Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost

Editors

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Multi-objective probabilistic optimization of bridge lifetime maintenance: Novel approach

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ABSTRACT: Due to the increase in deterioration of the existing civil infrastructure, in particular bridge networks, governments and highway agencies are trying to find methods that allow a consistent and rational management of existing bridges. In this paper, a novel approach is presented. This approach uses multi-objective probabilistic optimization over time and defines performance of existing bridges in terms of lifetime condition, safety, and cost. The proposed approach aims at providing a tool for optimal maintenance management policy definition of a large group of similar structures. Consequently, emphasis is put on the use of limited information and low computational cost. Applications to real cases are presented showing the applicability of the method as well as its advantages in terms of reduction of costs and improvements in performance.

1 INTRODUCTION

The cost of repairing, retrofitting, or replacing an existing bridge or bridge network is usually very high. In many cases this cost is significantly larger than the initial construction cost, as a consequence of an increase in user cost. This justifies the use of very detailed analysis of each deteriorated structure, in order to evaluate the need to perform maintenance.

However, the cost of performing this analysis for each existing structure would be too high for most highway agencies or governments. In particular, for structures presenting little or no deterioration this detailed analysis would represent a waste of funds. Moreover, this type of analysis can be used with confidence to predict current performance, but looses accuracy if used to forecast future performance. In most cases, a less detailed analysis is sufficient to predict future performance of a large group of similar structures. The tool used in this paper can provide an assessment of an entire group of similar structures, but will not be able to accurately predict the performance of a specific structure. Using such a tool will help the decision maker in better defining long term maintenance management policies of an entire bridge stock. Furthermore, it will allow a rational use of detailed analysis for deteriorating structures where maintenance might be required.

Such methods for a long term analysis of large groups of structures have been developed in most modern bridge management systems. The main aim of such a system is to provide, using relatively low cost, an accurate prediction of future structural performance.

2 EXISTING METHODOLOGIES

Most existing bridge management systems (BMS) use the condition index as an indicator of the need to apply maintenance or to perform a more detailed analysis. The condition index, obtained using only the result of visual inspections, is a fundamental indicator of the deterioration of a bridge. However, this performance indicator can not be considered an indicator of the safety of the structure. In fact it disregards the effect of deterioration not visible to the inspector, the initial safety of the structure, and the overall behavior of the structure as a redundant or weakest-link system. It is, therefore, an insufficient indicator in the management of existing structures.

Several authors (Thoft-Christensen 1998, Frangopol 1998) proposed simplified safety analysis tools for large groups of bridges. In these methods, a relatively simple time dependent safety function is used, considering no maintenance (Thoft-Christensen 1998) or the effects of preventive and essential maintenance actions (Frangopol et al. 2001).

These methods allow the definition of life-cycle maintenance management policies for existing structures using a more consistent measure of the need to perform maintenance.

Furthermore, the models proposed in Frangopol et al. (2001) and van Noortwijk and Frangopol (2004) allow the inclusion of the effects of maintenance actions in a consistent and realistic manner. This is a significant improvement over existing BMS which, by using Markovian chains, have a limited ability to consider all effects of maintenance actions.

The methods based only on the safety or reliability index are limited in terms of the use of large databases collected, over the years, in most developed countries. Furthermore, the updating of the safety or reliability index, based only on routine visual inspections is difficult.

For these reasons, the authors use in this paper a model in which the time dependent safety index is complemented by a time dependent condition index.

3 CONDITION-SAFETY-COST INTERACTION

Each maintenance action can have effects on both condition and safety. These effects can be considered as independent, dependent, or correlated. Each maintenance action is assumed to cause one, several, or all of the following effects: (a) increase in the condition index and/or safety index immediately after application; (b) suppression of the deterioration in condition index and/or safety index during a time interval after application; and (c) reduction of the deterioration rate of condition index and/or safety index during a time interval after application (Frangopol et al. 2001).

The cost of each maintenance action is also defined as independent or dependent of the effect of the action (Neves et al. 2004, Kong and Frangopol 2004).

