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Design of maintenance schedules for fatigue-prone metallic components using reliability-based optimization

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ABSTRACT

This contribution focuses on the design of optimal maintenance schedules for metallic structures prone to develop fatigue cracks. The crack propagation phenomenon is addressed using a fracture mechanics approach. The problem of maintenance scheduling is addressed within the framework of reliability-based optimization (RBO). Thus, it is possible to minimize the costs associated with maintenance and eventual failure while explicitly considering uncertainties in the crack propagation phenomenon and inspection activities. The underlying RBO problem is solved using an efficient method recently developed by the authors. A numerical example demonstrating the application of the proposed approach is presented.

1. Introduction

Metallic structural components operating under cyclic loading are prone to develop fatigue cracks during their respective life span. These cracks can lead to loss of serviceability, partial failure or even collapse, depending on the particulars of the structural system. An effective means for mitigating the negative effects of crack propagation is the scheduling of inspection and repair activities (see, e.g. [26,43,56,59,63,64,68,76]). The scheduling of maintenance activities usually involves the definition of the inspection frequency (e.g. monthly, annually), the type of inspection technique (e.g. visual inspection) and the definition of a particular repair strategy.

Although maintenance activities constitute an effective means for coping with deterioration, their scheduling is extremely challenging, as the propagation of fatigue cracks is a highly uncertain phenomenon (see, e.g. [24,37,69]). Moreover, inspection activities are also uncertain, e.g. inspection activities may assess the damage incorrectly or may not detect any damage at all.

In the involved decision-making scenario described above, optimization methods which explicitly model the effects of uncertainty have received increased attention (see, e.g. [8,67]). In particular, reliability-based optimization (RBO) has shown to be an adequate tool to seek the best tradeoff between the overall costs (i.e. construction, operation, maintenance and possible failure costs) and an adequate level of reliability (see, e.g. [27,40,61]).

This contribution presents an approach for scheduling maintenance activities such that the cost of operation associated with a particular fatigue-prone mechanical component is minimized. The damage due to fatigue is addressed using a fracture mechanics approach. This allows simulating the crack propagation phenomenon by integrating appropriate laws that describe the crack growth. Uncertainties are considered explicitly by modeling physical parameters related to crack propagation as random variables. Moreover, it is considered that a mechanical component may develop several fatigue cracks, i.e. the component may undergo multi-site damage. In order to mitigate the effects of crack growth in the mechanical component, inspection and repair activities are scheduled. Inspection activities attempt detecting cracks in the mechanical component; as inspection is – in most cases – imperfect the probability of detecting a crack is modeled explicitly. Once a crack is detected, it may be repaired (the decision to repair is taken according to some prescribed rules). In order to schedule the inspection and repair activities, two variables must be identified: the quality of inspection (q) — which influences the probability that a crack is detected — and the time at which inspection is performed (T_I); for the sake of simplicity, a single inspection activity and perfect repair are considered in this contribution. These two variables are selected based on the cost associated with the operation of the mechanical component, i.e. the summation of maintenance cost (the costs associated with inspection and repair for a particular value of the variables q and T_I) and eventual failure cost (the cost associated with failure due to downtime, damages, etc.).

The study of the crack propagation phenomenon considering uncertainties and the scheduling of maintenance activities has received considerable attention in the literature (see, e.g. [57,58,78]). A brief

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survey on some of the approaches developed within this context is presented in Appenidx A. Compared with these approaches, this contribution contains several innovative concepts. On one side, Subset Simulation – which was introduced in [4,7] – is applied for evaluating expected costs; the major advantage of applying this method is that it allows studying several different failure modes while being numerically efficient. One the other side, the RBO problem is solved using an efficient algorithm based on line search recently developed by the authors [31]; this algorithm combines standard optimization techniques with an efficient algorithm for estimating reliability sensitivity; the latter algorithm is extended in this contribution for estimating the sensitivity associated with expected costs.

The structure of this paper is as follows. Section 2 provides a general overview on the problem being studied and the relevance of maintenance activities. Then, the model for crack propagation considered in this contribution is described in Section 3. Section 4 discusses the different relevant events that may take place during the lifetime of a mechanical component and the economical costs associated with these events. Section 5 presents an approach for calculating the sensitivity of the aforementioned costs with respect to the variables defining the maintenance schedule. The strategy for solving the maintenance scheduling problem is addressed in Section 6. The features of the proposed approach are demonstrated by means of an application example in Section 7. The contribution closes with some final remarks and an outlook for possible future extension of the method reported herein.

