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Probabilistic Modeling of Chloride Contamination and Corrosion of Concrete Bridge Structures

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Abstract

This paper presents an approach to the uncertainty modeling and analysis of chloride contamination of concrete and corrosion of reinforcing steel of highway bridge structures that are subjected to the damaging effects of chlorides from deicing salts. The statistics of the governing parameters are generated from a field survey of an aging bridge structure that was exposed to the contaminants for about forty years. The uncertainty analysis and prediction of chloride concentration and reinforcement corrosion is carried out using the direct Monte Carlo method. The model predictions agree very well with the field data, which illustrates the capability of a probabilistic model to quantify the actual condition of a deteriorated structure.

1. Introduction

The deterioration of concrete bridge structures is recognized as one of the major challenges facing bridge owners and managers. Despite their better durability when compared to steel and timber bridge structures, reinforced and prestressed concrete structures are vulnerable to the damaging effects of corrosion induced primarily by chlorides (from deicing salts and seawater) and to a lesser extent by carbonation. It is estimated that one-third to one-half of the projected bridge rehabilitation costs in North America will be allocated for the rehabilitation of deteriorated bridge decks. The corrosion of the steel reinforcement leads to concrete fracture through cracking, delamination and spalling of the concrete cover, reduction of concrete and reinforcement cross sections, loss of bond between the reinforcement and concrete, reduction in strength (flexural, shear, etc.) and ductility. As a result, the safety and serviceability of concrete structures are reduced, and their useful service lives shortened.

Depending on the importance of a structure and the consequences of its failure, different rehabilitation methods may be implemented to upgrade it in order to ensure safety, serviceability and functionality and minimize the life cycle cost. The proposed probabilistic model takes into account the uncertainty associated with the material properties, structure geometry and dimensions, applied environmental

loads and corrosion resistance as well as the uncertainty associated with analytical models of chloride penetration into concrete and onset of reinforcement corrosion. The prediction capability of the proposed probabilistic model is illustrated for an aging corrosion-damaged concrete bridge deck that was exposed to chlorides from deicing salts for the forty years for which field data are available.

2. Uncertainty modeling in bridge management

Bridge maintenance management is a challenging task that involves the identification of optimal prioritization of bridge structures for maintenance and rehabilitation and the determination of the optimal rehabilitation strategy for each structure of a given bridge or a network of hundreds or thousands of bridges. This optimization should consider several objectives that may be of a conflicting nature, such as minimization of failure risk and minimization of rehabilitation costs over the life cycle of the structure. To achieve this goal, there is a need to develop and integrate reliable and effective decision support models that include: (i) condition assessment models; (ii) deterioration prediction models; (iii) risk assessment models; and (iv) maintenance optimization models as illustrated in Figure 1.

Figure 1. Decision models for bridge management

The available information regarding the material properties, loading, deterioration processes, risk of failure, and design and maintenance costs are incomplete or uncertain. There are different sources of uncertainty with varying magnitudes that affect the predictions of the above models, which constitute the building blocks of a comprehensive bridge

management system, as shown in Figure 1. These include: (i) physical uncertainty; (ii) model uncertainty; (iii) statistical uncertainty; and (iv) decision uncertainty. It is clear that the combination of these uncertainties lead to a considerable level of uncertainty in each model and in the overall bridge maintenance management system, in which decisions have to be made subject to uncertainty. Therefore, the need for probabilistic modeling of the different decision support tools illustrated in Figure 1 is of utmost importance in order to obtain reliable predictions and ensure effective management of aging bridges. In this paper, the emphasis is on the uncertainty modeling in the deterioration prediction of concrete bridge structures. This will be discussed in some detail, including the identification of the different sources of uncertainty affecting deterioration modeling.

3. Probabilistic deterioration models of concrete bridge structures

In most highway agencies, bridge maintenance management is based to a large extent on the results of bridge inspection combined with engineering experience and judgment for decision-making [1]. Structural concrete (reinforced and prestressed) is the main constituent material of the majority of highway bridge structures in North America. Chloride-induced corrosion is identified as the main cause of deterioration of concrete bridge structures. The sources of chlorides are the seawater and deicing salts used during winter. The application of a stochastic model based on the discrete Markov chain to the prediction of cumulative damage in structures by Bogdanoff [2] led to further developments and applications of the model for deterioration prediction and asset management, including highway bridges.

