Durability assessment of reinforced concrete structures due to chloride ingress up and beyond induction period

Journal:	*IABSE/Vancouver 2017*
Manuscript ID	YVR-0797-2017.R2
Theme:	Existing Structures into the Future
Date Submitted by the Author:	n/a
Complete List of Authors:	Smilauer, Vit; Ceske Vysoke Uceni Technicke v Praze, Structural Mechanics Hajkova, Karolina; Ceske Vysoke Uceni Technicke v Praze, Structural Mechanics Jendele, Libor; Cervenka Consulting s.r.o. Cervenka, Jan; Cervenka Consulting s.r.o.,
Material and Equipment:	Concrete, Prestressing, Steel
Type of Structure:	Bridges
Other Aspects:	Computational Methods, Durability, Structures and Environment

39th IABSE Symposium – *Engineering the Future*
September 21-23 2017, Vancouver, Canada

Durability assessment of reinforced concrete structures due to chloride ingress up and beyond induction period

Vít Šmilauer, Karolina Hájková

Czech Technical University in Prague, Faculty of Civil Engineering, Thákurova 7, 166 29 Prague 6, CZ

Libor Jendele, Jan Červenka

Červenka Consulting s.r.o., Na Hřebenkách 55, 150 00 Prague 5, CZ

Contact: vit.smilauer@fsv.cvut.cz

Abstract

Chloride ingress in reinforced concrete structures is the main cause for the corrosion of reinforcing steel. This paper presents a new chemo-mechanical model up and beyond induction period, taking into account concrete mix design, supplementary cementitious materials, concrete cover, effect of cracking, and environmental conditions. The 1D model of transient problem of chloride ingress is extended for crack effects, which accelerates propagation. Fracture–plastic constitutive model is used for the modelling of externally induced cracks. The influence of cracks is large, e.g. crack width 0.3 mm decreases the induction time approximately five times when compared to intact concrete. Once the end of induction period is reached, progressive corrosion stage takes place. The corrosion current density i_{corr} is used for calculating the time of concrete spalling for chlorides. After concrete spalling, reinforcement is subjected to corrosion without any protection. The models are validated using two practical cases; the Nougawa bridge from Japan and a strut of a concrete bridge from the Czech Republic.

Keywords: Chloride ingress, reinforcement corrosion, service life, durability

1 Introduction

Degradation of concrete and reinforced concrete structures is still important topic.This encounters reinforced beams, concrete bridges and other structures. For this reason, new models were formulated for the simulation of the corrosion of reinforced concrete structures due to carbonation and chloride ingress. The latter is caused by the effect of salts during winter periods or salts in the air and water in coastal areas. Kwon's model is used for chloride ingress [1], and is extended to account for the acceleration of these processes due to the presence of cracks in concrete [2]. Reinforcement corrosion starts when chloride concentration in the place of reinforcement exceeds approximately 0.6% of the concrete binder mass.

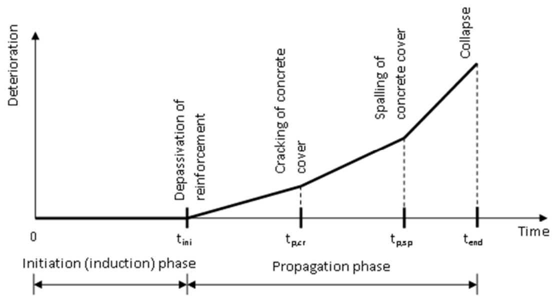

Figure 1: Initiation and propagation phase [5]

Corrosion of reinforcement during service life is described in Figure 1. It can be divided into two phases; the initiation (induction) period t_i and the propagation period t_p where corrosion of reinforcing steel takes place. The initiation period t_i has been described and validated in the previous paper [3]. The obtained results show strong influence of cracks on transport properties and speed of damaging mechanisms. For traditional cement-based materials, cracks 0.3 mm decrease induction time approximately 5 times for chloride ingress compared to non-cracked concrete. During the propagation period t_p, reinforcement corrodes and expanding corrosion products are formed. A uniform corrosion is characteristic for carbonation and a pitting corrosion for chlorides [4].