All the parameters associated with profiles under no maintenance, effects of maintenance actions, and cost, are defined as probabilistic correlated or independent random variables. This results in time dependent probabilistic condition, safety, and cumulative cost profiles (Frangopol and Neves 2004, Neves and Frangopol 2005).

Two types of maintenance actions are considered: preventive actions and essential actions. Preventive maintenance actions are applied at probabilistic defined intervals. Essential maintenance actions are applied when a deterministic or probabilistic condition index and/or safety index threshold is reached.

4 OPTIMIZATION

To decide if a structure must undergo extended repair or replacement, a detailed structural assessment must be performed. This assessment should include non-destructive testing, assessment of traffic and loads, and comparison of different maintenance actions, among others. Recent experience has shown that applying maintenance only if deterioration has endangered the safety of the structure, usually results in large life-cycle cost. Preventive maintenance can help in reducing costs significantly. However, a detailed analysis can not be performed in advance for all structures, due to large costs and uncertainties in the deterioration process.

For this reason, the definition of optimal maintenance policies must be made using the limited information available at present. This makes the use of simplified models, like the one used in this paper, particularly suitable, if coupled with optimization. In this paper, multi-objective optimization is used so that the decision maker can have a set of optimal solutions from which the best balance between cost and performance can be selected for a specific situation.

5 NUMERICAL IMPLEMENTATION

The proposed model was implemented in a computational platform developed in the University of Colorado. The platform has three major modules. In the first module, deterministic condition, safety, and cost profiles are computed. The second module is a simulation procedure based on Latin hypercube sampling. Each sample is computed calling the first module. The third module is the optimization procedure. It is based on Genetic Algorithms (GA) and each individual is calculated by calling the second module.

The computation of the deterministic profiles is performed considering that the effects of maintenance actions can be superposed (Frangopol et al. 2001).

The simulation module using Latin hypercube (McKay et al. 1979) is based on the probabilistic indicators of the performance under no maintenance, as well as, the effects, times of application, and costs of maintenance actions. This yields the probabilistic performance indicators, in terms of means, standard deviations, percentiles, and probability density functions.

The optimization module is based on a genetic algorithm proposed by Deb and Goel (2001). The use of genetic algorithms is appropriate in this situation since simulation is used to compute the profiles. When simulation is used, small numerical errors are unavoidable, and consequently, the use of finite differences combined with gradient-based optimization methods is usually difficult.

However, Genetic algorithms (GA) are slow, since a large set of solutions must be generated before convergence is reached. In the framework of multi-objective, this disadvantage is reduced, since a genetic algorithm produces, in each generation, a set of solutions, resulting in a convergence to a set of optimal solutions in a Pareto sense.

When GA are used in multi-objective, a tool defining the fitness of the individual must be used. This can be performed using dominance procedures (Deb and Goel 2001). In these procedures, a solution is found dominated, and consequently worse, if it is worse than any other, in all objectives. From the non-dominated solutions, those that better represent the feasible space are selected for the next generation. If not enough non-dominated solutions are found, a new wave of non-dominated solutions is found. The numerical implementation of this procedure is explained in detail in Neves et al. (2006a).

6 APPLICATIONS

The proposed method was applied to the analysis of a group of bridge structural elements in the United Kingdom. The deterioration of the safety and condition of these elements was evaluated based on engineering judgment (Denton 2002). Several maintenance actions were proposed, based on past experience. The condition index, *C*, is defined according to the results of visual inspections, as follows (Denton 2002): 0 – No chloride contamination; 1 – Onset of corrosion; 2 – Onset of cracking; 3 – Loose concrete/significant delamination.

The safety of bridge elements can be measured in terms of the safety index, *S*, which is defined as the load-carrying capacity factor (according to bridge code provisions in the United Kingdom this factor must be at least 0.91).

Considering the nature of the actions used, a classification in terms of their effects, times of application, and cost was defined.

