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Future Trends in Reliability-Based Bridge Management

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1. Introduction

Future bridge management systems will be based on simple stochastic models predicting the residual strength of structural elements. The current deterministic management systems are not effective in optimizing e.g. the life cycle cost of a single bridge or a system of bridges. A number of important factors are so uncertain that they cannot be modelled satisfactorily by deterministic techniques. In recent years several researchers have studied stochastic modelling of e.g. deterioration, inspection, reliability, and repair but real applications are only reported in a few cases. One of the earliest proposals for an optimal strategy for inspection and repair of structural systems was presented in 1987 by Thoft-Christensen & Sørensen [1]. Improved stochastic modelling of the deterioration of concrete as well as steel bridges is necessary to be able to formulate optimal strategies for inspection and maintenance of deteriorated reinforced concrete and steel bridges. Such optimal strategies will only be really useful if they are combined with expert knowledge. However, it is not possible to formulate all expert experience in mathematical terms. Therefore, it is believed that future management systems will be expert systems or at least knowledge-based systems.

In the paper it is shown how simple maintenance and repair decision systems can be developed. The use of expert systems as a powerful mechanism for helping human experts in everyday decision-making tasks is emphasized. Finally an example of a future advanced management system for reinforced concrete bridges is presented.

This paper is to some extent based on research performed within the EC supported research project BRITE/EURAM P3091 on "Assessment of performance and optimal strategies for inspection and maintenance of concrete structures using reliability based expert systems (see Thoft-Christensen [2] and de Brito, Branco, Thoft-Christensen & Sørensen [3]) and a research report by Thoft-Christensen & Jensen [4].

2. Service lifetime definitions for concrete bridges

The main purpose of bridge management systems is to handle deterioration of bridges in an optimal way from an economic point of view. Maintenance of bridges would be a minor problem if there were no deterioration. However, all bridges deteriorate in some way and it is now recognized worldwide that deterioration is a serious problem that must be handled in a rational way. Some bridges deteriorate very fast and some very slow. In the literature a lot of information regarding deterioration is presented. A close study of this information shows that the only rational way of model deterioration is using stochastic modelling.

It has been suggested by several authors, see e.g. Thoft-Christensen [5], [6] that the service lifetime of a reinforced concrete bridge should be defined as the time to initiation of corrosion of the reinforcement. This is a rational definition in relation to a life cycle cost since repair of corroded reinforced elements is a major contribution to the life cycle cost. It is shown in Thoft-Christensen [5] that a Weibull distribution, see figure 1, can be used to approximate the initiation time for a reinforced concrete slab when the cover is normally distributed N(40.0mm, 4.0 mm) and "high corrosion" condition is assumed. The modelling of corrosion initiation is based on Fick's law of diffusion.

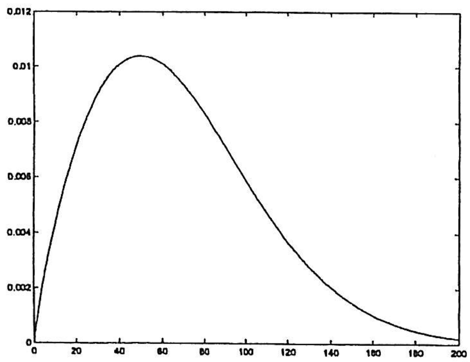

Figure 1. Modelling of the distribution of corrosion initiation time (years) using a Weibull distribution W(a,b) with a=0.00037952 and b=1.81.

This definition of service lifetime has been modified by Thoft-Christensen [7] where the service lifetime is defined as the sum of the corrosion initiation time and the time from corrosion initiation to crack initiation. The stochastic model is based on existing deterministic theories and the corrosion-cracking model is restricted to stresses resulting from the expansion of corrosion products. Three stages are considered in the model:

1. Free Expansion. It is assumed that a porous zone exists around the steel/concrete surface caused by the transition from paste to steel entrapped/entrained air voids, and corrosion products diffusing into the capillary voids in the cement paste.
2. Stress Initiation. When the total amount of corrosion products exceeds the amount of corrosion products needed to fill the porous zone around the steel, the corrosion products create expansive pressure on the surrounding concrete.
3. With increasing corrosion the internal stresses will exceed the tensile strength of the concrete and crack the cover concrete.

Using Monte Carlo simulation the distribution of the crack initiation time can be estimated. In this section only two different service lifetime definitions have been presented. Similar distributions can be estimated for any definition of service lifetime. However, to estimate these distributions data for the significant parameters must be available. This is seldom the case.

