# Bridge Management Systems

*present and future*

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STRUCTURAL RELIABILITY THEORY
PAPER NO. 164

Presented at the "US-European Bridge Engineering Workshop", Barcelona, July 15-17, 1996

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BRIDGE MANAGEMENT SYSTEMS. PRESENT AND FUTURE
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# BRIDGE MANAGEMENT SYSTEMS. PRESENT AND FUTURE

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**Summary**

In this paper bridge management systems are discussed with special emphasis on management systems for reinforced concrete bridges. Management systems for prestressed concrete bridges, steel bridges, or composite bridges can be developed in a similar way.

Present bridge management systems are in most cases based on a deterministic approach and the assessment of the reliability or the safety is therefore in general based on subjective statements. In future bridge management systems we will see a change to stochastically based systems with rational assessment procedures. Future management systems will be computerized and different types of knowledge based systems will be used. Further, recent developments in optimization techniques will make it possible to produce a much better decision tool regarding inspection and repair.

It is beyond the scope of this paper to give a complete presentation of existing bridge management systems. Most existing management systems are presented in detail in the literature. In this paper a number of changes which are expected in future management systems will be discussed.

The format of future bridge management systems is illustrated by the EU supported management systems BRIDGE1 and BRIDGE2.

## 1. INTRODUCTION

For many years it has been accepted that steel bridges must be maintained due to the risk of corrosion of steel girders etc. The situation is a little different for reinforced concrete bridges. Reinforced concrete bridges built in Europe in the past seventy years were designed on the basis of a general belief among engineers that the durability of the composite material could be taken for granted. Although a vast majority of reinforced concrete bridges have performed satisfactorily during their service life, numerous instances of distress and deterioration have been observed in such structures in recent years. The causes of deterioration of reinforced concrete bridges are often related to durability problems of the composite material. One of the most important deterioration processes which may occur in reinforced concrete bridges is reinforcement corrosion, caused by chlorides present in de-icing salts and/or carbonation of the concrete cover zone.

Future bridge management systems will probably be based on simple models for predicting the residual strength of structural elements. Improved stochastic modelling of the deterioration is needed to be able to formulate optimal strategies for inspection and maintenance. However, such strategies will only be useful if they are also combined with expert knowledge. 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.

This paper is mainly based on references [1] - [3]

## 2. FUTURE BRIDGE MANAGEMENT SYSTEMS

### 2.1 Optimal Strategies for Inspection and Maintenance of Bridges

*Diagnostic methods*

Diagnosis of bridges showing signs of functional or structural deterioration is the first step that has to be taken before making any decisions regarding maintenance or repair. It is necessary to define clearly what are the damage problems. The reasons for concern usually point out a direction for investigation. It is, however, very time and money consuming to start diagnosis without knowing which information one wants to gather.

When the diagnostic method (or methods) is selected, it is necessary to gather the know-how, equipment, manpower and facilities needed. The method procedure needs to be known accurately and the information needed has to be written down in order to avoid many visits to the site. Diagnostic work is usually disruptive for the normal functioning of the bridge and must be limited as much as possible in time and space.

*Correlations between defects and diagnostic methods*

A correlation matrix between the diagnosis methods and the defects can be established so that each line represents a defect and each column a diagnostic method. At the intersection of each line and column a number representing the correlation between defect and diagnostic method can then be introduced. Such a matrix may help the inspector in choosing the best inspection method, as a function of the detected defect.

*Fundamental parameters*

In practice, certain parameters are considered to be of fundamental importance in assessing the performance of structural materials, and, therefore, they dictate the investigation strategy and its implementation. A brief description of some of these parameters, and the errors commonly associated with their measurements must be analysed.

## 2.2 Development of Optimal Strategies

*Inspection strategies*

Methods and computer programs for determining rational inspection and maintenance strategies for bridges must be developed. The optimal decision should be 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. Inspections of bridges are usually 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 periodical at a fixed time interval which is a multiple of the current inspection time interval, e.g. 5 years (replacing the current inspection when it occurs). 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. The structural assessment can include laboratorial tests, in situ tests with non-portable equipment, static and dynamic load tests. The tests are usually very costly compared with the other two inspection types. A structural assessment will also be performed when changes in the use of the bridge are being planned.

*Maintenance and repair decision systems*

It is convenient to divide that part of the decision system which is used to assist in maintenance and repair planning into two subsystems:

The *maintenance subsystem* deals with maintenance repair techniques and small repair, i.e. repair of unimportant structural defects (either because such repair does not involve great sums of money or because no expert advice is needed to repair them). 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 (based obviously on structural and traffic engineering data) in which the costs are quantified. Generally this subsystem is used after a structural assessment.

## 2.3 Application of Expert Systems

*General comments*

Expert systems technology is nowadays being considered as a powerful mechanism for helping human experts in their everyday decision tasks. Being able to represent in the computer system the knowledge structures and reasoning strategies that the human expert follows when approaching a problem, enables other users to share this knowledge and the expert system thus constructed establishes a common decision criterion for the prospective users of the system.

The objective of using expert system technology in bridge management is to produce a software tool to assist bridge inspectors as well as engineering experts in their tasks of assessing and improving the reliability of concrete bridges.

*Architecture*

The first step is to identify the various software subsystems and the relations between them i.e. the software architecture that will set the basis for the development of the expert systems. It is natural in bridge management to develop two different modules aimed at different goals. The first should provide technical support to the inspector during the inspection process at the bridge site. The second should assist the engineer in the analysis of the safety of bridges as well as in the selection of maintenance and repair methods.

*Software modules*

A number of software modules will interact with the expert systems through specifically designed data files:

- *Updating analysis*: Based on inspection information and other new information the reliability estimates and the data in the databases must be updated.
- *Reliability analysis*: The reliability of the bridge must be evaluated as a function of time.
- *Structural analysis*: The system should be open so that the user is able to use his own finite element software.
- *Inspection program*: Based on the data in the databases and the reliability estimates the optimal time for the next inspection is calculated using the updating module.

*Representation schemes and inference mechanisms*

The next step is to identify the representation schemes and inference mechanisms best suited for the implementation of the expert systems, as well as the evaluation and selection of the most promising expert system shells available that would guarantee that the representation and inference requirements identified are fulfilled. The functional interrelations between the expert modules and the analysis programs must be defined.

*Implementation of the expert system*

As mentioned earlier in bridge management it is convenient to have at least two systems, namely one to be used in the inspection phase and one to be used during maintenance and for repair decisions.

In such a case the first system will be highly based on "correlation matrices". Correlation matrices must be defined for: defects/diagnostic methods, defects/causes and defects/repair methods. A pseudo-quantitative classification of the type no correlation, low and high correlation is useful. Correlation between defects as well as diagnostic and repair methods is also needed. Each matrix must e.g. be organised so that each line represents a defect and each column 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.

