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Reliability, risk and lifetime distributions as performance indicators for life-cycle maintenance of deteriorating structures

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ABSTRACT

Structural capacity deterioration is among the main causes of increasing failure probabilities of structural systems, thus maintenance interventions are a crucial task for their rational management. Several probabilistic approaches have been proposed during the last decades for the determination of cost-effective maintenance strategies based on selected performance indicators. However, benefits and drawbacks of each performance indicator with respect to the others should be further analyzed. The objective of this paper is to investigate probabilistic approaches based on the annual reliability index, annual risk, and lifetime distributions for life-cycle maintenance of structural systems. Maintenance schedules are obtained for representative series, parallel, and series–parallel systems considering total restoration of component resistances whenever a prescribed threshold, based on a selected performance indicator, is reached. Effects related to different structural configurations and correlation among failure modes are investigated. The superstructure of an existing bridge is used to illustrate the presented approaches.

1. Introduction

The economic growth of developed countries has led to the creation of extended civil infrastructure networks and facilities. During their life-cycle, these structural systems have often been subjected to natural hazards and aging phenomena caused by environmental and mechanical stressors that decrease their initial performance. At the same time, the current social and political trends promote maintaining existing structures for extended periods of time due to the high direct and indirect costs associated with their eventual replacement. Moreover, several of these structures have significantly lower structural performance today than was initially associated with their designs. This is due to the increasing demand during their operating conditions, and the often ineffective or inappropriate maintenance [1].

Accurate modeling of structures, hazards, stressors and load effects is a major challenge for the structural engineering community. Because of several uncertainties related not only to the structural models, but also to randomness inherent within natural phenomena and loads, probabilistic methods provide the most rational way to obtain high accuracy predictive models, aiming at making optimal decisions for maintenance of the structures. Remarkable contributions have been made to the development of techniques for performance and risk assessment during the structural life-cycle of both individual structures and networks in the effort of achieving a comprehensive integrated framework and ensuring adequate structural reliability through optimization techniques [2]. Risk assessment and subsequent decision making has been recognized, in recent years, as being of the utmost importance [3–5]. In this context, a comprehensive guideline on risk-based decision making, including system and network modeling, hazard analysis, risk quantification by risk indicators and risk reduction measures, has been proposed [6]. Indicators for assessing the time-dependent performance of damaged bridges, in terms of structural vulnerability, redundancy, and robustness, have been also investigated [7].

The objective of this paper is to investigate probabilistic approaches based on annual reliability index, annual risk, and lifetime distributions for life-cycle maintenance of structural systems. In particular, different approaches to the problem of determining maintenance schedules are discussed. The aim of this paper is to provide indications on advantages and drawbacks of these indicators. Threshold-based maintenance problems are solved by analyzing the effects of various system configurations and failure mode correlations. Maintenance options are restricted to essential maintenance, implying total restoration of component resistance after repair. It is assumed that, when a prescribed threshold is reached, maintenance is performed.

This paper is composed of two main parts. In the first one, two point-in-time performance indicators are introduced, the annual reliability index and annual risk, and are used for solving maintenance problems. The annual reliability index has been proposed as an important tool for the assessment of optimal maintenance

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plans in civil [8,9] and marine structures [10,11]. Single objective optimization [12] and multi-objective optimization techniques [13] involving reliability analysis and cost-based decision making have been reported. While the reliability index is uniquely connected to the failure probability of the structure, risk takes into account direct and indirect consequences associated with total or partial failure of the system and is defined as the product of failure probability and consequences estimated in monetary terms [14]. Risk analysis gives maintenance priority to those components having the worst consequences, not only economically, but also socially and environmentally.

In the second part of this paper, lifetime distribution approaches are discussed. Representation of structural performance through lifetime distributions has the advantage that it can be used via closed-form expressions. On the other hand, a lifetime distribution represents the overall effect of all variables involved in the structural resistance and loads, therefore the effect of a single random variable is not easy to find. A further limitation when dealing with system analysis is that closed-form solutions are usually known only for the two particular cases of statistically independent and perfectly correlated failure modes. Maintenance strategies based on lifetime distributions may take into considerations importance factors, giving indications on which components should be repaired to obtain the most beneficial effect on the entire system [15]. The main advantage of using lifetime distributions is their computational efficiency, making them particularly suitable for optimization methods [16]. Herein, threshold-based essential maintenance is examined with respect to availability and hazard functions. Finally, the considered approaches are applied to the superstructure of an existing bridge.

