10.2478/v10160-011-0006-y

Transactions of the VŠB – Technical University of Ostrava

No.1, 2011, Vol.XI, Civil Engineering Series

paper #6

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EVALUATION OF CHLORIDE INFLUENCE ON THE CRACKING IN REINFORCED CONCRETE USING KOROZEENECK SOFTWARE

MODELOVÁNÍ VLIVU CHLORIDŮ NA VZNIK TRHLIN V ŽELEZOBETONU PROGRAMEM KOROZEENECK

Abstract

Korozeeneck software allows for deterministic as well as stochastic modelling of chloride-induced degradation of reinforced concrete structures. To perform stochastic modelling it is necessary to use the Monte reliability framework. The Korozeeneck software ensures the modelling of both phases (initiation as well as propagation). It helps to estimate the time until initiation of corrosion in the steel reinforced concrete structures. Also, the time until unacceptable cracking caused by uniform corrosion can be assessed. The Paper consists of a description of the analytical model used in the Korozeeneck software as well as of the example of a deterministic application.

Keywords

Reinforced concrete, corrosion, crack, reinforcement, chlorides, initiation, propagation.

Abstrakt

Program Korozeeneck umožňuje provádět deterministické a stochastické modelování degradace železobetonové konstrukce. Ke stochastické aplikaci je nutné použít spolehlivostní nástavbu Monte. Korozeeneck modeluje jak iniciační, tak propagační fázi koroze. Umožňuje odhadnout dobu do vzniku koroze ocelové výztuže v železobetonové konstrukci, a také dobu do vzniku rovnoměrnou korozí vyvolaných trhlin. Příspěvek obsahuje jak popis analytického modelu užitého v programu Korozeeneck, tak příklad deterministické aplikace.

Klíčová slova

Železobeton, koroze, trhlina, výztuž, chloridy, iniciace, propagace.

1 INTRODUCTION

Reliability of reinforced concrete structures is in many cases affected by time-dependent degradation processes due to which many structures require premature reconstruction, or replacement. Reduction of effective life of the structure usually leads to an increase in total costs,

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which in the case of the bridge structures consequently results in increased expenditure of public budgets. Balance between starting (construction) costs and total costs of the structure plays an important role. It is therefore important to build structures with a long life, which can be achieved by an accurate prediction of degradation mechanisms. Quality estimation of degradation processes allow professionals to better design the reinfoced concrete structural systems so that they are resistant to long-term environmental effects and loading.

Incorporation of the structure life into public infrastructure and industrial buildings requires advanced knowledge of degradation mechanisms, construction materials, reliability assessment, quality control and engineering practices. Despite the obvious need to design structures with a long life, tools and aids to achieve this goal are still in the process of development.

There is a growing demand in the engineering community for a function-oriented approach to the design of building structures, which would reflect the required level of reliability, service life, optimization of the total cost of construction and environmental impact. Attention is thus mostly paid to a relatively new approach called Performance-Based Design (loosely translated according to [28] as Assessment of Reliability with regard to Functional Characteristics, see for example [27], [13]).

Chlorides penetrate through the cover to the steel reinforcement and cause corrosion of the reinforcement. Typical representatives are the structures exposed to the marine environment and road structures exposed to road-salt impact. De-icing agents are one of the most important factors that reduces the life of reinforced concrete road infrastructure, both in the Central Europe and the northeast U.S. Chloride-induced corrosion may cause a decrease in utility of the structure not only with regard to its applicability, but also to its strength, and ultimately may lead to increased costs in the life cycle of the bridge.

2 PURPOSE OF KOROZEENECK SOFTWARE

Korozeeneck software [17] is developing for the implementation of deterministic and stochastic modelling of degradation of concrete structures with regard to the effect of chlorides. The software aims to gain better understanding of the behaviour of structures exposed to aggressive environments. The current version [17] works with the 1D model, which is e.g. suitable for the description of the reinforced concrete slab.

The approach implemented in the Korozeeneck software supplements estimated time of the corrosion propagation according to VIDAL et al. [32]. Model [32] is completed with an estimate of the corrosion current by MORRIS et al. [25] and also with an initiation period, which helps estimate the total life of the structure. The software seeks to estimate the initiation time of the steel reinforcement corrosion in the reinforced concrete structure, and also the time remaining to initiation of the uniform corrosion-induced cracking. The stochastic application requires the use of the Monte reliability superstructure [2].