3. Life cycle cost evaluation

The usual definition of the life cycle cost W of a bridge is the sum of the initial cost C_I (investment costs) and the expected repair costs C_R (inspection, maintenance and repair costs) and the expected failure costs C_F, see e.g. Ellingwood [8]

$$W = C_I + C_R + C_F \tag{1}$$

A more elaborate model has been used by Thoft-Christensen [9], where it is proposed to maximize the benefits by having the bridge minus the costs W defined in (1), instead of minimizing the life cycle costs W.

In order to simplify the decision problem it is assumed that N_R repairs of the same type are performed in the residual lifetime T_L of the bridge. The first repair is performed at the time T_{R_1}, and the remaining repairs are performed at equidistant times at the time interval $t_R = (T_L - T_{R_1}) / N_R$, see figure 2.

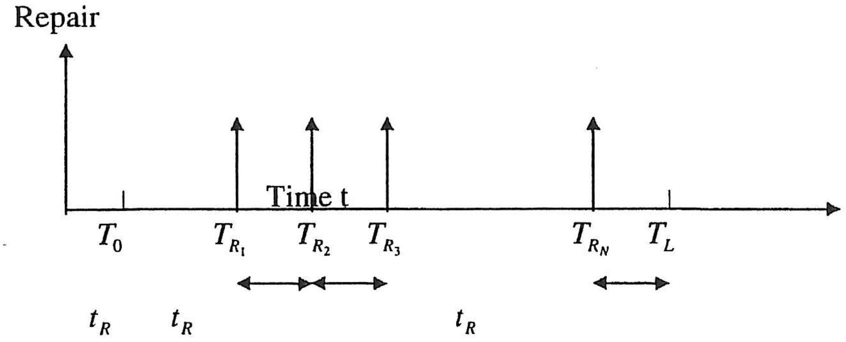

Figure 2. Simplified repair plan.

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 taken. Therefore, it is mainly the time of the first repair after a structural assessment, which is of importance.

In order to decide which type of repair is optimal after a structural assessment, the following optimization problem is considered for each repair technique, Thoft-Christensen [2]

$$\max_{T_R, N_R} W(T_R, N_R) = B(T_R, N_R) - C_R(T_R, N_R) - C_F(T_R, N_R) \tag{2}$$
$$s.t. \quad \beta^U(T_L, T_R, N_R) \geq \beta^{\min}$$

where the optimization variables are the expected number of repair N_R in the residual lifetime and the time T_R of the first repair. W is the total expected benefit minus costs in the residual lifetime of the bridge. B is the benefit. C_R is the repair cost capitalized to the time $t = 0$ in the residual lifetime of the bridge. C_F is the expected failure cost capitalized to the time $t = 0$ in the residual lifetime of the bridge. T_L is the expected lifetime of the bridge. β^U is the updated reliability index. $\beta^{\min}$ is the minimum reliability index for the bridge (related to a critical element or to the total system).

A simple model for the benefits is presented in Thoft-Christensen [9]

$$B(T_R, N_R) = \sum_{i=[T_0]+1}^{[T_L]} B_i (1+r)^{T_0 - T_{ref}} \frac{1}{(1+r)^{T_i - T_0}} \tag{3}$$

where $[T]$ signifies the integer part of T measured in years and B_i is the benefit in year i (time interval $[T_{i-1}, T_i]$. T_i is the time from the construction of the bridge. The ith term in (7) represents the benefits from T_{i-1} to T_i. The benefits in year i are modelled by

$$B_i = k_0 V(T_i) \tag{4}$$

k_0 is a factor modelling the average benefits for one vehicle crossing the bridge. It can be estimated as the price of rental of an average vehicle/km times the average detour length. The reference year for k_0 is T_{ref}. It is assumed that bridges are considered in isolation. Therefore, the benefits are considered marginal benefits by having a bridge (with the alternative that there is no bridge but other nearby routes for traffic). V is the traffic volume per year, which is estimated by

$$V(T) = V_0 + V_1(T - T_{ref}) \tag{5}$$

where V_0 is the traffic volume per year at the time of construction, V_1 is the increase in traffic volume per year, at T is the actual time (in years).

The remaining two terms $C_R(T_R, N_R)$ and $C_F(T_R, N_R)$ are modelled in the usual way, see e.g. [9].