2. Maintenance for improving life-cycle performance

Several strategies can be considered for improving the life-cycle performance of a system. Maintenance interventions have, in general, two different aims: (a) blocking or slowing down the structural deterioration process, therefore increasing the time required to reach a predefined limit state; or (b) restoring, partially or totally, the resistance of one or more components of the structure when a given condition is reached, to improve the performance of the system. The first strategy is usually categorized as preventive maintenance; in general, preventive maintenance is applied at prescribed time instants during the lifetime of the system. The second one, namely essential maintenance, is instead usually performed when one or more performance indicators reach predefined thresholds, representative of degrading states of the structure. In this paper, the latter approach is considered. Fig. 1 shows the effect of essential maintenance by assuming that the structural resistance is returned to its initial value after repair.

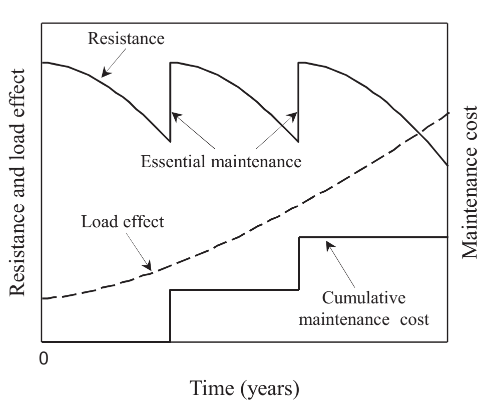

Fig. 1. Resistance, load effect and maintenance cost over time.

Time delay for performing repair is not considered; therefore, the resistance is instantaneously increased at the repair time, and the cost of the maintenance intervention is concentrated at the same instant. It has to be noted that the load is, in general, increasing over time due, for example, to the increasing demand in terms of traffic load to which bridges are usually subjected. Such load is not affected by maintenance actions during the structural life-cycle.

Repair priority can be given to one or more structural components, based on their effects on the system failure and possible consequences. The decision-making process may lead to different repair choices and different maintenance times depending on which performance indicator is considered. In the following, different configurations of a three-component system are analyzed, and essential maintenance schedules are evaluated with respect to different performance indicators and thresholds. In general, structural systems can be modeled as either series, parallel, or series–parallel systems. Herein, these three different configurations will be analyzed, considering for each one of them two cases: (a) statistical independence, and (b) perfect correlation between their failure modes. These cases are associated with lower and upper bounds of the system failure probability.

3. Annual reliability and annual risk as performance indicators

A rational way to treat uncertainties arising from natural randomness, modeling, and prediction imperfections is to consider probabilistic approaches. In this context, failure probability of a system is defined as the probability of violating one or more limit states associated with the system failure modes. The performance function $g(t)$ for a given failure mode is generally defined as:

$$g(t) = r(t) - q(t) \tag{1}$$

where $r(t)$ and $q(t)$ are the instantaneous resistance and load effect at the time instant t, respectively. Resistance and load are time-dependent random variables; for engineering systems, if no maintenance is considered, resistance is usually deteriorating over time, while loads are increasing. Considering a system with several failure modes, the point-in-time system failure probability P_{sys} at time t can be evaluated as:

$$P_{sys}(t) = P[\text{any } g_i(t) < 0] \quad \forall t > 0 \tag{2}$$

where $g_i(t)$ is the performance function associated with the ith system failure mode.

Determining the system failure probability is usually a formidable task, requiring solution of multiple integrals whose dimension increases with the number of failure modes. For this reasons, various approximation methods have been proposed. The most used approximate methods for obtaining the probabilities of occurrence of various failure modes are first-order reliability method (FORM) and second-order reliability method (SORM) that allow to solve the problem by approximating the limit state surface in the standardized normal space, at the most likely failure point, with a linear function and a second order surface, respectively. Given the definition of system failure state in Eq. (2), the associated reliability index $\beta(t)$ can be determined in approximate form as:

$$\beta(t) = \Phi^{-1}(1 - P_{sys}(t)) \tag{3}$$

where Φ is the standard normal cumulative distribution function. In usual applications, the probability of failure and the associated reliability index are evaluated at constant time intervals. Herein, a one year time interval is used, and reference will be made to the annual reliability index.