It is important for the applicability of the expert system that it gives all the information needed during and after inspections. Such information could be: general information about the bridge, related diagnostic methods, probable causes, associated defects and provisional defect report.

*Databases*

A crucial task in the development of expert systems is the definition of the databases. An exhaustive study of the data collected for concrete bridges, both at the design stage and after it has been constructed must be provided. At relevant moments of the bridge's service life (usually after construction and after important rehabilitation work is performed), its real situation must be thoroughly described so that future inspections have something to relate to. When the database definition is completed then the set of parameters required for the reliability estimation, the cost optimization, additional bridge parameters dealing with the bridge repair cost and corrosion descriptive parameters are added.

Most existing bridge management databases are insufficient for e.g. reliability assessment and for implementing modern decision making tools.

*Expert modules*

A number of expert modules is needed to define the architecture of the expert system: database module, inspection module and a decision module.

The decision module will in general be divided into a number of sub-modules such as: a maintenance/small repair submodule, an inspection strategy submodule and a repair/upgrading/replacement submodule.

*Expert strategies*

In the expert systems a number of strategies must be implemented, such as:

- Should technical knowledge regarding the need to perform a structural assessment be incorporated into the system and should it also be used to double check when the reliability index estimates that the condition of the bridge is good ?
- When defects are detected during an inspection, what should be the strategy to consider them either as maintenance or as repair? When is the most appropriate time for repairing the defect?.

*The inspector's functionalities*

The inspector must be able to perform activities like:

- Review all the information contained in the database of the bridges. Different types of data are recorded for each bridge: identification and bridge site information, design information, budget information, traffic information, strength information, load information, deterioration information, factors that model the costs and data for the cross-sections defined for the bridge.
- Define new cross-sections.
- Receive technical support regarding the most appropriate diagnostic methods to be used in order to conclude about the existence of a defect.
- Receive technical support regarding the possible causes responsible for a defect.
- Record the results of the inspection .

*The inspection engineer's functionalities*

The inspection engineer must at his office be able to:

- View the inspection results recorded at any previous inspection performed in any of the bridges of the database.
- Enter the data of a bridge in the bridge's database.
- View the data of a bridge and edit it.
- Define new critical cross-sections for any of the bridges in the database.
- Get a relation of the set of bridges contained in the database with the next inspection dates for each of the bridges.
- Complete the data of the defects detected at the inspection by describing the defect in greater detail and by entering the results of the tests performed on the concrete.
- Update data for the cross-sections and inspection results after repair.

## 3. BRIDGE MANAGEMENT SYSTEMS FOR CONCRETE BRIDGES

In this section some important issues related to advanced bridge management systems are discussed namely

- deterioration of bridges
- stochastic modelling of failure modes
- stochastic modelling of repair
- updating techniques
- reliability analysis.

*Deterioration of bridges*

An important reason for producing bridge management systems is the deterioration of bridges due to corrosion. Corrosion is one of the most important deterioration mechanisms for steel as well as reinforced concrete bridges. In this section a stochastic model for corrosion of reinforcement in reinforced concrete bridges is shown.

The rate of chloride penetration into concrete is often modelled by Fick's law of diffusion

$$\frac{\delta c(x,t)}{\delta t} = D_C \frac{\delta^2 c(x,t)}{\delta x^2} \tag{1}$$

where $D_C$ is the chloride diffusion coefficient , x is the distance from the surface and t is time. The solution of equation (1) is

$$C(x,t) = C_0 \left\{ 1 - \operatorname{erf}\left( \frac{x}{2\sqrt{D_C \cdot t}} \right) \right\} \tag{2}$$

where C(x,t) is the chloride content at the distance x from the surface and at the time t. $C_0$ is the initial chloride content.

The corrosion initiation period

$$T_I = \frac{(d_1 - D_1/2)^2}{4D_C} (\operatorname{erf}^{-1}(\frac{C_{cr} - C_0}{C_i - C_0}))^{-2} \tag{3}$$

where $C_i$ is the initial chloride concentration, $C_{cr}$ is the critical chloride concentration , and $d_1 - D_1/2$ is the concrete cover.

The diameter $D_1(t)$ of the reinforcement bars at the time t after initiation of corrosion can the be modelled by

$$D_1(t) = D_1(0) - C_{corr} i_{corr}(t) \tag{4}$$

where $D_1(0)$ is the initial diameter, $C_{corr}$ is a corrosion coefficient, and $i_{corr}$ is the rate of corrosion.

The area of a reinforcement bar is then e.g. modelled using the following formulation

$$A(t) = \begin{cases} nD_1(0)^2 \frac{\pi}{4} & \text{for } t \le T_I \\ n(D_1(t))^2 \frac{\pi}{4} & \text{for } T_I \le t \le T_I + D_i(t)/(0.0203 \cdot i_{corr}) \\ 0 & \text{for } t > T_I + D_i(t)/(0.0203 \cdot i_{corr}) \end{cases} \tag{5}$$

With this modelling the initiation time of corrosion is determined based on values of $C_0, C_i, D_C, x_d, C_{cr}$. Often the corrosion initiation time from a bridge management point of view can be considered equal to the lifetime of the structure since repair before corrosion has taken place is favourable. After the deterioration has started the corrosion rate is modelled by the rate of corrosion $i_{corr}$ only.

Based on a survey the following modelling for chloride penetration is proposed for areas with lot of rain (the initial chloride is assumed to be zero):

| | | |
|---|---|---|
| Model 0: | Diffusion coefficient $D_C$: | N(30.0, 5.0) [mm2/year] |
| | Chloride conc., surface $C_0$ : | N(0.65, 0.075 [%] |
| | Corrosion density $i_{corr}$: | Uniform[1.0, 3.0] [ $\mu$ A/cm2] |

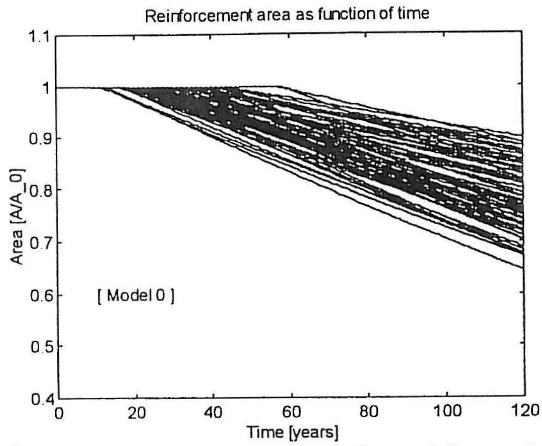


*Figure 1. Reinforcement area as a function of time. Corrosion model 0. (Cover on reinforcement $x_d$: N(40.0, 4.0) [mm]).*

