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CHAPTER 130

RELIABILITY AND CONDITION BASED BRIDGE MANAGEMENT SYSTEMS[1]

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ABSTRACT

In this paper two fundamentally different ways of combining reliability and conditions in assessing the state of a bridge are discussed. Clearly, assessing the state of a bridge solely on the basis of its reliability is not satisfactory since there are a number of potential structural damages which may seriously affect the state of the bridge without or with very little influence on the reliability of the bridge. In modelling the state of a bridge, therefore, it is necessary to formulate a modelling where the reliability as well as the condition is taken into account.

1. INTRODUCTION

The state of a bridge, the reliability of a bridge, and the condition of a bridge are defined and two models of the state of a bridge including its reliability and condition are included.

In the first approach the reliability and the condition are treated separately, but combined when decisions regarding bridge management (inspection and repair) are made. This approach is very useful when a single bridge is analyzed. The reliability is formulated by the now classical methodology based on stochastic modelling of significant quantities such as loads, strengths etc. The condition is taken into account using a knowledge-based approach obtained by expert knowledge. This methodology is discussed in detail in the paper on the basis of research done in an EU-supported project; Thoft-Christensen [1].

[1]Proceedings of ICOSSAR'05, Rome, Italy, June 19-22, 2005, Millpress, Rotterdam, 2005 (cd). ISBN 90 5966 040 4.

The second approach is based on in integration of the reliability and the condition and is very useful when statistical information is available. In this approach the state of the bridge as a function of time is estimated by simple Monte Carlo simulation where the reliability profile (reliability as a function of time) is modified when condition related activities are taking place. This methodology is discussed in detail in the paper on the basis of research supported by the Highways Agency in London, Thoft-Christensen & Frier [2].

1. THE EU RESEARCH PROJECT

In this project methods and computer programs for determining rational inspection and maintenance strategies for concrete bridges is developed. The optimal decision is based on the expected benefits and total cost of inspection, repair, maintenance and complete or partial failure of the bridge. Further, the reliability has to be acceptable during the expected lifetime.

2.1 Classification of bridge inspection

In this project inspections of bridges are divided into three types:

- *Current inspections*, which are performed at a fixed time interval, e.g. 15 months. The inspection is mainly a visual inspection.
- *Detailed inspections* are also performed at a fixed time interval. The detailed inspections are also visual inspections. The inspections can also include non-destructive in-situ tests.
- *Structural assessments* are only performed when a current or detailed inspection shows some serious defects, which require a more detailed investigation. Thus structural assessments are not periodical inspections. The structural assessment can include laboratory tests, in-situ tests with non-portable equipment, static and dynamic load tests.

2.2 Maintenance and repair systems

The decision system, which is used to assist in maintenance and repair planning, is divided into two subsystems:

- The *maintenance subsystem* deals with maintenance repair techniques and small repair i.e. repair of unimportant structural defects. Generally, this subsystem is always used after a current or detailed inspection.
- The *repair subsystem* helps choosing the best option of structural repair when an important deficiency that impairs the functionality of the bridge is detected. It is basically an economic decision. Generally this subsystem is used after a structural assessment.

2.3 Inspection, maintenances, and repair strategies

The application of the expert system modules in the general inspection, maintenance and repair model from inspection no. i at the time t_i to inspection no. $i+1$ at the time t_{i+1} is shown in figure 1, where the symbols used are: C/D is current or detailed inspection, A is structural assessment, M is maintenance work and repair of minor defects, R is repair, B1 is use of the expert system module BRIDGE1, B2 is use of the expert system module BRIDGE2. B2(M) is the maintenance/small repair submodules, B2(I) is the inspection strategy sub- module, and B2(R) is the repair sub module. Δt is the time between the periodic inspections.

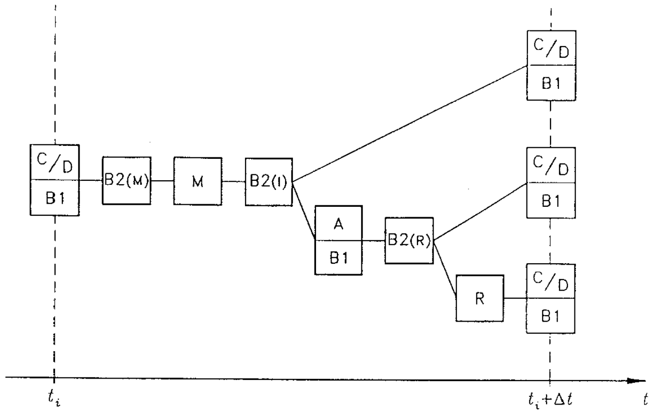

Figure1. Application of inspection, maintenance, and repair strategies.