4. Knowledge-based bridge management systems

The procedure of extracting knowledge from an expert system and encoding it in program form for a knowledge-based management system is called knowledge acquisition. This transfer and transformation of problem-solving expertise from a knowledge source to a program is the heart of the knowledge-based development process.

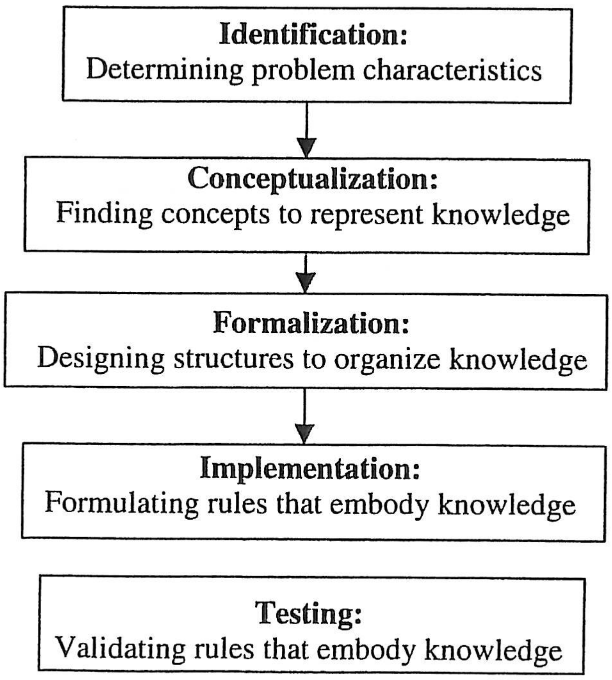

Figure 3. Stages in the evolution of an expert system.

The major stages in the development of an expert system are shown in figure 3 and are described in this section emphasizing how the bridge knowledge engineers take part in the knowledge acquisition process. The descriptions here are based on the excellent book by Haynes-Roth, Waterman & Lenat [11]. The first four stages are briefly described below in the way they were used in making an advance bridge management system for concrete bridges.

Identification stage:
Initially the participants in building the bridge management system must be identified. They are domain experts, knowledge engineers and programmers. The domain experts act as informants on their specific narrow areas of expertise. They must be willing to give out knowledge in some areas defined in the problem identification stage. They are typically employed by consulting companies. The knowledge engineers collect the relevant knowledge from domain experts and represent it in simple facts, objects and production rules to be used in the selected expert system building tool. The knowledge engineers must be willing and able to learn a great deal about the specifics of the domain. The programmers implement the simple facts, objects and production rules and test the system.

The expert knowledge to be collected and transformed to rules is used to answer questions like: Is a structural assessment to be performed before the next periodic inspection? Questions to the domain experts could be:

- When is a structural assessment needed?
- What are important tasks necessary to make the decision?
- What are the data?
- What is the solution?

Another set of questions is: Is repair to be performed? What sort of repair? When is the repair to be performed? In this case the questions to the domain experts could be:

- What influences the choice of repair of a bridge?
- What are the important tasks necessary to make a decision?
- What are the data?
- What is the solution?

All types of knowledge resources must be identified (books, journals, case studies etc.).

Conceptualization stage:
In the conceptualization stage a number of important concepts must be clarified e.g.:

- The main consequences of reinforcement corrosion are loss of steel cross-sectional area, cracking and spalling of the concrete cover, and loss of bond strength between steel and concrete
- The initiation and propagation of reinforcement corrosion depend on factors such as: depth of carbonation, rate of chloride penetration, etc.
- Diagnosis methods for concrete bridges must be classified and rated
- Defects in concrete bridges and repair techniques must be classified
- Correlation between corrosion related defects in concrete bridges and diagnosis methods must be estimated
- Correlation between corrosion related defects and repair techniques must be estimated.

Formalization stage:
The formalization process involves mapping the key concepts, subproblems, and information flow characteristics isolated during conceptualization into more formal representations based on various knowledge engineering tools. Existing tools must be evaluated. The output of this stage is a chosen tool and a set of specifications describing how the problem can be represented within the chosen tool.