Based on the deterioration model 0 three levels of deterioration are proposed: low deterioration, medium deterioration and high deterioration.

| | | |
|---|---|---|
| Low: | Diffusion coefficient $D_C$: | N(25.0, 2.5) [mm2/year] |
| | Chloride conc. , surface $C_0$ : | N(0.575, 0.038) [%] |
| | Corrosion density $i_{corr}$: | Uniform[1.0, 2.0] [$\mu$ A/cm2] |
| Medium: | Diffusion coefficient $D_C$: | N(30.0, 2.5) |
| | Chloride conc., surface $C_0$ : | N(0.650, 0.038) |
| | Corrosion density $i_{corr}$: | Uniform[1.5,2.5] |
| High: | Diffusion coefficient $D_C$: | N(35.0,2.5) |
| | Chloride conc. , surface $C_0$ : | N(0.725, 0.038) |
| | Corrosion density $i_{corr}$: | Uniform[2.0,3.0] |

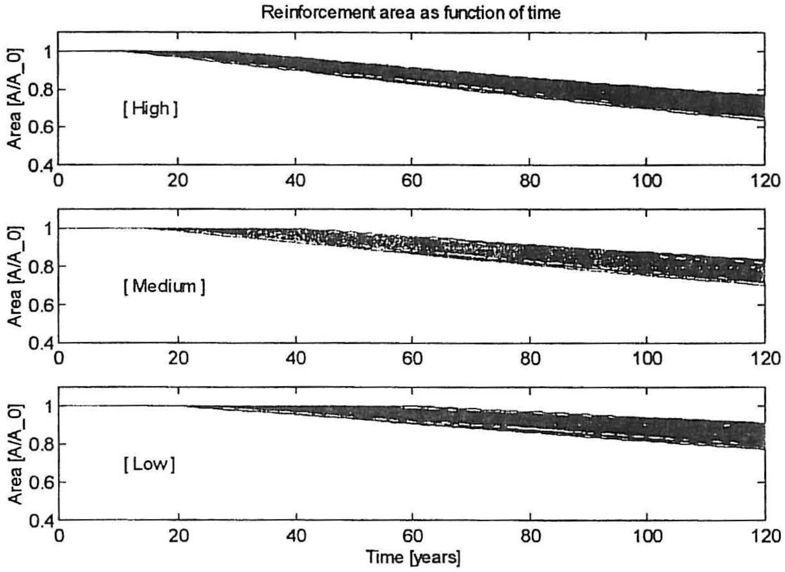


*Figure 2. Normalised reinforcement area $A / A_0$ as a function of time for low, medium, and high deterioration.*

*Stochastic modelling of failure modes*

A number of failure modes for structural elements must be modelled. In this section is shown as illustration modelling of an ultimate limit state (ULS) and a serviceability limit state for a concrete slab bridge namely ( see Thoft-Christensen et al. [2]) :

- an ultimate limit state (ULS): collapse limit state (using yield line analysis)
- a serviceability limit state (SLS): crack width limit state (using linear elastic analysis)

The following safety margin can be used for the collapse limit state:

$$Z = VE_D - W_D \tag{6}$$

where V is a model uncertainty variable, $E_D$ is the energy dissipated in yield lines, and $W_D$ is the work done by the applied loads.

The basic variables used in the yield line ULS are: thickness of slab, cube strength of concrete, density of concrete, depth of reinforcement, yield strength of reinforcement, and two load parameters.

Cracking shall be limited to a level that will not impair the proper functioning of the structure or cause its appearance to be unacceptable. In the absence of specific requirements (e.g. water tightness), it may be assumed that limitation of the maximum design crack width to about 0.3 mm will generally be satisfactory for reinforced concrete members with respect to appearance and durability.

The design crack width may be obtained from (see [2])

$$w_k = \beta s_{rm} \varepsilon_{sm} \tag{7}$$

where $w_k$ is the design crack width, $s_{rm}$ is the average final spacing, $\varepsilon_{sm}$ is the mean strain allowing, under the relevant combination of loads, for the effects of tension stiffening, shrinkage, etc., and $\beta$ is a coefficient relating the average crack width to the design value. For load induced cracking $\beta$ = 1.7. The value of $\varepsilon_{sm}$ may be calculated from the relation

$$\varepsilon_{sm} = \frac{\sigma_s}{E_s}(1 - \beta_1\beta_2(\frac{\sigma_{sr}}{\sigma_s})^2) \tag{8}$$

where $\sigma_s$ is the stress in the reinforcement calculated on the basis of a cracked section, $\sigma_{sr}$ is the stress in the reinforcement calculated on the basis of a cracked section under the loading conditions causing first cracking.

$\beta_1$ is a coefficient which takes account of the bond properties of the bars. It is = 1.0 for high bond bars, and = 0.5 for plain bars. $\beta_2$ is a coefficient which takes account of the duration of the loading or of repeated loading. It is = 1.0 for single, short-term loading, and = 1.5 for a sustained load or for many cycles of repeated loading.

The average final crack spacing (in mm) for members subjected mainly to flexure or tension can be calculated from the equation

$$s_{rm} = 50 + 0.25 k_1 k_2 \phi / \rho_r \tag{9}$$

where $\phi$ is the actualbar size (or the average bar size). $\rho_r$ is the effective reinforcement ratio, $A_s / A_{c,eff}$, where $A_s$ is the area of reinforcement contained within the effective tension area, $A_{c,eff}$. $k_1$ is a coefficient which takes account of the bond properties of the bar. It is equal to 0.8 for high bond bars and 1.6 for plain bond bars. $k_2$ is a coefficient which takes account of the strain distribution. It is equal to 0.5 for bending and 1.0 for pure tension.

The crack width limit state can then be formulated by

$$g(\cdot) = w_{\max} - z_c w_k \tag{10}$$

where $z_c$ is a model uncertainty stochastic variable.

The stochastic variables used in the crack width SLS are: concrete cover, distance between reinforcement bars, diameter of reinforcement bars, thickness of slab, elastic modulus of reinforcement bars, tensile strength of concrete, external bending moment, and one model uncertainty variable.

*Stochastic modelling of the inspection*

Two types of uncertainty in the models for inspections must be considered. The first type of uncertainty is related to the uncertainty (reliability) of an inspection method, i.e., how good is an inspection technique to detect a defect if a defect is present and what is the risk that the inspection method indicates a defect when there is no defect (false alarm). The second type of uncertainty is related to the measurement uncertainty when a detected defect is being quantified. Stochastic models must be derived for the most important inspection methods.