The following sections provide a description of the transformation relationships applied in the Korozeeneck software and also an example of deterministic application. An example of the probabilistic application is planned for subsequent works.

3 MODELLING OF CHLORIDE-INDUCED CORROSION

The level of reliability of reinforced concrete structures is changing together with the propagation of the degradation process and the durability of a reinforced concrete structure. If the corrosion induced by the penetration of chlorides to the steel reinforcement is considered the predominant parameter affecting degradation, this process can be, with regard to the corrosion, divided into two phases [31]:

$$t_{service} = t_{initiation} + t_{propagation} \,, \qquad (1)$$

where $t_{initiation}$ is time-to-corrosion-initiation, and $t_{propagation}$ is time-to-reaching a critical level of corrosion in the steel reinforcement.

3.1 Initiation of Corrosion

The initiation phase of corrosion is completed with depassivation of the reinforcement. The steel reinforcement may begin corroding and the corrosion products begin to form. The level of reliability - usability may be conservatively related to the time-to-corrosion initiation $t_{\text{initiation}}$ ([15], [29], [27] and [6]). The reliability can also be assessed in relation to the cracking, as described in Section 3.3 entitled *The Propagation of Corrosion*.

The end of the initial phase is expressed by comparing the concentrations of chloride ions at the steel reinforcement $C_{xy,t}$, and the chloride threshold C_{th}. (concentrations sufficient for initiation of the corrosion, see e.g., [12]). The concentration of chlorides at the reinforcement $C_{xy,t}$ is described below.

3.2 Degradation Model

Corrosion of steel reinforcement is primarily controlled by the diffusion of chlorides. The influence of hydraulic pressure and capillary sorption is not reflected in the applied model, because there are many cases where their influence can be neglected (e.g. reinforced concrete bridge deck [14]). Procedure of the chloride penetration through the concrete as a function of depth and time can be modelled using Fick's Second Law of Diffusion ([34], [29], [6], [23] and [24]). Solution of an appropriate differential equation, usually referred to as Crank's, is shown in the following equation [4]:

$$C_{x,t} = C_0\left[1 - erf\left(\frac{x}{\sqrt{4D_c t}}\right)\right], \tag{2}$$

where $C_{x,t}$ is the concentration of dissolvable chloride ions (as a percentage of the mass of materials with cementing properties) over time t (in yrs) and depth x (in meters). C_0 is the concentration of chlorides (% of the cement mass, etc.) in the surface layer of concrete and D_c is the so-called "apparent" diffusion coefficient (in m^2/year). The diffusion coefficient is considered during the structure's service life to be constant. Introduction of D_c dependence on the time is a part of the development plan of Korozeeneck software.

Equation (2) is widely used for 1D modelling of chloride penetration, even though it does not include a combined transport of water and chloride ions [5], and also does not enable description of the specific boundary conditions needed to reflect the influence of a crack. Numerical solution of equation (2) is represented by the polynomial listed below:

$$C_{x,t} = C_0\left\{1 - \frac{2}{\sqrt{\pi}}\sum_{n=0}^{14}\frac{(-1)^n\left(\frac{x}{\sqrt{4\mathrm{D}_c t}}\right)^{2n+1}}{n!(2n+1)}\right\} \tag{3}$$

TIKALSKY lists in [29] an acceptable error to be 0.001 for depth of the reinforcement 0-1 m, diffusion coefficient of concrete between 1×10^{-8} and 1×10^{-14} m^2/s and lifetime examined to be up to 100 years when using 14 members of a polynomial.

Behaviour of a reinforced concrete structure can be described with respect to initiation of the corrosion using the reliability function $RF_{t,initiation}$. The reliability function is expressed as a time-dependent excess of the corrosion threshold C_{th} of the chloride concentrations $C_{x,t}$ in a depth of the reinforcement:

$$RF_{t,initiation} = C_{th} - C_{x,t}. \tag{4}$$

The chloride limit concentration value C_{th} depends mostly on the type and preparation of reinforcing liners and components of concrete. Typical values for the reinforced concrete bridge decks are 0.2% of the chloride mass in proportion to the cement weight according to ACI 222R-01, and 0.4% according to the CEB [3]. Data for steel with special protection are described in [7]. The broader debate regarding the size of the chloride threshold is given in [12].

