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Memory effects in variable amplitude and multiaxial fatigue crack growth: an incremental approach

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Abstract

This paper presents an incremental approach for modelling fatigue crack growth with memory effects due to the non-linear behavior of the material. This approach is developed at LMT since 2003, in collaboration with several industrial partners, mainly with Snecma, SAFRAN Group, EDF and AREVA and SNCF. The first part of this paper presents the context and the objectives, and the key assumptions on which the model is based. The second part presents some examples of applications of the model, fatigue crack growth in mode I conditions, under variable amplitude loading; non-isothermal situations; crack growth in coupled environmental and fatigue loading conditions; extension of the model to non-proportional mixed mode loading conditions, and to short cracks. The last part presents some ongoing work, possible developments and scientific challenges that remain to be overcome.

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Keywords: fatigue ; crack growth ; memory effects ; mixed mode.

1. Introduction

Accurate predictions of fatigue crack propagation and of the service life of critical components in operating conditions, remains difficult, for the following reasons:

- **2D / 3D**: Stress concentration area where short cracks may be initiated usually display spatial gradient and a certain degree of multiaxiality over a domain which sizes is in the order of magnitude with the short crack to long crack transition length. However, data and crack propagation models are often based on mode I long crack growth behavior.

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- **Non-linear material behavior**: The materials used for critical components are usually ductile and hence display a non-linear behavior which is at the origin of memory effects in fatigue crack growth. The importance of these history effects on fatigue crack growth has been demonstrated and explained is numerous publications. Various crack propagation models (NASGRO, PREFFAS, Strip Yield …) have been developed to account for these history effects. If the material is non-linear, the entire load history (not only the peak to peak loads), is to be considered to predict the fatigue crack growth rate. However, since most models are predicting a fatigue crack growth rate per cycle, they require the use of a cycle counting method (e.g. rainflow) so as to be applied to load sequences in operating conditions that might be quite far from being cyclic. When the load sequence stemming from the cycle reconstruction differs significantly from the original one, the life prediction may be questionable. The incremental approach, which we have developed at LMT, avoids the use of a cycle reconstruction method by predicting a crack extent in each load increment.
- **Other non-linear mechanisms** may be involved (unilateral contact between the crack faces and friction, time dependent damage mechanism such as corrosion or creep …) and be coupled with pure fatigue crack growth. An incremental approach makes it easier to consider independently the effects of each non-linear mechanism in each time step and to model their synergetic effects.
- **Complex loading conditions**: Loading sequences in actual operating conditions can be rather complex. The mechanical loadings can be uniaxial or multiaxial, varying in space and time (variable amplitude loading in mode I, in phase or out of phase loadings in mixed modes conditions…). Similarly, it may be non-isothermal in space and time (thermal fatigue...).

2. Incremental approach, basic assumptions

Since 2003, an incremental approach was developed at LMT, step by step, to predict fatigue crack growth in complex loading conditions and in non-linear materials. The approach is based on the basic assumption that "pure" fatigue crack growth stems from crack tip plasticity (Neumann (1969) and Li (1989)). With such an assumption, an incremental model for "pure" fatigue crack growth could be derived from an incremental plasticity model for the crack tip region. The crack growth rate per second can then be predicted from the measure of crack tip plasticity. Quite a few authors have derived successful predictions of the fatigue crack growth rate in complex loading conditions, from the analysis of the plastic strain field around the crack front obtained from non-linear finite element simulations. However, non-linear finite element simulations remains out of reach for a use in an industrial context, where cracks are usually 3D. A simplified model is thus required, but the finite element method can be used to develop a simplified model and to verify its capabilities.

The simplified model that has been developed at LMT aims at condensing all the effects of the non-linear behavior of the material in the crack tip region in a set of constitutive equations based on the minimum number of variables necessary to reasonably represent the problem of crack tip plasticity. Moreover, the simplifying assumptions in the model are chosen to be suitable with a use in mixed mode conditions.

The approach is based on a sery of hypotheses that are briefly recalled below :

- **Infinitesimal strain** conditions are considered.
- The **local solution** is assumed to be dominated by the **local geometry** of the crack. The remote boundary conditions and their history are hence expected to control the intensity of the crack tip fields but **not their spatial distribution**, which is assumed to be given once for all, and be associated to the local crack geometry. This ensures the consistency between LEFM and the present approach.
- A curvilinear coordinate system R_T, can be attached to the local crack front and the local crack plane, considering a suitable characteristic scale. In this local coordinate system R_T, the crack is assumed to be **locally planar** and in **generalized plane strain conditions** along the locally **straight crack front**. This assumption allows partitioning the crack tip fields into mode I (symmetric), mode II (anti-symmetric) and mode III (anti-planar) local components (Fig. 1a).