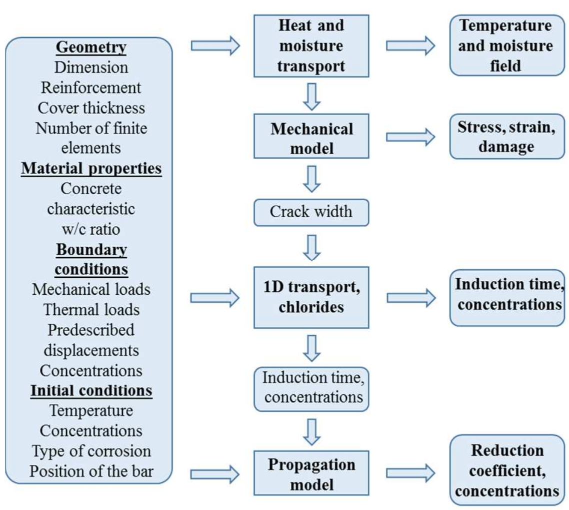

Figure 2: Workflow for chloride corrosion

The time $t_{p,cr}$ and $t_{p,sp}$ in Figure 1 corresponds respectively to a moment, when due to volumetric expansion accompanying corrosion, the concrete cracks and spalls. The corresponding depths of corrosion $x_{corr,cr}$ and $x_{corr,sp}$, are provided by DuraCrete model [5]. In the presented work we employed Liu and Weyer's model [6]. It is used for the calculation of the corrosion current density i_{corr} for chlorides up to time of concrete spalling.

Figure 2 shows workflow for chloride assessment with regards to reinforcement corrosion.

2 Model for initiation phase

The corrosion starts when the concentration of chlorides exceeds a critical value in the place of reinforcement. The 1D transient chloride ingress model reads [7]:

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_m(t)f(w)t}}\right)\right] \qquad (1)$$

where C_s is the chloride content at surface in [kg/m^3], $D_m(t)$ is the mean (averaged) diffusion coefficient at time t [m^2/s], x is the distance from the surface in [m] and $f(w)$ introduces acceleration by cracking (equals to one for a crack-free concrete). C_s and $C(x,t)$ can be related to a concrete volume or to a binder mass. The model for initiation phase is in detail described in [3].

3 Model for propagation phase

The corrosion rate for chlorides depends on the corrosion current density i_{corr} [μA/cm^2]. It depends on chlorides concentration in the concrete. This model predicts amount of corroded steel during the whole propagation period t_p. The corrosion rate is based on Faraday's law [8] determined as follows:

$$\dot{x}_{corr}(t) = 0.0116 i_{corr}(t) \qquad (2)$$

where $\dot{x}_{corr}$ is the average corrosion rate in the radial direction [μm/year], i_{corr} is corrosion current density [μA/cm^2] and t is calculated time after the end of induction period [years].

By integration of Eq. (2), we obtain the corroded depth for 1D propagation:

$$x_{corr}(t) = \int_{t_{ini}}^{t} 0.0116 i_{corr}(t) R_{corr} dt \qquad (3)$$

where x_{corr} is the total amount of corroded steel in radial direction [mm] and R_{corr} is parameter, which depends on the type of corrosion [-]. For uniform corrosion (carbonation) R_{corr} = 1, for pitting corrosion (chlorides) R_{corr} = <2; 4> according to [9] or R_{corr} = <4; 5.5> according to [10].

The effective bar diameter for both types of corrosion is obtained from:

$$d(t) = d_{ini} - \psi 2 x_{corr}(t) \tag{4}$$

where $d(t)$ is the evolution of a bar diameter in time t, d_{ini} is initial bar diameter [mm], ψ is uncertainty factor of the model [-], mean value ψ = 1 and x_{corr} is the total amount of corroded steel according to (4).

The corrosion rate for chlorides is affected by concentration of chlorides in the concrete. The calculation of the corrosion current density was formulated by Liu and Weyer's model [6]:

$$i_{corr} = 0.926 * exp\left[7.98 + 0.7771 ln(1.69 C_t) - \frac{3006}{T} - 0.000116 R_C + 2.24 t^{-0.215}\right] \tag{5}$$

where i_{corr} is the corrosion current density [μA/cm^2], C_t is the total chloride content [kg/m^3 of concrete] at the reinforcement location, which is determined from 1D nonstationary transport, T is temperature at the depth of reinforcement [K], R_c is the ohmic resistance of the concrete cover [Ω] [11] and t is the time after the initiation [years] with

$$R_C = exp[8.03 - 0.549 ln(1 + 1.69 C_t)] \tag{6}$$

4 Cracking of concrete cover

The cracking of concrete cover for chlorides can be estimated from DuraCrete model which provides realistic results [5]. The critical penetration depth for corrosion of steel $x_{corr,cr}$ is formulated as:

$$x_{corr,cr} = a_1 + a_2 \frac{C}{d_{ini}} + a_3 f_{t,ch} \tag{8}$$

where parameter a_1 is equal to 7.44e-5 [m], parameter a_2 is 7.30e-6 [m], a_3 is -1.74e-5 [m/MPa], C is the cover thickness of concrete [m], d_{ini} initial bar diameter [m], and $f_{t,ch}$ is the characteristic splitting tensile strength of concrete [MPa].

