Structural Safety 48 (2014) 40–50

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Life-cycle maintenance of deteriorating structures by multi-objective optimization involving reliability, risk, availability, hazard and cost

Giorgio Barone [a], Dan M. Frangopol [b,*]

[a] Department of Civil and Environmental Engineering, Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS Center), Lehigh University, 117 ATLSS Dr., Bethlehem, PA 18015-4729, USA

[b] Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture, Department of Civil and Environmental Engineering, Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS Center), Lehigh University, 117 ATLSS Dr., Bethlehem, PA 18015-4729, USA

ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 4 February 2014
Accepted 11 February 2014
Available online 22 March 2014

Keywords:
Reliability
Risk
Availability
Hazard
Life-cycle maintenance optimization

ABSTRACT

In recent years, several probabilistic methods for assessing the performance of structural systems have been proposed. These methods take into account uncertainties associated with material properties, structural deterioration, and increasing loads over time, among others. When aging phenomena have significant effects on the life-cycle performance of the structure, it becomes essential to perform actions to maintain or improve structural safety, in agreement with the system requirements and available funds. Various optimization methods and performance indicators have been proposed for the determination of optimal maintenance plans for simple and complex systems. The aim of this paper is twofold: (a) to assess and compare advantages and drawbacks of four different performance indicators related to multi-objective optimization of maintenance schedules of deteriorating structures, and (b) to assess the cost-efficiency of the associated optimal solutions. Two annual performance indicators, annual reliability index and annual risk, and two lifetime performance indicators (i.e., availability and hazard functions) are used in conjunction with total maintenance cost for evaluating Pareto fronts associated with optimal maintenance schedules of deteriorating structures. Essential maintenance actions are considered and optimization is performed by using genetic algorithms. The approach is illustrated on an existing deteriorating bridge superstructure.

1. Introduction

Decision-making problems associated with the optimal maintenance of civil and marine structures and infrastructures are a crucial research topic in the field of life-cycle structural engineering. The increasing number of structural systems reaching critical conditions, due to increasing demands and/or deterioration of the component resistances, has directed researchers' attention towards the development of methods for the determination of cost-effective maintenance strategies. Optimization algorithms, having prescribed goals and considering maintenance times as design variables, allow the identification of several possible optimal maintenance strategies during the system life-cycle. The most appropriate intervention can be chosen with respect to several constraints, such as available funds.

Maintenance actions can be preventive, aiming at arresting or slowing down the structural deterioration, or essential, totally or partially restoring the performance of single or multiple components of the system. These actions can be applied at prescribed regular time intervals. However, it has been shown [13] that non-uniform time intervals are more efficient for maximizing the structural performance over the life-cycle of the system while simultaneously minimizing the total cost of the maintenance plan.

A crucial task for the determination of optimal maintenance plans is to accurately model the system, as well as the stressors and loads acting on it during its entire life-cycle. Probabilistic approaches constitute the most reasonable way to deal with the various uncertainties inherent to this task. Several indicators have been proposed during recent years to represent the time-dependent structural performance of deteriorating structures [25,1,11,17,14].

Two classes of indicators can be easily distinguished. The first includes point-in-time performance indicators, such as annual reliability index, annual risk, redundancy, robustness, and vulnerability [21]. The second class consists of the lifetime distributions, such as survivor, availability, and hazard functions [23]. While some of these indicators have been extensively used in literature, the advantages and drawbacks related to their use into optimiza-

* Corresponding author. Tel.: +1 610 758 6103.
E-mail addresses: gib212@lehigh.edu (G. Barone), dan.frangopol@lehigh.edu (D.M. Frangopol).

http://dx.doi.org/10.1016/j.strusafe.2014.02.002
0167-4730/

tion frameworks for the determination of optimal maintenance plans have not been specifically addressed.

This paper aims at investigating four of the most commonly used performance indicators, namely annual reliability index, annual risk, availability and hazard functions, for determining optimal maintenance plans for deteriorating structures. A preliminary investigation has been conducted in [6] by considering a threshold-based approach. Instead, bi-objective optimization is considered herein. For each optimization problem, minimizing the total cost of the maintenance plan is considered as the first objective, while the second objective includes minimizing one of the above mentioned performance indicators. Essential maintenance of single or multiple components of a deteriorating system is considered, entailing total restoration of the performance of components to its original value. The components with the highest repair priority are determined differently for each performance indicator, considering minimum reliability, maximum risk, and availability and hazard importance factors.

The approach is illustrated on an existing bridge superstructure modeled as a series-parallel system whose components are the bridge deck and girders. Pareto fronts and optimal solutions obtained from the four different approaches are compared.