After a current or detailed inspection there are two possibilities: the next inspection after Δt years is a current or a detailed inspection according to the inspection plan or the next inspection is a structural assessment to be performed immediately after the periodic inspection. The quality control inspection after a repair is not included in the modelling. After the structural assessment the repair decision is made.

2.4 The expert module BRIDGE2

The main functions of the expert system module BRIDGE2 are:

- After a *current or detailed inspection* maintenance work is planned by the submodule BRIDGE2(M*)*. The decision is based on a classification of the defects based on three factors: rehabilitation urgency, structural importance and affected traffic. According to the inspector's experience and some pre-fixed rules, each defect is given a classification, which corresponds to a global number of deficiency points.
- After a *current or detailed inspection* it is decided if a structural assessment has to be performed before the next periodic inspection. The decision is based partly on estimates of the reliability of the bridge and partly on expert knowledge.
- After a *structural assessment* it is decided if repair work has to be performed and the time for the repair. The decision is partly based on expert knowledge and partly on a cost-based optimization where different repair possibilities and no repair are compared.

2.5 The optimal repair time

After a structural assessment at the time T_0 the problem is to decide if the bridge should be repaired and the time of repair. Solution of this optimization problem requires that all future inspections and repairs are taken into account. However, the numerical calculations are then very time-consuming. Therefore, some approximations are introduced:

- After each structural assessment the total expected benefits minus expected repair and failure costs in the remaining lifetime of the bridge are maximized considering only the repair events in the remaining lifetime.
- It is assumed that N_R repairs of the same type I_R are performed in the remaining lifetime. The first repair is performed at the time T_{R_1} and the remaining lifetime is performed at equidistant times at the time interval $t_R = (T_L - T_{R_1}) / N_R$, where T_L is the year corresponding to the expected lifetime of the bridge.

The above decision model can be used in an adaptive way if the stochastic model is updated after each structural assessment or repair and a new optimal repair decision is made. Therefore, it is mainly the time and type of the first repair after a structural assessment, which is of importance.

In order to decide which repair type (including no repair) and repair time to choose after a structural assessment, the following optimization problem is considered with three optimization variables, namely: the type of repair I_R (including no repair); the time T_{R_1} of the first repair; the total number of repairs N_R in the remaining lifetime of the bridge.

$$\begin{aligned} \max_{I_R, T_{R_1}, N_R} \; & C_T(I_R, T_{R_1}, N_R) = B(I_R, T_{R_1}, N_R) - C_R(I_R, T_{R_1}, N_R) - C_F(I_R, T_{R_1}, N_R) \\ \text{s.t.} \quad & \beta^U(T_L, I_R, T_{R_1}, N_R) \geq \beta^{\min} \end{aligned} \tag{1}$$

where C_T is the total expected benefits minus costs in the remaining lifetime of the bridge. B is the expected benefit in the remaining lifetime of the bridge. C_R is the expected repair cost in the remaining lifetime of the bridge. C_F is the expected failure cost in the remaining lifetime of the bridge. T_L is the year at the end of its expected lifetime. β^U is the updated reliability index. $\beta^{\min}$ is the minimum acceptable reliability index for the bridge.

2.6 Application of the expert system

The objective of the project is to apply the expert system to real bridges. Therefore, the system is tested on two Portuguese and two Danish reinforced concrete bridges.

At first a small Portuguese bridge built with pre-cast girders was selected. This type of bridges has been largely employed, especially for short and medium-span viaducts or overpasses. They consist of precast girders and in-situ built deck slabs. The advantages of this bridge for testing the expert system arise from the fact that its construction was well controlled, the bridge was fully instrumented, and load tests were performed to analyze its structural behaviour. The bridge was built in 1990 and it has been periodically inspected for deterioration. The bridge not expected to have important deterioration problems. The second Portuguese bridge is an old reinforced concrete arch structure built in 1940 with significant corrosion problems. Several tests, included in a structural assessment, were per-formed, and the results were used to check the two expert systems BRIDGE1 and BRIDGE2. At this stage the inspection recommendations obtained within BRIDGE1 were quite satisfactory.

The first of the Danish bridges is a beam-slab bridge built in 1921 and enlarged in 1936 to the double width. The bridge is a three-span structure with a total length of 33 m. The superstructure is supported at the ends and by two intermediate columns. Information about the bridge is based on an inspection report from a structural assessment made in 1988. During the inspection severe reinforcement corrosion was observed. The main cause of corrosion was carbonization. The chloride content in the bridge was not serious. The second Danish bridge is a beam-slab bridge built in 1945. In 1962 a complete overhaul of the bridge was performed. The superstructure is supported at the ends and by one intermediate column. The column cannot be analyzed by the expert system due to the materials used. Information about the bridge is based on an inspection report from a structural assessment made in 1988.

