as in the rainflow approach can no more be justified.

Hence one has to take one step back and analyze the mathematical theory lying behind the rainflow based approaches: the theory of hysteresis operators and especially the hysteresis operator that describes damage accumulation. In [4, 5, 6] the equivalence of the rainflow approach with the damage operator approach for the simple case of constant fatigue behavior is shown.

It shall be noted here that the hysteresis operators for elastoplastic stress-strain behavior can be identified with rheological models [7]. The operators for damage accumulation have the same structure and therefore can also be identified with rheological models. It should be warned that even though this is helpful for imagination and gives hope for a theoretical fatigue model, the parameters for these models are drawn from empirical tests, more explicitly from SN or ϵ N curves. The oxidation damage is integrated into the SN and ϵ N curves as the tests are carried out under isothermal ambient conditions and not in vacuum. The same holds for the creep master curves.

But again from an analogy to the stress-strain behavior the basic idea of damage operators can be indicated. In kinematic elastoplastic models one can associate the dissipated energy to the total movement of the yield surfaces. Reference [5] details on how to define from this a dissipation operator, for which the total change (Variation) over time gives the dissipated energy.

If $0 \leq t_1 < t_2 < \dots < t_i$ gives a sequence of the times the variation is defined as

$$\text{Var } \mathcal{W}(t_i) = \sum_{j=1}^i |\mathcal{W}(t_j) - \mathcal{W}(t_{j-1})| \quad (1)$$

Given the correct operator, the dissipated energy can then be written as

$$\mathcal{W}(t_i) = \text{Var } \mathcal{W}(t_i) \quad (2)$$

For the case of linear damage accumulation one can define a formally similar model and operator, for which the total variation corresponds to the accumulated Miner sum [5]. The methodology and extension to mean stress effects had been further developed in [6]. The thermal influences on stress-strain states, mean stress effect, time dependent material response and damage accumulation have been added recently in [1, 2, 3] and are briefly described below.