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Reliability of RC beams under chloride-ingress

Frédéric Duprat *

National Institute of Applied Sciences – INSA, Department of Civil Engineering, 135 Avenue de Rangueil, 31077 Toulouse Cedex 4, France

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Abstract

An assessment of the reliability of reinforced concrete beams with corroded reinforcement was proposed based on the computation of the reliability index. The corrosion was induced by chlorides provided from de-icing salts or marine breeze. Models for chloride diffusion and corrosion kinetics were chosen depending on the availability of consistent statistical data, and as well as to represent the physical phenomena realistically. The statistical distributions were specified from a wide review of previous studies for environmental parameters (surface chloride concentration or flux, coefficient of diffusion, corrosion current density) and also for geometrical parameters and mechanical properties of materials. Various design specifications were accounted for in designing the beams corresponding to different expected degrees of aggressiveness of the environment and the possibility of concrete cracking. The time-dependant reliability was evaluated taking into account the previous survival period of the structure. The results show the effect on reliability of exposure conditions, quality of concrete and design option according to the french design rules.

Keywords: Reinforced concrete; Chloride ingress; Corrosion risk; Reliability; Design provisions

1. Introduction

Chloride-induced corrosion of steel in reinforced concrete structures is one of the major causes of their deterioration over time. Chlorides from de-icing salts or marine breeze penetrate through the concrete cover and break down the natural protective oxide layer formed around the reinforcements by the strong alkalinity of pore solution. Once the protective layer has dissolved, corrosion is initiated if chloride concentration exceeds a threshold value. Pitting corrosion typically arises under chloride-ingress, in contrast to general corrosion occurring for similar reasons (destruction of the protective oxide layer) under exposure to atmospheric carbon dioxide or other pollutants. General corrosion affects large areas of reinforcement with more or less uniform loss over the perimeter of the rebars. Pitting corrosion is localized on small areas but causes a substantial reduction of the cross-section of the reinforcement and makes it brittle, implying that failure of the structure might occur without warning.

The prediction of the aging of concrete structures subjected to corrosion of reinforcement is complicated not only because the mechanical and chemical phenomena concerned are complex but also because of their random nature. There is indeed a high degree of uncertainty associated with the environmental parameters, physical properties of materials and loading. In order to protect structures against early deterioration, design considerations often include particular specifications for concrete cover, concrete mix (type of cement, aggregates, compacity) and reinforcement placement. Particular quality assurance during construction is also added to these design provisions.

However the owners of structures frequently resort to maintenance strategies that limit the cost of possible repairs to or replacement of degraded existing structures. Such strategies require planning and in-site measurements which are also costly. The optimal decisions about the experimental plan and the maintenance methods can be made on the basis of a probabilistic assessment of the risk

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* Corresponding author. Tel.: +35 561 559 930; fax: +35 561 559 900.
E-mail address: frederic.duprat@insa-toulouse.fr.

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of failure. In addition, this provides a rational criterion for comparison of the various choices for design.

In the present paper, a time-dependent reliability analysis of a reinforced concrete girder is developed. The girder is exposed to de-icing salt or to marine breeze. Probabilistic information about uncertainties related to the environment and physical properties of the materials have been estimated from a wide review of previous experimental or statistical studies. The probability of failure is given throughout the time for which the beam is subject to deterioration. Various design options are considered in order to emphasize their influence on reliability and their consequences on the maintenance strategy.

2. Chloride penetration

The flexural cracking of concrete structures under service loading allows direct ingress of chlorides if crack widths are sufficiently large. Nevertheless it can stated that cracking can only affect the initiation of corrosion and does not affect the subsequent propagation process [1,2]. Therefore, it is assumed here that chloride transport is a diffusion process through the saturated concrete cover.

2.1. Diffusion model

According to Fick's first law, the free chloride flux $F_{\mathrm{L}}(x,t)$ in the pore solution (in only one direction of propagation) is given by

$$F_{\mathrm{L}}(x,t) = -D_{\mathrm{L}}\frac{\partial C_{\mathrm{L}}(x,t)}{\partial x} \tag{1}$$

where D_{L} is the diffusion coefficient of free chlorides (m^2/s) and $C_{\mathrm{L}}(x,t)$ is the free chloride concentration (kg/m^3).