5 Spalling of concrete cover

The critical penetration depth of corroded steel $x_{corr,sp}$ for chlorides is calculated from DuraCrete model [5] as:

$$x_{corr,sp} = \frac{w^d - w_0}{b} + x_{corr,cr} \tag{9}$$

where parameter b depends on the position of the bar (for top reinforcement 8.6 μm/μm and bottom position 10.4 μm/μm), w_d is critical crack width for spalling (characteristic value 1 mm), w_0 is the width of initial crack (from mechanical analysis).

After spalling of concrete cover, corrosion of reinforcement takes place in direct contact with the environment. The rate of corrosion of reinforcement after spalling is given by aggressivity of environment [12].

6 Validation of the models

The above-mentioned models are implemented in software [13], using multi-physics approach for mechanics and transport. It predicts induction time and extent of corrosion for chloride ingress, and calculates remaining steel area. This yields a realistic estimation of the induction time, the propagation period and an estimation of service life, even considering the spalling of concrete cover. The mechanical behavior and concrete cracking is simulated using the fracture-plastic model [13]. The presented chemo-mechanical model is validated on several engineering structures suffering from chloride ingress, e.g. the Nougawa bridge, Japan a concrete strut of a prestressed bridge in Prague, Czech Republic. The model is capable of predicting durability due to chloride ingress with regards to intrinsic/extrinsic factors and it opens a path for performance-based design.

6.1 The Nougawa bridge, Japan

The Nougawa bridge was built in 1930 in a Japanese coastal area. The bridge is three span reinforced concrete structure with the total length 131 m. Due to high chloride presence in air and fast corrosion after 30 years from its erection the bridge had to be repaired by mortar. In 2006 (80 years after the construction), two beams from the bridge were cut out and further investigated

(Figure 3). In the mid-spans, the concentration of chlorides and the loss of reinforcement were evaluated. Carbonation depth was almost zero everywhere. Due to that fact, the assessment of chloride ingress was performed only.

Figure 3: The validation beam from the Nougawa bridge [15]

The longitudinal reinforcement of beams had diameter 25.4 mm, stirrups 9.5 mm and the concrete cover was 47 mm.

First, the bridge was mechanically loaded by the self-weight and the corresponding design life load. The following material parameters of the beams were assumed: the compressive strength 26 MPa and Young's modulus 25 GPa. Cracks up to 0.3 mm emerged due to loading. Figure 5 shows the calculated deflection and the reinforcement arrangement.

Second, the surface of the beams was exposed to chlorides with the following parameters: D_{ref} = 1.2e-7 m^2/day, t_{Dref} = 3650 days, m_{coeff} = 0.37, t_{mcoeff} = 10950 days, C_s = 0.014 kg/kg on ocean side (beams 8,9) and C_s = 0.011 kg/kg on bottom surface (beams 2,5), Cl_{crit} = 0.004 kg/kg, a_1 = 7.44e-5 m, a_2 = 7.30e-6 m, a_3= -1.74e-5 m/MPa, $f_{t,ch}$ = 3.5 MPa, w_d = 0.001 m, pitting corrosion R_{corr} = 3, corrosion rate after spalling 30 µm/year. Those parameters were mostly estimated from DuraCrete model [5].

The chloride concentration on longitudinal reinforcement at 80 years is depicted in Figure 6. Figure 4 validates chloride concentration in the point P2 at 80 years of service.