The concrete bridge management system must be able to support statements like IF...THEN..ELSE and FOR loops etc., and to deal with uncertainty. An example of the knowledge to be implemented is the following: If the measured potentials by a chloride content test are more negative than -350 mV there is a 90% probability that corrosion is active. This can be done in the following way:

```
IF
   the diagnosis method is the potential test
THEN
   IF
   the measured potential is less than -350 mV
   THEN
   corrosion is active with certainty 0.90
   ELSE
     IF
   the measured potential is greater than -200 mV
     THEN
   corrosion is not active with certainty 0.90
     END
END
```

5. Expert knowledge regarding inspection

In this paper "expert knowledge" is used for elicited knowledge to be included in a bridge management system. The (subjective) inspection results obtained by the bridge inspector during an inspection is not included in "expert knowledge", but is being used for updating the stochastic modelling. In a bridge maintenance system, the inspector always has the final decision regarding inspection, maintenance and repair. However, the expert knowledge is integrated into the maintenance system so that it can make suggestions to improve the inspectors' decision and make it more rational and hopefully also more objective.

A decision model will usually be composed of two parts, namely an analytical part and an expert knowledge part. In the analytical part the state of the bridge is evaluated on the basis on the stochastic modelling and inspection-based updating. The state may e.g. be the reliability of the bridge calculated on the basis of the stochastic modelling of the strength, the loading, and the deterioration. If the reliability is below a certain limit then the decision on e.g. a more detailed investigation or repair can be made on the basis of this estimation only. However, if the reliability is greater than a certain critical limit then a more detailed investigation is needed if, from a structural point of view, one or more serious defects have been detected the decision is based on expert knowledge. A serious defect is a defect that, in the short or middle term, questions the structural safety or the global integrity (functionality) of the bridge.

This simple decision model is illustrated in figure 4.

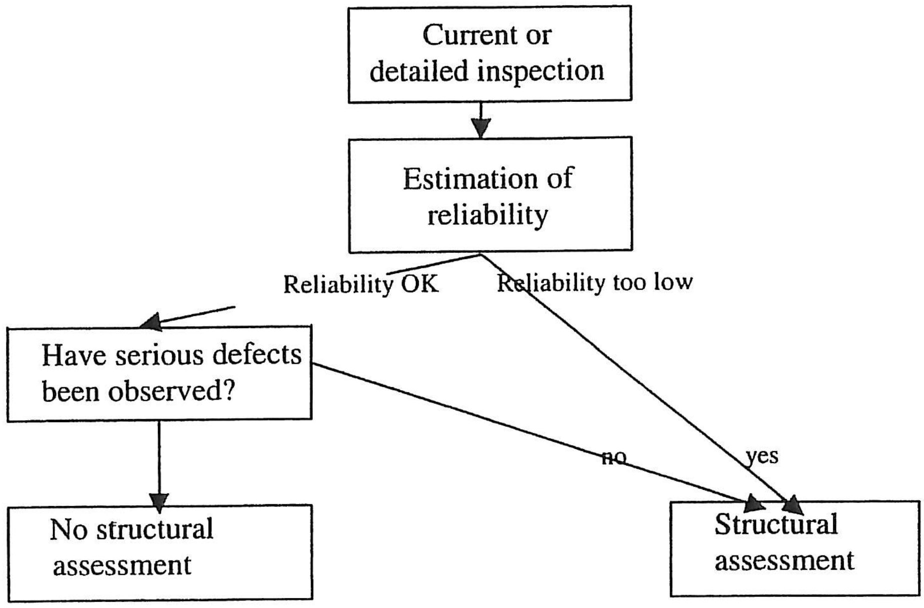

Figure 4. Illustration of a decision model

The decision whether a detailed structural assessment is recommended may of course be different for bridge owners and experts in different countries. Very typical defects observed by direct visual observation for corrosion are rust stains, delamination/spalling, and cracks over/under reinforcement bars. In this section very simple decision rules are described in relation to rust strains. Similar decision rules can easily be formulated for other types of defects.

The most important parameters with regard to rust stains are the extent of the rust stains and the location of rust stains. To formulate relevant decision rules, experts must answer a number of questions:

1. What is the extent of rust stains?

Possible answers are:

- Single rust stains: no structural assessment is needed since single rust stains do not impair the structural safety or the global functionality of the bridge
- Many local rust stains: go to question 2 below.
- Widespread rust stains: A structural assessment is needed since it can be assumed that there is global corrosion of the reinforcement.

2. What is the location of rust stains?

Possible answers are:

- A critical place regarding humidity: A structural assessment is needed since a critical place is e.g. a place exposed to splash of water from cars passing under the bridge.
- Near places where maximum bending moments occur: A structural assessment is needed, since corrosion in such places may affect the strength of the bridge significantly.
- Other places: A structural assessment is not needed.

