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A probabilistic computational framework for bridge network optimal maintenance scheduling

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ABSTRACT

This paper presents a probabilistic computational framework for the Pareto optimization of the preventive maintenance applications to bridges of a highway transportation network. The bridge characteristics are represented by their uncertain reliability index profiles. The in/out of service states of the bridges are simulated taking into account their correlation structure. Multi-objective Genetic Algorithms have been chosen as numerical tool for the solution of the optimization problem. The design variables of the optimization are the preventive maintenance schedules of all the bridges of the network. The two conflicting objectives are the minimization of the total present maintenance cost and the maximization of the network performance indicator. The final result is the Pareto front of optimal solutions among which the managers should chose, depending on engineering and economical factors. A numerical example illustrates the application of the proposed approach.

1. Introduction

For the economic and cultural development of any nation, the transportation infrastructure plays a role of utmost importance. Moreover, after the occurrence of an extreme event, either natural or man-made, the efficiency of the highway system is critical for a prompt response to the emergency and for the recovery activities. Nevertheless, according to ASCE [1], in the next five years the investment shortfall for civil infrastructure will be $1.176 trillion. In this situation, an optimal allocation of the limited available resources is necessary.

The main actions that can improve the reliability of an existing transportation network are maintenance, monitoring, repair, and replacement. The focus of this paper is the optimal bridge maintenance scheduling at the network level under uncertainty.

In the literature, it is possible to find many studies that deal with the optimal maintenance planning for individual bridges (see the comprehensive review paper [2] and references therein). Some of these studies have been a source of inspiration for the present paper. However, the maintenance management is usually planned by institutions and agencies that are in charge of entire transportation networks or, at least, of several bridges. For this reason, many studies have been focusing on bridge network analysis. For instance, Liu and Frangopol [3,4] developed a procedure for the time-dependent reliability analysis of a bridge network; Shinozuka and his co-workers [5,6] performed a cost–benefit analysis of maintenance in terms of seismic retrofit on transportation networks; Lee et al. [7] proposed a technique for the assessment of the flow capacity of a transportation network after the occurrence of an extreme event. Similar studies have focused on other civil infrastructure lifelines, such as power lines [8–10], and on the interaction between different networks [11–14]. In particular, some papers treat the topic of bridge maintenance optimization at the transportation network level [15–17] and the interest in this topic is strongly increasing lately [18–20].

Under the assumption that accurate profiles of the variation in time (due for instance to corrosion, external stressors, aging, and fatigue) of the individual bridge reliabilities are available, it is possible to assess the effect of the time-dependent reliability of individual bridges on the reliability of the overall network. Unfortunately, this assumption is not realistic in most of the cases. Only the most important bridges of a network are usually thoroughly modeled and sometime monitored, so that their predicted reliability profiles can be considered realistic. For all the other bridges, this information is, in general, unavailable. For this reason, in the present study, the proposed network analysis technique is used together with life-cycle reliability models developed by Frangopol and his co-workers [21–24]. This kind of model, that includes uncertainties, can be assessed knowing some basic characteristics of the individual bridges. Therefore, the reliability profile can be assessed without the need (and the cost) of thorough studies on every bridge. The associated epistemic uncertainty (as well as the intrinsic one) is accounted for by the proposed approach, through simulation.

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Another numerical tool that is part of the framework is the computer program HAZUS-MH MR4 [25]. HAZUS is a free software distributed by the US Federal Emergency Management Agency that is specially meant for loss estimations and therefore is coupled with a very rich Geographic Information System (GIS) that collects data on all the bridges in the US. These data and HAZUS are used to assess the degree of correlation between the states of the bridges in the network by means of a series of seismic fragility analyses [26]. It should be specified that earthquakes scenarios are used solely with the purpose of assessing the correlation [27]. This kind of external load effect has been chosen because it is particularly well addressed by HAZUS, but other extreme events (such as hurricanes) or a combination of different actions could be used. In fact, the assessment of the optimal maintenance scheduling is not based on earthquake actions, but on the generic bridge reliability, as provided by the time-dependent models mentioned previously.

The two pillars of the stochastic model are the time-dependent reliability functions (which provide the marginal distribution of the bridge state) and the HAZUS-based technique [27] that assesses the correlation among the state of different bridges of the same network.