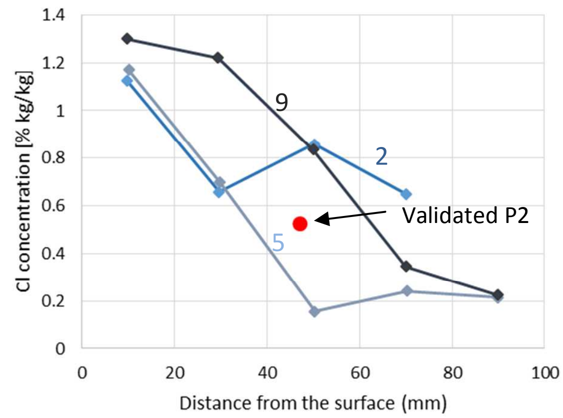

Figure 4: Evolution of chloride concentrations for beams 2, 5, 9 in 80 years

Figure 7 shows evolution of reinforcement area including patching of concrete cover. Predicted reinforcement area of 64% agrees well with the measured value of 62.5%.

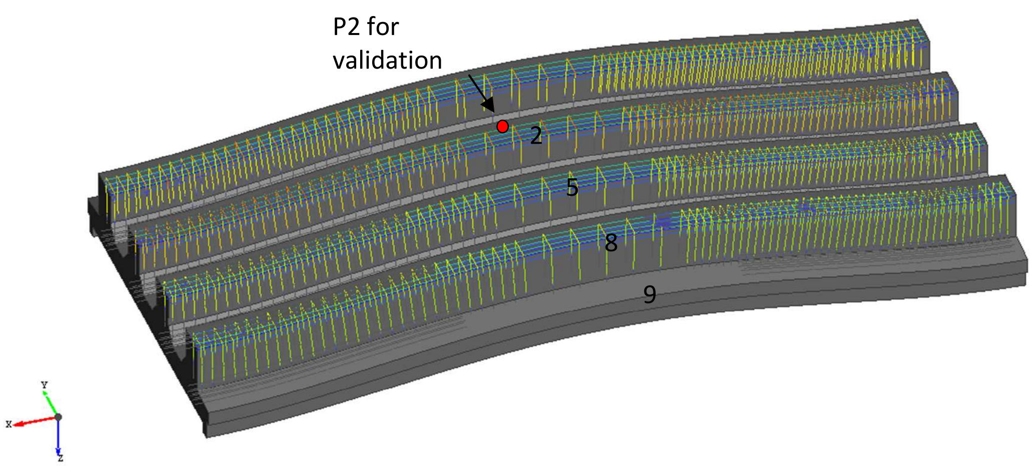

Figure 5: Deformed shape of the bridge section with the reinforcement model, bottom view of the model

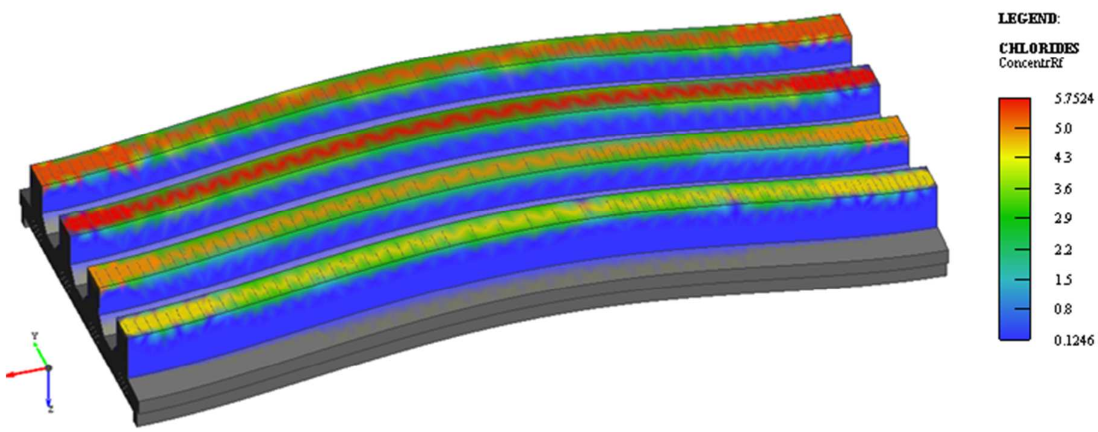

Figure 6: Concentration of chlorides (% kg/kg) in the place of reinforcements after 80 years at depth 60 mm