Maintenance actions applied at regular time intervals, associated with low impact on the performance of the structure at time of application, and low cost, were defined as preventive maintenance actions. This group includes the application of silane and the replacement of expansion joints. The second group includes action applied when a performance threshold is reached, such as concrete repair or replacement of the element. These actions, defined as essential, are associated with a large impact at time of application, as well as very high cost. The maintenance actions used in this work, as well as their effects on performance and cost, are presented in Tables 1 and 2.

Table 1. Cost of maintenance actions and effects on the condition index (after Denton 2002)

Maintenance Strategy	Effect on Condition Index				
	Improvement	Delay in Deterioration (years)	Deterioration Rate During Effect (year^{-1})	Duration of Mainteance Effect (years)	Cost (k£)
(1)	(2)	(3)	(4)	(5)	(6)
Minor Concrete Repair	to 0	0	α_c	0	16
	0.5				3605
	1.0				14437
Silane	0	0	0	7.5	0.3
			0.01	10	39
			0.03	12.5	77

Note: Triangular density distributions for the random variables are characterized by three values: minimum, mode, and maximum.

Table 2. Times of application of maintenance actions and effects on the safety index (after Denton 2002)

Maintenance Strategy	Time of Application of First Maintenance (years)	Time Interval Between Subsequent Applications (years)	Effect on Safety Index			
			Improvement	Delay in Deterioration (years)	Deterioration Rate During Effect (year^{-1})	Duration of Mainteance Effect (years)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Minor Concrete Repair	when $C = 3$	when $C = 3$	0	while $C < 1$	α	T_d
Silane	0	10	0	0	0	7.5
	7.5	12.5			0.007	10
	15	15			0.018	12.5

Note: Triangular density distributions for the random variables are characterized by three values: minimum, mode, and maximum.

The analysis of these maintenance actions, considering the times of application defined by Denton (2002), results in the time dependent condition, safety and cost profiles shown in Figure 1, where minor concrete repair is denoted as MCR, and the discount rate for money is considered $\nu = 6\%$.

The results show that minor concrete repair results in a much higher lifetime cost than silane. However, minor concrete repair also results in a better condition index profile during the entire life, and similar safety index.

If both maintenance actions are combined, there is a significant reduction in costs, due to more infrequent application of essential maintenance. The combined strategy is also associated with condition and safety profiles close to those obtained with minor concrete repair alone.

For this reason optimization was used to select the best times of application of both silane and minor concrete repair. For silane, the optimization variables considered were the mean time of first application and the mean time interval between applications of maintenance actions. As defined previously, minor concrete repair is applied when the condition index reached a certain threshold. For this reason, this condition threshold is defined as an optimization variable.

The multi-objective probabilistic optimization formulation is defined as:

- Minimize present value of mean cumulative maintenance cost at time horizon;
- Minimize maximum mean condition index during time horizon;
- Maximize minimum mean safety index during time horizon.

Subject to the following constraints:

- Maximum mean condition index $C_{\max} \leq 3.0$; and
- Minimum mean safety index $S_{\min} \geq 0.91$.