The deterioration models adopted in recently developed bridge management systems are based on the first-order Markov chain and are used to predict the deterioration of different bridge elements as well as the deterioration of a network of elements and bridges. Despite their practicality and ease of updating, they have serious shortcomings: (i) qualitative deterioration models that predict the future condition of the bridge element in terms of discrete condition ratings, which are subjective in nature; (ii) these condition ratings are based on the measurement of observable and some non-observable damage using non-destructive evaluation methods without considering their impact on structural performance; and (iii) the models assume a constant rate of deterioration as the cumulative damage after a stress cycle is assumed to depend only on the length of the stress cycle and the initial condition of the structural element.

Furthermore, a recent investigation by the U.S. Federal Highway Administration on the reliability of visual inspections of bridges [3] revealed that there was a significant variability in the assignment of condition ratings for the same bridge structure by different inspectors with

differences ranging from ± 1 to ± 2 condition rating points [3]. To address some of these shortcomings, a reliability-based quantitative model is proposed to predict the time-dependent chloride contamination of the concrete deck and the time to the onset of reinforcing steel corrosion. A brief description of the model is given in the following sections, including an illustrative application of the proposed model.

3.1. Chloride contamination of concrete structures

A reliable prediction model of chloride penetration into reinforced concrete structures is of utmost importance in predicting their time-dependent deterioration. The aggressive agents such as chlorides, water, and oxygen penetrate into concrete through the pore spaces in the cement paste matrix or micro-cracks. The rate of penetration is dependent primarily on the quality of concrete and more particularly on the water-cement ratio of the concrete mix and the presence of protective systems that delay or slow down the chloride ingress.

The governing transport mechanisms of chlorides into structures are the ionic diffusion in saturated concrete and water absorption in partially saturated concrete. Chloride diffusion is a transfer of mass by random motion of free chloride ions in the pore solution resulting in a net flow from regions of higher concentration to regions of lower concentration [4]. The rate of chloride ingress is proportional to the concentration gradient and the diffusion coefficient of the concrete (Fick's first law of diffusion).

However, in porous solids, such as concrete, moisture may flow via the diffusion of water vapor, as well as non-saturated or even saturated capillary flow may occur in finer pores [4]. Although chloride ingress into concrete is due to multiple transport mechanisms, Fick's law of diffusion may be applied to quantify the chloride ingress. A concentration gradient is considered as the common driving force. Given the fact that concrete is a heterogeneous and ageing material, temporal and spatial variability is associated with the diffusion coefficient. Since in the field, chloride ingress occurs under transient conditions, Fick's second law of diffusion can be used to describe the time variation of chloride concentration for one-dimensional flow, as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left[D \frac{\partial C}{\partial x} \right] \quad (1)$$

Under the assumption of a constant diffusion coefficient, and boundary condition specified as $C=C_s$ and the initial condition specified as $C=0$ for $x>0$, $t=0$, Crank's solution of Eq. (1) yields:

$$C(x, t) = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right] \quad (2)$$

where C_s is the chloride concentration at the surface; $C(x, t)$ is the chloride concentration at depth x after time t ; D is the diffusion coefficient; and t is the time of exposure.

Despite its simplicity and extensive use, this model has some shortcomings, because: (i) the diffusion coefficient is not a constant but rather depends on time, temperature, and depth because of the heterogeneous nature and aging of concrete; and (ii) for bridge decks, the top surface is subjected to a continually changing chloride exposure. The chloride concentration at the deck surface varies with the season, however at some shallow depth near the deck surface it can be assumed as a quasi-constant [4, 6]. In general, the values of the surface chloride concentration and “apparent” diffusion coefficient can be estimated from Eq. (2) by determining the best-fit curve through field data obtained from chloride profiles at different depths and exposure times.

