PREDICTING AND OPTIMIZING LIFETIME PERFORMANCE OF EXISTING STEEL BRIDGES UNDER PREVENTIVE AND ESSENTIAL MAINTENANCE ACTIONS

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ABSTRACT
In this paper, the lifetime performance of existing steel bridges under preventive and essential maintenance actions is analyzed. Performance is measured by the reliability index (resulting from structural analysis) and the condition index (resulting from visual inspections). The analysis of performance using these two indicators allows the incorporation of the results of visual inspections in the assessment of the safety of a structure, resulting in a more accurate prediction of the need to perform maintenance. Due to the uncertainty in the deterioration process and time of application and effect of maintenance actions, a probabilistic framework is used. The reduction in structural performance due to corrosion of the steel profiles is simulated using an extension of the model proposed in 1998 by Frangopol [1], considering all parameters defining the condition and reliability profiles as random variables. The effect of maintenance actions on the condition and reliability profiles is defined in terms of the improvement in performance and the reduction or suppression of deterioration for a period of time after application of maintenance. Monte-Carlo simulation is used to compute the probabilistic properties of the condition, reliability, and life-cycle cost profiles associated with each maintenance strategy. The model described is applied to steel bridges located in Colorado. The results show the importance, in terms of life-cycle cost, of considering both preventive and essential maintenance in a rational lifetime maintenance strategy.

Keywords: Deterioration, Existing Structures, Genetic Algorithms, Maintenance, Management, Optimization, Preventive Maintenance.

1 INTRODUCTION
Due to increasing deterioration of existing bridges, a need for systematically addressing the prioritization of maintenance actions on existing civil infrastructure arose during the late 1960s and the 1970s. This was first addressed by Departments of Transportation in the United States, resulting in implementation of a set of computer-based management systems.

Bridge management systems currently in use, including PONTIS [2] and BRIDGIT [3], use the condition states of bridge elements as measure of performance. The number of condition
states is limited (e.g., five) for each bridge element. The condition state describes the type and severity of element deterioration in visual terms. Both PONTIS and BRIDGIT assume that the condition states incorporate all the information necessary to predict future deterioration and a Markovian deterioration model is used to predict the future deterioration of the structure, in terms of the annual probability of transition among condition states [2,3]. As indicated in [4], the Markovian approach used in currently available bridge management systems has several important limitations, such as: (a) severity of deterioration is described in visual terms only; (b) condition deterioration is assumed to be a single step function; (c) transition rates among condition states of a bridge element are not time dependent; and (d) bridge system condition deterioration is not explicitly considered.

Experience gained in more recent past showed that most maintenance and reinforcing work on existing structures is dependent on the load carrying capacity (or structural reliability) of the bridge system rather than the condition states of the bridge elements alone [4]. Condition states alone are not an accurate measure of the need for maintenance as structural defects that are not visible and/or not discovered by visual inspections can be extremely detrimental to the structural safety. Consequently, bridge management systems have to also consider the load carrying capacity (or structural reliability) deterioration.

In this paper, recent progress in probabilistic maintenance and optimization strategies for deteriorating structures with emphasis on bridges is summarized. A novel model including interaction between structural safety analysis, through the reliability index, and visual inspections and non destructive tests, through the condition index, is presented. Multi-objective optimization is used to simultaneously consider several performance indicators such as reliability, condition, and cumulative cost. Realistic examples of the application of some of these techniques and strategies are also presented.

2 CONDITION-RELIABILITY-COST INTERACTION

As previously indicated, a model incorporating condition, reliability, and cost is herein proposed for the analysis of deteriorating structures under maintenance.

The model used for describing the condition and reliability profiles is based on that proposed by Frangopol [1] and Frangopol et al. [5]. The structure performance under no maintenance is defined by two bi-linear functions. The condition and reliability are considered constant until the times of initiation of deterioration of the condition and reliability indices are reached. After this instant, the deterioration rates of condition index and reliability index are considered constant.