*Stochastic modelling of repair*

Repair implies that new and/or modified values of parameters are needed to model the behaviour of the bridge after the repair. In relation to stochastic modelling of repair the quantities can be divided into the following groups:

- Quantities (deterministic or stochastic) which are the same before and after repair.
- Quantities which can be modelled by deterministic variables. The values for these quantities are known rather precisely after the repair.
- Quantities which can be considered new outcomes of the old stochastic variables used before the repair. A variable of this type is modelled by introducing a new stochastic variable with the same distribution function but statistically independent of the old stochastic variable.
- Quantities modelled by new stochastic variables correlated or not correlated with the old stochastic variables.

In addition to the above models it can be relevant to update the distribution functions of the stochastic variables when observations are obtained in connection with the repair. The following important structural repair types must be modelled: concrete patching (with deteriorated concrete removal), concrete patching (with reinforcement cleaning), concrete patching (with reinforcement splicing/replacement) and concrete encasing (with reinforcement splicing/replacement).

*Updating techniques*

When new information becomes available the estimates of the probability of failure (and the reliability) of structures can be updated. New information can be divided in three types:

- Sample information on basic variables
- General information on stochastic variables
- Linguistic information.

When new information is available as samples of one or more stochastic basic variables Bayesian statistical methods are used to obtain updated (predictive) distribution functions of the stochastic variables.

In some cases the information obtained by measurements is not directly related to a basic stochastic variable. The information is generally modelled by using a stochastic variable which is a function of the basic stochastic variables. The event margin is a stochastic variable and it is therefore possible to estimate the probability that the event occurs. Further, this type of information can be used to update the probability of failure of a structural element.

Basic variable updating is performed within the framework of Bayesian statistical theory (Lindley [5], Aitchison & Dunsmore [4]). The updating based on general information is mainly based on the Bayesian methods suggested by Madsen [6] and Rackwitz & Schrupp [7].

Let the density function of a stochastic variable $X$ be given by $f_X(x,\Theta)$, where $\Theta$ are parameters defining the distribution of $X$ The parameters $\Theta$ are treated as uncertain parameters (stochastic variables). $f_X(x,\Theta)$ is therefore a conditional density function $f_X(x|\Theta)$. The initial (or prior) density function for $\Theta$ is called $g'_\Theta(\theta)$.

When an inspection is performed $n$ realizations $\overline{x}^* = (x_1,\dots,x_n)$ of the stochastic variable $X$ are obtained. The inspection results are assumed to be independent. An updated density function $\Theta$ taking into account the inspection results is then defined by

$$g''_\Theta(\theta|\overline{x}^*) = \frac{f(\overline{x}^*|\theta)g'_\Theta(\theta)}{\int f_n(\overline{x}^*|\theta)g'_\Theta(\theta)d\theta} \tag{11}$$

where $f_X(x|\overline{x}^*) = \prod_{i=1}^{n} f_X(x_i|\theta)$.

The updated density function of $X$ taking into account the realizations $\overline{x}^*$ is then obtained by

$$f_X(x|\overline{x}^*) = \int f_X(x|\theta)g''_\Theta(\theta|\overline{x}^*)d(\theta) \tag{12}$$

In the expert systems the functions $g'_\Theta(\theta)$ , $g''_\Theta(\theta)$ , and $f_X(x|\overline{x}*)$ are implemented for several distributions.

*Reliability analysis*

The reliability of the bridge is measured using the reliability index $\beta$ for a single failure element or for the structural system (the bridge) (Thoft-Christensen & Baker [5], Thoft-Christensen & Murotsu [6]). The reliability is assumed to decrease with time due to the deterioration. The failure modes can e.g. be stability failure of columns, yielding or shear failure in a number of critical cross-sections of the bridge. If a system modelling is used then it is assumed that the structure fails if any one of these failure modes fails, i.e. a series system modelling is used.

It is assumed that uncertain quantities like loading, strength and inspection results can be modelled by $N$ stochastic variables $\overline{X} = (X_1,...,X_N)$. At present the stochastic variables shown in table 1 are used. Further, the structure is modelled by $m$ potential failure modes $F_i$, i = 1, 2... $m$. Failure mode i is described by a safety margin.

$$M_{F_i} = M_{F_i}(\overline{X},t) \tag{13}$$

The element reliability index $\beta_i(t)$ at the time t for failure mode $F_i$ is connected to the probability of failure $P_{F_i}(t)$ by (see Thoft-Christensen & Baker [8])

$$\beta_i(t) = -\Phi^{-1}(P_{F_i}(t)) \tag{14}$$

where $\Phi$ is the standard normal distribution function. The probability of failure $P_{F_i}(t)$ in the time interval [0, t] is determined from

$$P_{F_i} = P(M_{F_i} \leq 0) \tag{15}$$

In a time-invariant reliability analysis the estimate of the probability of failure can approximately be obtained by considering the extreme load in the lifetime $T_L$ and the strength at time i. The calculation time of a time-variant reliability index calculation is much higher than the calculation time of a time-invariant reliability index calculation. Therefore, a time-variant reliability analysis should only be performed if it is absolutely necessary.

*Example*

The following example taken from Thoft-Christensen et al. [2] is used to illustrate the reliability assessment of a concrete bridge taking into consideration corrosion of the reinforcement. The example is based on an existing UK bridge, but some limitations and simplifications are made. The bridge was built in 1975.

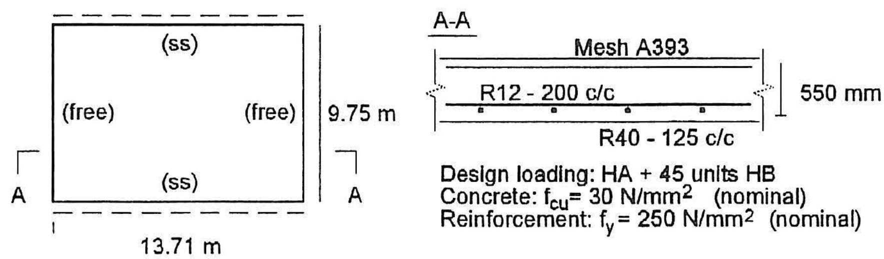


*Figure 3. Concrete bridge used in the example.*

The bridge was designed for 45 units HB load, see [15]. The bridge has a span of 9.755 m, the width is $2 \times 13.71$ m, and the slab thickness is 550 mm.

The general traffic highway load model in the Eurocode 1, Part 3 (ENV 1991-3:1995) for lane and axle load is applied. The load effects produced by the Eurocode model (lane and axle load) are multiplied by a static load factor (extreme type 1) and a dynamic load factor (normal). Several load cases must be considered. However, in this paper only the load case with packed lanes of 3 m width is included.

The plastic collapse analysis and estimation of the load are performed using the COBRAS program, see [16]. The reliability analysis (element and system) is done using the programs RELIAB01 and RELIAB02, see [17,18]. The RELIAB and COBRAS programs have been interfaced and include an optimization algorithm to determine the optimal yield line pattern for each iteration of the reliability analysis. The estimation of the deterioration of the steel reinforcement is based on the program CORROSION, see [19].

