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STRUCTURAL RELIABILITY THEORY
PAPER NO. 158

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P.Thoft-Christensen[1]

Abstract

In this paper two aspects of re-assessment of the reliability of concrete bridges are discussed namely modelling of the corrosion of reinforcement and updating of uncertain variables. The main reason for deterioration of concrete bridges is corrosion of the reinforcement. Therefore, modelling of the corrosion process is an important aspect of the re-assessment. Re-assessment of bridges is often based on inspection results, so it is essential to be able to update stochastic variables when inspection data have been obtained.

Introduction

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.

To assess the reliability of an existing bridge stochastic models for deterioration of reinforced concrete structural elements, for inspection, for maintenance and for repair must be formulated. Likewise a number of failure modes for structural elements must be modelled.

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.

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As an example of how re-assessment can be done the EU supported research project "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*" is presented .

Estimation of corrosion of reinforcement

Corrosion of steel reinforcement in concrete structures occurs in three successive stages, namely: the initiation stage, the propagation stage and the final stage.

Corrosion initiation period refers to the time during which the passivation of steel is destroyed and the reinforcement starts to corrode actively. Practical experience shows that the initiation stage is completely dominated by the carbonation of the concrete cover zone, and the excessively high chloride content around the embedded steel.

Corrosion propagation period refers to the time which follows corrosion initiation until failure occurs. The rate at which corrosion proceeds during the propagation period is believed to be governed mainly by the concrete characteristics and dimensions, and the exposure conditions.

The concrete structure is considered to be within the *final stage of corrosion* when a certain amount of damage is believed to be inflicted upon it, however no universal criteria is available yet to define the state of failure.

Carbonation of concrete is caused mainly by the reaction of CO_2 in the atmosphere with $Ca(OH)_2$ of the cement hydration products in the presence of water. The result is loss in alkalinity in the concrete cover, approaching pH values of neutrality, and the passivation of the reinforcement is no longer maintained. The penetration of CO_2 into concrete pores tends to move as a front, which proceeds at a rate controlled mainly by the CO_2 diffusion coefficient. The depth of carbonation can be determined as follows:

$$d = K \cdot \sqrt{t}$$

where d is the carbonation depth in millimetres, t is the time elapsed in years and K is the carbonation constant.

The presence of chloride ions in the vicinity of the steel reinforcement depassivates the steel. The rate of chloride penetration into concrete , as a function of depth from the concrete surface and time, can reasonably be represented by Fick's law of diffusion as follows:

$$\frac{\delta c}{\delta t} = D_C \frac{\delta^2 c}{\delta x^2}$$

where c is the chloride ion concentration, as % of the weight of cement, at distance x cm from the concrete surface after t seconds of exposure to a chloride source. D_C is the chloride diffusion coefficient expressed in cm^2/sec. The solution of that differential equation is as follows:

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

where C_0 is the equilibrium chloride concentration on the concrete surface, as % of the weight of cement, x is the distance from the concrete surface in cm, t is the time in sec, erf is the error function, D_C is the diffusion coefficient in cm^2/sec and $C(x,t)$ is the chloride concentration at any position x at time t. In a real structure, if $C(x,t)$ is assumed to be the chloride corrosion threshold and x is the thickness of concrete cover, then the corrosion initiation period t can be calculated based on a knowledge of the parameters C_0 and D_C. Typical values for C_0, as % of cement weight, for a bridge deck and a bridge column exposed to de-icing salt are 1.6 and 5.0 respectively.

For plain concrete of moderate strength ($f_{cu} \approx 30$ N/mm^2) reported values of D_C are in the range between $1 \cdot 10^{-8}$ and $5 \cdot 10^{-8}$ cm^2/sec. Based on vast experimental results on chloride diffusion into concrete samples, it has been concluded that D_C is time dependent. The relationship between chloride diffusion coefficient D_C and time t can be approximated by the following empirical equation:

$$D_C = D_1\sqrt{t}$$

where D_C is the chloride diffusion coefficient (cm^2/sec), t is the elapsed time (sec) and D_1 is a coefficient (cm^2/sec) that represents a D_C value at time equal to one second. The modified diffusion equation taking into account the time dependence nature of D_C is:

$$C(x,t) = C_0\left\{1 - \mathrm{erf}\frac{x}{2\sqrt{2D_1}\sqrt[4]{t}}\right\}$$

When corrosion of reinforcement has been initiated, results obtained from the experimental work project suggests that the deterioration process starts to proceed slowly in the early stages of the corrosion propagation period. As cracking, spalling and the loss in the bond strength start to take place a sharp increase in the deterioration process will occur. This behaviour can be described by the following expression:

$$B = 1 - \sin^2(90 \cdot t / T)$$

where B is a deterioration indicator defining the residual capacity of a deteriorated structure as a percentage of the design capacity, t is the actual time elapsed and T is the life span less the corrosion initiation period.

