PROBABILISTIC MODELING OF STEEL CORROSION IN RC STRUCTURES

Dita Matesová, Břetislav Teplý, Jan Podroužek, Markéta Chromá
Brno University of Technology
Veveří 95, 602 00 Brno, Czech Republic

SUMMARY

The corrosion of reinforcement leads to a decrease in the effective area of the steel. The growth of rust products leads to concrete cracking, and later, the spalling of concrete cover, thus affecting the durability and reliability of a RC structure. The rate of reinforcement corrosion is governed by the availability of water, oxygen and chlorides on the steel surface. Durability limit states are explained, followed by a relevant model for degradation processes based on steel corrosion. Efficient design software is introduced which enables the probabilistic durability assessment of concrete structures. The development of the concentration of chlorides at the vicinity of the rebar surface is solved by a specific technique using cellular automata which is explained and then applied in an illustrative example showing the ingress of chlorides into a reinforced concrete cross section and the corresponding drop in the rebar's diameter due to corrosion.

1. INTRODUCTION

Utilization of design for durability may bring pronounced economical and sustainability impacts. Unfortunately, the prescriptive approach of current standards (e.g. Eurocodes EN 1990 and EN 1992) does not directly allow a design focused on a specific (target) service life and/or a specific level of reliability. This would require the consideration of inherent uncertainties in material and technological and environmental characteristics to be dealt with while assessing the service life of a structure. To overcome this, a full probabilistic approach should be utilized.

The service life of a building or structure is determined by its design, construction, ageing and maintenance during use. While assessing service life, the combined effect of both structural performance and ageing should be considered, wherever relevant. Generally, the limit state approach is applicable, governed by the probability condition:

$$P_f = P\left[A(t) \geq B(t)\right] < P_d \tag{1}$$

In case of design for durability a new category of limit state has recently been introduced – Durability Limit States (DLS). This kind of limit state precedes the occurrence of both Serviceability Limit States (SLS) and Ultimate Limit States (ULS), and represents a simplified limit state intended to prevent the onset of deterioration. It is based on the initiation of deterioration – see the future documents (fib Bulletin 34 and ISO 13823); more can be found in (Teplý et al., in press). In Eq. (1) A = action effect, B = barrier; both A and B (and hence the probability of failure P_f) are time dependent. This has not been considered for common cases of ULS or SLS in design practice very frequently up to now. The time t_S

relevant to the limit given by (1), i.e. the service life, and the deteriorating effect A are assessed by utilization of the appropriate degradation models and the relevant LS, making use of a probabilistic approach. *Note*: Instead of the probability of failure P_f, the index of reliability β is alternatively (and rather frequently) utilized in practice – see e.g. (Eurocode EN 1990). The level of reliability in the context of durability should be left to the client's decision together with the target service life. When considering the LS caused by the degradation of reinforced concrete structures, several kinds of attack may be distinguished. The present paper focuses on corrosion of reinforcement and its consequences – i.e. on the propagation period of structure degradation.

The utilization of stochastic approaches (a combination of analytical models and simulation techniques) was involved in the creation of specialized software for assessing the durability of newly-designed as well as existing concrete structures - FReET-D, see (Teplý et al., 2007). This code encompasses about 30 different degradation models, for assessment of both the initiation and propagation period.

2. CORROSION

Once the corrosion of reinforcement starts, its detrimental effects may occur. The rate of steel corrosion is governed by (among other factors) the availability of water and oxygen. Also, the presence of chlorides in the concrete surrounding the steel bars may accelerate the corrosion. During the propagation period, i.e. after reinforcement depassivation, several states/effects may be encountered:
(i) the volume expansion of rust products develops tensile stresses in the surrounding concrete leading to concrete cracking (mainly of concrete cover). The relevant limit condition should be constructed either with the tensile stress limit or the crack width limit;
(ii) while the corrosion progress continues, which consequently is responsible for the spalling of concrete cover;
(iii) a decrease in the effective reinforcement cross-section due to the corrosion, leading to excessive deformation and finally to the collapse of the bearing capacity of the cross section or structural member. Either general or pitting corrosion may be considered. In the following text a model suitable for handling case (iii) is shown.

