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Dynamic approach for optimal inspection planning of fatigue cracked components

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ABSTRACT

The Fatigue Crack Growth (FCG) is one of the main processes that can lead to unexpected failure of mechanical components. To ensure appropriate operation of mechanical systems, an inspection maintenance scheduling is required. The goal of this paper is to establish a predictive model for the optimal inspection time based on reliability analysis. The combination of response surface method with the first order reliability method is used to assess the reliability with respect to uncertainties related to geometrical parameters, materials and loading. The proposed approach takes into account the results of previous inspections, where the reliability is reevaluated in this case by using Bayesian approach. The main feature of the proposed model lies in the dynamic consideration of inspection results. A formulation of the total cost function is determined according to the maintenance strategy to be performed; the optimal inspection time is calculated by minimization procedure. A generalization of this method is performed in the case of multiple inspections. In order to validate the proposed method, three applications are discussed in this paper, where the results show the interest of considering dynamic planning of crack inspections.

1. Introduction

Traditional fracture mechanics considers the crack size, the applied loading, the material properties and the crack growth rate as deterministic quantities. However, due to the random character of these parameters, the fatigue crack propagation is random in nature [1] and requires an appropriate planning of inspections in order to avoid the risk of failure and to improve the maintenance strategy.

Several works have dealt with the problem of fatigue crack propagation with probabilistic approaches, such as [2–4], where the crack length is determined by a probability density function, but most of these works used a purely mathematical basis. Recently, some works based on coupling fatigue–reliability have been developed [5], leading to a better prediction of the lifetime of mechanical component because, they used a randomization of the traditional equations for crack growth such as Paris–Erdogan law.

During the lifetime of mechanical components, inspections are required for monitoring and tracking their state, in order to determine the nature of interventions and the types of maintenance to be applied [6–9]. Several methods can be applied to define the optimal inspection program. Some authors compute the optimum time of maintenance such that the admissible failure probability is not exceeded [10,11]. Other authors [12,13] use a cost–benefit approach where the optimum inspection program is determined by minimizing the total cost function.

Regarding interventions, preventive maintenance strategy differs in terms of operation sequence and quality. Some authors consider the maintenance plan without repair [14,15], while others consider repair (welding, grinding, …) [12] or even full replacement [16]. These approaches deal with the optimization problem over the lifespan of the component in a static way by considering all possible maintenance scenarios during the lifetime. In other words, these approaches consider the total cost along the lifetime, although the real degradation (i.e. crack growth) differs from the predicted one at the time of inspection planning. Therefore, most of these methods do not take into account the results of previous inspections which give interesting information to improve the lifespan prediction. In fact, setting the whole inspection planning on the basis of predictive models at the initial time will lead to large deviation between predictions and real behavior, and therefore the optimality of the initial inspection plan is often lost.

The aim of this work is to develop a new formulation of the total cost function for maintenance with replacement plan taking into account the results of previous inspections. The advantage of this approach is to address the problem of optimization of inspection time by using a

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dynamic approach. This method is applied to optimize the time of the first inspection, then according to the obtained result, it determines the optimal time of the second inspection and so on.

To illustrate this approach, three applications are considered: the first one is analytical and aims at studying the convergence of the proposed procedure. The second example deals with the case of crack propagation in mode I, in order to demonstrate the complete procedure. The last one deals with optimal inspection time for the case of the mixed-mode crack propagation in an industrial component, in order to generalize the proposed method for practical engineering mechanics.

2. Background

2.1. Fatigue crack growth

In order to schedule the maintenance, it is required to define the fatigue lifespan of mechanical components. Among the crack growth models available in the literature [17–19], the well-known Paris law [20] is used in this study:

$$\frac{da}{dN} = C.(\Delta K)^m \tag{1}$$

where a is the crack length, N is the number of loading cycles, ΔK is the stress intensity factor range and C and m are the model parameters.