The rules can be illustrated by the flow chart in figure 5.

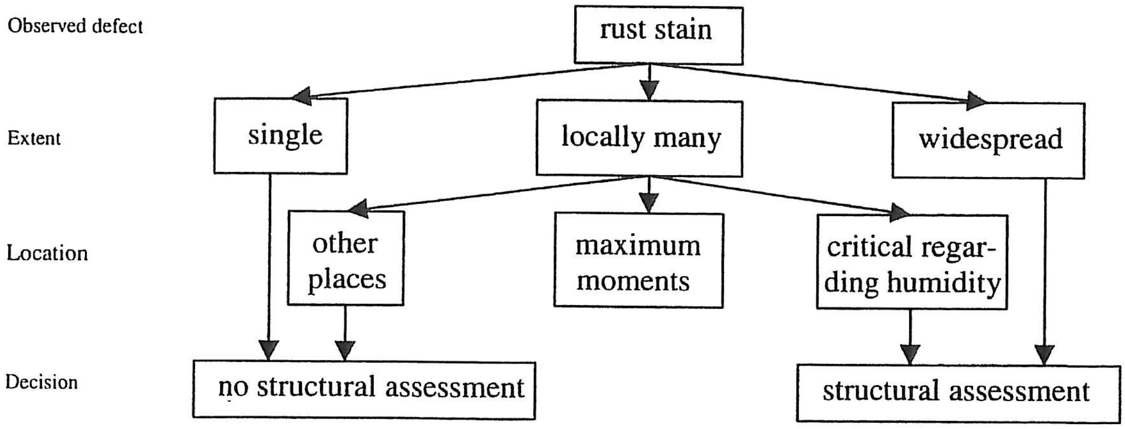

Figure 5. Decision process when rust stains are observed.

Similar simple decision rules are based on elicitation formulated for other types of defects.

5. Expert knowledge regarding repair

In this section the same defect "rust stain" will be considered. The same elicitation procedure as in section 4 is used to identify relevant repair techniques when "rust stain" has been observed during the inspection and when a structural assessment has been performed. To formulate relevant decision rules, experts must answer a number of questions:

1. Is there a crack in the rust stain (Y/N)?
Possible answers are:
Yes. A crack over/under the bar in the same cross-section has been observed during the inspection. Go to the next question.
No. A crack has not been observed during the inspection.

2. Has the crack depth reached the reinforcement (Y/N/U)? U means unknown.
Possible answers are:
Yes. A crack depth greater than or equal to the measured concrete cover has been identified using magnetometer/covermeter/Pachometer.
No. The same diagnosis method as above has been used and the crack depth is less than the measured concrete cover.
Unknown. The above mentioned diagnosis method has not been used. No more questions are asked.

3.1 Has the critical chloride concentration reached the reinforcement (Y/N/U)?
Possible answers are:
Yes. The calculated chloride concentration (using Fick's law and measured chloride concentration values) at the level of the reinforcement is greater than or equal to the critical chloride content. Go to question 4.

No. The calculated chloride concentration (using Fick's law and measured chloride concentration values) at the level of the reinforcement is less than the critical chloride content. Go to question 3.2.
Unknown. Go to question 3.2.

3.2 Has the rust color reached the reinforcement (Y/N/U)?
Possible answers are:
Yes. Go to question 4.
No. If the answer to question 3.1 is also *no,* then go to question 5. If the answer to question 3.1 is
Unknown. No more questions are asked.

4. Is the maximum cross-sectional loss of the reinforcement ≥20% (Y/N)?
The possible answers are:
Yes. No more questions are asked.
No. No more questions are asked.

5. Is the maximum chloride content > 0.5% by weight of cement (Y/N/U)?
The possible answers are:
Yes. No more questions are asked.
No. No more questions are asked.
Unknown. No more questions are asked.

These questions and answers as well as relevant repair methods are illustrated in the flow chart in figure 6.

