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Optimal inspection planning and repair under random crack propagation

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Operation of damage-tolerant structures or components subject to random crack propagation requires constant monitoring by non-destructive inspections and systematic maintenance actions. Optimization of inspection schedules and repair strategies is a compromise between costs of inspections and repairs, and expected costs of failure. This paper advances the state of the art by: considering accurate polynomial chaos model of the random crack propagation process; considering number of inspections and crack repair size as design variables and; by performing sensitivity analysis of optimal inspection schedules and repair strategies with respect to the assumed costs of inspection and failure, as well as to the level of loading.

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1. Introduction

Fatigue and crack propagation have long been recognized as stochastic processes [1,2], with experimental data showing significant scatter [3,4]. In structural design, uncertainty in crack propagation can be addressed by adopting large conservative safety margins, as in the design of off-road vehicles or battle tanks. However, for high performance structures such as aircraft, spacecraft or missiles, overdesign is not an option, as it compromises performance. Moreover, for structural systems such as pipelines, which are operated continuously and indefinitely, overdesign only works for a limited time. For these types of structures, failure by fatigue or crack propagation can be averted by costly periodic inspection and maintenance activities. In fact, expenditure in inspection, maintenance, repair and retrofit of civil infra-structure aged by fatigue has been accounted for making up a significant fraction of Gross National Products. Still, fatigue and crack propagation have been a primary cause of structural failures in recent years.

For high performance structures such as aircraft, spacecraft or missiles, the concept of damage tolerance has been developed. According to this concept, these structures are designed to safely withstand some level of damage, including fatigue cracks. However, excessive damage may still lead to very costly catastrophic failures. The thin line between safe, tolerated damage and catastrophic damage is controlled by periodic inspection and maintenance activities. The investment of resources in inspection and maintenance activities must be seen as a trade-off: more investment in inspection and maintenance activities should lead to safer structures, averting the high costs of failure. However, wrong investments may not lead to significant reductions on expected costs of failure. The trade-off between the costs of inspection and maintenance and the costs of failure can be addressed by means of reliability-based optimization [5,6], also called risk-based optimization [7–10].

Optimal inspection and maintenance scheduling under fatigue was addressed, for example, by Valdebenito and Schuëller [5], Beaurepaire et al. [6], Madsen et al. [11] and Faber et al. [12]. These authors have shown that optimal scheduling involves finding a trade-off between the costs of inspection, repair, and eventual failure. Single-handed consideration of any of these costs alone leads to sub-optimal planning, hence to larger total expected costs. The present paper addresses the problem by investigating some relevant issues not addressed in [5,6,11,12].

In addition to the inherent uncertainties in fatigue life or in crack propagation parameters, the optimal scheduling of inspections and maintenance is also affected by imprecision of non-destructive inspection techniques. Hence, an existing crack may not be detected for being too small for a particular inspection method. When detected, the size of such crack may be imprecisely estimated due to limited accuracy of inspection methods.

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In recent years, several authors have addressed inspections and maintenance under random fatigue, but not all get to the point of obtaining optimal scheduling. For instance, Cremona [14] and Madsen et al. [15] established methodologies for reliability updating, which can be useful for optimization of maintenance strategies, but the authors have not solved the optimization problem. Riahi et al. [16] focused on reliability updating and its applications.

Other authors have addressed the optimal scheduling of inspections and maintenance, by adopting different levels of simplifications. For instance, Kulkarni and Achenbach [17] addressed optimal inspection schedules for a surface-breaking crack subject to fatigue loading, investigating the effects of critical depth for repair and the quality of the inspection technique, this latter described by different Probability of Detection (POD) curves. Relevance of the results by Kulkarni and Achenbach [17] was limited, as only the initial crack size was considered random, allowing the authors to employ analytical expressions to determine updated probability density functions of crack depth.

In Valdebenito and Schuëller [5], maintenance schedules for fatigue-prone metallic components were determined by means of reliability-based optimization. The Finite Element Alternating Method (FEAM) was employed for estimating stress intensity factors, in a numerical example consisting of a plate with 8 cracks emanating from 4 rivet holes. The quality (POD) and time to the first (and only) inspection were considered as design variables. By limiting their analysis to a single inspection, discontinuities of the objective function were avoided. This allowed the authors to solve the optimization problem by using a local, gradient-based method [18]. In the present paper, it is shown that considering the (discrete) number of inspections as a design variable leads to a discontinuous optimization problem, which cannot be solved directly by local gradient-based techniques. Moreover, Valdebenito and Schuëller [5] employed as stochastic model of crack propagation a randomized version of the Paris–Erdogan law, with arbitrarily chosen parameters. It was assumed by the authors that when the component is repaired, it should survive until the end of the design life; and in case no repair takes place, the component may fail or survive until the end of the design life. Without any demerit to the relevant findings by Valdebenito and Schuëller [5], in the present article some of these approximations are overcome.