The normalized reliability profile for the yield line and the corresponding probability of failure profile are shown in figure 4. The reliability index at the time t=0 is $\beta_0$=10.7. Due to the size of the concrete cover (mean value 60 mm) the deterioration does not have any effect until year 70.

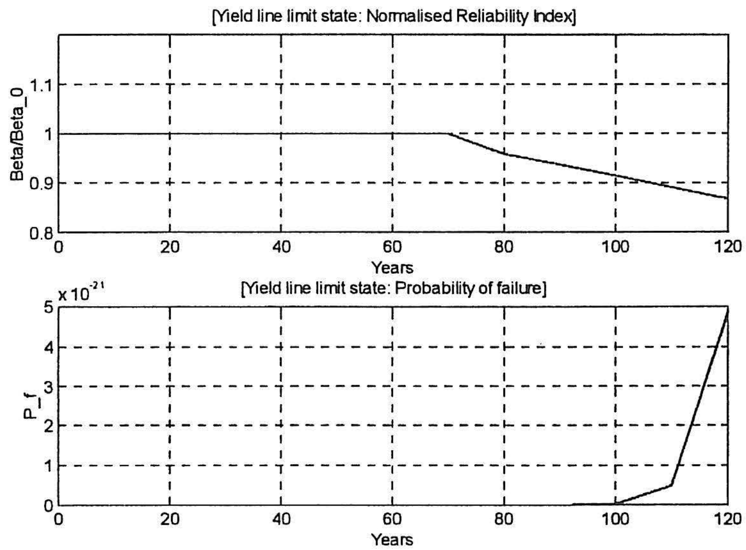


*Figure 4 : Reliability profiles using a yield line limit state.*

The results from the sensitivity analysis with regard to the mean values are shown for t=0 years and t=120 years in figure 5. The most important variables are, as expected, the thickness of the slab, the yield strength of the reinforcement, and the model uncertainty.. Observe that the magnitude of sensitivity with regard to the cover changes from negative at the time t=0 to positive at time t=120 due to the corrosion.

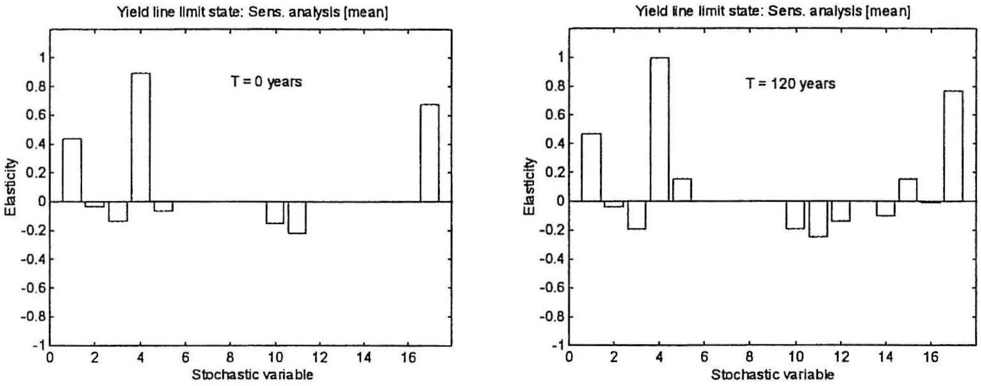


*Figure 5 : Sensitivity analysis for yield line limit state at t = 0 years and at t = 120 years.*

The normalized reliability profile for the crack SLS and the corresponding probability of failure profile are shown in figure 6. The reliability index at the time t=0 is $\beta_0$=7.3. Due to the size of the concrete cover (mean value 60 mm) the deterioration does not have any effect until year 90.

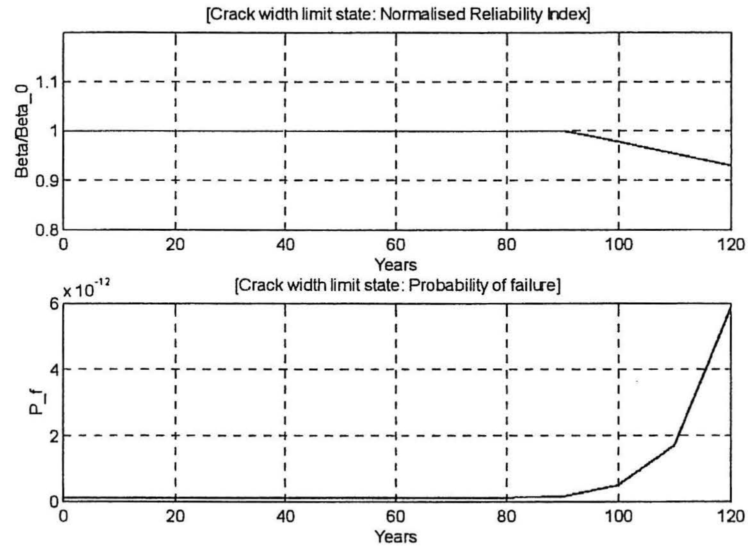


*Figure 6 : Reliability profiles using a crack width limit state.*

The results from the sensitivity analysis with regard to the mean values are shown for t=0 years and t=120 years in figure 7. The most important variables are as expected the concrete cover, the diameter of the reinforcement, the thickness of the slab, and Young's modulus . Observe that the magnitude of the sensitivity with regard to the cover is decreasing from the time t=0 to the time t=120 due to the corrosion.

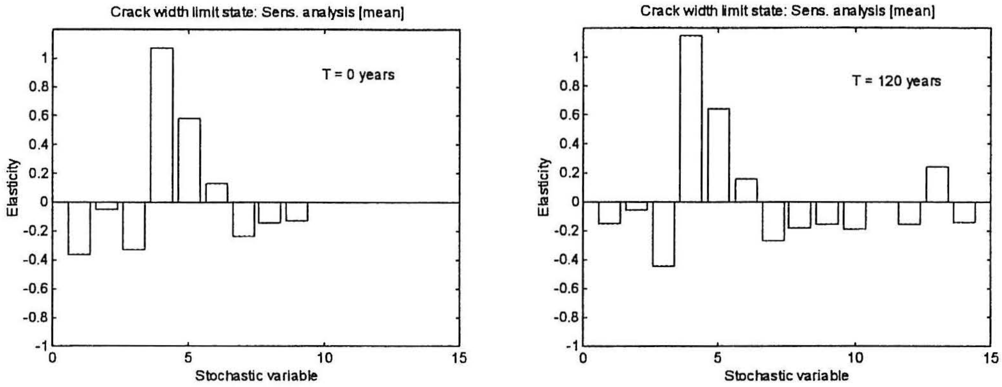


*Figure 7 : Sensitivity analysis for yield line limit state at t = 0 years and at t = 120 years.*

## 4. BRIDGE1 & BRIDGE2 BRIDGE MANAGEMENT SYSTEMS

### *Introduction*

Results from the research project "Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems", supported by CEC within the BRITE/EURAM research programme, is presented in this chapter.