Corrosion of the embedded steel reinforcement is believed to affect the strength of concrete beams in two ways. Firstly, by reducing the rebar cross sectional area, leading to premature steel yielding. Secondly, by changing the conditions at the steel/concrete interface, mainly loss of surface roughness with development of flaky layer of corrosion products.

For the same degree of corrosion, the corrosion-induced damage is more pronounced with high corrosion rates. When corrosion of reinforcement has already initiated, it is suggested that the performance of the structure concerned may be described by the following empirical model:

$$B\% = 100 - 1600\frac{R \cdot T}{D}$$

where $B\%$ is the percentage residual strength, R is the corrosion rate (mm/year), T is the time elapsed (years), and D is the rebar diameter (mm)

Commercial software estimating the corrosion of reinforcement in concrete structures is available. As an example the graphic output from the software module CORROSION is shown in figure 1. In figure 1 is shown the expected corrosion development for a given reinforcement bar in a concrete bridge deck. This software module is used in the bridge management software package BRIDGE briefly presented later in this paper.

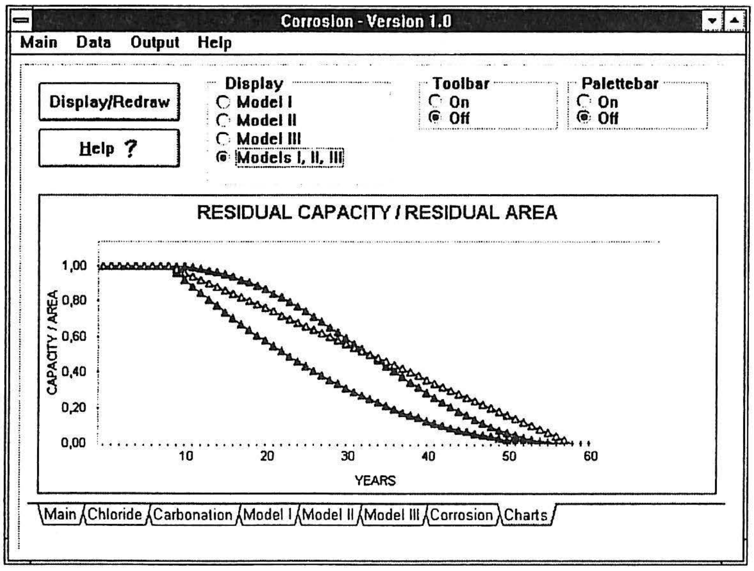

Figure 1. Graphic output from CORROSION.

Updating of stochastic variables

When new information is available as samples of one or more stochastic basic variables Bayesian statistical methods can be used to obtain updated (predictive) distribution functions of the stochastic variables (Lindley 1976, Aitchison & Dunsmore 1975).

Let the density function of a stochastic variable X be given by $f_X(x, \Theta)$, where Θ are parameters defining the distribution of X. The parameters Θ 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 Θ is called $g'_\Theta(\theta)$.

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

$$g''_\Theta(\theta|\bar{x}^*) = \frac{f(\bar{x}^*|\theta) g'_\Theta(\theta)}{\int f_n(\bar{x}^*|\theta) g'_\Theta(\theta) d\theta} \tag{1}$$

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

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

$$f_X(x|\bar{x}^*) = \int f_X(x|\theta) g''_\Theta(\theta|\bar{x}^*) d(\theta) \tag{2}$$

In the software module UPDATE the functions $g'_\Theta(\theta)$, $g''_\Theta(\theta)$, and $f_X(x|x*)$ are implemented for several distributions. In figure 2 for a given stochastic variable the initial and the predictive density functions are shown, that is the density function before and after some samples of the stochastic variable has been included. This software module is used in the bridge management software package BRIDGE briefly presented later in this paper.