2. Life-cycle maintenance optimization with different performance indicators

Life-cycle maintenance of a structural system is a fundamental requirement for maintaining the performance above safety thresholds. A comprehensive maintenance framework should include inspections and maintenance interventions. Inspections can be used to identify structural properties at various stages during the system life-cycle, assess the structural performance and, possibly, update the structural models established in the design phases. Maintenance interventions are, instead, needed to maintain, improve, or restore the system performance. Maintenance actions can be preventive or essential. Preventive maintenance is applied before reaching critical conditions and it is used to stop or delay the structural deterioration processes for a period of time. Typical examples of preventive maintenance are painting and coating of steel girders for corrosion prevention. Essential maintenance is, instead, required when the structure has reached prescribed performance thresholds, threatening the system safety. Essential maintenance actions provide a recovery of the structural performance of one or more components that may be partial (e.g., repair of structural components) or total (e.g., replacement of structural components). Since preventive maintenance can be performed when the actual structural deterioration is not critical for the safety of the structure, it is usually applied at regular time intervals over the system life-cycle. On the other hand, to maximize its cost-efficiency, essential maintenance has to be performed at optimal times, before the system failure occurs.

Therefore, life-cycle maintenance should be formulated as an optimization problem with design variables describing the number of repairs and their optimal application times. This optimization can be performed with respect to one or more prescribed performance indicators, considering constraints relative to maintenance costs and to repair times (e.g., minimum time interval between maintenance actions, maintenance effectiveness, among others). An alternative is to use multi-objective optimization techniques considering performance indicators and the maintenance cost as objectives. In this case, the result of the optimization is a set of optimal solutions (i.e., Pareto solutions). Subsequently, the most appropriate solution can be identified.

At each repair time, prescribed components must be repaired. Therefore, it is necessary to establish criteria for selecting which component(s) should be repaired at each intervention time. These criteria have to be defined depending on the performance indicator selected for the life-cycle maintenance optimization problem; in addition, they should be able to assign repair priority to components with the highest impact on the system condition.

A formal multi-objective framework to optimize the lifetime maintenance of deteriorating structures involving reliability, risk, availability, hazard and cost is presented herein by considering an existing deteriorating bridge superstructure.

3. Maintenance optimization of a deteriorating bridge superstructure

Four different optimization problems will be discussed in this paper for the determination of the optimal maintenance planning of the superstructure of the E-17-HS bridge located in Colorado, over an Interstate Highway. The bridge failure modes, considered in the following sections for computational purposes, are briefly described herein; further details can be found in [3,16]. For illustrative purposes, the reinforced concrete end span of the bridge, whose cross-section is shown in Fig. 1(a), has been modeled as a series-parallel system so that the failure occurs when either the deck or two consecutive girders fail (Fig. 1(b)). Material properties and bridge resistances and loads are modeled following the data provided in [3]. In particular, for the bridge deck, the limit state function associated with bending is:

$$g_0 = K_1 A_d f_{y,d} \lambda_d \gamma_d - K_2 \frac{A_d^2 f_{y,d}^2 \gamma_d}{f_{c,d}} - K_3 \lambda_{trk} = 0 \quad (1)$$

where the cross-sectional area of the deck steel reinforcement A_d, the associated yield strength $f_{y,d}$, the compressive strength of the concrete $f_{c,d}$, the reinforcement depth uncertainty factor λ_d, the modeling uncertainty factor γ_d, and the effect of the load λ_{trk} due to a HS20 truck are modeled as lognormal random variables. The deterministic coefficients $K_1, \ldots, K_3$ assume the following values: $K_1 = 4.323 \times 10^{-1}$, $K_2 = 4.085 \times 10^{-3}$, $K_3 = 5.287$. Additionally, the most critical failure mode for the girders is associated with the shear; therefore, the following limit state has been considered:

$$g_i = K_4 \sqrt{f_{c,g}} \lambda_{d,i} \gamma_g + K_5 A_{g,i} f_{y,g} \lambda_{d,i} \gamma_g - V_{trk} I_f D_f = 0 \quad (2)$$

The cross-sectional area of the shear reinforcement in each girder $A_{g,i}$, the associated yield strength $f_{y,g}$, the compressive strength of the girder concrete $f_{c,g}$, the uncertainty factor related to the depth of the reinforcement $\lambda_{d,i}$, the modeling uncertainty factor γ_g, the shear load V_{trk}, the girders impact factor I_f, and the distribution factor D_f have been considered lognormal distributed. The deterministic coefficients K_4 and K_5 assume the following values: $K_4 = 30.925$, $K_5 = 5.093$. The means and standard deviations of the variables considered into Eqs. (1) and (2) are defined in [3].

A continuous reduction over time of the cross-sectional area of the reinforcement bars in the bridge superstructure, due to chloride contamination, is considered over the life-cycle of the structure. Loads acting on the bridge are due to the average daily traffic. Readers are referred to [3] for numerical details regarding both the corrosion model and loads. Failure probability for the bridge superstructure, as well as failure probabilities associated with each component (deck, exterior and interior girders) have been evaluated by the First Order Reliability Method (FORM) using the RELSYS software [12]. The results are shown in Fig. 1(c).

Optimal maintenance plans are investigated for the superstructure of the E-17-HS bridge, based on four different approaches. All the maintenance plans entail essential maintenance actions on the system components, and either deck or girders are considered “as new” after repair. The design variables for each optimization pro-