The main objective of the project was to optimise strategies for inspection, maintenance and repair of reinforced concrete bridges by developing improved methods for modelling the deterioration of existing as well as future structures using reliability based methods and expert systems.

### *Reliability assessment*

In this bridge management system the probability of failure is estimated using the reliability program RELIAB®. The stochastic variables used in the reliability assessment are defined in table 1.

The system reliability index $\beta^s(t)$ is connected to the probability of failure $P_{F_I}(t)$ of the series system in the time interval [0, t] by

$$\beta^s(t) = -\Phi^{-1}(P_F(t)) \qquad (14)$$

where the probability of failure $P_F(t)$ is determined by the approximation (see Thoft-Christensen & Murotsu [6])

$$P_F(t) \approx 1 - \Phi_m(\bar{\beta}(t), \bar{\bar{\rho}}(t)) \qquad (15)$$

where $\bar{\beta} = (\beta_1, \ldots, \beta_m)$ and $\bar{\bar{\rho}}(t)$ is a matrix whose elements are the correlation coefficients between the linearised failure margins of the elements in the series system. $\Phi_m$ is the $m$-dimensional normal distribution function.

| | Stochastic variable | Distribution type |
|---|---|---|
| $X_1$ | Concrete cover | Normal |
| $X_2$ | Depth of beam | Normal |
| $X_3$ | Height of deck | Normal |
| $X_4$ | Initial diameter of reinforcement | Normal |
| $X_5$ | Width of column | Normal |
| $X_6$ | Depth of column | Normal |
| $X_7$ | Compression yield stress, concrete | Normal |
| $X_8$ | Yield stress of reinforcement | Normal |
| $X_9$ | Uniformly distributed dead load | Normal |
| $X_{10}$ | Uniformly distributed traffic load | Gumbel |
| $X_{11}$ | Point traffic load | Gumbel |
| $X_{12}$ | Chloride concentration on concrete surface | Normal |
| $X_{13}$ | Chloride diffusion coefficient | Lognormal |
| $X_{14}$ | Coefficient rate of carbonation | Normal |
| $X_{15}$ | Rate of corrosion | Normal |
| $X_{16}$ | Measurement uncertainties | Normal |

*Table 1: Definition of stochastic variables*

*Failure probability updating*

In the bridge management systems BRIDGE1 and BRIDGE2 the updating of stochastic variables etc. is performed using the techniques described in section 3.

*Functionalities of BRIDGE1 and BRIDGE2*

The expert system is divided into two expert system modules BRIDGE1 and BRIDGE2 which are used in two different situations, namely by the inspector of the bridge during the inspection at the site and after the inspector has returned to his office.

During the inspection the expert system will supply information on: the causes of observed defects, appropriate diagnostic methods, and related defects. Further, the inspector will be asked to record the inspection results so that they can be used later for e.g. assessment of the reliability of the bridge and in the decision whether a detailed structural assessment is needed.

A detailed analysis of the state of the bridge after an inspection is performed when the inspector has returned to his office, and after testing in the laboratory has been performed. The output of the analysis includes an updated estimation of the reliability of the bridge, decision whether a structural assessment should be made, decision whether to repair or not, relevant repair procedures, and the time for repair. Expert knowledge is used to improve the quality of the decisions.

*Application of BRIDGE1 and BRIDGE2*

The general inspection, maintenance, and repair model from inspection no. *i* at time $t_i$ to inspection no. *i*+1 at the time $t_{i+1} = t_i + \Delta t$ is indicated in figure 8 , where also the application of the modules BRIDGE1 and BRIDGE2 is shown.

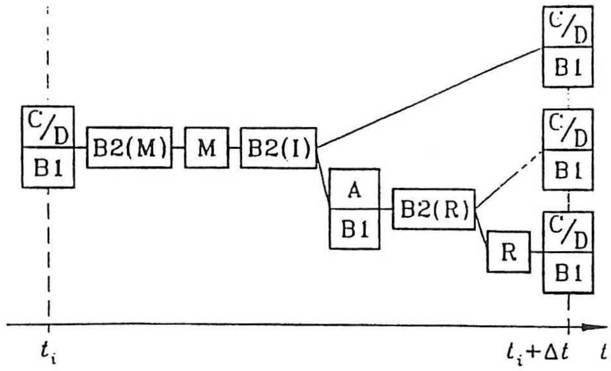


Figure 8. The inspection, maintenance, and repair model.

The symbols used in figure 1 are:

C: *Current inspections* are performed at a fixed time interval,e.g. 15 months.
D: *Detailed inspections* are also periodical at a fixed time interval which is a multiple of the current inspection time intervals, e.g. 5 years.
A: *Structural assessments* are only performed when a current or detailed inspection shows some serious defects which require a more detailed investigation.
M: *Maintenance* and repair of minor defects.
R: Structural *repair*.
B1:Application of *BRIDGE1* during the inspections.
B2(M): The *maintenance subsystem in BRIDGE2* assists in the selection of maintenance work and repair of minor structural defects to be performed.
B2(I): The *inspection module in BRIDGE2* assists in selecting the next type of inspection.
B2(R): The *repair subsystem in BRIDGE2* assists in selecting the best repair technique. The selection is based on economic considerations and expert knowledge.

After a current or a detailed inspection BRIDGE2 is used to rate the maintenance and minor repair work needed and to decide if a structural assessment has to be performed. The decision is based partly on estimates of the reliability of the bridge and partly on expert knowledge. The decision does not include economic considerations.

After a structural assessment BRIDGE2 is used to decide if a repair has to be performed and also to give the optimal point of time for the repair. Expert knowledge as well as numerical algorithms are used. The decisions are partly based on a cost-based optimization where different repair possibilities (selected by expert knowledge) and no repair are compared.

*Decision model with regard to structural assessment*

Let $t_i$ be the time of a periodic inspection and let the updated reliability index at the time $t$ be $\beta(t,t_i)$. The general decision model with regard to the structural assessment can then be formulated as:

- If $\beta(t_{i+1},t_i) > \beta^{min}$ then the inspection at the time $t_{i+1}$ should be a current or detailed inspection unless the damage is so serious that a structural assessment is needed. This decision is based on expert knowledge. $\beta^{min}$ is the minimum acceptable reliability index (e.g. 3.72).

- If $\beta(t_{i+1}, t_i) \le \beta^{\min}$ then a structural assessment should be performed before the next periodic inspection.