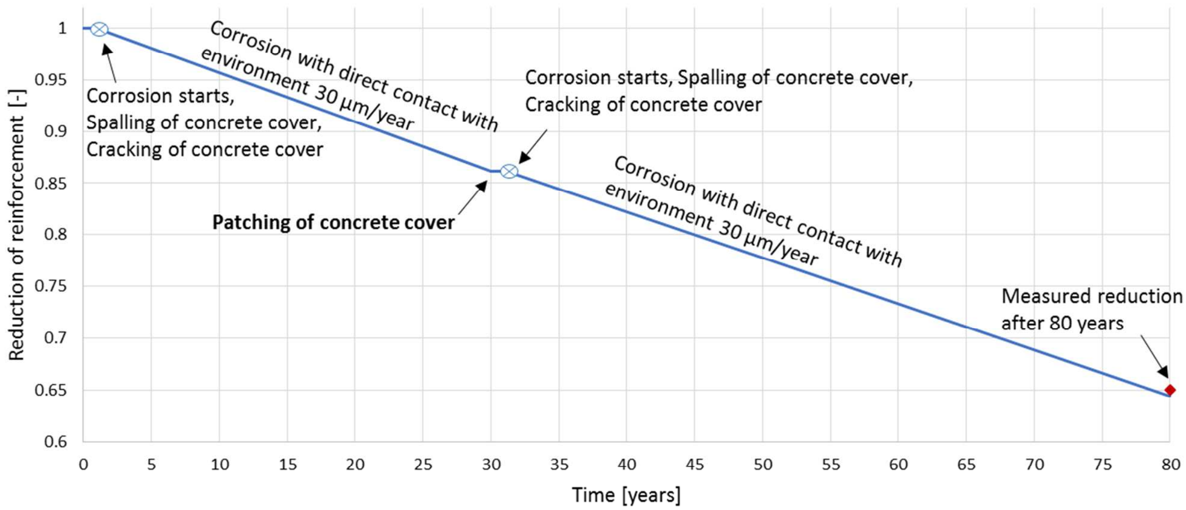

Figure 7: The Nougawa bridge, the evolution of reinforcement loss at point P2 in 80 years

6.2 Concrete strut of the pre-stressed bridge, the Czech Republic

The state of the pre-stressed concrete bridge X-567 in Prague was evaluated after 32 years of service life. The total width of the bridge is 12 m, the bridge is built as a precast frame with spans of 14 + 36 + 14 m. The reinforced concrete strut marked in Figure 8 is regularly attacked by chlorides from de-icing salts. Its bottom part was analysed to assess reinforcement corrosion due to presence of chlorides.

Figure 8: View of bridge with the analyzed strut

Concrete of the struts was classified as class C40/50. An estimated composition yields CEM I 42.5 350 kg/m^3 and water content 180 kg/m^3. The strut is reinforced by vertical bars with the diameter 32 mm and the concrete cover 35 mm. The surface of the strut was exposed to chlorides with the following parameters: D_{ref} = 1.37e-7 m^2/day, t_{Dref} = 3650 days, m_{coeff} = 0.37, t_{mcoeff} = 10950 days, C_s = 0.017 kg/kg, Cl_{crit} = 0.004 kg/kg, a_1 = 7.44e-5 m, a_2 = 7.30e-6 m, a_3 = -1.74e-5 m/MPa, $f_{t,ch}$ = 3.5 MPa, w_d = 0.001 m, pitting corrosion R_{corr} = 2, the rate of corrosion after spalling of the concrete cover 30 μm/year.

Figure 9 shows the geometry and chloride exposition of the modeled strut. Figure 10 - Figure 12 show the comparison of calculated and measured data. It came out that the sound concrete without cracks would yield excessively long induction time, therefore, hypotheses of crack widths 0, 0.05 and 0.1 mm were tested. Figure 11 demonstrates those scenarios.

The most realistic assumption favours crack width of 0.05 mm. In this particular case, the corrosion of reinforcement starts after 18 years, followed by spalling of concrete cover after another three years. The concentration of chlorides reaches 0.551% after 32 years at the reinforcement depth while the measured concentration is 0.51%. The remaining area of reinforcement reaches 0.944 after 32 years of service. This value is in good agreement with the measured value of 0.95, see Figure 12.

