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Selective maintenance planning of a steel truss bridge based on the Markovian approach

E. Garavaglia [a], L. Sgambi [b,*]

[a] Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy
[b] Faculty of Architecture, Architectural engineering and Urbanism [LOCI], Université catholique de Louvain, Louvain-la-Neuve, Belgium

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ABSTRACT

Structures of strategic importance, such as bridges, require careful planning in terms of reliability, durability and safety, qualities which must be guaranteed throughout the entire life cycle of the structure. However, due to the ageing of materials and to aggressive environmental actions which cause deterioration, the response of these structures, just like others, changes over time, resulting in a loss of performance. Yet it is important to maintain a satisfactory level of performance in a bridge throughout its service. To ensure such a performance it is important to apply properly planned maintenance strategies. Appropriate maintenance strategies require knowledge of the process of deterioration and the consequent damages to be expected in order to schedule proper maintenance procedures. It would be fundamental to define a selective maintenance plan which may involve only some parts of the structure, thus allowing bridge viability even during the maintenance activity.

This paper proposes the study of strategies of selective maintenance for a steel bridge immersed in an aggressive environment, starting from the simulation of each individual member. Simulation of deterioration is obtained through the application of an appropriate damage law implemented with a Monte Carlo methodology, while the time prediction of occurrence of the deterioration is obtained through the application of a Markovian probabilistic approach. The results of the Markovian approach were the starting point for choosing strategies of selective maintenance, as the Markov process allowed the identification, in probabilistic terms, of the structure members with the highest risk of collapse and the timing for achieving levels of damage related to the possible collapse of compromised members. This timing was used to identify possible intervals of maintenance. Proposed scenarios are compared with each other both in terms of associated risk, and in terms of life-cycle cost effectiveness.

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1. Introduction

In the last few decades scientific research has pointed out how it is important, when designing a structural system, to guarantee compliance of the performance requirements during the entire life cycle of the structure. This change of thought has led to the consideration, during planning, of factors of uncertainty such as the increase in demand for performance, the presence of aggressive environmental factors, and the inevitable human errors, which, over time, may compromise the safety of the entire structural system [2,14,45]. Recent studies have addressed the issue of uncertainty in structural planning, paying adequate attention to problems of reliability [52,53,6], robustness [29,43], safety [38,3] and developing study approaches based on statistical and probabilistic methods that consider the random aspects present in the potential causes of risk for the structure [5,8,4,44].

Among the major causes of risk for structures such as bridges, designed to be immersed in the environment while showing their entire structural system, is certainly damaged due to aggressive environmental factors [48,49,37]. In fact, it is well known that during its life cycle, the characteristics of a structure are modified due to ageing; such changes are often accelerated by aggressive environmental actions which, causing a rapid deterioration of structural elements, lead to the inevitable and progressive loss of performance capabilities of the entire system [16,15,39,47]. Such actions occur with a force and in a time period which cannot be predicted, therefore they become difficult to model. On this topic, the scientific community is facing the development of not only probabilistic-type, but also semi-probabilistic, combinatorial or fuzzy-type intervention methods, making it possible to take due account of the uncertainties which afflict the occurrence of aggres-

* Corresponding author.
E-mail addresses: elsa.garavaglia@polimi.it (E. Garavaglia), luca.sgambi@polimi.it (L. Sgambi).

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sive environmental phenomena and the resulting uncertainties in structural response [36,28,33].

In strategic structures such as bridges, it is clear how important it is to maintain a satisfactory level of performance throughout their service life. To ensure this performance, it is essential to apply properly planned maintenance strategies.

Appropriate maintenance strategies require knowledge of the process of deterioration over time and the consequent damages to be expected in order to schedule proper maintenance procedures. In the literature, different authors have tackled the problem by developing probabilistic-type methods [13,21,50,20] also associated with appropriate cost-benefit analyses [32,19].

Clearly, major maintenance interventions on bridges involve considerable discomforts and disruptions to large areas of the territory. Certainly selective maintenance interventions, which may involve only some parts of the structure, would be more adequate, thus allowing bridge viability even during maintenance. In the literature, the most common approach to the issue of selective maintenance is the use of Monte Carlo simulations which imply a remarkable computational expenditure [35,24,40].

The scenario just described is one of the new frontiers in scientific research of interest for civil engineering and it is within this context that this work fits. Indeed, this work studies strategies of selective maintenance for an existing steel bridge immersed in an aggressive industrial environment. The starting point is simulation of the damage which each member of the bridge may suffer, over its useful life, due to aggressive environmental attacks and changes in performance demand.