Beaurepaire et al. [6] addressed the optimal scheduling of inspection and maintenance policies under random fatigue, using a numerical cohesive crack model to represent initiation, stable and unstable growth of a fatigue crack. Random parameters of the cohesive crack model were obtained from experimental data, where crack propagation rate was represented as a random variable. As done in [5], the quality (POD) and time to the first (and only) inspection were considered as design variables. Hence, again the number of possible inspections during the design life was not considered as a design variable.

In Madsen et al. [11], four different strategies for repair were compared. By adopting an analytical crack growth model and a linear corrosion model, it was possible to convert the time-dependent reliability problem into a time-independent one. Failure probabilities were estimated by the First Order Reliability Method (FORM), leading to smooth estimates of the total expected costs. The optimization problem was solved for fixed numbers of inspections, by means of gradient-based optimization methods. For each discrete number of inspections, the design variables were a stress related design parameter, inspection times and inspection qualities. The authors evaluated total expected costs by conditional and non-conditional probabilities. In contrast, a cost model based on expected numbers of failures and repairs, instead of probabilities, is adopted herein; thus, the computation of total expected cost requires only one probabilistic analysis, and the consideration of different inspection techniques and repair methods, within the same inspection/maintenance strategy, becomes much easier.

Faber et al. [12], focused on the use of sensitivity measures as decision tools, discussing how important it is for the decision maker to be able to estimate how uncertain the estimated expenditures are, with respect to some quantities used to estimate probabilities and costs. A number of simplifications were applied to the description of the optimal inspection and maintenance planning, in order to achieve a more appropriate formulation for practical purposes. For example, the authors assumed that if failure occurs, then the component cannot be repaired. Only the next inspection time, method and repair strategy were optimized; and by calculating failure probabilities by FORM, again, smooth estimates of total expected costs were obtained, avoiding the fluctuations inherent to Monte Carlo simulation.

In comparison to some of the most comprehensive papers covering optimal inspection and maintenance planning under random fatigue [5,6,11,12], the present paper advances in four main lines:

1. An accurate (polynomial chaos) stochastic crack propagation model is used, representing variability of crack growth in time.
2. The number of inspections during design life is considered a design variable, leading to a challenging discontinuous objective function with multiple local minima.
3. The critical crack size at which repair is performed is considered a design variable.
4. Sensitivity of optimal inspection schedules is investigated with respect to the estimated costs of inspection and failure, and with respect to the level of loading.

In a compromise to addressing the challenging issues above, the present paper includes a simple example problem requiring only analytical modelling of stress intensity factors. Also, the quality of non-destructive inspection method (POD curve) is fixed and not considered as a design variable. The results presented herein are readily extendable to numerical modelling of stress intensity factors by means of Boundary Element Method [19–21], Generalized Finite Element methods [22–24], and Extended Finite Element Method [25–28]. Cohesive crack modelling [6] could also be incorporated, but by rebuilding the stochastic crack propagation model employed herein. Moreover, many aspects of system reliability are not addressed in this paper, but could be taken into account in the future, for example, by combining the methodology presented herein with the procedures proposed by Straub and Faber [13]. In this regard, the (polynomial chaos) stochastic crack propagation model adopted herein is directly applicable for problems involving multiple site damage, and also allows considering the inter-dependency of multiple crack growth. Such extensions are easily achieved by the proper computation of stress intensity factors.

The remainder of this paper is organized as follows. The random crack propagation model is presented in Section 2. Modelling of non-destructive inspections and repairs is presented in Section 3. Section 4 describes the limit state and reliability functions, and Section 5 describes formulation of the risk optimization problem. In Section 6, the probabilistic Latin Hypercube simulation analysis is described. The application problem is described in Section 7, and results are presented in Section 8. The paper is finished with some concluding remarks in Section 9.

2. Random crack propagation model

Large replicate experimental tests show that crack propagation is subject to significant scatter [3,4]. For tests developed in closely monitored laboratory conditions, such scatter can only be

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