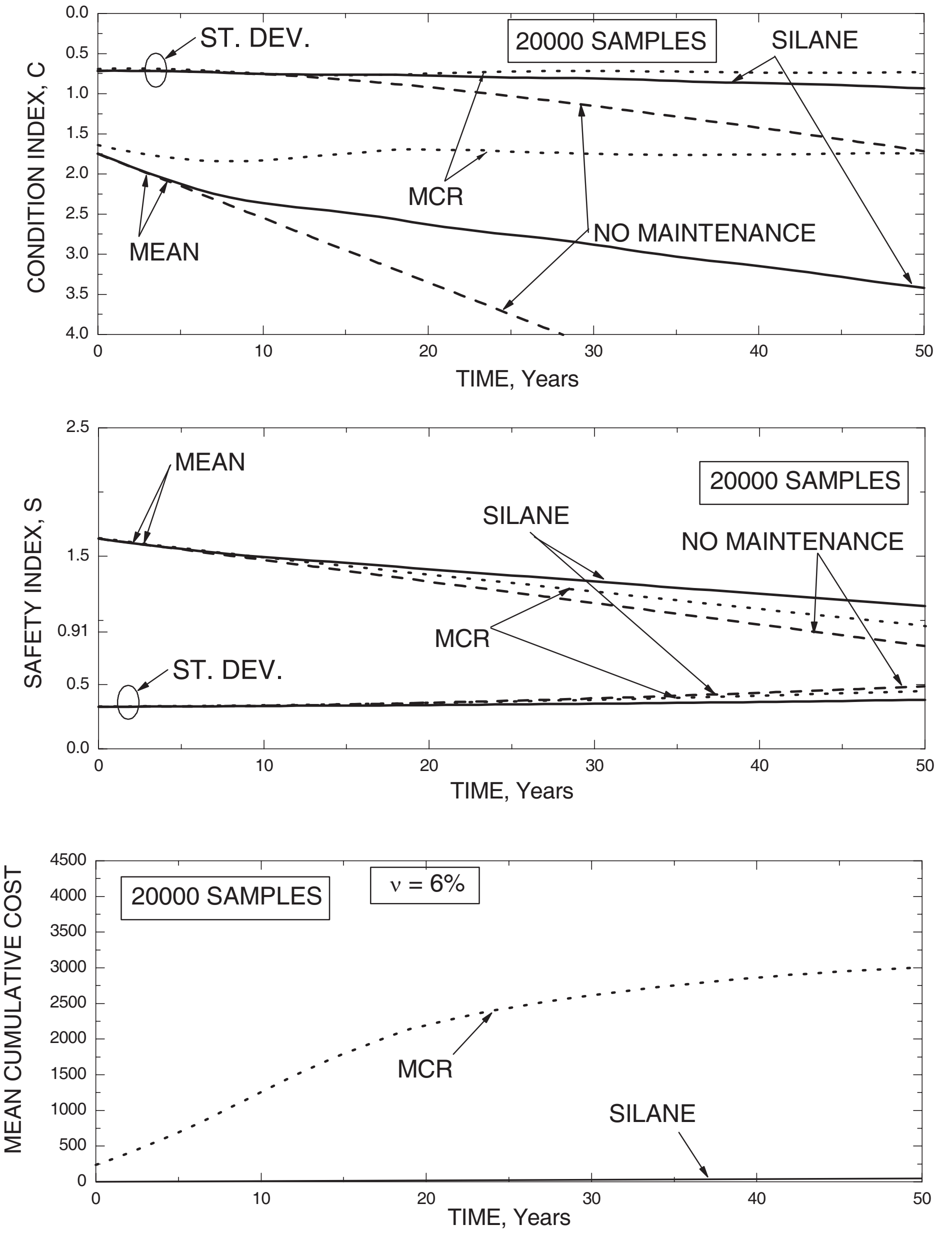

Figure 1. Condition index, safety index, and cumulative cost profile considering the application of silane and minor concrete repair

In Figure 2 the optimal (Pareto) and non-optimal (dominated) solutions obtained considering the application of silane and minor concrete repair are indicated. The results show that the optimization procedure allows a significant reduction in cost, for the same condition and safety index. This highlights the need for a consistent definition of maintenance policies.

The optimal Pareto solutions obtained considering minor concrete repair alone and a combination of minor concrete repair and silane are presented in Figure 3.

These results show the significant impact of combining a essential maintenance action (minor concrete repair) and a preventive action (silane). In fact, the use of silane causes a significant reduction in the present value of cumulative cost for the same performance level.

If the optimal times of application of both maintenance actions are compared (see Figure 4) it is clear that optimal solutions are associated with frequent application of silane. This is a result of the lower cost of silane compared to minor concrete repair. Applying silane causes a delay in the application of minor concrete repair, resulting in a lower lifetime cost. On the other hand, Figure 5 shows that performance is, for all optimal solutions, a function of the threshold at which minor concrete repair is applied.