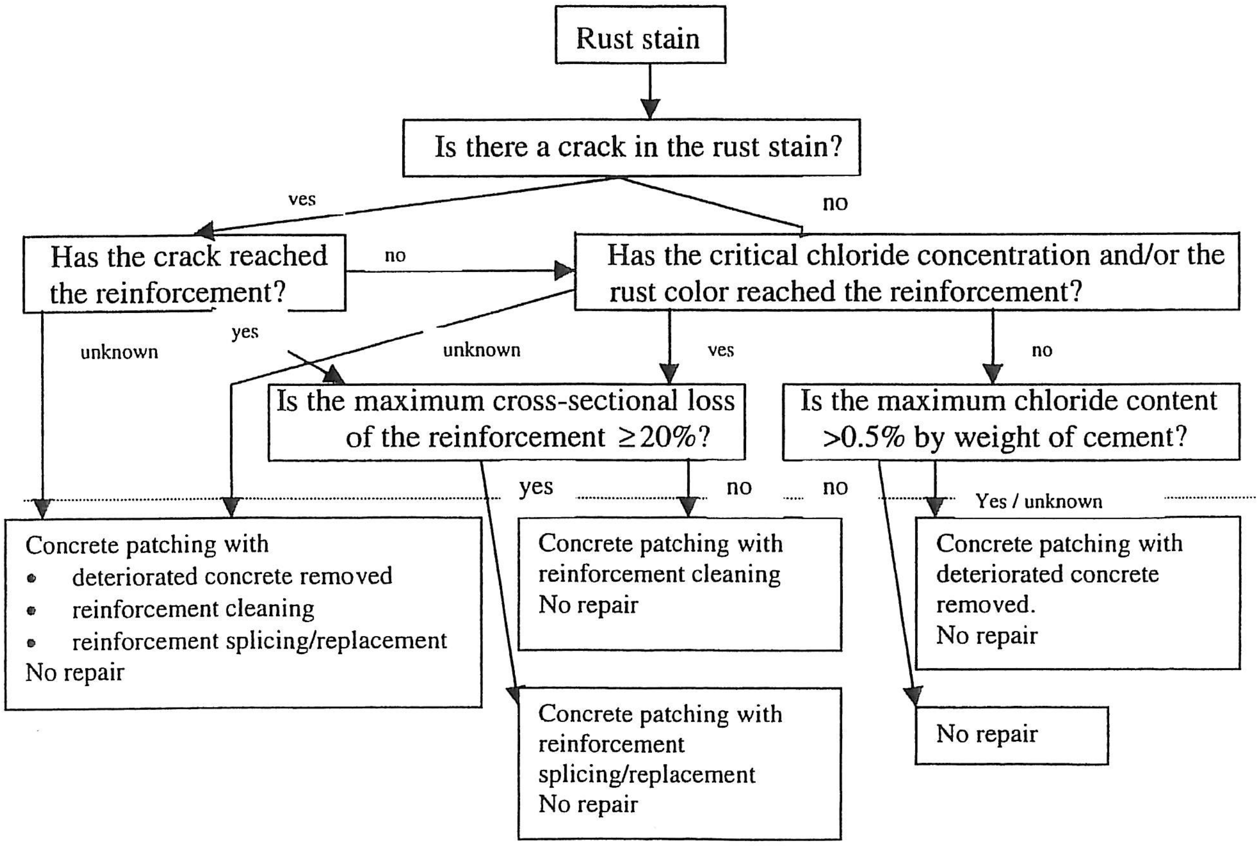

Figure 6. Expert knowledge to identify relevant repair techniques for defect "rust stain".

7. Lifetime profiles for concrete bridges

Whole life reliability profiles for bridges are needed when a bridge management system is designed. These reliability profiles play a dominant role when decisions regarding detailed assessment of bridges are made and when optimal maintenance strategies are derived. The Highways Agency in London, UK, initiated a major research project on this subject in 1995 for reinforced concrete slab bridges. The results from this project have been published in a number of papers, see e.g. Thoft-Christensen & Jensen [4] and Thoft-Christensen [10]. In this section a very brief presentation of this work is given.

In the project a detailed analysis of 15 bridges was performed using all available information from drawings to inspection results. 3 of the bridges are of the beam/slab type and the remaining ones are all simply supported bridges. The reliability assessment is based on yield line failure modes and bending failure as well as shear failure is used.

A major problem in this project was modelling of the deterioration. It was decided only to consider one deterioration mechanism namely chloride induced corrosion of the reinforcement. The response of the concrete to chloride exposure was described by the so-called chloride profile, i.e. the distribution of the chloride content of the concrete in its near-to-surface layer or by its concentration-distance curve. Estimation of the chloride profile is a very uncertain matter since it is controlled by a number of factors, which are difficult to model. The controlling factors with regard to the corrosion initiation time are the initial chloride content, the chloride content at the surface, and the chloride diffusion coefficient. After corrosion has been initiated then the controlling parameter is the rate of corrosion. The parameters were modelled by stochastic variables based on observations.