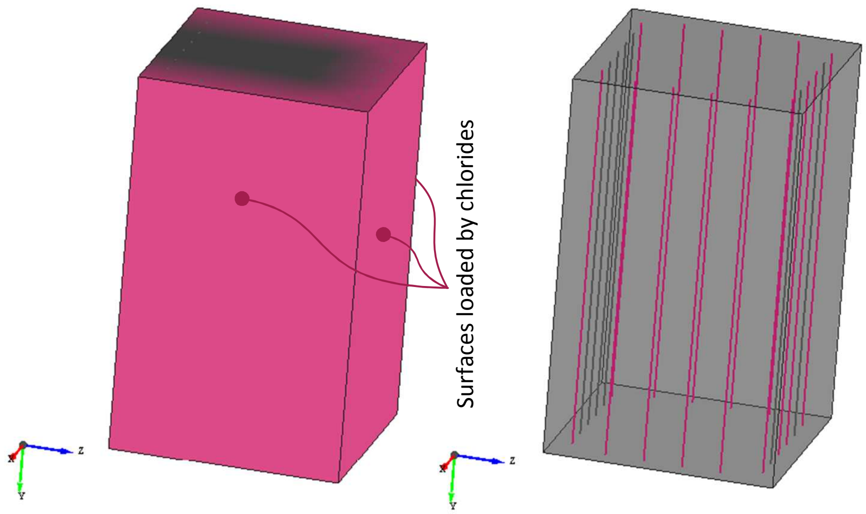

Figure 9: The geometry of the bridge strut and assigned chloride surfaces load

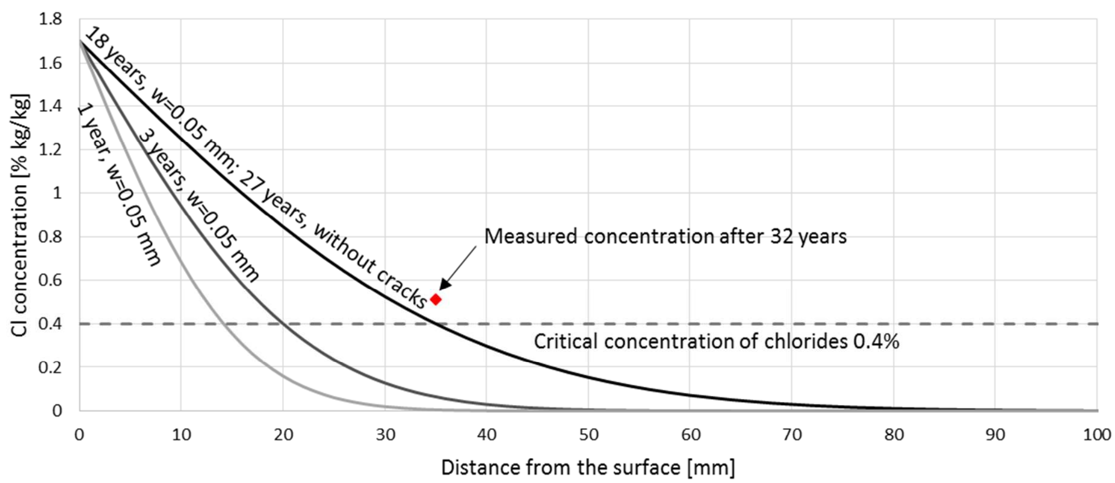

Figure 10: Chloride distribution in the depth of the bridge strut for the surface concentration of 1.7%

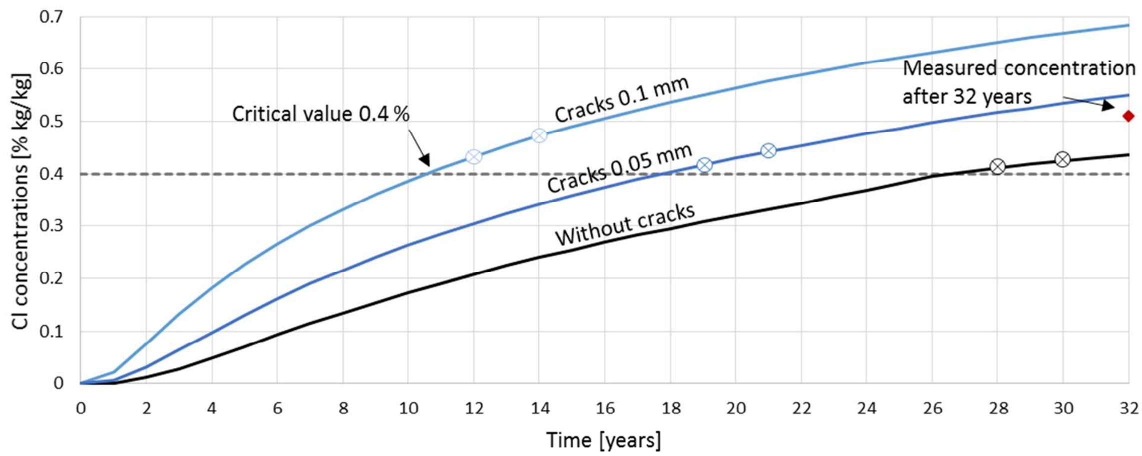

Figure 11: Chloride concentrations at the reinforcement depth, concrete cover = 35 mm