The choice to proceed with the adoption of a rather flexible damage law, and the simulation of damage to structural members over time is necessary. Structures are rarely monitored frequently, even though monitoring would be capable of providing sufficient experimental data to ensure a reliable statistical interpretation of the temporal evolution of deterioration.

Deterioration is simulated through the application of a time-dependent damage law whose parameters, assumed as random variables and associated with proper functions of probability, can grasp all uncertainties inherent to phenomena of environmental aggressiveness and the possible variations in performance demand required by the structural system. The damage law is implemented with a methodology of Monte Carlo simulation, which generates different and possible laws of damage to be applied to the structure. Once certain levels of damage are established and which are significant for the structure under consideration, the structural analysis, performed for each damage law generated, gives back, at any given time, the level of damage reached by each member and the time to reach and overcome same damage. In this way the process of deterioration is interpreted as a process of transition through different performance stages, characterised by different significant levels of damage.

The time prediction of transition from a state of damage and the next one is obtained through the application of a Markovian-type probabilistic approach [18]. Indeed, starting from the current performance condition, the Markovian approach is able to assess the possible evolution of the damage to the structural system, and evaluate the transition probability for the system throughout different performance states.

The results of the Markovian approach, applied to the large sample size of transition times obtained from the Monte Carlo simulation, are the starting point for choosing strategies of selective maintenance.

As already mentioned, a thorough maintenance plan can definitely guarantee protection of the features of structure reliability. However, every maintenance intervention involves a cost in terms of intervention on the structure, the use of handling means and discomfort for the partial or total unavailability of the structure during the maintenance operations. The situation becomes particularly delicate for bridges, since their total or partial closure would result in remarkable inconveniences for the traffic flow the entire area. For all these reasons, it would be important to define a selective maintenance plan which may involve only some parts of the structure, thus reducing the inconveniences and guaranteeing, at the same time, the appropriate reactivation of the reliability features of the bridge itself.

Whenever selective maintenance is carried out, each member involved in the maintenance renews its own performance capabilities, which leads to an increase in its service-life and in the service-life of the whole structural system.

In this work, appropriate scenarios of selective maintenance have been studied which involve only members with a high probability of failure. Each maintenance operation is intended as an action which renews the performance of the concerned member. It is an action that can be repeated at more or less regular intervals, which depend on how structural member deterioration progresses after every maintenance operation. The process as intended is a renewal process which can adequately be modelled as a Markovian Renewal Process (MRP).

The processes of Markov renewals are suitable for modelling repetitive phenomena which renew their features after every event. For example, MRP processes are used when modelling the waiting times of strong earthquakes, in fact, this process is considered a renewal process: during a violent earthquake there is a total release of energy but such energy is recharged again during the entire period of suspension, renewing itself, to be then released in the next event [1,27,41,46,51]. Recently MRP processes have been applied in predicting the return periods of hurricanes and tornadoes, obtaining good results [42].

The MRP is able to predict, with different levels of probability, the transition from the current state of the system, i.e. at the time t_0, in a previous or next state. One special form of such processes, called semi-Markovian processes, predicts the next transition taking into account the time already spent by the system in its current state, in other words: the time interval between the previous transition and the current instant t_0 [27,41,51]. The application of this type of process allows the probabilistic prediction of the future state, and its likely time of achievement, starting from the actual instant of investigation. The Markov approach proposed in this paper refers to a renewal semi-Markov process.

The transition times modelled in the MRP are those obtained from the application of Monte Carlo simulation. Members involved in any action for selective maintenance are suggested by the structural analysis performed for every damage law generated during the Monte Carlo simulation.

The approach proposed in this paper combines two methodologies that are well known in the literature but hardly used contemporaneously in the solution of a problem: the Monte Carlo simulation and the Markov approach at the time when the occurrence of the damage is predicted. In this case, the authors demonstrate how the synergistic use of the two approaches could lead to the definition of satisfactory maintenance strategies, reducing the computation time. In fact, in the proposed methodology, the Monte Carlo simulation is applied only once, unlike other approaches where a new simulation is required after each maintenance action [11].

To show the possible application proposed, different maintenance scenarios have been studied:

- three scenarios of non-selective maintenance which involve the whole structure (scenarios 1, 2, 3) with different maintenance times;
- two scenarios of selective maintenance which keep the structure:

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