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LIFE-CYCLE OF FATIGUE SENSITIVE STRUCTURES UNDER UNCERTAINTY

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Abstract. Fatigue is the one of the main contributors to problems related to structural safety of civil and marine structures. Life-cycle management (LCM) techniques considering various uncertainties can be used to predict the safe service life of fatigue sensitive structures, plan for their future inspections and support the decision making process regarding maintenance and repair actions. This paper provides a brief overview of the LCM of fatigue sensitive civil and marine structures under uncertainty. Probabilistic performance prediction, inspection scheduling and maintenance optimization for such structures are discussed.

1 INTRODUCTION

Fatigue damage can cause a considerable reduction in the structural reliability of bridges and ship structures. Fatigue cracks reduce the structural integrity and may lead to fractures and catastrophic failures [1,2]. Fatigue is the process of damage accumulation caused by repeated fluctuating loads. The damage may accumulate at regions of stress concentration where the local stress exceeds the yield limit of the material. Initiation and propagation of cracks in the plastic localized region occurs due to the cumulative damage acting over a certain number of stress fluctuations [3]. These cracks can eventually cause the fracture of the component at stress levels well below the service ones. Although multiple research reports and design standards provide methods to minimize fatigue effects for newly designed structures, fatigue damage may still exist. Service life prediction, under fatigue effects, is subjected to various types of uncertainties associated with randomness (i.e., aleatory) in loading conditions, resistance, and modeling (i.e., epistemic) uncertainties [4-6]. The latter may be reduced by the proper modeling of the damage accumulation process or the growth of fatigue cracks.

Given the impact of fatigue related problems on the structural integrity and the cost associated with the proper inspection and maintenance activities, life-cycle management

(LCM) techniques under uncertainty can be used to predict the safe service life of fatigue sensitive structures, plan for future inspections and support the decision making process regarding maintenance and repair actions. This paper provides a brief overview of the LCM of fatigue sensitive civil and marine structures under uncertainty. Probabilistic performance prediction, inspection scheduling and maintenance optimization under the required financial and reliability constraints are discussed.

2 LIFE-CYCLE MANAGEMENT

The aging of infrastructure systems and the scarcity of funds required to maintain the functionality of these systems pushed the research communities to find innovative techniques which enable maintaining the reliability of these structures while satisfying financial constraints. LCM under uncertainty can effectively accomplish this task [7]. In this approach, the assessment is divided into successive processes. Each process, represented by its corresponding module in the management framework, is responsible for executing one of the LCM tasks. The general framework and its associated modules are shown in Figure 1. The first process in this framework is the performance assessment and prediction. In this process, the damage in the susceptible locations is investigated and the time-dependent deteriorating structural performance is predicted. Uncertainties inherently exist in this stage. These uncertainties are associated with the loading conditions, resistance evaluation as well as the performance prediction methodology. Needless to say, relying on the structural health monitoring (SHM) information can greatly assist in reducing the uncertainties with respect to loading evaluation and structural response [8-11]. The predicted structural performance profiles are subsequently used to find the optimum inspection and maintenance types and times.

The next phase of the LCM framework is the inspection/monitoring/maintenance scheduling. This process provides the main outcome of the LCM framework given by the optimal intervention schedules which fulfill the management goals. The optimal scheduling can be achieved with various objectives such as maximizing the probability of damage detection, minimizing the damage detection delay, minimizing the life-cycle cost or maximizing the service life, among others. Additionally, the optimization process may have two or more conflicting objectives, such as minimizing the inspection cost, which will require low number of inspections to be performed, along with minimizing the damage detection delay, which will require additional inspections.

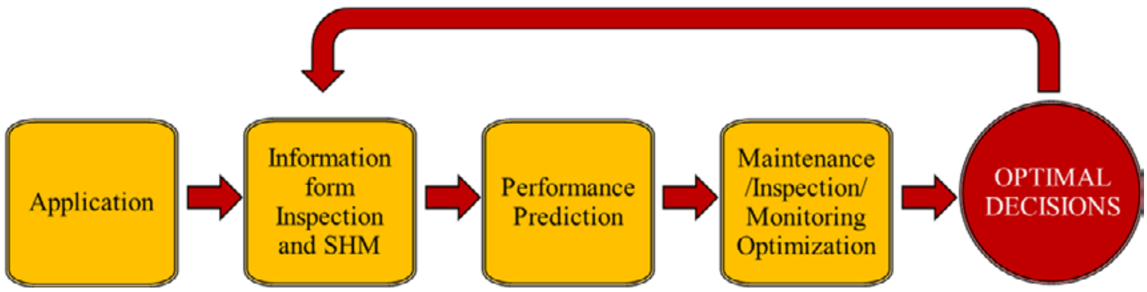

Figure 1: Schematic of the general LCM framework.