2.1 Corrosion model

The uniform and the pitting types of corrosion are generally differentiated. The formula for the time related net rebar diameter $d(t)$ at exposure time t [years] for the prediction of the corrosion reads according to Andrade et al. (1996):

$$d(t) = d_i - 0.0116\, i_{corr} R_{corr} R_{Cl}\, t \tag{2}$$

where d_i is the initial bar diameter [mm] and parameter R_{corr} [-] expresses the type of corrosion. In the case of uniform corrosion, which is assumed in the example presented below, R_{corr} equals 2. Note that in the case of pitting corrosion R_{corr} equals 4-8 according to Rodriguez et al. (1996). Apart from parameter R_{corr}, other coefficients may be present in the formula, relating to the influence of chlorides, humidity, etc. Such coefficients may be applied only when appropriate data is available. The parameter R_{Cl} [-] regarding the effect of chlorides was added to Eq. (2) by the authors of this paper. The values of R_{Cl} may be determined by the results of experiments (Rovnaníková, 2002) governed by chloride concentration, see Fig. 1. Due to the method used in these experiments and the consideration of real conditions the values of R_{Cl} are certainly somewhat on the safe side. The constant 0.0116 is a conversion factor from μA/cm^2 to mm/years under the assumptions that steel (Fe) has n = 2 (number of electrons freed by the corrosion reaction), M = 55.85 g/mol (atomic mass) and ρ = 7.88 g/cm^3 (specific gravity). The same approach may be applied to the pitting type of corrosion, see e.g. (Gonzales et al. 1995).

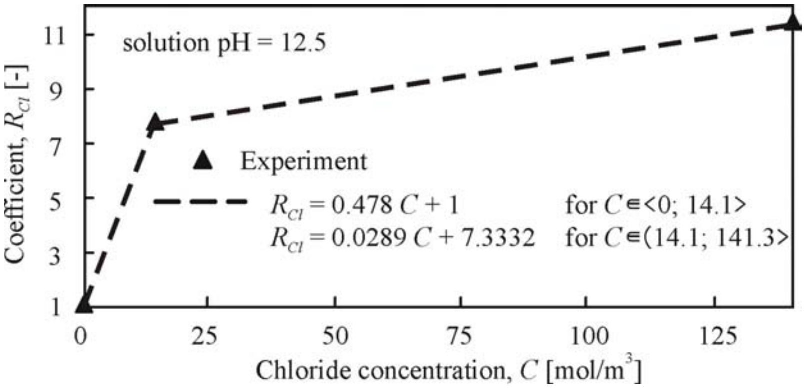

Fig. 1 The dependence of corrosion rate on chloride concentration.

In order to gain appropriate information about the chloride concentration at different locations of a structural member or cross-section of complex shape a relatively sophisticated technique of cellular automata has been adopted and is introduced in the following section.

2.2 Cellular Automata

A cellular automaton is a special class of evolutionary algorithm, which is a mathematical idealization of physical systems in which space and time are discrete (Wolfram, 1994). In principle, any physical system satisfying differential equations may be approximated as a cellular automaton by introducing discrete coordinates and variables, as well as discrete time steps. A cellular automaton consists of a collection of cells on a grid of specified shape that evolves through a number of discrete time steps according to a set of local rules based on the states of neighboring cells. The rules are then applied iteratively for as many time steps as desired. The overall simulation time is then the sum of all time steps.

The cellular automata solution of the diffusion equation was adopted from Biondini et al. (2004). The cross section is represented for our purposes by a 2D grid of regular uniform cells. Each cell has its state value representing the concentration of chloride ions. A visualization of the degradation evolution is shown in Fig. 2 for the time steps 0, 5, 25 and 50. The grey color represents the undamaged state of a cell while the black color represents the degraded state. The process of chloride ingress is governed by a local rule in which the evolutionary coefficients assign the level of chloride concentration redistribution within the cell's neighborhood. The relationship between the cell size, time step, evolutionary coefficient and chloride distribution constant is mandatory for the whole grid of cells within a time step. When the chloride supply changes, the distribution constant may change affecting the time step duration length. Stochastic effects may be treated as well, modifying the procedure by assuming the evolutionary coefficients to be random values with a given PDF.

In order to test the proposed methodology the standalone software SAPI is being developed by the third author (deterministic application of cellular automata). The application supports cooperation with ATENA 2D non-linear fracture mechanics software (Červenka and Pukl, 2005). The geometry of the construction is primarily modeled in ATENA and afterwards loaded by SAPI. At this point a grid of cellular automata is created according to the initial parameters. The main parameters are: the diffusion coefficient, cell size, time step and the evolution coefficient. After defining the aggressive environment (e.g. supply of chlorides from a deicing salt solution) the transformation process may begin. After each time step a text file with the current system state is created. The whole process is displayed on the screen as a real-time graphical visualization. Proper interpretation of these results provides information about local changes to the cross section's material properties (chloride concentration) over time. For this purpose several types of boundary rule have been implemented. The best rule suitable for the comparison with conventional analytical models is the mirror neighbor rule of hemisphere action.

Fig. 2 Degradation evolution visualization.