2.7 Implementation of the expert system

The main purpose of a first prototype of BRIDGE1 was to implement the correlation matrices. The correlation matrices were defined for: defects/diagnosis methods, defects/causes and defects/repair methods. A pseudo-quantitative classification of the types: no correlation, low, and high correlation was proposed. The correlation between defects and both diagnosis and repair methods were presented. Each matrix is organized so that each line represents a defect and each column represents a possible diagnosis/method, cause or repair method. At the intersection of each line and column a number representing the correlation between defect and possible element of reference is to be introduced.

BRIDGE1 is divided into five main blocks: general information about the concrete bridge, related diagnosis methods, probable causes, associated defects and provisional defect report. A crucial task in the development of the expert systems is the definition of the databases. Therefore, an extensive study of the comprehensive data related to concrete bridges, both at the design stage and after it has been built is made. All relevant events in the service life of the bridges are carefully described. In this database, the set of parameters required for the reliability estimation, the cost optimization, and additional bridge parameters concerning bridge repair cost and corrosion parameters are included.

The architecture of the expert system BRIDGE2 includes the following three modules: a database; an inspection module; and a decision module. The expert systems are related to six typical corrosion related defects: rust stain, delamination/spalling, crack over/under a bar, exposed bar, corroded bar and bar with reduced cross-section.

3. THE LONDON HIGHWAY AGENCY RESEARCH PROJECT

In this research project results from crude Monte Carlo simulations of the following five preventive maintenance strategies for underbridges are obtained; Thoft-Christensen [3]:

- Minor concrete repairs
- Silane proactive preventive maintenance
- Do nothing & rebuild
- CP, with no associated repair
- Replace expansion joints.

However, in this paper only the detailed results for the minor concrete repair strategy are presented. The study is deterministic in the sense that no stochastic modelling is used. All relevant parameters are given by statistical distributions. A more up-to-date study is a stochastic approach where the initial safety state is based on the failure probability, where the time for deterioration initiation as well as the deterioration rate is based on a stochastic modelling.

No sensitivity studies have been performed. However, a satisfactory sensitivity study can be made simply by modifying the relevant data and redo the simulations. The discount rate used is 0 %, but any other value can easily be introduced.

3.1 Data collection and strategy assumptions

The simulations are primarily based on data received from Denton [4]. A few extra data are included to make the data set complete. These extra data and assumptions are not the same for all strategies.

The costs of the strategies are compared in section 3.6. The very wide spreading is primarily due the difference in repair costs, but also to some degree due to the different assumptions made. It is also important to bear in mind when comparing the costs that essential maintenance costs are not included.

The first SI downcrossing (SI=0.91) distributions (first rehabilitation distributions) for all five strategies are compared in section 3.6. It is interesting to observe that they are very similar to rehabilitation distributions estimated in earlier research projects sponsored by the HA.

3,2 Realization of the condition index, the safety index and costs of the minor concrete repair strategy

The initial condition index CI is drawn from a triangular distribution with (minimum mean, maximum) = (0, 1.75, 3.5) conditioned on CI<3. The approach is only valid for CI < 3. The deterioration slopes of CI (initial and after repair) is drawn from a triangular distribution (0 year^{-1}, 0.08 year^{-1}, 0.16 year^{-1}). Repair is undertaken when CI reaches an upper critical limit of 3. After repair CI is drawn from a triangular distribution (0, 1.75 3.5). A realization of the condition index CI for a minor concrete repair strategy is shown in figure 2.

The initial SI is drawn from a triangular (0.91, 1.5, 2.5) distribution. The deterioration slope of SI (initial and after CI = 1) is drawn from a triangular distribution (0 year^{-1}, 0.015 year^{-1}, 0.035 year^{-1}). The SI slope immediately after repair is zero. When CI = 1 is crossed, then the SI slope is changed from zero to the triangular distribution (0 year^{-1}, 0.015 year^{-1}, 0.035 year^{-1}). A realization of the safety index SI for a minor concrete repair strategy is

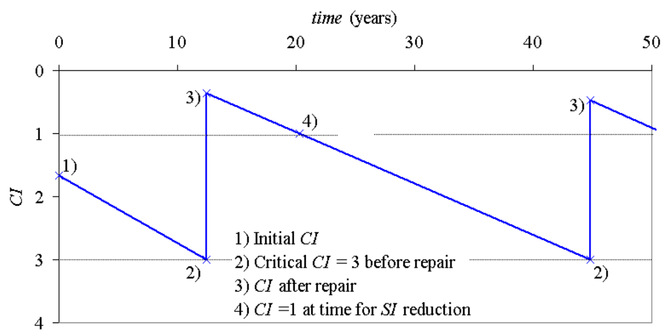

Figure 2. A realization of the condition index CI for the minor concrete repair strategy.