If the concentration of chlorides at the steel reinforcement $C_{x,t}$ is greater than the chloride threshold C_{th}, the initiation phase ends and the corrosion starts. Time, under which the corrosion initiation occurs, is marked $t_{initiation}$.

3.3 Propagation of Corrosion

Corrosion products of different physical and chemical properties than the original material are generated during the corrosion process. There is an increase in the volume of steel reinforcement and at the same time a decrease in the effective cross-sectional area, leading to a decline in capacity.

The software deals with estimated time to the crack initiation in the concrete cover due to volume changes in the reinforcement for the uniform corrosion induced by the effect of chloride ions. The procedure allows for consideration of the effects of pitting corrosion.

Calculation of the formation of cracks is based on relationships derived from the VIDAL et al. [32] experiments. These laboratory experiments were carried out on the reinforced concrete beams exposed to chlorides and accelerated corrosion. Model [32], supplemented by the calculation of corrosion current by MORRIS et al. [25] is interesting regarding the possibility to describe the course of pitting corrosion. The selected approach was, through the case of uniform corrosion, compared with the model [LIU and WEYERS [19]. The results obtained described by duration of the propagation phase were similar.

The model described in [32] places limits on the propagation phase by the crack initiation of unacceptable width:

$$w_{cr} < w = K(\Delta A_s - \Delta A_{s0})\,, \tag{5}$$

where w_{cr} is the limit size of the crack and w the crack size predicted by the model depending on the regression coefficient K, the corrosion-induced loss in cross-sectional area ΔA_S and the decrease in cross-sectional area ΔA_{S0} at the time of initiation of an unacceptable crack. The regression coefficient K is defined in [32] as equal to 0.575.

The following equation shows the corrosion-induced loss in cross-sectional area ΔA_S

$$\Delta A_s = \frac{\pi}{4}(2\alpha_{corr\_type} x_{\mathrm{D}} D - \alpha^2_{corr\_type} {x_{\mathrm{D}}}^2)\,, \tag{6}$$

where $\alpha_{\mathrm{corr\_type}}$ reflects a type of corrosion, x_D represents the corrosion depth, and D is the diameter of the reinforcement [mm]. The depth of corrosion x_D is then:

$$x_D = V_{corr} \times t = 11.6 \times i_{corr} \times t, \tag{7}$$

where the density of corrosion current is i_{corr} [μA/cm^2]. In the applied model, the dependence on concrete resistivity ρ (in [Ohm-cm]) was chosen for the density of corrosion current (Fig. 12, MORRIS et al. [25]):

$$i_{corr} = 55000 \times \rho^{-1.3} \tag{8}$$

and where the corrosion rate V_{corr} [μm/year] below depends on the density of corrosion current

$$V_{corr} = 11.6 \times i_{corr}\,. \tag{9}$$

Other models describing the density of corrosion current is e.g. shown in [8].

In the equation to estimate the crack width (12), the calculation of the loss of cross-sectional area at the time of initiation of unacceptable crack ΔA_{s0} is featured, where the x_C is the thickness of the concrete cover:

$$\Delta A_{s0} = \frac{\pi \times D^2}{4}\left[1 - \left[1 - \frac{\alpha_{corr\_type}}{D} \times \left(7.53 + 9.32 \times \frac{x_C}{D}\right) \times 0.001\right]^2\right], \tag{10}$$

Loss of the reinforcement area over time (6) is described by a quadratic function. Time-to-corrosion t can be solved as follows:

$$\mathrm{A}t^2 + \mathrm{B}t + \mathrm{C} = 0, \tag{11}$$

where t represents $t_{\text{propagation}}$, and where the A, B and C constants are defined as follows:

$$\mathrm{A} = \sqrt{0.0001 V_{corr}} \frac{\pi}{4} \alpha^2_{corr\_type}, \quad \mathrm{B} = 0.0001 V_{corr} \frac{\pi}{4} 2D\alpha_{corr\_type}, \quad \mathrm{C} = \Delta A_{s0} + \frac{w_{cr,\lim}}{0.0575}. \tag{12}$$

Limit crack width is considered to be w_{cr}= 0.1 mm. The software uses $\alpha_{\text{corr\_type}}$ = 2 for the uniform corrosion. Higher values are described through the pitting corrosion.