3. EXAMPLE

In the present example a reinforced concrete cross section is exposed to chloride ingress simulated by cellular automaton technique. Three different cases are assumed that differ by the surface areas exposed to chloride action as illustrated in Fig. 3 together with cross section geometry. The figure also documents chloride distribution in the cross sections after 30 years of exposure. The following input data for chloride diffusion simulation by cellular automata was used: surface concentration of chlorides 60 mol/m^3, cell size 0.0032 m, time step 7.402 days, diffusion coefficient 2×10^{-12} m^2/s and evolution coefficients 0.5 and 0.125 for central and surrounding cells, respectively. The development of chloride concentration over time in the vicinity of steel reinforcements R1, R2 and R3 for three types of boundary exposed to chlorides (I, II and III) is plotted in Fig. 4. Due to certain symmetries in boundary conditions in this example some of the rebars are attacked identically - the chloride concentrations differ rather slightly.

When we apply Eq. (2) using R_{corr} = 2 (uniform corrosion), i_{corr} = 1 μA/cm^2, d_i = 16 mm and the experimental results in Fig. 1 we obtain a drop in the rebars′ diameters over time due to corrosion. The results of deterministic analysis are plotted in Fig. 5 and a comparison with the case of a rebar which is not attacked by chlorides is also shown. The results of stochastic analysis performed for rebar R1_II at time t = 20 years by software FREeT-D are also depicted by means of the best fit of the probabilistic distribution function (PDF) found using the Kolmogorov Smirnov goodness-of-fit test. The input parameters for stochastic analysis were the following: d_i = 16 mm (lognormal two parametric PDF with a coefficient of variation (COV) of 2.5 %), i_{corr} = 1 μA/cm^2 (normal PDF, COV = 20%), R_{corr} = 2 (deterministic) and R_{Cl} = 8.34 (normal PDF, COV = 20%). The degradation of the structural capacity of the cross section would be high, so the concrete cover of 30 mm would be not feasible in the case of such an exposition type (heavy attack of de-icing salt without consideration of seasonal application).

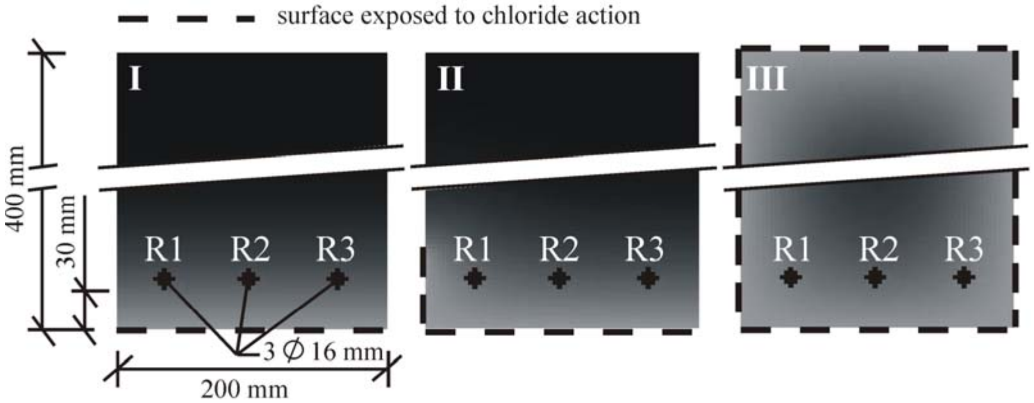

Fig. 3 Three cases of chloride ingress (I, II and III). Cross sections attacked by chloride are in grey color and sections without chloride are black.

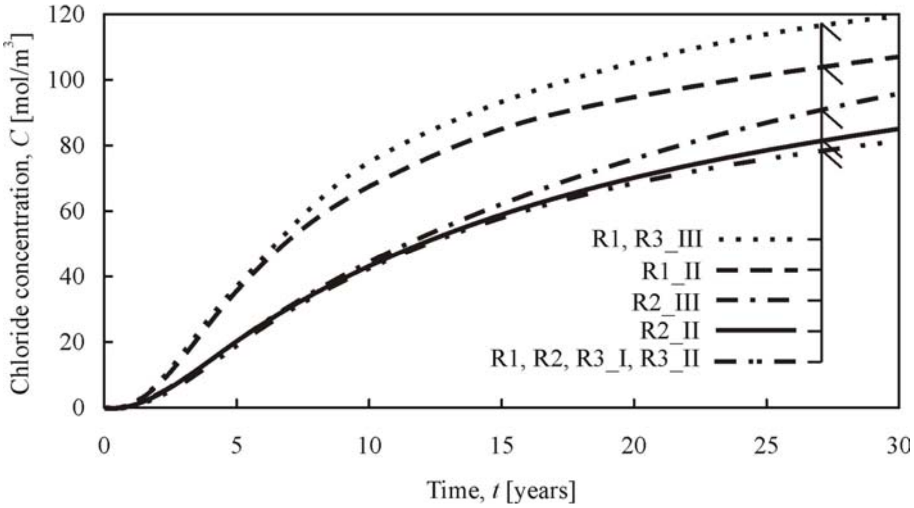

Fig. 4 Development of chloride concentration in the vicinity of steel rebars.