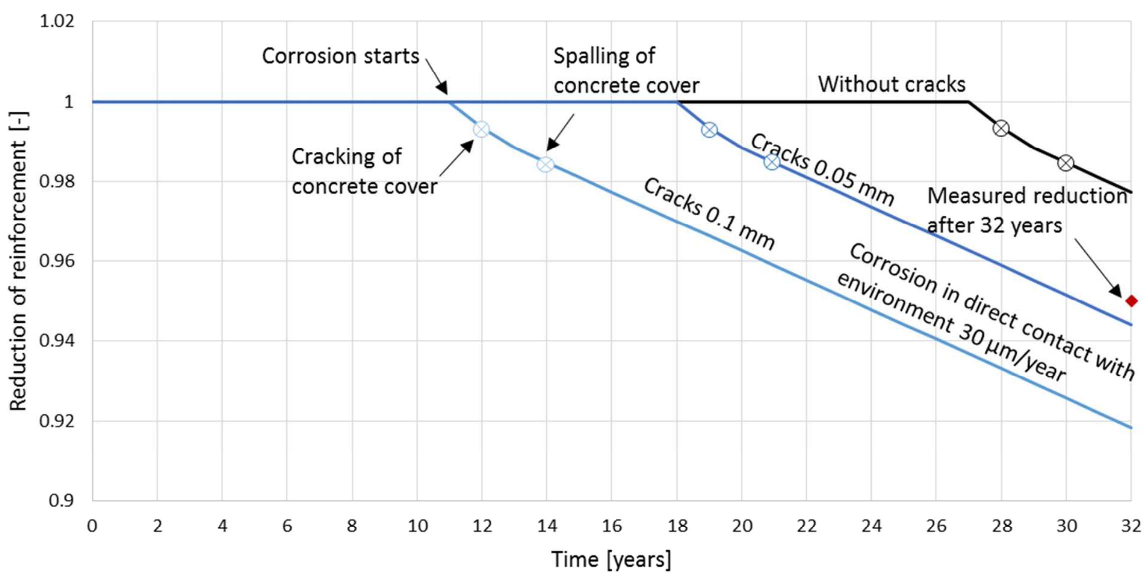

Figure 12: Reduction of the reinforcement area during service life

6.3 Acknowledgements

We gratefully acknowledge the financial support from the Technology Agency of the Czech Republic TAČR under the project TA04031458 and SGS12/116/OHK1/2T/11 granted by the Czech Technical University in Prague.

7 Conclusions

The paper focuses on reinforcement corrosion due to chloride ingress. Implemented models in ATENA software allow the simulation of the most important degradation events during the service life of a structure, i.e. induction time, time of concrete cover cracking, time of concrete cover spalling and direct corrosion of reinforcement and reinforcement loss rate. The models take into account diffusion acceleration due to cracks in the structure.

The present models can be extended for SLS, ULS or probability analysis, while assessing load-bearing capacity of a structure in dependence on the state of reinforcement corrosion.

8 References

[1] Kwon S.J., Na U.J. Prediction of Durability for RC Columns with Crack and Joint under Carbonation Based on Probabilistic Approach. *International Journal of Concrete Structures and Materials.* 2011; **5**(1): 11-18.

[2] Kwon S.J., Na U.J., Park S.S., Jung S.H. Service life prediction of concrete wharves with early-aged crack: Probabilistic approach for chloride diffusion. *Structural* Safety. 2009; **31**(1): 75-83.

[3] Smilauer V., Jendele L., Cervenka J. Prediction of Carbonation and Chloride Ingress in Cracked Concrete Structures. *In: B.H.V. Topping and P. Iványi, Editors. Proceedings of the Fourteenth International Conference on Civil, Structural and Environmental Engineering Computing.* Civil-Comp Press; 2013.

[4] Duprat F. Reliability of RC Beams Under Chloride-ingress. *Construction and Building Materials.* 2007; **21**: 1605-1616.

[5] Muthena A., Andrade C., Nilsson L.O., Edvardsen C., et al. DuraCrete, Final Technical Report, *Technical report*; 2000.

