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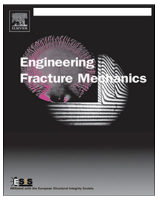

Crack propagation methodology under complex loadings

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ABSTRACT

In this paper, a novel methodology for analyzing crack propagation under complex loadings is presented. It includes various kinds of complexities such as multiple non-proportional load cases, LCF/HCF interaction, eigenmode actualization and load spectrum under proportional loading. After being validated on simple test cases, this methodology is applied on two full-scale industrial cases. The results demonstrate that this methodology, when compared to simulations using simplified load cases, has a great impact on fatigue life assessment. This methodology achieves higher accuracy and more representative results and therefore can lead to more radical optimization in a design process.

1. Introduction

A wide range of industries, especially in the aeronautic and automotive sectors, are often confronted with problems involving complex geometries and complex loadings. Accurate fracture fatigue predictions for such cases are advantageous and highly appreciated. Popular commercial software such as NASGRO[1] can evaluate crack propagations for complex loadings, but are limited to a finite number of catalog geometries. In general, such software are not able to compute the SIF for complex (3D) geometries.

When dealing with complex geometries, SIF can be evaluated using 3D XFEM. XFEM was first proposed by Moës et al. [1], and was then followed by various improvements and related developments such as error estimators [2–4] and industrialization [5–7]. This methodology has been thoroughly validated [8–10] and is now used for crack analysis of industrial applications [11,12]. Alternative methods also based on partition of unity theory have also been developed [13–16] to handle crack propagation issues, the meshless methods being prime examples. Recent improvements of these methods can be found in [17,18]. Numerous examples [19–21] have demonstrated that combined LCF and HCF loadings can reduce lifetimes compared to pure LCF or HCF loadings. For example, in [21], LCF/HCF interaction decreases the pure HCF lifetime by a factor of 3 and decreases the pure LCF life by a factor of over 100. Powell et al. [22] explains that at lower values of ΔK, only the LCF contributes to the crack growth. As soon as ΔK_{onset}, the threshold for pure HCF, is surpassed, the crack growth rate is dictated by both LCF and HCF [23–25], generally by a simple linear summation relationship. Because of a high number of HCF cycles, when ΔK_{onset} is reached, the crack growth rate increases drastically, leading to a rapid failure. Consequently, one of the simplest ways to increase the accuracy of lifetime predictions is to take into account the various load cases into a single crack propagation analysis. If a load spectrum under proportional loading is considered, a common and efficient solution is to use rainflow counting [26,27].

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[1] http://www.swri.org/4org/d18/mateng/matint/nasgro/.

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Nomenclature

Symbols

da	crack increment
dadn/dadb	crack increment per cycle/per block
K	SIF (see below)
K_{IC}	critical SIF
K_{th}	threshold SIF
n	number of cycles
R_{SO}	shut-off value of the load ratio
ΔK	amplitude of SIF

Acronyms

CCF	combined cycle fatigue
EPFM	Elastic Plastic Fracture Mechanics
FE(M)/XFE(M)	Finite Element (Methodology)/eXtended Finite Element (Methodology)
HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue
LEFM	Linear Elastic Fracture Mechanics
SIF	Stress Intensity Factor
SSY	Small Scale Yield

The interaction between the load cycles is not limited to linear superposition. Less straightforward interactions can exist because of overloads or underloads. In many cases, a single overload causes a retardation effect, stunting crack growth for cycles immediately following the overload cycle. When an overload occurs, the crack growth rate first increases, then, quickly decreases to values lower than the initial rate [23]. After a certain number of cycles, the fatigue crack growth rate increases and might reach the initial value. In some cases, overloads can even totally arrest crack growth. The impact of repeated overloads leads to an increase of the total lifetime as demonstrated in [23,28]. Contrary to overloads, underloads have been demonstrated to accelerate crack growth for a number of cycles. As a consequence, the impact of repeated underloads is a decrease of the total lifetime [19,29]. When an underload is applied after a previous overload, the retardation effect due to the overload is then reduced. This observation highlights the importance of how loading cycles are ordered during a crack propagation. Various propagation models have been developed to take into account these interaction effects. The more popular models can be divided into three main categories [29–31]: Yield zone models, Crack closure models and strip yield models.

Material micro-structures also play a great role during the propagation of cracks. In some cases, the micro-structure can impact the crack propagation direction or can result in varying behavior due to differences in intergranular or transgranular crack propagation. These differences can be observed under various conditions depending, for example, on the magnitude of ΔK, the frequency or the temperature. In this paper, the impact of micro-structure is considered to be accounted for on a macroscopic scale by the propagation law.

The propagation of a crack in a structure can lead to a softening of said structure. Consequently, it can induce a reduction of the natural frequencies of the structure. This observation has instigated numerous works on the non-destructive identification of cracks using vibrational analysis [32–34]. Regarding crack propagation, a frequency shift may lead to unpredicted LCF/HCF interaction. During design phases of compressor blades, Campbell diagrams are used in order to ensure that there is no overlap between blade natural frequencies and harmonics of the functional rotation speed. NATO research and technology organization considers that a 3% change in the natural frequency is an important shift which has to be considered [35]. A shift of this magnitude can occur as result of the presence of a crack.

As previously described, there are various methods and concepts that can be used to improve the accuracy of crack propagation analyzes. The objective of this study is to unify these methods and concepts into a single methodology. Four main links have been considered: multiple non-proportional load cases, LCF/HCF interaction, eigenmode actualization and load spectrum under proportional loading. For each link, a benchmark is used to validate the methodology. Some industrial cases are then used to assess the impact of the methodology on the crack propagation analysis and to verify its agreement with experimental observations.

This methodology can represent a great improvement with respect to the common practice of using simplified load cases, for the computation of fatigue life predictions.

2. Methods description

A methodology has been implemented in order to improve crack propagation analyzes. In the following, first the methodology is described and then three validation cases are illustrated. The first validation case is a classical test case with a