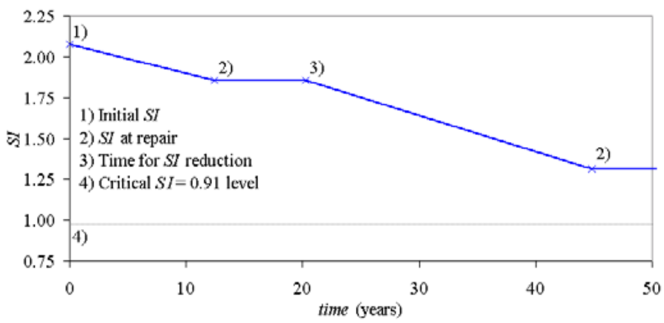

Figure 3. A realization of the safety index SI for a minor concrete repair strategy.

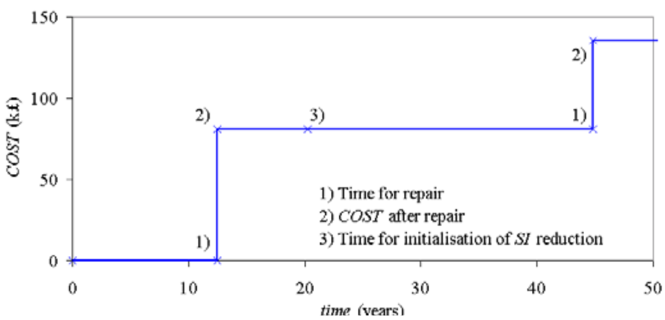

Figure 4. A realization of the cost for a minor concrete repair strategy.

shown in figure 3.

When repair is undertaken, the maintenance cost increment is drawn from the triangular distribution (6 k£, 68.5 k£, 131 k£). The discount rate is 0 %. A realization of the accumulated cost for a minor concrete repair strategy is shown in figure 4. Simulations are continued until SI < 0.91 and time is larger than 50 years.

3.3 Simulation results for the minor concrete repair strategy

The condition index CI at the times 0, 10, 20, 30, 40 and 50 years are shown in figure 5 when the minor concrete repair strategy is used. The data in figure 5 are based on 50,000 simulations. The similar statistics of the safety index SI and the cost are shown in figures 6 and 7, respectively.

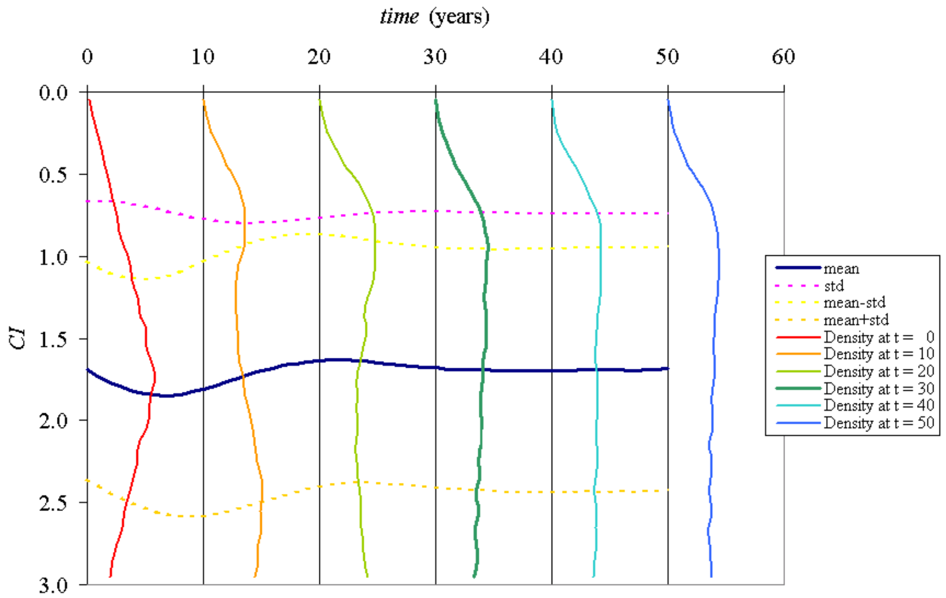

Figure 5. The condition index CI for the minor concrete repair strategy based on 50,000 simulations. Density functions are multiplied by a factor 10.