[6] Liu Y., Weyers RE Modeling the Dynamic Corrosion Process in Chloride Contaminated Concrete Structures. *Cement and Concrete Research.* 1998; **28**(3): 365-367.

[7] Kwon S.J., Na U.J., Park S.S., Jung S.H. Service life prediction of concrete wharves with early-aged crack: Probabilistic approach for chloride diffusion. *Structural Safety.* 2009; **31**(1): 75-83.

[8] Rodriguez J., Ortega L.M., Casal J. & Diez J. M. Corrosion of Reinforcement and Service Life of Concrete Structures. *In Proc. of Int. Conf. on Durability of Building Materials and Components*. 1996; **1**: 117-126.

[9] Gonzales J. A., Andrade C., Alonso C. & Feliu S. Comparison of Rates of General Corrosion and Maximum Pitting Penetration on Concrete Embedded Steel Reinforcement. *Cement and Concrete Research*. 1995; **25**(2): 257-264.

[10] Darmawan M. S. & Stewart M. G. Effect of Pitting Corrosion on Capacity of Prestressing Wires. *Magazine of Concrete Research*. 2007; **59**(2): 131-139.

[11] Liu Y. Modelling the Time-to-corrosion Cracking of the Cover Concrete in Chloride Contaminated Reinforced Concrete Structures. *Virginia: Polytechnic Institute*; 1996.

[12] SPEC-NET Corrosivity Zones for Steel Construction from Galvanizers Association. Spec-net [document on the Internet]; 2015. Available from: http://www.spec-net.com.au/press/1014/gaa_081014.htm

[13] Cervenka J., Jendele L., Cervenka, ATENA Program documentation. www.cervenka.cz [document on the Internet]; 2016. Available from: http://www.cervenka.cz/products/atena/documentation.

[14] Cervenka J., Papanikolaou V.K. Three dimensional combined fracture-plastic material model for concrete. *Int. J. Plast*. 2008; **24**: 2192-2220.

[15] Tanaka Y. et al. Loading Test of RC Beam Bridge Built 80 Years Ago in Japanese Coastal Area. *Modelling of Corroding Concrete Structures.* RILEM Bookseries. 2010; **5**: 159-177.

[16] Papadakis V. G., Tsimas S. Supplementary cementing materials in concrete. Part I: efficiency and design. *Cem. Concr. Res.* 2002; **32**(10): 1525–1532.

39th IABSE Symposium – *Engineering the Future*
September 21-23 2017, Vancouver, Canada

Durability assessment of reinforced concrete structures due to chloride ingress up and beyond induction period

Vít Šmilauer, Karolina Hájková

Czech Technical University in Prague, Faculty of Civil Engineering, Thákurova 7, 166 29 Prague 6, CZ

Libor Jendele, Jan Červenka

Červenka Consulting s.r.o., Na Hřebenkách 55, 150 00 Prague 5, CZ

Contact: karolina.hajkova@fsv.cvut.cz, vit.smilauer@fsv.cvut.cz,
libor.jendele@cervenka.cz, jan.cervenka@cervenka.cz

Abstract

Chloride ingress in reinforced concrete structures is the main cause for the corrosion of reinforcing steel. This paper presents chemo-mechanical material models up and beyond induction period, taking into account concrete mix design, supplementary cementitious materials, concrete cover, effect of cracking, and environmental conditions. The 1D model of transient problem of chloride ingress is extended for crack effects, which accelerates propagation. Fracture–plastic constitutive model is used for the modelling of externally induced cracks. The influence of cracks is significant, e.g. crack width 0.3 mm decreases the induction time approximately five times when compared to intact concrete. Once the end of the induction period is reached, progressive corrosion stage takes place. The corrosion current density i_{corr} is used for calculating time of concrete spalling due to chlorides. After concrete spalling, reinforcement is subjected to corrosion without any protection.

The above-mentioned models are implemented in a finite element software, using multi-physics approach, i.e. combining transport and mechanical analysis. They predict induction time, extent of corrosion for chloride ingress, and calculate remaining steel area. The presented chemo-mechanical approach is validated on several engineering structures suffering from chloride ingress, e.g. Nougawa bridge, Japan, or concrete strut of a prestressed bridge in Prague, Czech Republic. The present models are applied for ULS analysis, while assessing load-bearing capacity of a structure in dependence on the state of reinforcement corrosion.

Keywords: Chloride ingress, induction period, reinforcement corrosion, service life, durability