2. Importance of maintenance and the effect of uncertainties

2.1. General overview

The crack propagation phenomenon in metallic components (operating under cyclic loading) can be characterized in three different stages: the crack initiation (CI) stage, where micro cracks nucleate (e.g. at points of stress concentration); the stable crack growth (SCG) stage, where the crack propagates in a stable manner; finally, the unstable crack growth (UCG) stage, at which the fast growth of the crack leads to the collapse of the component. For design purposes, the duration of the UCG stage is commonly ignored. On the other hand, the duration of CI stage will vary according to the system being analyzed: for weldments, the duration of CI phase may be neglected [14]; in aerospace components, the duration of the CI phase may account for the vast majority of the lifetime due to high quality standards of fabrication [37] and, hence, it must be explicitly modeled. A schematic representation of the crack propagation stages is shown in Fig. 1, where a represents the crack length and N, the number of load cycles.

It should be noted that in a particular mechanical component, one or more cracks may develop. For example, in an aircraft, fatigue cracks may develop at multiple sites of a critical component, i.e. multi-site damage, causing drastic reduction of the lifetime [71].

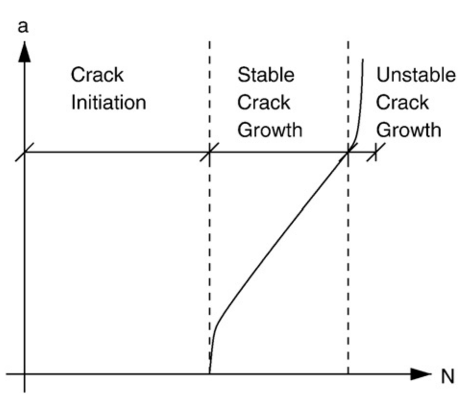

Fig. 1. Stages of fatigue crack propagation phenomenon.

Maintenance activities can be an extremely cost-effective means for controlling the damage accumulation due to crack propagation. That is, inspection activities during the lifetime of a mechanical component allow identifying the presence of cracks. Based on the information provided by inspection, a decision on repairing the mechanical component may be taken, e.g. in case the detected cracks exceed a prescribed threshold level, they can be removed using a special procedure. In this way, the chances that the mechanical component does not fail during the design lifetime are highly increased. It should be noted that the costs associated with inspection and repair of a component are – usually – much cheaper than assuming the costs associated with the failure (collapse). In this context, it is important to remark that inspection and repair activities attempt at mitigating *partial damage states*, i.e. although damage is present in the component, it does not cause failure at the time being considered. The relevance of considering partial damage states in practical design situations has been widely acknowledged in the literature [25,40].

Within the scope of this contribution, the definition of a maintenance schedule involves the selection of two design variables. The first one refers to the *quality of inspection* (q). This variable characterizes the ability of a particular non-destructive inspection (NDI) method for detecting a crack. For example, while a low quality inspection method may fail in detecting a certain crack, a high quality method will (most likely) detect the same crack. For simplicity, it is assumed that q can be modeled by means of a positive, real number [68]. The second design variable is the *time of inspection* (T_I), which determines at which instant of the lifetime of a component inspection and repair are performed. This variable plays a major role, as maintenance activities scheduled at an inappropriate time may be completely ineffective [77]. In this contribution, T_I is modeled as a positive, real number, just as in the case of q. However, it should be noted that depending on the scope of the specific application being studied, a more suitable model for either q or T_I could be a discrete variable; however, for the sake of simplicity, this last option is not pursued further in this contribution.

2.2. Uncertainties and their effect

One of the major challenges in the scheduling of maintenance activities is that both the crack propagation phenomenon and the inspection activities are affected by uncertainties. In the case of the crack propagation, the time to appearance and length of a crack at a particular instant cannot be characterized as deterministic variables (see, e.g. [37,69]). Therefore, the uncertainty in the crack propagation phenomenon should be explicitly model, e.g. by means of random variables.

As in the case of the crack propagation, the inspection activities are also subject to uncertainties. This is due to the fact that inspection is not infallible, i.e. a certain inspection technique may fail in detecting a particular crack. The uncertainties related with the detection of crack can be modeled by means of the probability of detection (POD), i.e. the probability that a crack of length a is detected by inspection. In addition, the length of a crack that has been detected may be measured incorrectly, thus affecting the decision of repair.

The effect of the aforementioned uncertainties is reflected in the performance of the mechanical component; more specifically, these uncertainties prevent from predicting the behavior of the component during its target lifetime in a deterministic way. Instead, a spectrum of possible events may occur. For a better understanding of these different events and their interaction, consider the schematic representation in Fig. 2, which corresponds to an event tree (see, e.g. [16,23,43]). This figure illustrates the possible events that may take place during the life span of a metallic stripe subject to cyclic loading that develops a single edge crack. The occurrence of any of these events will be defined by the physics of the problem (in this case, the crack propagation phenomenon), the particulars of the maintenance