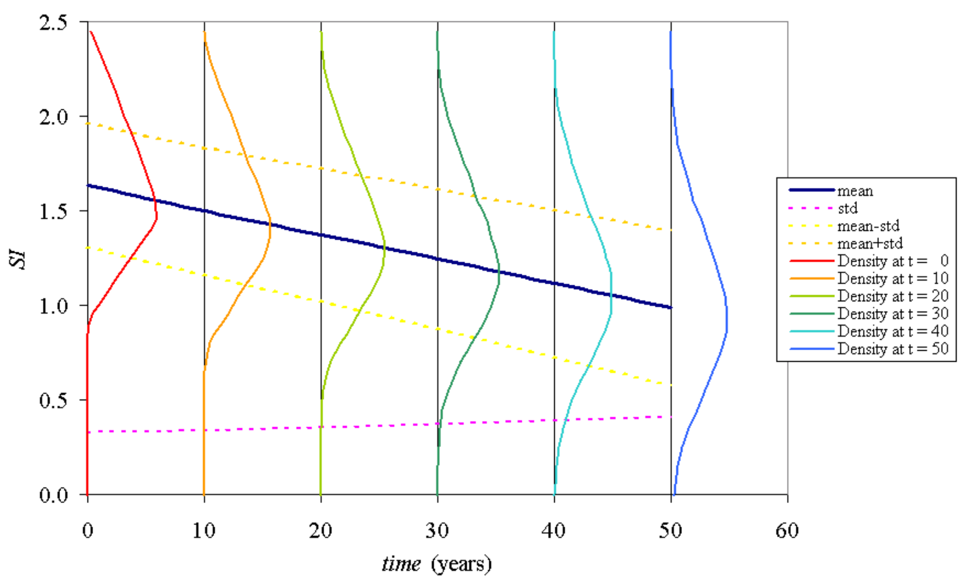

Figure 6. The safety index SI for the minor concrete repair strategy based on 50,000 simulations. Density functions are multiplied with a factor 5.

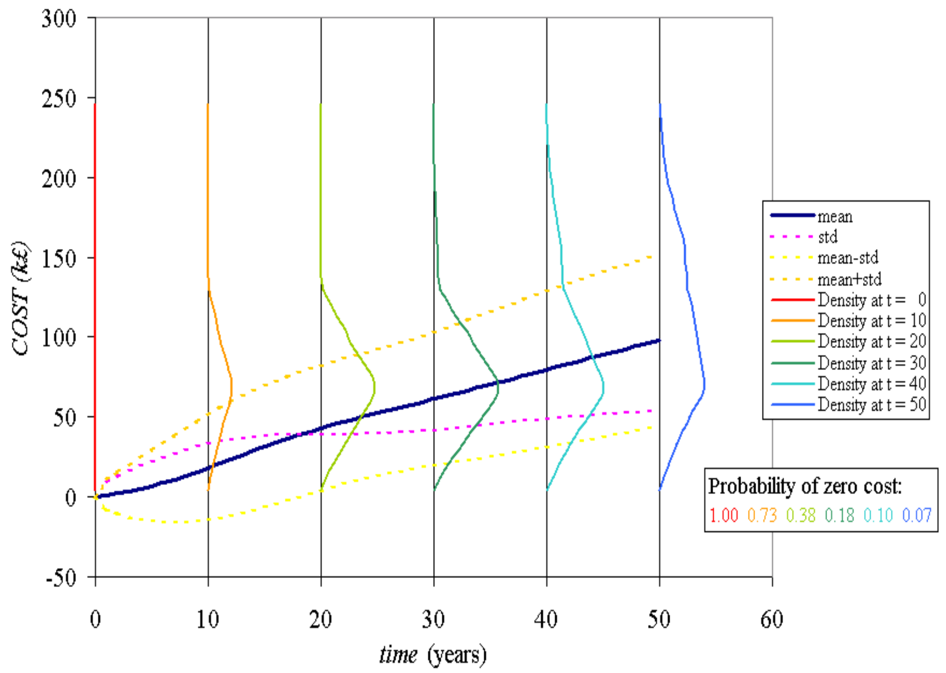

Figure 7. The cost for minor concrete repair strategy based on 50,000 simulations. Density functions are multiplied by a factor 500.