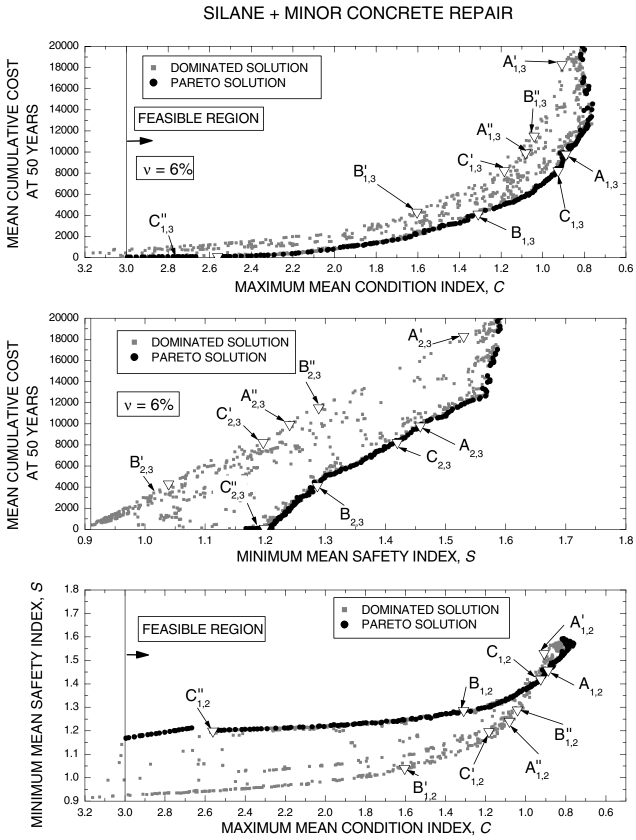

Figure 2. Pareto and dominated solutions associated with optimization considering minor concrete repair and silane

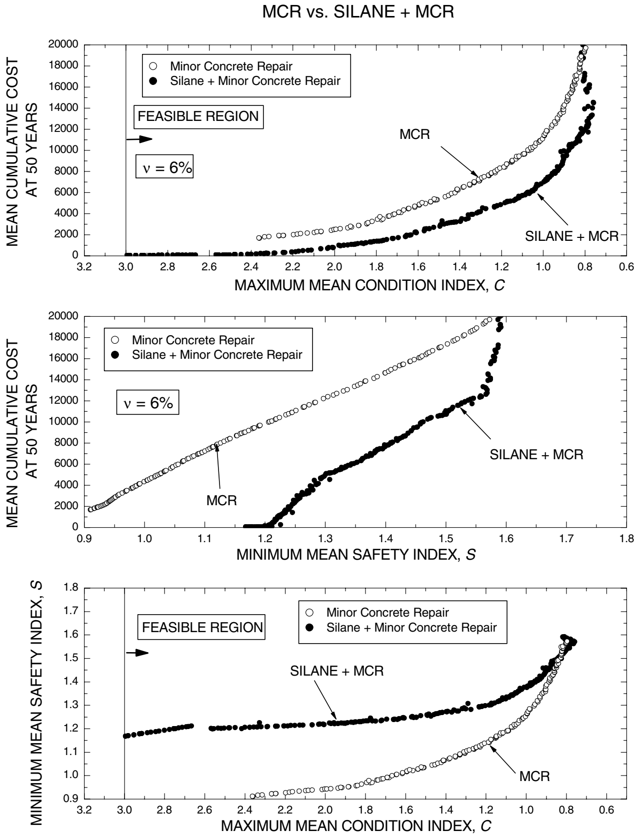

Figure 3. Comparison of optimal solutions obtained considering Minor Concrete Repair and Minor Concrete Repair + Silane