*Modelling of repair*

After a structural assessment it must be decided whether the bridge should be repaired and if so, how the repair is to be performed. Solution of this problem requires that all future inspections and repairs are taken into account.

In order to decide which repair type is optimal after a structural assessment, the following optimization problem is considered for each repair technique:

$$\max_{T_R, N_R} W(T_R, N_R) = B(T_R, N_R) - C_R(T_R, N_R) - C_F(T_R, N_R) \tag{16}$$

$$s.t. \quad \beta^U(T_L, T_R, N_R) \ge \beta^{\min} \tag{17}$$

where the optimization variables are the expected number of repair $N_R$ in the remaining lifetime and the time $T_R$ of the first repair. *W* is the total expected benefits minus costs in the remaining lifetime of the bridge. *B* is the benefit. $C_R$ is the repair cost capitalised to the time *t*=0 in the remaining lifetime of the bridge. $C_F$ is the expected failure costs capitalised to the time *t*=0 in the remaining lifetime of the bridge. $T_L$ is the expected lifetime of the bridge. $\beta^U$ 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).

The repair decision is then based on the results of solving this optimization problem but also on expert knowledge.

*BRIDGE1*

As mentioned earlier, the expert system module BRIDGE1 is used at the bridge site during an inspection. This expert system module contains useful information concerning the bridge inspected and the defects observed. The information includes: general information about the bridge, appropriate diagnostic 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 general information about the bridge stored in the database for the selected bridge can be reviewed. The database contains information about: bridge site, design, budget, traffic, strength, load, deterioration, factors that model the costs, and the cross-sections entered for the bridge.

New cross-sections can be entered for the selected bridge. The information stored in the database for each cross-section contains: cross-section identification, geometry of cross-section (detailed description of the reinforcement layers for cross-sections in the deck), failure mode, and load data. Technical support can be provided for a defect, see figure 9.

```
BREU P3091 -- BRIDGE1 -- Bridge Inspection Aid on Site 3-Aug-93 12:26pm v6.00

BRIDGE INSPECTION

                  Choose a defect detected on the bridge

        A_C01 Rust stain
        A_C07 Delamination / spalling
        A_C13 Crack over / under a bar
        A_D01 Exposed bar
        A_D04 Corroded bar
        A_D05 Bar with reduced cross-section
        A_D06 Broken bar
        A_E02 Obstruction due to rust in bearings
        A_E03 Broken retainer-bars
        A_E06 Corrosion in bearings
                          More ↓
```

*Figure 9. List of defects included in the expert systems.*

The technical support includes a list of diagnostic methods that can be used to observe a selected defect. The list is divided into high and low correlated diagnostic methods for the selected defect, see figure 10.

```
BREU P3091 -- BRIDGE1 -- Bridge Inspection Aid on Site 3-Aug-93 12:26pm v6.00

BRIDGE INSPECTION

              ** RELATED DIAGNOSIS METHODS **

   REFERENCE DEFECT: A_C01 Rust stain

(A) HIGH CORRELATION

1. M_A01 Unaided direct visual observation (or using binoculars, camera or
         video equipment)
2. M_K01 Phenolphtalein

(B) LOW CORRELATION

1. M_A02 Using telescopes,binoculars,micrometer, camera or video equipment
2. M_A04 Using special means of aerial access
3. M_B01 Surface hammering / chain dragging
                          More ↓
```

*Figure 10. List of diagnostic methods related to the defect "rust stain".*

```
BREU P3091 -- BRIDGE1 -- Bridge Inspection Aid on Site 3-Aug-93 12:26pm v6.00

BRIDGE INSPECTION

                    PROBABLE CAUSES

   REFERENCE DEFECT : A_C01 Rust stain

(A) HIGH CORRELATION

1. C_A14 Insufficient reinforcement/prestressing design cover
2. C_A24 Drainage directly over concrete, joint, bearing or an anchorage
3. C_B09 Deficient concrete compaction / curing
4. C_B11 Inaccurate reinforcement/prestressing positioning/detailing
5. C_F01 Water (wet / dry cycles)
6. C_F02 Natural carbon dioxide
7. C_F03 Salt / salty water (chlorides)
8. C_G01 Water (man-caused)
9. C_G02 Man-caused carbon dioxide
10. C_G03 Man-caused deicing salts
                          More ↓
```

Figure 11. List of probable causes for the defect "rust stain".

The technical support also includes a list of probable causes of a selected defect. The list is divided into high and low correlated causes for the selected defect, see figure 11.

A list of defects associated with the selected defect is also included. This list is very useful since the defects which can be found with a high probability can be reviewed if the selected defect is observed. Measures for the correlations between the selected defect and the related defects are shown, see figure 12.

```
BREU P3091 -- BRIDGE1 -- Bridge Inspection Aid on Site  3-Aug-93 12:26pm   v6.00

 BRIDGE INSPECTION

    OBSERVED DEFECT : A_C01 Rust stain

    OTHER PROBABLE DEFECTS :                                   Measure
                                                               (Max. 75)
   1.  A_D04 Corroded bar                                         55
   2.  A_D05 Bar with reduced cross-section                       55
   3.  A_I14 Deteriorated edge beams                              37
   4.  A_C07 Delamination / spalling                              32
   5.  A_C13 Crack over / under a bar                             30
   6.  A_D01 Exposed bar                                          20
   7.  A_E02 Obstruction due to rust in bearings                  17
   8.  A_E06 Corrosion in bearings                                17
   9.  A_E07 Deteriorated base plate / pot                        17
  10.  A_F05 Obstruction due to rust in joints                    17
  11.  A_F06 Corrosion in joints                                  17
  12.  A_E08 Detachment/failure of anchor bolts/pins              14
  13.  A_F07 Detachment / failure of anchorages                   14
                                More ↓
```

*Figure 12. List of defects associated to the defect "rust stain".*

*BRIDGE2*

The expert system module BRIDGE2 is used to make a detailed analysis of the bridge after an inspection when testing has been performed in the laboratory. New bridges and cross-sections can be entered into the database and existing bridges and cross-sections can be edited. For the bridges in the database the following options are available: review provisional defect reports, enter inspection results, estimate the reliability index, plan maintenance work and estimate costs, plan structural repair work and estimate costs, and review the agenda of inspection for one bridge or all bridges. Further, the database can be updated after repair.