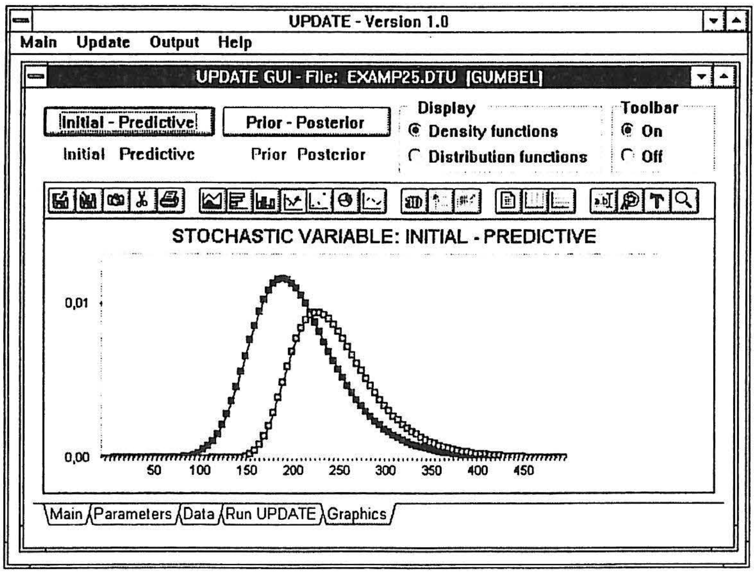

Figure 2. Graphic output from UPDATE.

Example: BRIDGE software

The proposed methodology for assessment of concrete bridges is illustrated by the management expert system BRIDGE. This management system is developed in the research project "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*" supported by EU within the BRITE/EURAM research program (Thoft-Christensen, 1994, 1995). Results from this research project are presented with special emphasis on the software modules used to estimate the corrosion process and the updating of the reliability of the bridge.

The main objective of the project is to optimize 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.

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 of the bridge (BRIDGE1) and after the inspector has returned to his office (BRIDGE2).

The architecture of the expert system consists of the two main modules BRIDGE1 and BRIDGE2, a number of dBASE IV databases, several FORTRAN programs, and INPUT and OUTPUT modules.

In figures 3 to 6 are shown some screens from the BRIDGE2 module. In figure 3 is shown how the reinforcement in the bridge deck is defined and entered into the expert system.

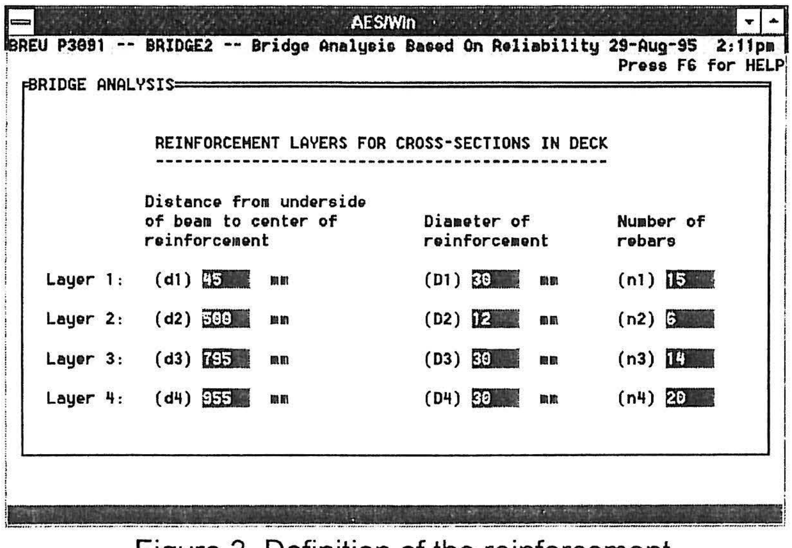

Figure 3. Definition of the reinforcement.

The parameters needed to estimate the corrosion process are entered into the expert system as shown in figure 4.

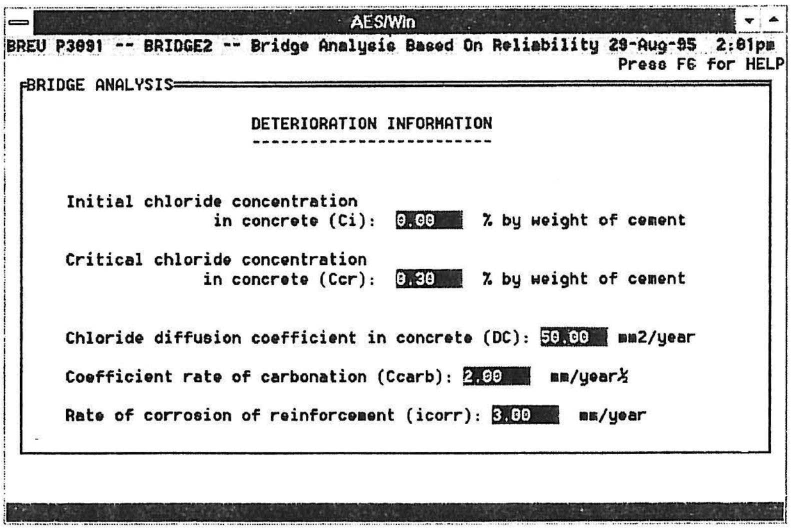

Figure 4. Corrosion parameters in BRIDGE2.