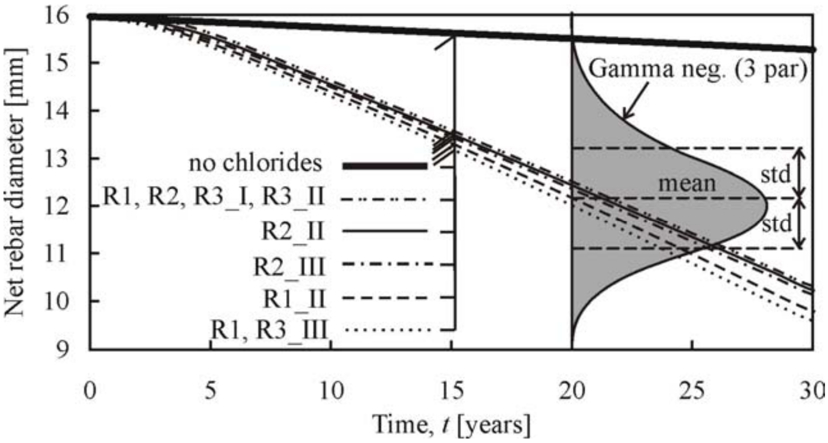

Fig. 5 A drop in rebars´ diameters over time due to corrosion.

4. CONCLUSIONS

A probabilistic approach for the durability assessment of concrete structures, focusing on reinforcement corrosion, has been presented together with suitable numerical model and software tools enabling the user to assess RC structure durability – the propagation period. The impact of chloride presence on corrosion rate is shown together with a special technique – cellular automata – for capturing the distribution of chloride concentration in the structural member. This creates the potential for more complex durability design, making use of statistical, sensitivity and reliability analyses of durability, serviceability and ultimate limit states. However, more complex data for the chloride concentration effect on the rate of reinforcement corrosion is lacking, as well as an assessment of the seasonal effects of de-icing salt application.

5. ACKNOWLEDGEMENT

This outcome has been achieved with the financial support of the Ministry of Education, Youth and Sports, project No. 1M0579, within the activities of the CIDEAS research centre.

6. REFERENCES

Andrade, C., Sarria, J. and Alonso, C. (1996), "Corrosion rate field monitoring of post-tensioned tendons in contact with chlorides", in proc. of Int. *Conf. on Durability of Building Materials and Components* 7 (vol. 2), Stockholm, 1996, pp. 959-967.

Biondini, F., Bontempi, F. and Frangopol, D. M., Malerba, P. G. (2004), "Cellular Automata Approach to Durability Analysis of Concrete Structures in Aggressive Environments", *Journal of Structural Engineering ASCE*, Vol. 130, No. 11, 2004, pp. 1724-1737.

Červenka, V. and Pukl, R. (2005), "ATENA Program Documentation", Červenka Consulting, Prague, 2005.

EN 1990 (2002), "Basis of Structural Design", Eurocode 0, CEN, 2002.

EN 1992-1-1 (2003), "Design of concrete structures – Part 1.1: General rules and rules for buildings", Eurocode 2, CEN, 2003.

fib Bulletin No. 34 (2006), "Service Life Design", part of the future *fib Model Code* 2008.

Gonzales, J.A., Andrade, C., Alonso, C., Feliu, S. (1995), "Comparison of rates of general corrosion and maximum pitting penetration on concrete embedded steel reinforcement", *Cement and Concrete Research* 25(2), 1995, pp. 257-264.

ISO/WD 13823, "General Principles in the Design of Structures for Durability" (currently under development), ISO TC 98/SC2/WG10.

Rodriguez, J., Ortega, L.M., Casal, J. and Diez, J.M. (1996), "Corrosion of reinforcement and service life of concrete structures", in Proc. of *Int. Conf. on Durability of Building Materials and Components* 7 (vol. 1), Stockholm, 1996, pp. 117-126.

Rovnaníková, P. (2002), "Corrosion of steel in different solutions – laboratory tests", Dept. of Chemistry, BUT Brno (unpublished).

Teplý, B., Matesová, D., Chromá, M. and Rovnaník, P. (2007), "Stochastic degradation models for durability limit state evaluation: SARA – Part VI", in proc. of *3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3 2007)*, Vancouver, Canada, 2007, in press.

Teplý, B., Chromá, M. and Rovnaník, P. (in press), "Durability assessment of concrete structures: Reinforcement depassivation due to carbonation", *Structure and Infrastructure Engineering*, in press.

Wolfram, S. (1994), "Cellular Automata and Complexity – Collected papers", WolfrAddison-Wesley, 1994.