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Probabilistic optimization framework for inspection/repair planning of fatigue-critical details using dynamic Bayesian networks

David Y. Yang, Dan M. Frangopol *

Department of Civil and Environmental Engineering, ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA, USA

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Bridges, ships, and other civil and marine structures are subjected to fatigue damage due to repeated load fluctuations. Fatigue damage is likely to jeopardize the functionality and even structural safety of these structures. Therefore, inspections and timely repair actions are needed to ensure adequate structural performance throughout their lifetime. Nevertheless, inspection/repair actions involve additional life-cycle costs. Therefore, efficient planning of inspection and repair actions of fatigue-critical details are not only essential to ensure structural functionality and safety, but also important to control the total life-cycle cost. In this paper, a novel framework for optimizing inspection/repair planning is developed by using efficient Bayesian updating with dynamic Bayesian network. Specifically, inspection plans, including inspection schedules and inspection techniques, are optimized using pre-posterior analysis. Decisions of repair actions are made based on inspection results following an evidence-informed and cost-driven repair strategy. This strategy allows for time-dependent and adaptive repair actions considering fatigue damage development, available inspection results, and previous repair actions. Optimal inspection/repair plans with the lowest expected life-cycle cost are then obtained using both single- and multi-objective optimizations.

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1. Introduction

Bridges, ships, and other civil and marine structures are subjected to repetitive loads that may induce fatigue damages or even fatigue failures. Therefore, inspections of fatigue-critical details should be conducted during the lifespan of these structures to detect any dangerous fatigue damages and provide useful evidence for appropriate repair actions. However, inspections, as well as the following decisions on repair, will increase the life-cycle cost of a structure. As a result, effective planning of inspection and repair actions of fatigue-critical details are not only essential to ensure structural functionality and safety, but also important to control the total life-cycle cost [1,2].

The fatigue damage of a structure involves considerable amount of uncertainties arising from both materials and loading conditions [3,4]. Inspections, besides detecting damages detrimental to structural performance, can also deliver useful information to update the deterioration process using Bayesian updating [5–11]. Therefore, a probabilistic approach with the ability to conduct Bayesian updating based on inspection results should be used for decision-making on inspection/repair actions.

A large number of studies have been conducted for inspection/repair planning [12–21]. Different objectives, including the expected life-cycle cost, expected service life and expected damage detection delay, have been used in both single- and multi-objective optimizations in order to obtain the optimal inspection plans. In all the aforementioned studies, a prescribed repair threshold, an observed damage condition that triggers repair actions (e.g. a critical fatigue crack size in fatigue problems), is usually used to dictate "repair" or "no repair" decisions. Based on this repair policy, Bayesian decision theory using pre-posterior analysis [22,23] can be used to conduct risk-based inspection planning, in which a single fixed repair threshold is assumed or optimized [14–16,19–21]. Nevertheless, it should be realized that fatigue is a time-evolving problem. Therefore, it is not always rational to use the same repair threshold in early and late stages of the design service life. Consider for example a fatigue-sensitive detail with a design service life of 20 years and a critical fatigue size of 30 mm. If the inspected crack size at year 3 is 10 mm, it is nearly certain that this detail cannot be used for the remaining design service life and should be repaired; the same crack size measured at year 18, on the other hand, may support the use of the detail until the end of the design service life. Therefore, the repair threshold should have a a time-dependent value.

The inspection/repair plans should also be adaptive to inspection results available and previous repairs. For instance, the result

* Corresponding author.
E-mail address: dan.frangopol@lehigh.edu (D.M. Frangopol).