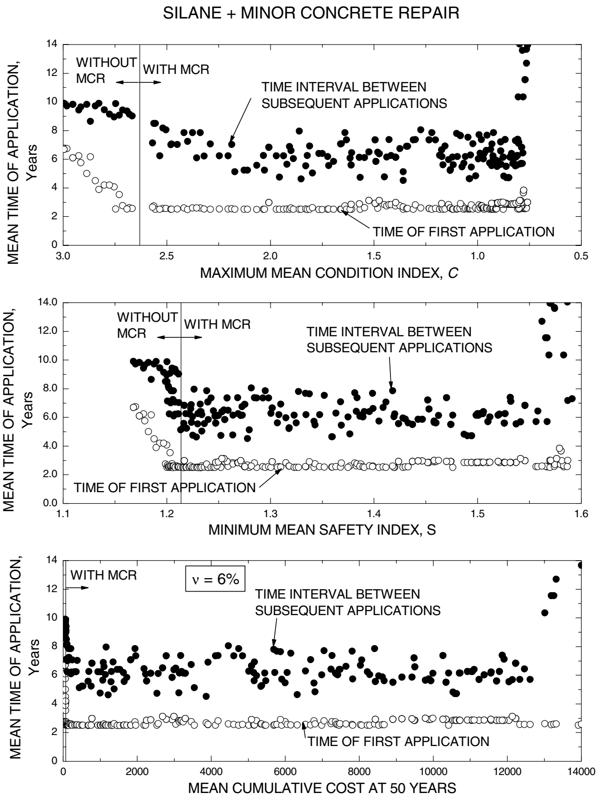

Figure 4. Comparison of design variables and objective functions associated with time of application of silane

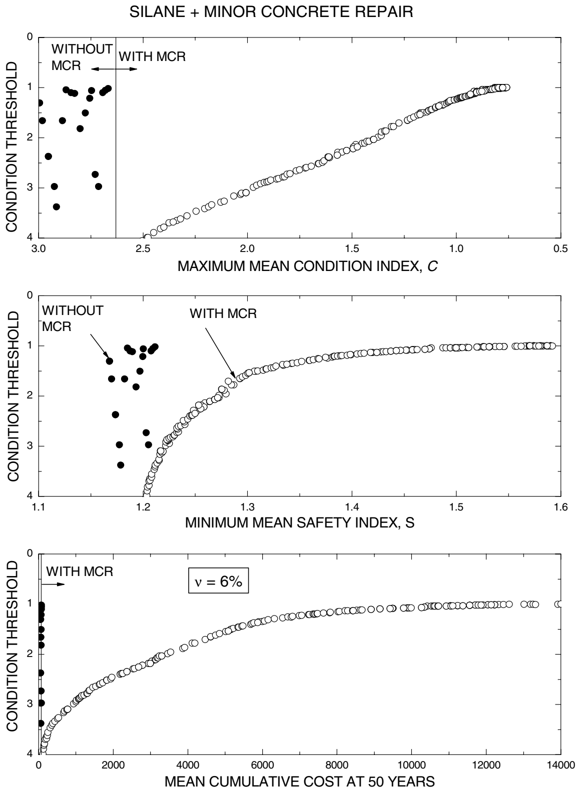

Figure 5. Comparison of design variables and objective functions associated with condition threshold at which minor concrete repair is applied

7 CONCLUSIONS

In this paper, a novel multi-objective probabilistic approach to the lifetime maintenance of deteriorating bridges considering condition, safety, and cost, is presented. The proposed approach overcomes some of the limitations of existing bridge management systems, by using more consistent indicator of performance, continuous condition and safety profiles, and including the effect of both preventive and essential maintenance actions. The use of multi-objective optimization gives the decision maker a large set of optimal solutions from which the best solutions can be chosen, considering the specific conditions at a given point in time of each bridge or bridge group. Results obtained emphasize the importance of preventive maintenance, in terms of reduction of overall cost. However, these results show that preventive maintenance alone is not enough to keep deteriorating structures safe and serviceable, during their entire lifetime. The proposed probabilistic framework for multiple objective optimization of bridge lifetime maintenance allows the inclusion of the uncertainty associated with the performance of deteriorating structures in a consistent and rational manner. This is further explained in Neves et al. (2006a, 2006b).

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