As previously stated, the main goal of the proposed approach is the optimization of the maintenance scheduling under uncertainty. Unfortunately, the main objectives of the optimization, that are the maximization of the network performance and the minimization of the maintenance cost, cannot be computed in closed form, but only numerically. When the closed form expression of the objective function(s) is not available, traditional optimization techniques cannot be employed. In this kind of problem, numerical optimization methods that make use only of discrete values of the objective function(s) and do not require additional information (such as gradients) are required. These optimization procedures are generally known as heuristic methods. Points in the feasible design domain are generated and tested for the satisfaction of objectives through the evaluation of the objective function(s). The most used class of heuristic techniques are Evolutionary Algorithms. They are numerical optimization procedures that find their origin in the Darwinian theory of evolution. Genetic Algorithms [28–30] are a set of specific methodologies that belong to this class. Genetic Algorithms (GAs), or the more general case of Evolutionary Algorithms, have been widely used in many fields of civil engineering, including structural identification [31–34] and maintenance optimization [35,36]. In the present paper, multi-objective GAs [37] are used to find the Pareto front of optimal preventive maintenance schedules at the network level. It should be noted that multi-objective GAs are particularly suitable to this purpose, also because their characteristic to simultaneously evaluate the objective functions at many points of the domain, automatically yields a tentative Pareto front. The decision makers must chose one solution among the various Pareto optimal ones, based on economic and engineering considerations.

Section 2 provides a description of the different types of maintenance interventions that are considered in the proposed framework. Section 3 and its subsections detail the theoretical background and the computational aspects of the procedure. Section 4 presents the numerical application of the technique to a bridge network of 13 bridges, for which maintenance interventions are planned over a period of 75 years. Finally, Section 5 collects the concluding remarks.

2. Preventive, essential and required maintenance

Three different types of maintenance can be considered: (i) preventive, (ii) essential, and (iii) required. Fig. 1 provides a graphical representation of these types of maintenance.

Preventive maintenance (PM), also called "time-based" maintenance, consists of all those interventions that are scheduled *a priori* in order to always keep the bridge at a good service level. Usually, this kind of intervention has the lowest impact on the bridge safety and the lowest cost.

Essential maintenance (EM) is a "performance-based" intervention. This maintenance intervention is applied when an indicator of the bridge performance crosses a predefined threshold. The most used indicator is the bridge reliability index, but several other indicators can be considered. For instance, Okasha and Frangopol [38] investigated also availability and redundancy. The most common case of reliability index threshold crossing is considered henceforth. First of all, a bridge limit state has to be defined, for instance it can be the collapse or just the excessive deformation of the main girders. Event E_1 is defined as the bridge reaches the investigated limit state. For this specific event E_1, it is possible to define the "time to failure" TF_{E_1} as the time between a reference instant $t=0$ and the moment at which E_1 occurs. The reliability at time t is then defined as the probability that E_1 does not occur in the interval $[0,t]$:

$$REL_{E_1}(t) = \mathcal{P}(t < TF_{E_1}) \tag{1}$$

where $\mathcal{P}(\cdot)$ denotes the probability of the event in brackets. There are many available techniques to compute the reliability index. Each of these techniques has advantages and shortcomings (in terms of simplicity and accuracy). A popular way is to assume that the reliability index $\beta_{E_1}(t)$ is obtained from the reliability as follows:

$$\beta_{E_1}(t) = \Phi^{-1}[REL_{E_1}(t)] \tag{2}$$

where Φ^{-1} is the inverse standard Gaussian cumulative distribution function. If a lower threshold $\overline{\beta}$ for the reliability index is fixed, a second event E_2 can be defined as $\beta_{E_1}(t) \le \overline{\beta}$. EM is applied whenever event E_2 occurs.

Required maintenance (RM) is a "failure-based" intervention. For a specific limit state, RM is applied when event E_1 (as previously defined) is imminent, or when it has just occurred. A special case of RM is when event E_1 is assumed to be the collapse of the bridge; in this case, RM is the bridge restoration. However, RM is a more general concept than restoration, since it includes minor interventions if E_1 is a different limit state (e.g. serviceability limit, excessive corrosion, excessive deformation).

Since the occurrence of EM (triggered by event E_2) is based on the definition of the event that yields RM (event E_1), it is evident that the two are strongly interconnected. However, they are not the same. On one hand, E_2 can occur even if E_1 never happened. In fact, the threshold $\overline{\beta}$ is usually high, therefore when $\beta_{E_1}(t)$ downcrosses it, the reliability is still very close to one (i.e. event E_1 is still very unlikely to occur). On the other hand, E_1 can happen at any time, even much earlier than E_2 (e.g. during or just after the bridge construction, since the bridge reliability is never equal to unity, that means that there is always a chance of failure).

When the focus is on an individual bridge, it makes perfect sense to focus on EM (event E_2). In fact, if a single bridge is studied, it means that this bridge is considered important, and that not only the distress caused by the occurrence of event E_1 should be avoided, but even the probability of having a low reliability level.

On the contrary, when an entire transportation network is considered, RM seems more realistic. For most of the bridges, thorough studies on the time-dependent reliability profile $\beta_{E_1}(t)$ could be unavailable. Therefore, if the moment in which $\beta_{E_1}(t)$ downcrosses the threshold $\overline{\beta}$ is unknown, there will certainly be no EM interventions applied at that unknown instant. It appears much more realistic to assume that only RM will be applied when the bridge shows an imminent state of distress or when the distress has just occurred.