The second root of the quadratic equation is then time $t_{propagation}$ of the propagation phase, time from the corrosion initiation to the initiation of unacceptable cracks. The total time to the unacceptable crack initiation is in the software marked as t_{service} and is a sum of the initiation time and propagation time of the corrosion (1).

The reliability function describing the lifetime of structures with regard to cracking is expressed by comparing the time to an unacceptable crack initiation $t_{service}$, and the required service life of the structure $t_{required}$:

$$RF_{t,service} = t_{service} - t_{required} \tag{13}$$

3.4 Stochastic Modelling - Simulation-Based Reliability Assessment

Due to the large scatter of input parameters, the probabilistic solution to the given issue is appropriate. The Simulation-Based Reliability Assessment method (SBRA) [21] (SBRA, see MAREK, et. al. [21], [22], [20]) can be selected for the solution. This method is suitable for application in the field of stochastic analysis of degradation processes.

Random variables are, as a part of the SBRA, characterized by the probability function (usually bounded histograms). Random variable inputs can be correlated using the approach [26]. The possibility of correlation was verified in [18], and is implemented in the Monte Carlo simulation tool [2]. The probability of exceeding the selected reference values is computed using simulation tools e.g. Monte Carlo, and the level of reliability is expressed by comparing the probability of failure P_f with the design probability P_d. The required reference criteria and design values can be customized to a specific engineering problem to match the purpose of a building, its location, client expectations, etc.

BRADÁČ [1] introduced the SBRA method to the field of durability assessments of reinforced concrete structures. TIKALSKY et al. consequently enhanced the use of the SBRA method with the Performance-Based Design of reinforced concrete structures ([29], [20], [30] and [16]). The enhancement lies in the analogy between the loading and the effects of aggressive chemicals, and also between the resistance and the ability to resist aggressive substances. Road salt represents the loading by chlorides, which penetrate to the concrete over time, and the corrosion begins if there is sufficient quantity of chloride ions, moisture and oxygen available at the level of reinforcement.

It should be noted that, especially in case of the large structures (bridges, long or high walls, etc.) the surface variability of the basic variables C_0 and D_c is often considered (see e.g. [33] and [9]).

4 EXAMPLE OF DETERMINISTIC CALCULATION

The illustrative example of reinforced concrete slab representing the bridge deck with an unprotected reinforcement exposed to road salt shows the estimated time to corrosion and subsequent corrosion-induced cracks.

4.1 Input

Input parameters can be entered from the command line, or it is possible to download these quantities from the input file. The first input parameter is the diffusion coefficient D_c = 4.91 [$m^2s^{-1}\times10^{-12}$], followed by the depth of reinforcement x_C = 0.075 [m], the concentration of chlorides on the concrete surface, C_0 = 1.11 [% of cement-like material properties], the resistance of concrete to the passage of an electric current (resistivity) ρ = 6.6 [kOhm-cm], the diameter of reinforcement D = 19 [mm], the chloride threshold for unprotected steel reinforcement C_{th} = 0.27 [% of material with cement-like properties].

Parameter D_c, x_C, C_0 and C_{th} values are obtained as averages of random variables applied in [11]. It describes the issues related to a reinforced concrete bridge deck exposed to effect of chlorides. The resistivity value was chosen with regard to laboratory measurements [10] and the chloride threshold value C_{th} is chosen based on data available in [7].

4.2 Estimated duration of the initiation and propagation phase

The Korozeeneck software [17], containing the model noted in Section *3 Modelling of chloride-induced corrosion*, is used to estimate the development of corrosion. The corrosion is initiated when the road salt concentration at the reinforcement $C_{xy,t}$ (see (2) and (3)) exceeds the chloride threshold C_{th},, see (4). In the selected example depassivation of the reinforcement occurs at the time $t_{initiation}$ = 13.7 yrs. At the $t_{initiation}$ time the steel reinforcement will begin to corrode. Expanding corrosion products place stress on the concrete cover of the reinforcement. Whenever the stress in the cover exceeds the tensile strength limit of concrete, the cracking in the concrete cover occurs. Whenever the crack size in the cover exceeds the selected limit value the structure is considered to be unreliable; the corrosion propagation phase $t_{propagation}$ is completed in the model. The structure is seriously threatened by exposure to road salt. In this case the $t_{propagation}$ = 10.7 yrs, see (12). Chlorides penetrate to the reinforcement with much greater intensity, and development of corrosion accompanied by a decrease in structural resistance also becomes faster. The sum of the initiation and propagation phases gives the service life of the structure $t_{service}$ = 24.3 yrs, see (1).