The corrosion due to chloride ingress will usually be pitting corrosion that is a very localized corrosion of the reinforcement, When corroded rebars become pitted their properties change. Pitting is particularly vicious because it is a localized and intense form of corrosion, and failure of the bar in question often occurs with extreme suddenness. For a reinforced concrete slab bridge pitting corrosion of a single rebar or a few rebars will not drastically change the ductility due to the "parallel" behaviour of the rebars. In the project it was therefore considered acceptable to model the corrosion as a uniform corrosion of the rebars to avoid the difficult task of modelling pitting corrosion. Fick's law of diffusion modelled the rate of chloride penetration into concrete.

Based on an extensive literature study and inspection data from the bridges in question, the following general stochastic modelling of the significant corrosion parameters was used in the reliability profile study:

Diffusion coefficient:	Normally distributed N(30.0;5.0) [mm^2/year]
Chloride concentration on surface:	Normally distributed N(0.65;0.075) [%]
Corrosion density:	Uniform distributed U(3.0;4.0) [μ A/cm^2]

A simulation study showed that this modelling of corrosion resulted in a very wide spreading of the corrosion. Therefore, the general model was divided into three models low, medium, and high deterioration, see Thoft-Christensen & Jensen [4]. Using these three deterioration models, reliability profiles for one of the considered UK bridges are shown in figure 7. A substantial difference in the reliability profiles is observed for the three deterioration models. Since the reliability models are essential for developing rational bridge management systems, this conslusion suggests that the deterioration should be more closely studied.

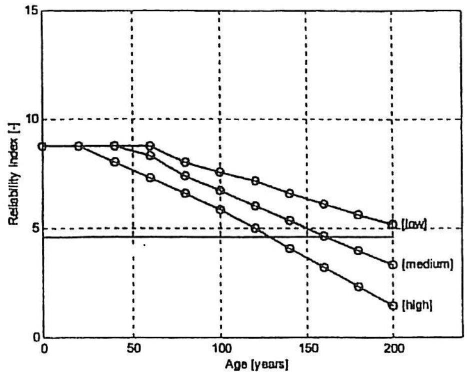

Figure 7. Reliability profiles for low, medium, and high deterioration for an UK bridge.

8. BRIDGE1 and BRIDGE2 management systems

In this section the functionality of two prototype bridge management systems BRIDGE1 and BRIDGE 2, see also Thoft-Christensen [2], are briefly described.

The expert system BRIDGE 1 is used at the site of the bridge during the inspection. It contains useful information concerning the bridge being inspected and the defects being observed. The information includes: general information about the bridge, appropriate diagnosis methods for each defect, probable causes for each defect and other defects related to a defect. It is also possible to create a provisional defect report.

The expert system BRIDGE 2 is used to make a detailed analysis of the bridge after an inspection and when testing in the laboratory has taken place. The analysis is based on the results of inspections recorded with BRIDGE I. BRIDGE 2 includes the following tasks:

- New bridges and cross-sections can be entered into the database.
- Data concerning existing bridges and critical cross-sections can be edited.
- Enters and edits Data, which are independent of the bridges can be entered and edited.
- Reviews Provisional defect reports that have been recorded at the bridge site by using BRIDGE1 can be reviewed.
- The inspection results can be completed.
- The reliability of the bridge can be estimated using several techniques.
- The decision whether a structural assessment of a bridge is necessary before the next periodic inspection is supported.
- Defects requiring maintenance can be rated. Lists of relevant maintenance techniques for an observed defect and the corresponding estimated costs are produced.
- Lists of relevant structural repair techniques for an observed defect are shown.
- BRIDGE2 can optimize the repair plan and estimate structural repair costs.
- Information in the database is automatically updated after repair.
- An agenda of inspections is displayed.

Three types of bridge inspections are included in BRIDGE2:

Current inspections are performed at a fixed time interval, e.g. 15 months. The results of current inspections are used to plan maintenance work that prevents the bridge from further deterioration.

Detailed inspections are also periodical at a fixed time interval, which is a multiple of the current inspection time interval, e.g. 5 years. The results of detailed inspections are used to plan maintenance work that prevents the bridge from further deterioration.

Structural assessments are only performed when a current or detailed inspection shows some serious defects that require a more detailed investigation. Thus, structural assessments are not a periodical assessment. The results of a structural assessments is used to plan structural repair work. Figure 8 shows the general inspection, maintenance, and repair model.