3.2. Corrosion of reinforcing steel

The corrosion of steel in reinforced concrete structures is considerably different from the corrosion of steel exposed to the atmosphere, as the reinforcing is protected by the concrete cover (“skin”), which provides a barrier, or protection that slows down the penetration of aggressive agents needed for the initiation and propagation of corrosion, namely chloride ions, water and oxygen. The corrosion of the reinforcing steel is assumed to start when the concentration of chlorides at the level of the reinforcement (chloride contamination over the concrete cover) has reached the so-called “chloride threshold level”. The time to onset of corrosion (t_i) depends on the rate of ingress of chlorides into concrete, surface chloride concentration, depth of concrete cover, and the value of the threshold chloride level. Using Eq. (2) and assuming the same initial and boundary conditions, the time to onset of corrosion is determined as follows:

$$t_i = \frac{d_c^2}{4D[\text{erf}^{-1}(1 - \frac{C_{th}}{C_s})]^2} \quad (3)$$

where C_s : surface chloride concentration; C_{th} : threshold level of chloride concentration; D : chloride diffusion coefficient; and d_c : depth of concrete cover. There is no consensus regarding the definition of a single value for the threshold chloride level. A considerable scatter of this threshold value is found in the literature [4, 6].

3.3. Uncertainty modeling in chloride contamination and reinforcement corrosion

As mentioned earlier, a considerable level of uncertainty is associated with the prediction of chloride contamination of concrete and reinforcing steel corrosion. This uncertainty may be divided into physical uncertainty, statistical uncertainty, model uncertainty, and decision uncertainty. The physical or inherent uncertainty is that identified with the inherent random nature of a basic variable such as: (i)

variability of the concrete cover depth; (ii) variability of the surface chloride concentration and chloride diffusion coefficient; and (iii) variability of the loading from traffic, superimposed load and structure weight. The statistical uncertainty arises from adopting a probability density function or estimating statistical parameters from a limited sample size.

The model uncertainty results from the use of a simplified physical model or relationship between the basic variables to represent the actual phenomena, such as: (i) assumption of chloride transport mechanism governed by diffusion; (ii) use of simplified models of the diffusion coefficient and driving chloride concentration; (iii) assumption of non-correlated variables; and (iv) use of simplified chloride threshold level to define the corrosion resistance of concrete structures. The decision uncertainty is that associated with the definition of an appropriate failure criterion, such as onset of corrosion, or maximum acceptable level of chloride contamination in concrete, or corrosion, or total damage (cracking, spalling and delamination). This acceptable level of damage or failure criterion depends on the risk of loss of life and injury, importance of the structure in terms of location and traffic, costs of repair and replacement, impact on bridge users and redundancy.

In light of the above, it is clear that a deterministic prediction model can be quite inadequate owing to the considerable uncertainty in the governing parameters and structural response. Therefore, the level of chloride contamination of concrete structures and corrosion of the reinforcing steel should be determined using probabilistic methods. The uncertainties associated with the surface chloride concentration, diffusion coefficient, concrete cover depth, and threshold chloride level are considered by modeling them as random variables with probability density functions $f_{Cs}(c)$, $f_D(D)$, $f_{dc}(d_c)$, and $f_{Cth}(C_{th})$, respectively that are fitted to the data obtained from the field measurements of the chloride profiles, measurements of corrosion activity, and observed damage on the bridge structure.

3.4 Uncertainty analysis using Monte Carlo method

Monte Carlo methods are the most widely used techniques for uncertainty analysis, with a wide range of applications. These methods involve sampling at “random” from the distribution of inputs to simulate artificially a large number of experiments until a statistically significant distribution of the structure response is generated [7]. The direct sampling Monte Carlo is the most widely used method, although not as efficient as those based on importance sampling. The probability of an event $g(\mathbf{x}) \leq 0$ under consideration, typically termed “failure” (e.g. probability that the chloride concentration at the steel level exceeds a threshold level) may be expressed as [7]:

$$P_f = \int \dots \int I[g(\mathbf{x}) \leq 0] f_{\mathbf{x}}(\mathbf{x}) d\mathbf{x} \quad (4)$$