After obtaining the optimum inspection/maintenance schedule, the final step would be to apply the proposed plan and use the future inspection and monitoring outcomes to evaluate the proposed plan, and if needed, update the adopted deterioration model to find a new inspection/maintenance plan. The main modules of the proposed framework and the research work associated with them are discussed next.

2.1 Performance prediction

At this module, the current condition of the studied structural component or detail is assessed and the future damage propagation is predicted to quantify the service life. This stage represents the foundation of the life-cycle optimization; thus, care should be taken when defining different variables and parameters associated with the performance prediction. Two approaches for the fatigue assessment and evaluation are currently used within the LCM framework; namely, the S-N approach and the crack growth approach. The former provides the fatigue life, in terms of the number of cycles to failure, as a function of the type of the detail and the stress range acting on it. The S-N relationship is represented by linear or multilinear relationships, drawn in logarithmic scale, between the stress range acting on the detail and the number of cycles to failure. Using the equivalent constant amplitude stress range S_{re}, fatigue life, measured as the number of cycles to failure, is calculated as [12]

$$N = \frac{A}{S_{re}^{m}} \tag{1}$$

in which A is a fatigue detail coefficient for each category, N is the number of cycles, and m is a material constant defining the value of the single slope of the *S-N* line. The number of cycles N can be used in conjunction with the average annual number of cycles N_{avg} to estimate the fatigue life as

$$t\left(years\right) = \frac{N}{N_{avg}} \tag{2}$$

This approach is adopted by most of the design specifications for bridges and ships (e.g., [13-16]) due to the ease of its application. Additionally, it is widely adopted for the reliability assessment of fatigue critical ships and bridges [5,12,17]. To investigate the fatigue reliability index β of a detail, a performance function can be defined as

$$g\left(t\right) = \Delta - D(t) \tag{3}$$

where Δ is Miner's critical damage accumulation index, indicating the allowable accumulated damage [18]; $D(t)$ is Miner's damage accumulation index [12] which represents the demand. Kwon and Frangopol [12] used the S-N approach to evaluate the fatigue reliability of bridge details based on SHM. The study evaluated the effect of the probability density function (PDF) of the stress range on the fatigue reliability. The same approach was also used in [5,19] to evaluate the reliability of steel and aluminum ships from fatigue point of view. The general procedure of reliability assessment using S-N approach is provided in Figure 2.

However, this approach cannot be used to study the crack condition at a damaged detail. For steel bridges and ships, linear elastic fracture mechanics can be used to establish this task.

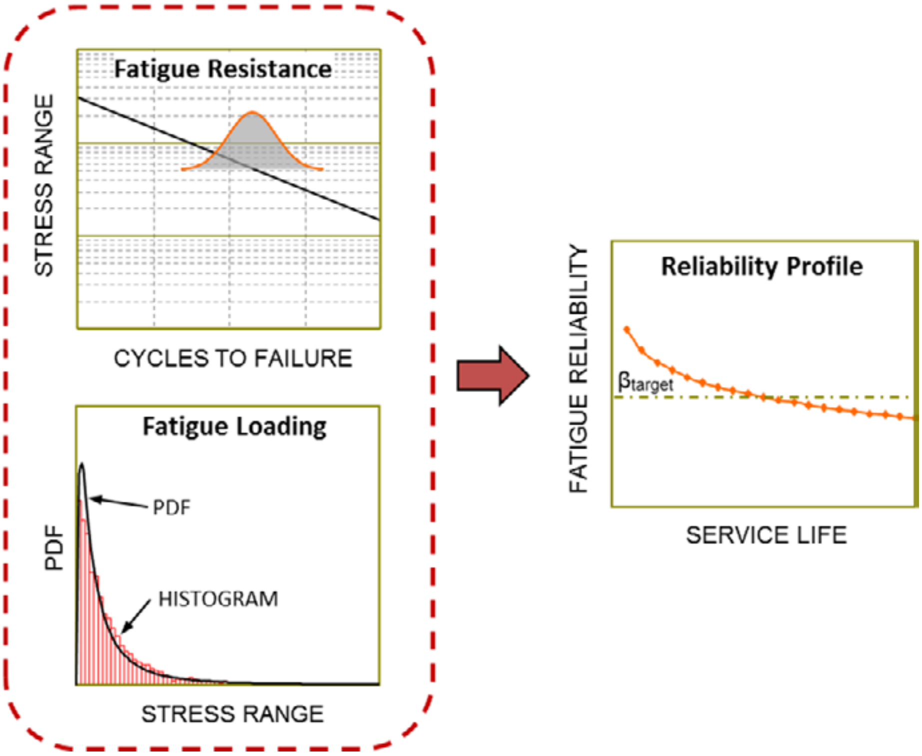

Figure 2: Reliability evaluation using the S-N approach.