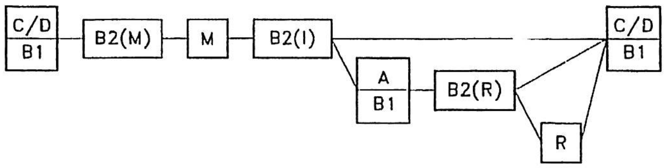

Figure8. General inspection, maintenance, and repair model

The following symbols are used in figure 7:

C/D is a current or detailed inspection
A a structural assessment
M is maintenance work and repair of minor defects
R is structural repair work
Bl is use of BRIDGE 1, and B2 is use of BRIDGE 2.

The following submodules are integrated in BRIDGE 2:

BRIDGE 2(M) is the maintenance/small repair submodule
BRIDGE 2(I) is the inspection strategy submodule
BRIDGE 2(R) is the structural repair submodule.

The defects are divided into two subsystems:

- For defects related to the *maintenance subsystem* the submodule BRIDGE 2(M) assists in selecting maintenance work and repair of minor structural defects to be performed and estimates the maintenance costs. The defects are rated based on the defect classification in terms of rehabilitation urgency, importance of the structural stability, and affected traffic recorded during the inspection. This submodule is always used after a current or detailed inspection.

- For defects related to the *repair subsystem* the submodule BRIDGE 2(R) assists in selecting the best structural repair technique (including no repair) to be performed, when the repair should be performed, and the number of repairs in the residual lifetime of the bridge. Further, the expected benefits minus costs are estimated. The repair plan is optimized based on a cost-benefit analysis. This submodule is always used after a structural assessment.

After a current or detailed inspection the inspection submodule BRIDGE 2(I) assists in the decision whether a structural assessment is needed for a bridge before the next periodic inspection. The decision taken in BRIDGE 2(I) is mainly based on the updated reliability index for the bridge. If the value of the updated reliability index for the bridge, is acceptable then each of the defects detected is investigated. Based on expert knowledge it is investigated whether, from a structural point of view, a defect requires a structural assessment.

The reliability program RELIAB is used in BRIDGE 2 to estimate the reliability of a reinforced concrete bridge. Two different failure modes are considered, namely bending failure of the main beam of a bridge and compression failure of a column. For bending failure both 'positive' and 'negative' bending failure are considered. For compression failure two models for deterioration of the column are considered, namely one model where the concrete deteriorates on all four sides of the column and one model where the deterioration is concentrated on one side. In the models the diameter of the reinforcement is assumed to decrease with time due to corrosion. In the failure modes both chloride and carbonate initiated corrosion are considered. The failure modes are modelled as elements in a series system. When inspection results are obtained the reliability indices for single failure modes and for the bridge are updated.

The inspection program INSPCT is used in BRIDGE2 to estimate the optimal repair time and the number of repairs for a given repair method. The estimates are based on a cost-benefit analysis for the bridge. The total expected benefits minus expected repair and failure costs in the residual lifetime of the bridge are optimized. The optimization variables are the time of the first repair and the number of repairs in the residual lifetime of the bridge. The constraint of the optimization problem is that the updated reliability index for the bridge must be greater than or equal to a minimum acceptable reliability index for the bridge.

9. Conclusions

Future bridge management systems will be based on stochastic modelling of all significant quantities. More reliable data will in the future improve the quality of this modelling. The cost of maintaining bridge stocks is so high that it is worthwhile to spend resources on developing bridge management systems, which are based on the most recent research results.

Compared with the relatively simple bridge management systems used in most countries now, the future bridge management systems will be much more rational and will be relevant for a meaningful optimization of maintenance based on life cycle costs. More research and data collection are needed before this can be fully implemented into workable management systems, but several important improvements can be made today and are already in use in some countries.

Initially a number of new contributions will be introduced in future management systems in very simplified versions. Some of these new contributions, which can already now be included in bridge management systems, are:

- Improved deterioration modelling including all sorts of deterioration like corrosion, cracks, etc. is needed to make realistic lifetime profiles for concrete as well as steel bridges.
- Ultimate as well as serviceability limit states must be integrated in the system so that critical reliability level assessment and relevant maintenance can be performed.
- It will be necessary to include expert knowledge in the systems to make sure that e.g. optimization of maintenance makes sense.
- Interactive knowledge based inspection and repair strategies will be part of most future systems.

10. Acknowledgements

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