A maintenance action is defined as causing one, several, or all of the following effects [6]: (a) increase in the condition index and/or reliability index immediately after application; (b) suppression of the deterioration in condition index and/or reliability index during a time interval after application; and (c) reduction of the deterioration rate of condition index and/or reliability index during a time interval after application. The random variables defining these effects are: (a) increase in condition and reliability index immediately after application, $\gamma_c$ and $\gamma_r$, respectively; (b) time interval during which the deterioration process of condition and reliability is eliminated, $t_{dc}$ and $t_{dr}$, respectively; (c) time during which the deterioration rate in condition and reliability is eliminated or reduced, $t_{pdc}$ and $t_{pdr}$, respectively; and (d) deterioration rate reduction of condition and reliability, $\delta_c$ and $\delta_r$, respectively.

The model allows for probabilistic and deterministic relations between the condition index and reliability index profiles to be included in the data. The first way to include this relation is by considering the random variables describing condition index and reliability index as correlated. The second way of including relations between condition and reliability is by defining
deterministic relations between profiles. For example, one can state that the time of initiation of deterioration of reliability is equal to the time for the condition index to reach the level corresponding to onset of corrosion.

![Condition Index vs Time](a)

![Reliability Index vs Time](b)

**Fig. 1:** Performance profiles under no maintenance and under maintenance: (a) condition index, and (b) reliability index.

Maintenance actions can be classified, according to their times of application, as preventive and essential actions. Preventive actions are those applied on structures for which an undesirable state has neither occurred nor is eminent. These actions can be scheduled a priori and, consequently, their times of application are independent of the performance of the structure. On the other hand, essential maintenance actions are applied when the structure reaches, or is close to, an undesirable state, namely an advanced deterioration of condition or a very low reliability level. Therefore, the time of application of such maintenance actions is dependent on the structural performance and can not be predicted a priori.

In the proposed model the time of application of preventive maintenance actions is defined by two random variables: time of first application, $t_{f1}$, and time interval between subsequent applications, $t_p$ (Figure 1). The time of application of essential maintenance actions is defined implicitly by thresholds in terms of condition and/or reliability. These thresholds can be either deterministic or probabilistic.

### 3 COMPUTATION OF PROFILES

The parameters defining the condition, reliability, and cost profiles are taken as random variables. To compute the probabilistic properties of the profiles, simulation coupled with Latin Hypercube is used. The use of simulation requires that an effort must be made to reduce the computational time necessary to obtain each realization of the profiles. In order to achieve this goal, keeping the model as versatile as possible, superposition of different profiles calculated at one year intervals was employed.

The use of superposition can be defined as the assumption that the condition and reliability profiles result from adding the profiles associated with the structure under no maintenance to those of the several maintenance actions applied during the lifetime. This technique is extremely efficient and allows the use of a wide range of different profiles under no maintenance or profiles defining the effect of each maintenance action. However, if more than one maintenance action is active at any point in time, the superposition method might result in erroneous results, associated with negative deterioration rates. To avoid these results, the deterioration rates are computed at each one year interval and corrected if necessary.
Considering the profiles defined at one year interval reduces significantly the amount of computation as well as the necessary computation resources. However, as random variables can be continuous, a weighted average of the deterioration rate during each one year interval must be computed and used to calculate the performance profiles.

This model was implemented in a Windows platform under a software package named Condition and Reliability Analysis under Maintenance (CRAM). In a very general flowchart describing the implementation of CRAM is shown.

![Flowchart](image)

**Fig. 2:** General flowchart of simulation process of condition, reliability, and cost probabilistic indicators.

4 **GENETIC ALGORITHMS**

Genetic algorithms (GAs) loosely emulate the evolution of species according to Darwin theory, simulating the optimization process as a sequence of generations where each new generation is produced based on the properties of the fittest individuals of the previous generation. The use of multi-objective genetic algorithms allows, in a simple manner, the computation of a large number of Pareto-optimal solutions, particularly in problems involving discontinuous objective functions and/or constraints and/or frequent local optimal solutions. GAs do not require the computation of gradients, making them particularly well suited for problems where numerical gradients are imprecise. The main disadvantage of the approach based on GAs is the number of times the objectives and constraints must be computed. In this paper, GA algorithms are used to optimize the time of application of maintenance actions that lead to better condition and reliability, and lower cumulative cost.

