Fatigue crack propagation modeling using a local approach to fracture

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Résumé

Fatigue crack propagation analysis is commonly conducted at the macroscopic level through a global energetic approach which considers that the material mainly remains in its elastic domain. Within this framework, the plastic zone is assumed to be small enough and confined at the crack tip, in the singularity area. However, under complex loadings and/or at high temperature (for example 550◦C for a Nickel-based superalloy), recent experimental observations tend to highlight nonlinear phenomena occurring at the process zone, ahead of the crack tip. This plasticity leads to damage mechanisms, and to a disturbed crack front. For instance, we observe a flat to slant fracture in mode I fatigue loading or a "tunneling effect" under holding-time. Under these observations, the Linear Elastic Fracture Mechanics framework can no longer be considered.
To model fatigue crack propagation in a Ni-based superalloy used in the high-pressure stages of aeroengines, the present study proposes to use a local approach to fracture. It consists in estimating more accurately the stress and strain fields in the crack tip area where plasticity occurs. The knowledge of these mechanical fields offers the possibility to characterize the fracture processes by the use of a fully coupled damage model. This one can be phenomenological and established within the Thermodynamics of Irreversible Processes and the Continuum Damage Theory frameworks, by fully coupling the elasto-viscoplastic behavior and damage. This damage is the combination of different deterioration mechanisms. The most relevant one is the fatigue damage which represents persistent slip bands that appear after several reversal loadings. In addition, creep damage also needs to be taken into account, representing holding-period degradation processes at the grain boundaries when the load is sustained. Finally, ductile damage can have a contribution for the highly loaded plastic zone in the vicinity of the crack tip.

All these damage mechanisms being taken into account, the cyclic crack propagation can be simulated for complex loading cases such as pure fatigue or fatigue-holding time.

Fatigue damage is, most of the time, cyclically estimated by the use of a damage law written in terms of loading parameters such as the loading ratio or the stress amplitude. The innovative aspect of the present study is to model fatigue damage in an incremental manner to avoid using cycle-counting algorithms. However, the main issue with incremental fatigue damage is to describe properly the mean-stress effect. As part of the solution, this study proposes to take into account, in the constitutive equations, some adequate mechanisms such as the microcracks' closure effect.

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Another issue arises due to the fact that there is a full coupling between damage and the elasto-viscoplastic behavior. In this case, the stress/strain curve will progressively exhibit a softening behavior. Then, the constitutive equations lose their ellipticity and there is no longer unicity of the solution. When performing Finite Element calculations, this leads to spurious localization problems. To obtain mesh-independent results, nonlocal formulations with regularization of internal variable can be used. They consist in introducing an internal parameter that allows to consider the nonlocal interactions between neighbor material points. In this study, we consider the introduction of the gradient of a suitable internal variable into the free energy density of the constitutive material model. The penalization of this gradient leads to a smoother spatial distribution of the considered variable, thus avoiding both plastic and damage localization.

Mots-Clés: fatigue, creep, ductile, fracture, incremental, damage, local approach, nonlocal, regularization, modeling, elasto, viscoplasticity, cyclic