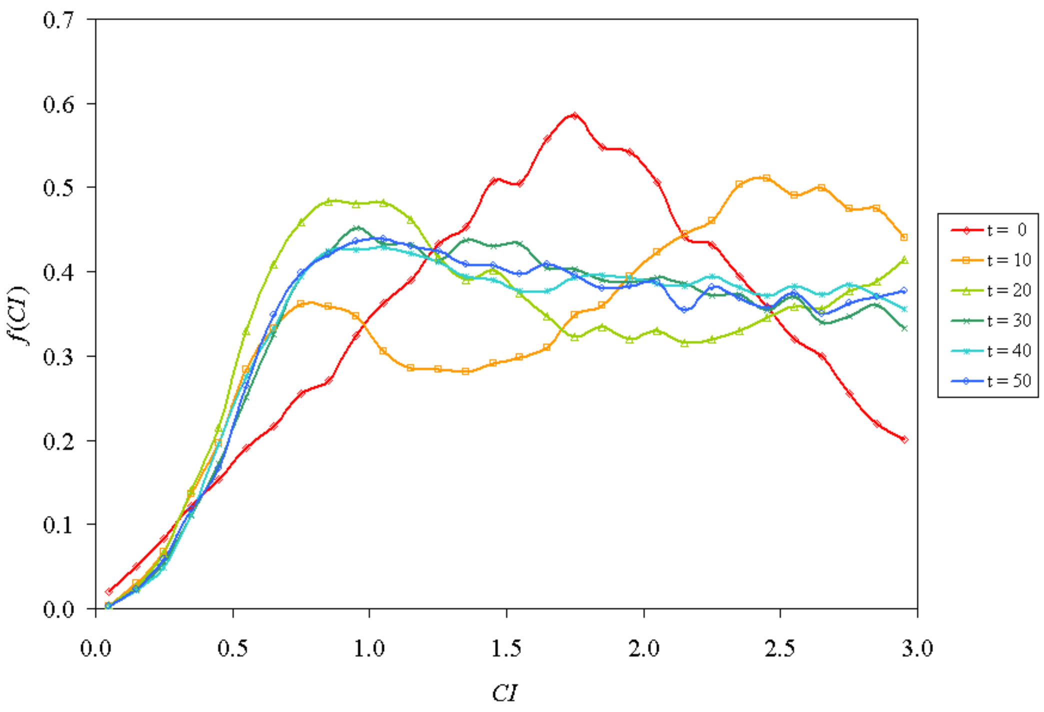

Figure 8. Density function of condition index CI for minor concrete repair strategy based on 50,000 simulations.

3.4 Density functions of the condition index CI, the safety index SI, and costs for the minor concrete repair strategy

The minor concrete repair approach is only valid for the 95.9 % best bridges. Simulations are performed based on the assumption that the initial condition index CI of the bridges is smaller than 3. Thus, the resulting statistics and distributions are conditioned on CI < 3.

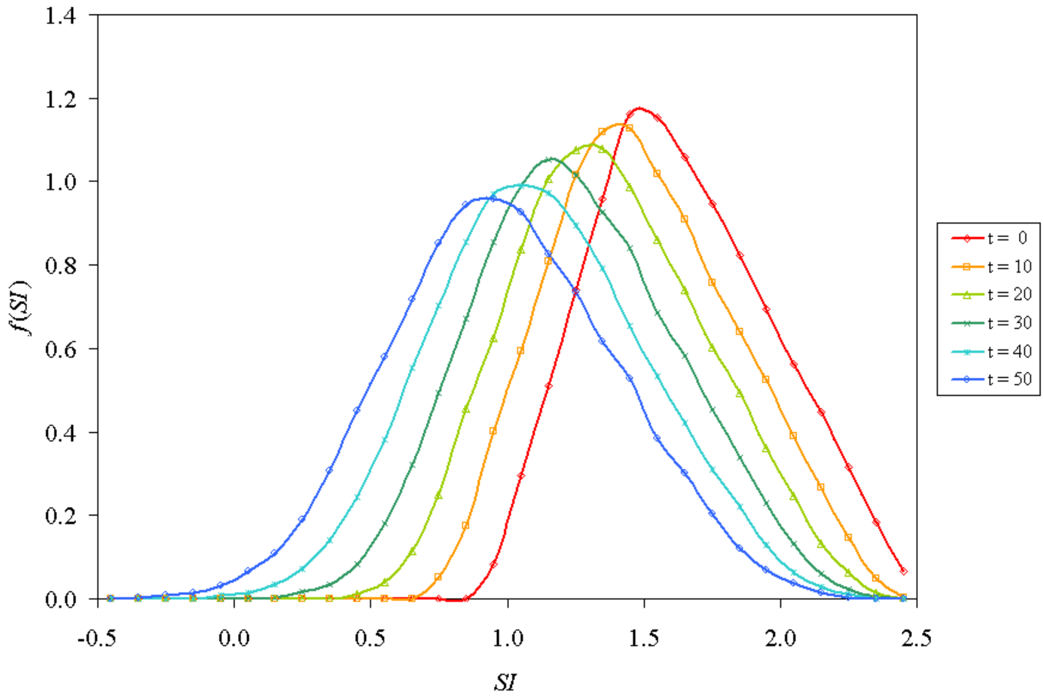

Figure 9. Density function of safety index for minor concrete repair strategy based on 50,000 simulations.