5 **EXAMPLES OF APPLICATION**

An existing bridge located in Colorado is presented herein as a case study example using the probabilistic approach described above. Bridge E-17-LE is located over Interstate Highway 25, on 88th Street, between US Highway 36 and State Highway 128. The bridge has two continuous spans with lengths of 110ft and 115ft and a total length of 225ft. The deck consists of a 6.5in layer of reinforced concrete and a 2in surface layer of asphalt. The total width of the
bridge is 64.5ft. The slab is supported by eleven steel welded composite plate girders. A comprehensive description of this bridge can be found in [7].

The time dependent reliability profiles of this bridge under no performance were developed by Akgül and Frangopol [8]. Petcherdchoo et al. [9] proposed a set of maintenance actions for the girders. The profiles under no maintenance and the effect, time of application, and cost of application of maintenance actions were defined in a probabilistic framework. The condition index is defined according to the recommendation of the Colorado Department of Transportation [10]. Five condition states are defined as indicated in Table 1 [10].

<table>
<thead>
<tr>
<th>Condition Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>There is no evidence of active corrosion and the paint system is sound and functioning as intended to protect the metal surface.</td>
</tr>
<tr>
<td>2</td>
<td>There is little or no active corrosion. Surface or freckled rust has formed or is forming. The paint system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.</td>
</tr>
<tr>
<td>3</td>
<td>Surface or freckled rust is prevalent. The paint system is no longer effective. There may be exposed metal but there is no active corrosion which is causing loss of section.</td>
</tr>
<tr>
<td>4</td>
<td>The paint system has failed. Surface pitting may be present but any section loss due to active corrosion does not yet warrant structural analysis of either the element or the bridge.</td>
</tr>
<tr>
<td>5</td>
<td>Corrosion has caused section loss and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.</td>
</tr>
</tbody>
</table>

The condition and reliability index profiles of the girders under no maintenance are defined in Table 2, where the unit of the deterioration rates is year$^{-1}$.

<table>
<thead>
<tr>
<th>Random Variable</th>
<th>Distribution Type</th>
<th>Min. Value</th>
<th>Mode</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_i$</td>
<td>Triangular</td>
<td>2.18</td>
<td>2.90</td>
<td>3.62</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Triangular</td>
<td>0.0037</td>
<td>0.005</td>
<td>0.0063</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>Triangular</td>
<td>0.056</td>
<td>0.075</td>
<td>0.094</td>
</tr>
</tbody>
</table>

The initial condition is deterministic and equal to 1.0. The maintenance actions considered for the girder were minor painting (MP) and girder repair (GR). Minor painting is a preventive maintenance action applied at regular interval, independently of the performance of the structure at time of application. Girder repair is an essential maintenance action applied when the condition index reaches $C = 4.0$. The effects, times of application and cost of application of these two maintenance actions are shown in Tables 3 and 4. These tables show that the preventive maintenance actions have a much lower impact on condition and reliability indices than the essential maintenance actions, but also a much lower cost.

<table>
<thead>
<tr>
<th>Maintenance Action</th>
<th>Time of First Application</th>
<th>Time of Subsequent Application</th>
<th>Condition Improvement</th>
<th>Deterioration Rate During Effect</th>
<th>Duration of Maintenance Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Painting</td>
<td>T(0;7.5;15)</td>
<td>T(10;12.5,15)</td>
<td>$\chi$</td>
<td>$\theta = \alpha - \delta \text{ (year}^{-1})$</td>
<td>T(10;12.5,15)</td>
</tr>
<tr>
<td>Girder Repair</td>
<td>when $C = 4.0$</td>
<td>when $C = 4.0$</td>
<td>T(2.5;2.75;3.0)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

T(a,b,c) represents a triangular density distribution with minimum = a, mode = b, and maximum = c
Table 4: Effects of maintenance actions on the reliability index and cost of application