It is assumed that the diffusion coefficient D_{L} does not depend on the concentration. The mass balance leads to an expression for Fick's second law

$$\frac{\partial C_{\mathrm{T}}(x,t)}{\partial t} = -\frac{\partial F_{\mathrm{L}}(x,t)}{\partial x} \tag{2}$$

The total chloride concentration $C_{\mathrm{T}}(x,t)$ is the sum of free chlorides and bound chlorides chemically reacting with the cement paste or physically adsorbed to the cement gel. Consequently expression (2) becomes

$$\begin{aligned}\frac{\partial C_{\mathrm{T}}(x,t)}{\partial t} &= \frac{\partial C_{\mathrm{T}}(x,t)}{\partial C_{\mathrm{L}}(x,t)}\frac{\partial C_{\mathrm{L}}(x,t)}{\partial t}\\ &= \left(1+\frac{\partial C_{\mathrm{I}}(x,t)}{\partial C_{\mathrm{L}}(x,t)}\right)\frac{\partial C_{\mathrm{L}}(x,t)}{\partial t} = -\frac{\partial F_{\mathrm{L}}(x,t)}{\partial x}\end{aligned} \tag{3}$$

where $C_{\mathrm{I}}(x,t)$ is the bound chloride concentration. The binding isotherm is necessary to solve Eq. (3). If this isotherm is considered linear, the free chloride concentration in a semi-infinite field can be estimated by

$$C_{\mathrm{L}}(x,t) = C_0\,\mathrm{erfc}\left(\frac{x}{2\sqrt{D_{\mathrm{a}}t}}\right) \tag{4}$$

where C_0 is the surface chloride concentration (time-invariant – kg/m^3); x is the penetration depth (m); t is the time (s); D_{a} is the apparent diffusion coefficient (m^2/s) and erfc() is the complementary error function.

Eq. (4) is clearly a simplified diffusion model. In fact, binding is not linear and other parameters interact with chloride-ingress in concrete:

- –the binding between chlorides and other ionic species in the pore solution,
- –the binding between these other species and the cement paste,
- –the porosity of concrete and the internal pore structure,
- –the external conditions (humidity and temperature).

More accurate and comprehensive models of chloride penetration have been developed; most of them based on numerical solving of the transport equations together with empirical expressions for the physical parameters (binding capacities derived from Freundlinch or Langmuir isotherms, flux or molar concentrations of ionic species in the pore solution, diffusion coefficients). Meijers et al. [3], Johannesson [4] and Kong et al. [5] have proposed such models. These models are suitable and efficient as long as the experimental data required for empirical expressions are available. These input data can be *w*/*c* ratio, porosity of concrete, weight of hydration products, weight and volume percentages of cement paste and aggregates, temperature and humidity of concrete, and intrinsic diffusion coefficients of ionic species in cement paste and aggregates. Although possible in the laboratory, obtaining such properties for existing concrete structures is very difficult. There is therefore a lack of statistical data even for the *w*/*c* ratio. In such conditions, the use of a simplified model (Eq. (4)) appears justified provided that the parameters C_0 and D_{a} are estimated from numerous measurements. Hence in Eq. (4) $C_{\mathrm{L}}(x,t)$ will be replaced by $C_{\mathrm{T}}(x,t)$ because nearly all values of C_0 and D_{a} given in the literature have been obtained by fitting Fick's law to total concentration measured profiles (acid-soluble).

2.2. Surface concentration and diffusion coefficient

In the case of structures exposed to de-icing salts, statistical distributions have been suggested (see Tables 1a and 1b) from wide experimental investigations. Most of them were conducted on bridge decks in the USA [6–8]. Wallbank also gathered numerous data on bridges in the UK [9].

Table 1a
Surface concentration (kg/m^3) for structures exposed to de-icing salts

Reference	Range	Mean	Coefficient of variation	Distribution
[9]	0.25–15	6.5	0.7	Lognormal
[6]	1.2–8.2	3.5	0.5	Lognormal
[7]	2.45–9.8	5.63	0.1	Lognormal
[8]	0.15–5.25	2.51	0.68	Gamma