The Stress Intensity Factors (SIF) represent the crack growth governing force. These factors depend on the crack, the component geometry and the applied load. The determination of these factors is performed either by analytical solutions [21] for simple component geometry, or by Finite Element Analysis (FEA) for complex component geometry. In mixed-mode crack growth, it is necessary to calculate the equivalent stress intensity factor and the crack bifurcation angle θ. Thereby the maximum circumferential stress criterion [22–24] can be adopted to determine the bifurcation angle θ, leading to:

$$\sigma_{\theta\theta} = \frac{2}{\sqrt{2\pi r}}\left[K_I\left(1+\cos(\theta)\cos\left(\frac{\theta}{2}\right) - 3.K_{II}\sin(\theta)\cos\left(\frac{\theta}{2}\right)\right)\right] \tag{2}$$

$$\frac{\partial\sigma_{\theta\theta}}{\partial\theta} = 0 \quad \text{and} \quad \frac{\partial^2\sigma_{\theta\theta}}{\partial\theta^2} < 0 \tag{3}$$

where K_I and K_{II} are the stress intensity factors for mode I and mode II respectively, r is the distance from the crack tip and θ is the crack orientation.

The bifurcation angle θ_0 is obtained by maximizing Eq. (2) with respect to crack bifurcation, leading to the solution:

$$tg\left(\frac{\theta_0}{2}\right) = \frac{1}{4}\left(\frac{K_I}{K_{II}}\right) \pm \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}. \tag{4}$$

Then the equivalent stress intensity factor in mixed mode K_{Ieq} is defined as follows [24]:

$$K_{Ieq} = K_I(1+\cos(\theta)).\cos\left(\frac{\theta}{2}\right) - 3.K_{II}.\sin(\theta).\cos\left(\frac{\theta}{2}\right). \tag{5}$$

2.2. Reliability of cracked components

The reliability method aims at analyzing the effect of system uncertainties, which is very useful to make appropriate decisions regarding the inspection scheduling. The reliability is estimated with respect to the limit state function describing the failure scenario. This function corresponds to the difference between the component capacity and the loading effect [25,26]. In the present study, the limit state function is defined by the difference between the critical crack length a_c and the crack length $a(t)$ at time t:

$$G(t, X_i) = a_c - a(t). \tag{6}$$

The failure probability of cracked component is given by [27]:

$$P_f(t) = P[G(t, X_i) \leq 0] \int_{G(t,X_i)\leq 0} f_{X_i}(x_i)dx_i \tag{7}$$

where $f_{X_i}(x_i)$ is the joint density function of the random variable X_i.

Since the information concerning the joint probability density is not often available, the most relevant approach developed in the literature to evaluate the above integral (Eq. (7)) is based on the calculation of the reliability index β [28]. This index is defined as the minimum distance between the origin of the normalized space and the limit state function. It is evaluated by solving the constrained optimization problem:

$$\beta(t) = \text{minimize}\sqrt{\sum_i [T_i, (x_j)]^2} \text{subject to } G(t, X_j) \leq 0 \tag{8}$$

where $T_i(x_j)$ represents the probabilistic transformation of the physical space to the normalized space. The solution of such a problem could be performed by optimization algorithms such as Rackwitz–Fiessler [29] and the failure probability can be determined by First Order Reliability Method (FORM) [27].

2.3. Inspection techniques

The management of fatigue loaded components requires Non Destructive Testing (NDT) to be carefully operated by highly qualified specialists. The choice of the inspection technique to use depends on several parameters, namely the material, the type of defect and the detectability threshold.

Several techniques for NDT are available, such as Liquid Penetrant Inspection (LPI), Ultrasonic Inspection (UI), Magnetic Partial Inspection (MPI), and Eddy Current Inspection (ECI), which are mostly used for fatigue crack detection [30]. All these techniques have advantages and drawbacks. Although LPI requires a specific preparation of the surface to be tested, the UI technique, widely used in aerospace and marine fields, requires no special treatment of the surface. In order to reduce the inspection cost, a monitoring technique is usually required. Once the defect is detected, a diagnostic technique is applied to locate the crack and to determine its form, nature and dimensions, which can thereby be followed over time.

2.4. Reliability updating based on inspection results

In order to avoid cracking, periodic inspections are planned during the lifetime of components and consequently ensure human and material safety. The inspection results lead to one of the two cases: either crack is not detected or crack is detected, which could be written with