<table>
<thead>
<tr>
<th>Maintenance Action</th>
<th>Reliability Improvement</th>
<th>Deterioration Rate During Effect</th>
<th>Duration of Maintenance Effect</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Painting</td>
<td>γ</td>
<td>θ = α − δ(year⁻¹)</td>
<td>t_{pd}(years)</td>
<td>T(15;30;45)</td>
</tr>
<tr>
<td>Girder Repair</td>
<td>T(0.125; 0.25; 0.375)</td>
<td>-</td>
<td>-</td>
<td>T(750;1500;2250)</td>
</tr>
</tbody>
</table>

T(a,b,c) represents a triangular density distribution with minimum = a, mode = b, and maximum = c.

These tables also show that the preventive maintenance actions has a much lower impact on condition and reliability indices than the essential maintenance actions, but also a much lower cost.

The mean and standard deviation of the condition and reliability indices considering no maintenance, each of the two maintenance actions defined, and both maintenance actions applied during the time horizon considered (i.e., 50 years), was computed using the model proposed. The results obtained, considering a discount rate of money v = 6%, are shown in Figure 3.

Fig. 3: Mean and standard deviation of condition and reliability indices and mean cumulative cost; No Maintenance, Minor Painting (MP), Girder Repair (GR), and Minor Painting + Girder Repair (MP+GR).
These results show that preventive maintenance alone (minor painting) although resulting in the lowest mean cumulative cost, has a small impact on the mean condition and reliability indices. The combination of preventive with essential maintenance actions (girder repair) leads to a more significant improvement in performance and a lower mean cumulative cost than essential maintenance alone.

GA were used to optimize the time of application of minor painting and the condition threshold at which girder repair is applied. The optimization problem can be defined as:

**Goal:**
Find the mean time of first application and mean time interval between subsequent applications of minor painting and the condition index threshold at which girder repair is applied

**Such that:**
- Maximum (i.e., worst) mean condition index during entire lifetime is minimized;
- Lowest (i.e., worst) mean reliability index during entire lifetime is maximized;
- Present value of mean cumulative maintenance cost at time horizon is minimized.

**Subject to:**
- Maximum (i.e., worst) mean condition index during entire lifetime \( \leq 4.0 \); and
- Lowest (i.e., worst) mean reliability index during entire lifetime \( \geq 3.0 \).

Genetic algorithms using a population of 100 elements and considering 50 generations were employed. In Fig. 4 the worst mean condition during the entire time horizon and mean cumulative cost at time horizon are compared for the optimal and non-optimal solutions obtained.

![Graph showing mean cumulative cost at time horizon vs. worst mean condition index associated with Pareto and non-optimal solutions under minor painting + girder repair.](image)

**Fig. 4:** Mean cumulative cost at time horizon vs. worst mean condition index associated with Pareto and non-optimal solutions under minor painting + girder repair.

The results in Fig. 4 show a fast convergence of the GA to the optimal objective function. A non-linear relation between the worst mean condition index and the present value of mean cumulative cost exists. This results from a smaller impact of maintenance actions if the interval between applications is severely reduced. In fact, if one maintenance action is applied before the end of effect of the previous one, there is no further reduction in deterioration resulting in a smaller effect on performance of each action, without reduction in cost.

**CONCLUSIONS**

In this paper, recent progress in probabilistic maintenance and optimization strategies for deteriorating civil infrastructures with emphasis on bridges is summarized. A novel model that includes structural reliability analysis, through the reliability index, and visual inspections and
non destructive tests, through the condition index, is presented. The results obtained show the differences between the two indicators, highlighting the need for the use of both in order to obtain a more accurate characterization of future deterioration of existing civil infrastructures. Multi-objective optimization is used to simultaneously consider several performance indicators such as reliability, condition, and cumulative cost. Realistic examples of the application of some of these techniques and strategies are also presented, showing the crucial role of preventive maintenance actions in reducing the overall maintenance costs, and the need for essential maintenance actions in keeping structures safe and serviceable, during their entire service life.

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