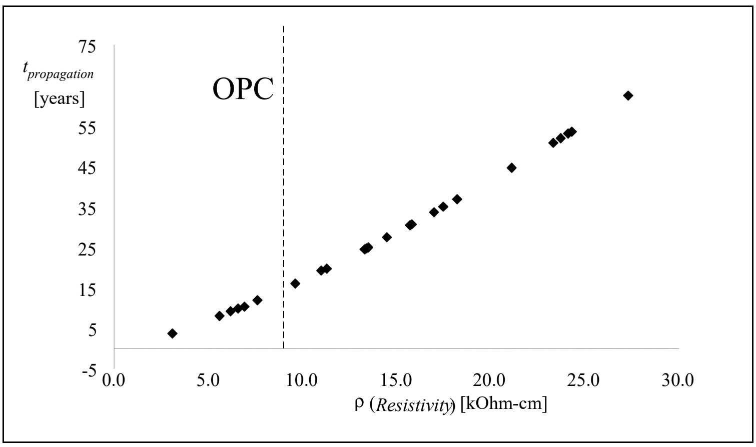

Figure 1: Estimation of the propagation phase of the corrosion $t_{propagation}$ depending on the quality of concrete described by the resistance to the passage of an electrical current– the resistivity ρ to cover x_C = 63,5 mm and a diameter of reinforcement D = 19 mm (OPC represents the ordinary-performance concrete, HPC represents the high-performance concrete). See [10] for details.

10.2478/v10160-011-0006-y

5 COMPARISON OF PROPAGATION PHASE OF CORROSION RELATIONSHIP WITH CONCRETE QUALITY

The graph in Fig. 1 illustrates the effect of the quality of concrete on corrosion propagation. The applied model [32] estimated that the propagation phase of ordinary-performance concrete would last between 5 and 20 years, while the duration of propagation phase for high-performance concrete is between 20 and 65 years.

6 CONCLUSION

The paper has demonstrated the possibilities of use of Korozeeneck software 1.0 [17] to estimate the effect of chloride on the durability of reinforced concrete structures. Time-to-corrosion initiation, and subsequent time to unacceptable development of cracks caused by volume changes of the reinforcement are being modelled herein.

The selected model solves the 1D problem with a reinforced concrete slab exposed to chlorides. The initial phase is modelled using diffusion. Propagation phase of corrosion is described using the model for uniform corrosion [32]. The chosen model is enhanced with by an estimate of the initial phase and its output is the service life of the structure composed of the initiation and the propagation phase of corrosion. The procedure described in [32] was chosen because it allows for future modelling of the pitting corrosion, which is typical for the effect of chlorides.

Due to the large scatter in input parameters the probabilistic solution to the given issue is appropriate. The suggested procedure includes only a deterministic solution, but the probabilistic application is possible in combination with a Monte Carlo simulation [2]. An example of a probabilistic application is planned for a subsequent work.

Approximation of crack width using a regression coefficient K (see [32]) allows capture of the trends of dependence between material properties and the duration of the corrosion propagation phase in the concrete structure exposed to chlorides. This area deserves further attention; especially with regard to the possibility of applying non-linear fracture mechanics in order to numerically model the behaviour of the concrete cover exposed to an increased volume of the steel reinforcement.

ACKNOWLEDGEMENT

This paper was implemented with the financial support of the Ministry of Education, Youth and Sports under the Operational Programme: OP for Education for Competitiveness (ECOP) as part of the project "Creation and the internationalization of top research teams and enhancing their excellence at the Faculty of Civil Engineering, VSB-TUO" project No. CZ .1.07/2.3.00/20.0013.

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