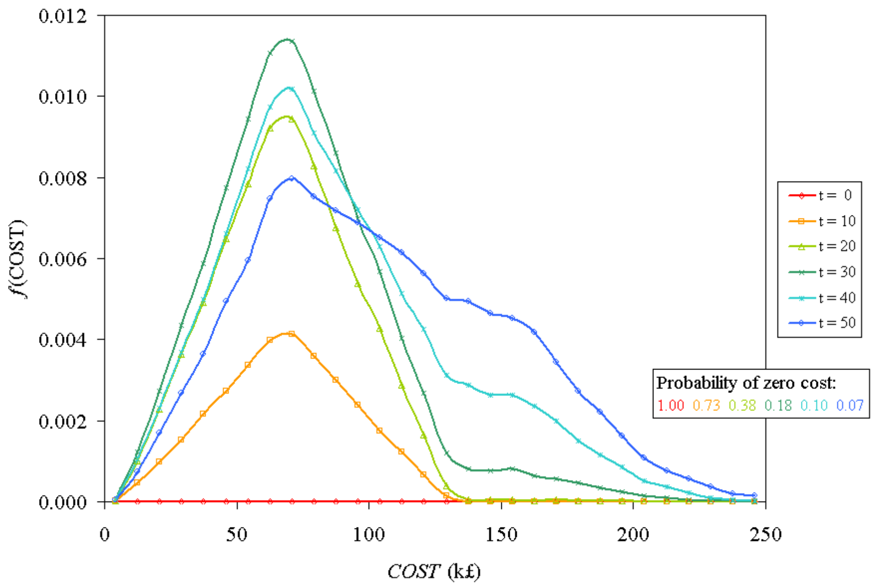

Figure 10. Density function of cost for minor concrete repair strategy based on 50,000 simulations.

A finite probability of zero cost is encountered during the simulations. Thus, the cost density function consists of a continuous and a discrete part. The continuous part is plotted in figures 7 and 10 and the discrete part is given as numbers in the figures.

Density functions of the condition index CI, of the safety index SI and the costs are shown in figures 8, 9, and 10, respectively.

3.5 Density functions for the first downcrossing

The density function for the first SI down at the critical level SI=0.91 is shown in figure 11.

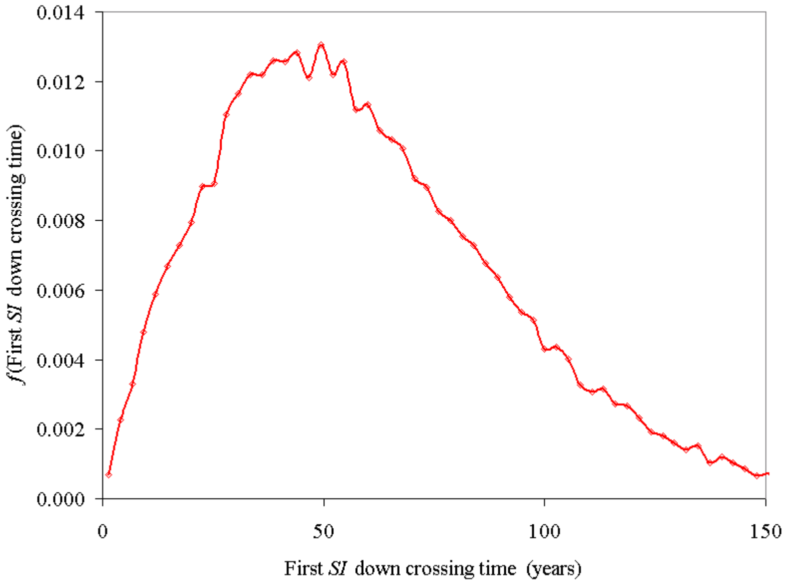

Figure 11. Density function of first SI downcrossing time for minor concrete repair strategy based on 50,000 simulations.

3.6 Comparison of preventive maintenance costs for the five preventive maintenance strategies

In sections 3.2-3.5 results from the simulations are only shown for the preventive maintenance action called minor concrete repair. However similar results are also obtained for the remaining four preventive maintenance strategies mentioned above. In this section the results from all five strategies are compared. The five strategies are:

- Minor concrete repairs
- Silane proactive preventive maintenance
- Do nothing & rebuild
- CP, with no associated repair
- Replace expansion joints.