This approach is based on Paris' law which relates the crack growth rate to the range of the stress intensity factor as [1]

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{4}$$

where a is the crack size, N is the number of cycles, and ΔK is the range of the stress intensity factor. C and m are material parameters. The range of the stress intensity factor can be expressed as [1]

$$\Delta K = Y(a) \cdot S \cdot \sqrt{\pi a} \tag{5}$$

where S is the stress range and $Y(a)$ is a correction factor depending on the crack orientation and shape. This correction factor takes into account the effects of the elliptical crack shape, free surface, finite width (or thickness), and non-uniform stress acting on the crack. More detailed empirical and exact solutions for these correction factors can be found in [20]. Accordingly, denoting the allowable crack size as a_f, the time required to grow the crack from an initial size of a_o to a_f can be calculated as [1]

$$t(years) = \frac{1}{N_{avg} \cdot C \cdot S^m} \cdot \int_{a_o}^{a_f} \frac{1}{\left(Y(a) \cdot \sqrt{\pi a}\right)^m} da \tag{6}$$

However, due to various uncertainties associated with the material properties, loading and modeling, this equation can be evaluated using Monte Carlo simulation resulting in the PDF of the time to failure of the detail. Uncertainties in the damage propagation are considered by describing different model parameters by their representative probability density functions (PDFs). For instance, Kim and Frangopol [4,6,21] described the initial crack size, stress range, number of cycles, and material crack growth parameters by their respective PDFs. The damage level represented by the time-dependent crack size is obtained by using Monte Carlo simulation. Both approaches for the fatigue assessment, using the S-N approach or the crack growth approach can be combined in the life-cycle analyses. Kwon and Frangopol [22] integrated the crack growth profile in a reliability-based model to find the optimum intervention types and times for extending the service life of steel bridges.

2.2 Inspection and repair scheduling

The next stage in the life-cycle planning is to find the appropriate inspection/monitoring/ repair schedules that can insure that damage is detected and repaired before causing any progressive or catastrophic collapses. The main focus of this module is to develop management procedures for fatigue critical structures which can support the decision making process under uncertainty. Applications to this process include steel ships, aluminum ships and steel bridges. Single and multi-objective optimization procedures can be constructed to fulfill the management objectives. Within the last decades, different scheduling techniques have been introduced. Chung et al. [23] formulated an optimization algorithm for inspection scheduling that minimizes the cost while considering the safety of the detail. The cost in their study included both the inspection cost and failure cost. Their approach was used to find the optimal time interval between inspections for different inspection methods.

Kwon and Frangopol [22] proposed a reliability-based approach for the LCM of fatigue critical steel bridges to find the optimum inspection and repair actions for a given fatigue detail. Their approach used a probabilistic crack growth model integrated into a reliability-based approach. The main goal of their study was to extend the life of critical details by applying the appropriate and timely inspection and maintenance actions. The approach allows the use of single or combined maintenance options to extend the service life. The outputs of the management process are the optimum inspection and repair times when adopting different inspection/maintenance methods. The appropriate maintenance actions are selected using the probability of detection (PoD) functions associated with each inspection method and a crack size based threshold. Figure 3 shows a typical result of such management plans.

Kwon and Frangopol also investigated the fatigue LCM of aluminum ships [19]. The study in [19] presented an incorporation of fatigue reliability into a life-cycle cost optimization procedure with the goal of finding the optimal inspection and repair times. A single objective optimization problem was formulated to find the inspection and repair times which minimize the total life-cycle cost. Another multi-objective problem was formulated to find the inspection and repair times which simultaneously minimize the maintenance cost, maximize the time-dependent reliability index and minimize the time-dependent damage level.