where $I[\cdot]$ is an “indicator function” that equals 1 if $[\cdot]$ is “true” and 0 if $[\cdot]$ is “false” [7]. Eq. (4) represents the expected value of $I[\cdot]$. If $\mathbf{x}_j$ represents the j^{th} vector of random observations from $\mathbf{f}_x$, then it follows directly from sample statistics that;

$$P_f \cong \frac{1}{N} \sum_{j=1}^N I[g(\mathbf{x}_j) \leq 0] \quad (5)$$

Eq. (5) represents an unbiased estimator of P_f [7].

4. Illustrative example

The prediction capability of the Monte Carlo method is illustrated on an aging corrosion-damaged concrete bridge deck that was exposed to chlorides from deicing salts for forty years. An extensive investigation of the deck that included detailed visual inspection, non-destructive and partial destructive evaluation of the deck was undertaken. The field data showed a considerable level of variability in all parameters that govern the chloride contamination of concrete and the corrosion of the reinforcing steel and are summarized in Table 1, in which μ and V represent the mean value and coefficient of variation, respectively [6].

Table 1 - Summary of data from field assessment

Variable	Distribution	μ	V
d_c (cm)	Normal	3.66	45%
C_s (kg/m ³)	Lognormal	4.56	40%
D_a (cm ² /year)	Lognormal	0.51	30%
C_{th} (kg/m ³)	Lognormal	1.35	10%

4.1. Prediction of chloride contamination of a concrete bridge deck

In the assessment of the ingress of chlorides into an aging concrete bridge deck exposed to the periodic application of deicing salts, diffusion can be assumed to be the governing transport mechanism. The chloride diffusion coefficient is determined by fitting the solution of Fick’s second law of diffusion to measured chloride profiles expressed in terms of total chloride concentrations (including both free and bound chlorides). Since only the chlorides dissolved in the pore solution (free chlorides) are responsible for the initiation of the corrosion process, this procedure yields only the value of the apparent diffusion coefficient “ D_a ” because chloride binding is not taken into account.

The random variable vector is $\mathbf{x}=[C_s, D, dc]^T$. Using the direct Monte Carlo simulation method, the chloride concentration at the steel level after 40 years is shown in Fig.2. This figure illustrates the skewed form of the distribution. It can be approximated by a gamma distribution with parameters 2 and 0.783, mean value of 2.57 kg/m³ (0.71% by cement weight), standard deviation of 1.36 kg/m³ (0.38% by cement weight) and a coefficient of variation of 0.53. The simulation results are very close to the field

measurements that yielded a mean value of 0.73% by cement weight and a coefficient of variation of 0.72 [6].

Figure 2. Chloride concentration at steel level

4.2. Prediction of reinforcement corrosion

The random variable vector is $\mathbf{x}=[C_s, C_{th}, D, dc]^T$. Using the direct Monte Carlo simulation method, the distribution of the time to onset of corrosion is generated. It has also a skewed distribution that was approximated by a lognormal model, with a mean of 10.23 years and a coefficient of variation of 100%. If t_i can be approximated by a lognormal distribution with mean μ_{ti} and coefficient of variation V_{ti} , it is possible to derive the following relationship for the time-dependent probability of reinforcement corrosion $P_f(t)$ as Follows::

$$P_f(t) = \frac{1 - \text{erf}(\beta_t / \sqrt{2})}{2} \quad (6a)$$

$$\beta_t = \beta(t) = \frac{\ln[(\mu_{ti} / t) \sqrt{1 + V_{ti}^2}]}{\sqrt{\ln(1 + V_{ti}^2)}} \quad (6b)$$

5. Conclusions

This paper illustrated the application of a probabilistic approach for the uncertainty modeling and prediction of chloride contamination of concrete and reinforcement corrosion in bridge structures that are subjected to the application of deicing salts during winter. The proposed probabilistic model provided very good predictions of the level of chloride contamination at different depths as well as the extent of corrosion of the reinforcing steel in the top mat of a deteriorated reinforced concrete bridge deck.

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