Table 1 shows the sample means for the five strategies for 0, 10, 20, 30, 40, and 50 years.

A finite probability of zero cost is encountered during the simulations. Thus, the cost density function consists of a continuous part and a discrete part. The continuous part is plotted in figures 7 and 10 and the discrete part is given as numbers in the figures.

It follows from table 2 that Cathodic Protection (CP) has the lowest expected time to the first SI downcrossing of the critical value SI = 0.91, namely about 20 years.

Maintenance type	E[C] k£ 0 years	E[C] k£ 10 years	E[C] k£ 20 years	E[C] k£ 30 years	E[C] k£ 40 years	E[C] k£ 50 years
Minor concrete repairs	0	18	43	61	80	98
Silane	0	1	1	2	3	3
Do nothing & rebuild	0	12	48	100	155	208
CP	0	15	39	67	95	124
Replace expansion Joints	0	124	305	314	389	561

Table 1. Sample means of costs for different maintenance strategies based on 50,000 simulations.

Maintenance type	E[first SI down crossing time] years
Minor concrete repairs	61.24
Silane	56.81
Do nothing & rebuild	61.17
CP	20.71
Replace expansion joints	56.16

Table 2. Sample means of first SI downcrossing times for different maintenance strategies based on 50,000 simulations.

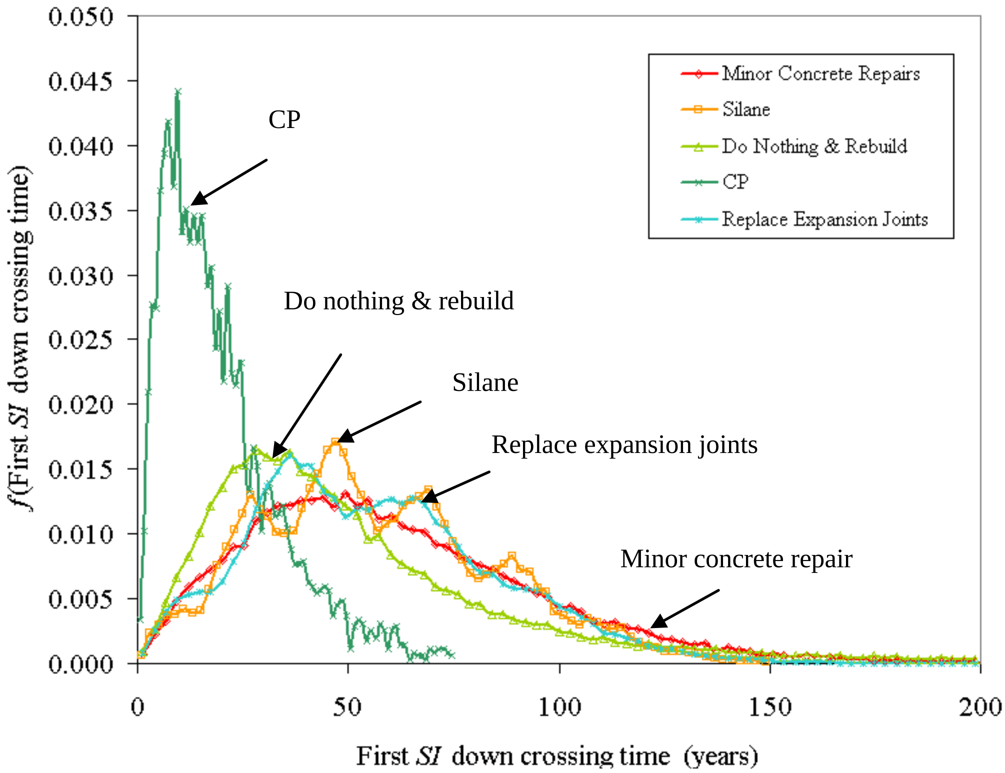

Figure 12. Comparison of first safety index SI downcrossing distributions (for CP strategy, only 3,535 realizations (7.07 %) had finite downcrossing times, therefore the distribution conditioned on downcrossing is shown).

The downcrossing times for the other four strategies are 50 – 60 years. Further, it follows from figure 12 that the downcrossing distributions for the same four strategies are similar while the downcrossing for CP is significantly different and with a much smaller standard deviation.

4. CONCLUSIONS

Two completely different bridge management systems are presented in this paper. The first system is designed for individual bridges in the sense that it guides the inspection engineer through the inspections and help with difficult decision problems regarding e.g. repair. The second system is designed for a (large) group of bridges and is a tool which may be used by bridge management agencies in making decisions regarding preventive maintenance. Both systems take into account safety issues (reliability) and bridge condition problems (minor defects).

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