In figure 5 is shown how the measured chloride content in a certain distance from the surface and in a given cross-section is entered into the expert system.

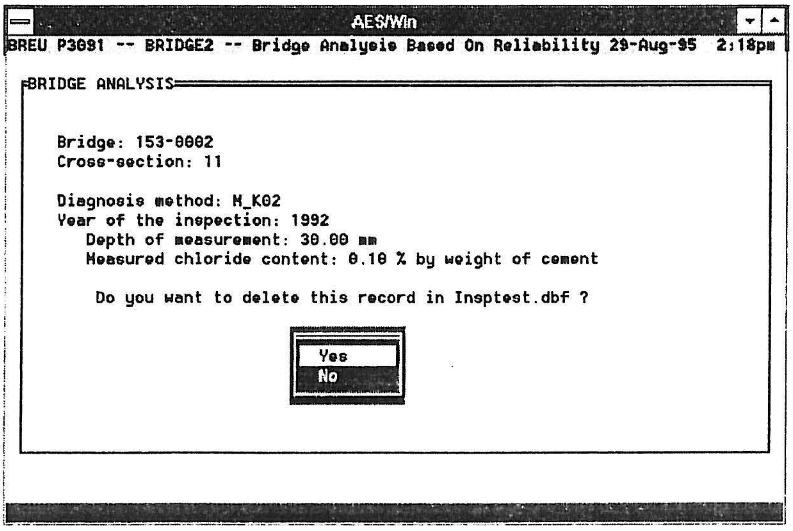

Figure 5. Input of measured value for the chloride content.

Finally using the software modules UPDATE and CORROSION and the reliability software RELIAB the reliability index before the inspection and after the inspection can be estimated, see figure 6.

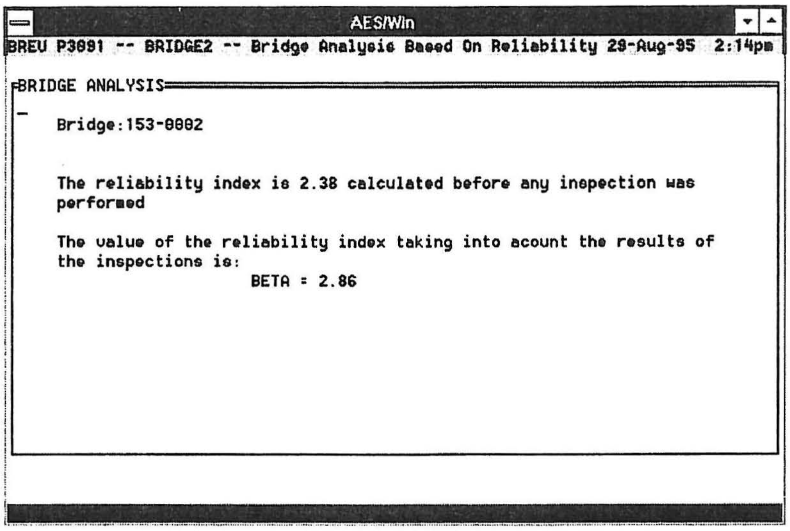

Figure 6. Re-assessment of the reliability of the concrete bridge.

Acknowledgement

Partners in the EU supported research project "*Assessment of Performance and Optimal Strategies for Inspection and Maintenance of Concrete Structures using Reliability Based Expert Systems*" resulting in the BRIDGE1 and BRIDGE2 expert systems are CSR, Aalborg, Denmark; University of Aberdeen, Aberdeen, UK; Sheffield Hallam University, UK; Jahn Ingenieurbureau, Hellevoetsluis, Holland; Instituto Superior Téchnico, Lisboa, Portugal; and LABEIN, Bilbao, Spain.

The software modules RELIAB, UPDATE and CORROSION are CSR software modules[2].

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