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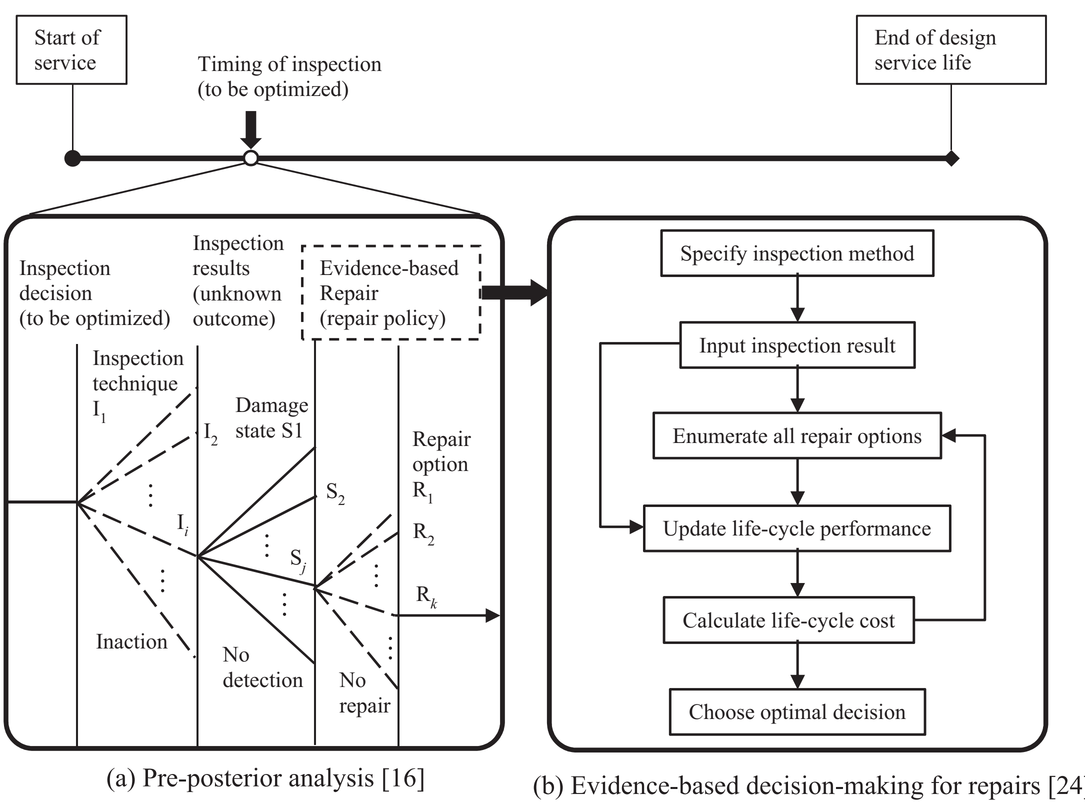
from one inspection may influence the schedule of future inspection plans. Alternatively, when the inspection plan is fixed, the previous inspection results and their associated repair actions should change the repair thresholds in future inspections. To this end, Soliman and Frangopol [9] proposed an adaptive inspection planning framework based on evidence from previous inspection results, adapting future inspection plans based on the current information available. Markov Chain Monte Carlo (MCMC) simulation, a computationally intensive method, was used to conduct Bayesian updating. More recently, Yang and Frangopol [24] proposed a real-time management tool to decide optimal repair actions based on the posterior expected life-cycle cost. The proposed method does not need to specify repair threshold explicitly. By contrast, the repair threshold is an implicit and time-variant property that depends on the entire life-cycle performance of the detail. By capitalizing on discrete Bayesian networks to conduct Bayesian updating efficiently, optimal decisions on following-up repair actions can be obtained nearly instantly after inspection results are available. It should be noted that both methods mentioned previously require attained information from inspections. They fall into the category of posterior analysis in the context of Bayesian decision theory [22].

Though posterior analysis is able to update the deterioration process and guide repair decisions, it is not helpful for inspection planning as the available evidence implies that an inspection has already taken place. In this paper, a comprehensive probabilistic framework is proposed for optimal inspection/repair planning of fatigue-sensitive details. The proposed framework can be schematically represented as shown in Fig. 1. It tackles three aspects of inspection/repair planning: (a) when the structure is inspected; (b) what technique is used for inspection; (c) what action is taken based on inspection results. For the first two aspects, Bayesian decision theory based on pre-posterior analysis is used by repetitively updating the fatigue performance based on all possible inspection results. The third aspect is considered by leveraging the decision-making method (decision policy) proposed in [24], which is briefly summarized by the flowchart in Fig. 1(b).

Different from existing inspection planning methods, the proposed framework does not need to specify any prescribed repair threshold. Instead, the associated repair action is decided based on the entire life-cycle fatigue performance and is obtained directly based on the method described in Yang and Frangopol [24]. Implicitly, the adopted decision policy achieves time-variant and adaptive repair thresholds that depends on the underlying fatigue process, all the inspection results available, and all the repair actions already implemented. This feature of the proposed framework is a major improvement to previous studies and constitutes an important step towards data-driven life-cycle management of fatigue-sensitive structures.

Because of the decision policy used, conventional sampling-based methods [9,15,16,21] cannot solve the problem of inspection planning. In order to replicate the implicit time-variant repair thresholds, a large number of design variables representing these thresholds would have to be added to the optimization problem, which can easily invalidate all of these methods computationally. As no inspection results are available in the phase of inspection planning, evidence-based decision making for repairs must be conducted in a pre-posterior manner for all possible inspection outcomes; one scenario in this process is illustrated in Fig. 1(a). The final framework then attempts to explore a space of all possible inspection timings and their associated inspection techniques to arrive at a set of optimal solutions based on single or multiple objectives. The scale of this optimization problem indicates the necessity of an efficient computational procedure. This computational difficulty is dissolved by virtue of efficient Bayesian updating in discrete Bayesian networks. In this paper, the considered



(a) Pre-posterior analysis [16]
(b) Evidence-based decision-making for repairs [24]

Fig. 1. Illustration of the proposed framework.

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