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability  3-Aug-93 12:27pm

 BRIDGE ANALYSIS

                          STRENGTH INFORMATION
                          --------------------

 Maximum compression strain for the concrete (ec): 0.0035

 Modulus of elasticity for the reinforcement steel (Es): 200000  N/mm2

                                       DECK       COLUMNS
     Mean value of compression
     strength for the concrete         30          30          N/mm2

     Mean value of yield stress
     for the reinforcement steel       225         225         N/mm2
```

*Figure 13. Example of strength data.*

New bridges can be entered and existing bridges can be edited. The general information about the bridges stored in the database contains information about: bridge site, design, budget, traffic, strength, load, deterioration, factors that model the costs, and the cross-sections entered for each bridge. In figures 13-15 examples of strength, load, and cost data are shown.

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability 3-Aug-93 12:27pm

BRIDGE ANALYSIS

                         LOAD INFORMATION
                         ----------------

   Mean value of uniformly distributed dead load (G): 49      N/mm

   Mean value of uniformly distributed traffic load (Q): 30      N/mm

   Mean value of point traffic load (P): 180000   N
```

*Figure 14. Example of load data.*

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability 3-Aug-93 12:27pm

BRIDGE ANALYSIS

                      FACTORS THAT MODEL THE COSTS
                      ----------------------------

Factor used to model the benefits (k0): 3       ECU/vehicle

Factor used to model the functional repair costs (k1): 3      ECU/vehicle

Direct failure costs (CFO): 3000000  ECU

Number of days needed for replacement of a failed bridge (nr): 365

Distance from the headquaters of the bridge owner (LB): 100   km
```

*Figure 15. Example of cost data.*

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability 3-Aug-93 12:28pm

BRIDGE ANALYSIS

Bridge:   153-0002          Date of Inspection: 12-Dec-1992
Section:  11
Defect:   Rust stain

** Causes reported for the defect **

- Insufficient reinforcement/prestressing design cover
- Drainage directly over concrete, joint, bearing or an anchorage

** Diagnosis Methods used to conclude the defect **

- Unaided direct visual observation (or using binoculars, camera or
    video equipment)
- Phenolphtalein
- Using telescopes,binoculars,micrometer, camera or video equipment
- Using special means of aerial access

                         More ↓
```

*Figure 16. Defect "rust stain". Causes and used diagnostic methods.*

After an inspection the provisional defect reports recorded at previous inspections can be reviewed. A description of the detected defects and measurements of diagnostic methods can be entered. After a repair the databases can be updated. In figure 16 a description corresponding to the observed defect `rust stain' is shown.

The reliability index for the bridge can be estimated by the integrated FORTRAN program RELIAB ®. The reliability index when no inspection results are taken into account and the updated reliability index when all inspections performed for the bridge are both taken into account can be estimated.

The following submodules are integrated in BRIDGE2:

- BRIDGE2(M) is the maintenance/small repair submodule. This submodule assists in selecting the 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 structure's stability, and affected traffic recorded during the inspection, see figure 17.

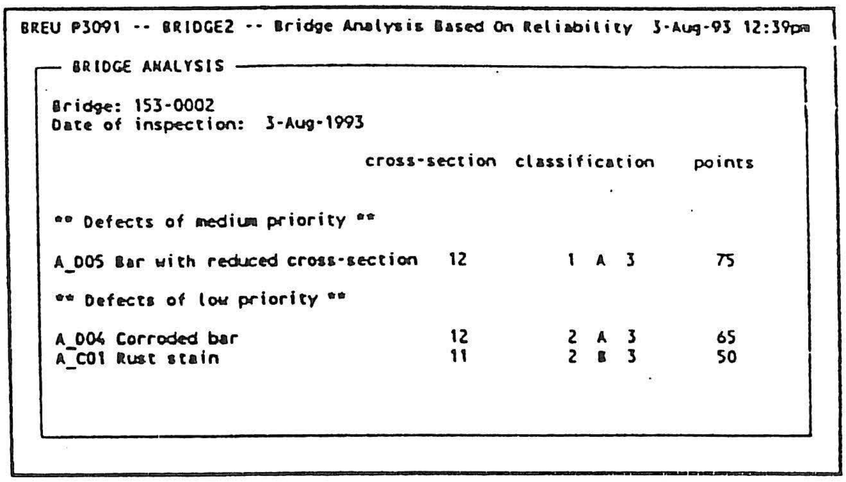


*Figure 17. Rating of defects in the maintenance subsystem.*

- BRIDGE2(I) is the inspection strategy submodule. This assists in the decision whether a structural assessment is needed before the next periodic inspection. The decision made in BRIDGE2(I) is mainly based on the updated reliability index for the bridge calculated by RELIAB ® (see figure 18). If the value of the updated reliability index for the bridge is acceptable then each of the defects detected at the latest periodic inspection and the combination of defects are investigated. Based on expert knowledge it is investigated whether a defect or combinations of defects from a structural point of view require a structural assessment.

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability  3-Aug-93 12:28pm

 BRIDGE ANALYSIS

   Bridge: 153-0002

   The reliability index is 2.38 calculated before any inspection was
   performed

   The value of the reliability index taking into acount the results of
   the inspections is:
                        BETA = 2.86

   *** STRUCTURAL ASSESSMENT IS TO BE PERFORMED BEFORE THE NEXT CURRENT
   OR DETAILED INSPECTION ***
```

*Figure 18. Decision tool related to structural assessment.*

- BRIDGE2(R) is the repair submodule. This submodule is always used after a structural assessment. It assists in selecting the optimal structural repair technique (including no repair) to be performed, when the repair should be performed, and the number of repairs in the remaining lifetime of the bridge. Further, the expected benefits minus costs are estimated. The repair plan is optimised based on a cost-benefit analysis by the FORTRAN program INSPEC ® (see figure 19).

```
BREU P3091 -- BRIDGE2 -- Bridge Analysis Based On Reliability  3-Aug-93 12:38pm

 BRIDGE ANALYSIS

   Bridge: 153-0002
   Date of inspection: 12-Dec-1992
   Section: 11
   Defect: A_C01 Rust stain

  Repair technique           Time    Number   Benefits-costs  Repair Cost
  ----------------           ----    ------   --------------  -----------

  R_C02 Concrete Patching    1995       1        26431713          5228
  R_D02 Concrete Patching    1995       1        26303962        145988
  R_D01 Concrete Patching    1995       1        26118570        366800
```

*Figure 19  Optimised repair plan for the defect "rust stain".*

The FORTRAN program RELIAB® can be used to estimate the reliability of a bridge. The FORTRAN program INSPEC ® can be used to estimate the optimal repair time and number of repairs for a given repair method. The estimation is based on a cost-benefit analysis for the bridge. The total expected benefits minus expected repair and failure costs in the remaining lifetime of the bridge is optimised.

## 5. ACKNOWLEDGEMENT

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- University of Aberdeen, Aberdeen, UK /Sheffield Hallam University, Sheffield, UK
- Jahn Ingenieurbureau, Hellevoetsluis, Holland
- Instituto Superior Técnico, Lisboa, Portugal
- LABEIN, Bilbao, Spain

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The expert systems BRIDGE1 and BRIDGE2 are implemented by LABEIN. RELIAB ® and INSPEC ® are CSR software.

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