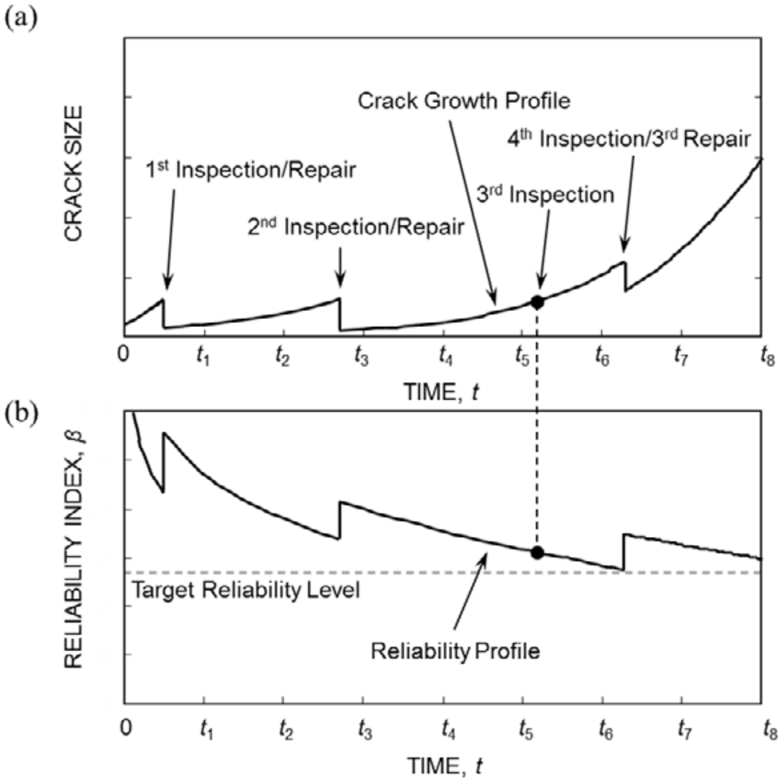

Figure 3: Optimum inspection/repair strategy using peening repair (a) updating crack growth model, and (b) updating reliability profile (adapted from [22])

Kim and Frangopol [6] proposed an approach for establishing optimum inspection schedules of steel ship details which minimize the damage detection delay. This delay may lead to late maintenance and is critical for structures which have high damage propagation rates such as fatigue in aluminum ships. Probabilistic event tree analysis was used in [6] to formulate the damage detection delay with different inspection scenarios. The process starts with identifying the PDF of damage occurrence $f_T(t)$ using a predefined damage threshold integrated in the damage propagation model. Next, this PDF is integrated into an event tree model along with the probability of damage detection and the proposed number of inspections to find the expected damage detection delay $E(t_{del})$ for a given number of inspections n. This formulation of the damage detection delay is integrated in a single objective optimization process to find the optimum inspection times which minimizes the damage detection delay as follows [6]

Find $\mathbf{t_{ins}} = \{t_{ins,1}, t_{ins,2}, \ldots\ldots\ldots, t_{ins,n}\}$ (7a)

To minimize $E(t_{del})$ (7b)

Such that $t_{ins,i} - t_{ins,i-1} \geq 1$ year (7c)

Given $n, \delta_{0.5}, f_T(t)$ (7d)

where $\mathbf{t_{ins}}$ is a vector consisting of the design variables of inspection times $t_{ins,1}$, $t_{ins,2}$, ..., $t_{ins,n}$; $t_{ins,i}$ is the ith inspection time (years); $\delta_{0.5}$ is the damage intensity at which the given inspection method has 50% probability of detection. This optimization problem gives the optimum inspection times as an output for a given number and quality of inspections.

Kim et al. [24] proposed an approach for the inspection/maintenance planning for fatigue critical structures. The approach uses the crack growth model and the PoD function, associated with the adopted inspection method, to evaluate the relationship between the degree of damage and the probability of damage detection. Next, optimization is performed to maximize the expected service life simultaneously with minimizing the expected total life-cycle cost including the inspection and maintenance costs. Multiple maintenance types can be used in their approach in which the optimization scheme provides damage level thresholds to be used for selecting the appropriate maintenance action based on the degree of damage identified during future inspections.

3 CONCLUSIONS

With the presence of multiple sources of uncertainty associated with the fatigue loading, resistance, and damage propagation, the LCM techniques provide a solid platform to obtain the optimal management actions which fulfill the required goals and constraints while integrating these uncertainties. The LCM starts with the assessment and prediction of the time-dependent performance level. SHM and inspection actions can enhance this process by providing a deeper insight into the damage level and the actual structural responses under normal loading. Next, optimization is performed to establish the optimal intervention schedules under uncertainty. This paper briefly discussed the various modules of the LCM process including performance prediction and intervention planning. Future research will enhance the proposed framework by including additional deterioration mechanisms such as corrosion induced fatigue.

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