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DETERMINATION OF STEEL CORROSION RATE

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Abstract: *Carbonation and chloride ingress are considered as the most serious damaging mechanisms for steel corrosion in reinforced concrete. The service life is divided into two main phases. The initial phase and propagation phase. The initial phase was explored recently and results show high influence of cracks on accelerating of carbonation and chloride ingress in concrete structures. Our model focuses on the propagation period and predicts x_{corr} presents a loss of mass for radial corrosion depth, including cracking and spalling of concrete cover. The presented model was implemented in ATENA software. A prestressed box-girder bridge is analyzed in greater detail, showing corrosion of reinforcement and its impact on bridge's bearing capacity.*

Keywords: Concrete, Corrosion, Propagation phase, Carbonation, Chlorides

1. Introduction

Reinforcement corrosion due to carbonation and chloride ingress are the most damaging mechanisms in reinforced concrete structures (P. Basheer at al., 1996).

The service life t_l of reinforced concrete structures is generally divided into two time phases, Figure 1. The initiation period t_i and the propagation period t_p. Calculation of the initiation period was solved in the previous project and preliminary results show high influence of cracks to transport properties and acceleration of damaging mechanisms. For traditional CBM, cracks 0.3 mm decrease induction time approximately 6x for carbonation and approximately 9x for chloride ingress in salt water. Preventing macrocracks and designing proper concrete is essential for durable concrete (V. Červenka et al., 2012)

Our model is focused on the propagation period t_p where corrosion of reinforcing steel take place. During this time is reinforcement weakened and grow corrosion products on the surface of reinforcement. In the model, two types of corrosion are considered. A uniform corrosion (corrosive attack proceeding evenly over the entire surface area) typical for carbonation and pitting corrosion (caused by depassivation of a small area, leads to the creation of small holes in the material) typical for chlorides (F. Duprat, 2007).

2. Model for carbonation and chloride penetration

Model for steel cross section loss during the propagation period. Model is based on Faraday's law (Rodriguez, 1996).

2.1 The corrosion rate for the carbonation

The corrosion rate for the carbonation depends on the corrosion current density i_{corr} [μA / cm^2], which ranges between 0.1-10 and depends on the quality and the relative humidity of the concrete (Page CL,

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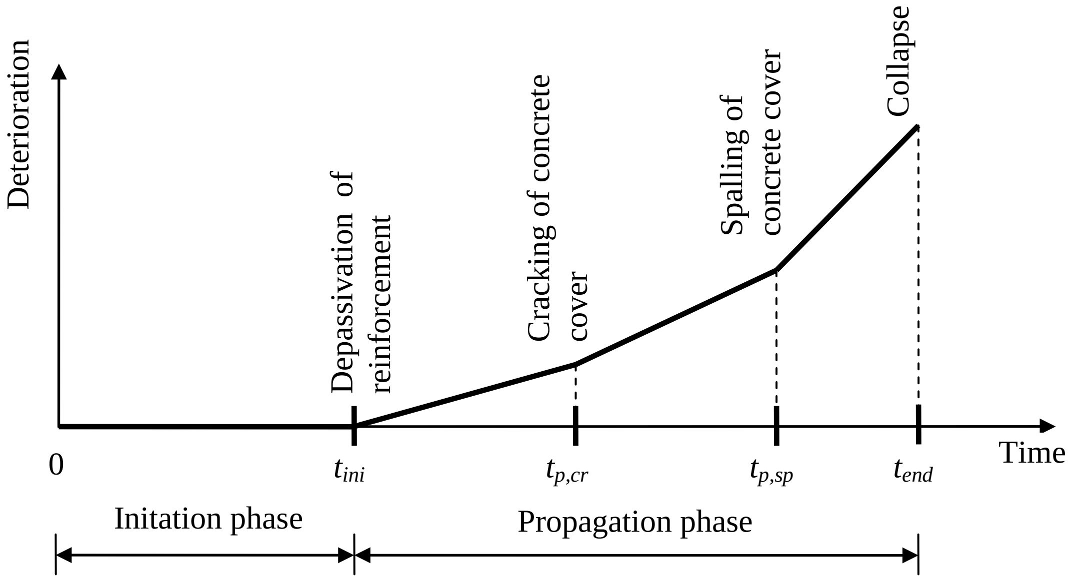

Fig. 1: Initiation and propagation phase

1992). This model is suitable for prediction of steel cross section loss during the whole propagation period t_p. Principal task is to determine the proper current density, i_{corr} in each stage of the propagation period. The corrosion rate is determined as follows:

$$\dot{x}_{corr}(t) = 0.0116 i_{corr}(t) \tag{1}$$

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

2.2 The corrosion rate for chlorides

The corrosion rate for chlorides is more complicated because it is affected by concentration of chlorides in the concrete and their transport. For this calculation is used model Liu and Weyer (Y. Liu et al., 1998):

$$i_{corr} = 0.926 * \exp\left[7.98 + 0.7771 \ln(1.69 C_t) - \frac{3006}{T} - 0.000116 R_C + 2.24 t^{-0.215}\right] \tag{2}$$

Where i_{corr} is corrosion current density [µA/cm^2], C_t Total chloride content [kg/m^3 of concrete], C_t must exceed the threshold (about 0.36 kg/m^3 of concrete). This is computed from ATENA model for chloride ingress, T is temperature at the depth of reinforcement [K] and R_c is ohmic resistance of the cover concrete [Ω] (Y. Liu, 1996) and t is time after initiation [years]:

$$R_C = \exp[8.03 - 0.549 \ln(1 + 1.69 C_t)] \tag{3}$$

The average corrosion rate in radial direction is determined according to Eq. (1).

After spalling of concrete cover, corrosion of reinforcement take place in direct contact with the environment. To determine the rate of corrosion of reinforcement after spalling is used direct determination of the value of the rate of corrosion of reinforcement (Spec-net).

Table 1: Corrosion rates of steel under atmospheric exposition

Corrosivity zones (ISO 9223)	***Typical environment***	***Corrosion rate for first year (µm/yr)***

Category	*Description*		*Mild stell*	*Zinc*
C1	***Very low***	***Dry indoors***	***≤1,3***	***≤0,1***
C2	***Low***	***Arid/Urban inland***	***>1,3 a ≤25***	***>0,1 a ≤0,7***
C3	***Medium***	***Coastal and industrial***	***>25 a ≤50***	***>0,7 a ≤2,1***
C4	***High***	***Calm sea-shore***	***>50 a ≤80***	***>2,1 a ≤4,2***
C5	***Very High***	***Surf sea-shore***	***>80 a ≤200***	***>4,2 a ≤8,4***
CX	***Extreme***	***Ocean/Off-shore***	***>200 a ≤700***	***>8,4 a ≤25***

2.2. Cracking of concrete cover

The cracking of concrete cover in propagation period $t_{p,\ cr}$ corresponds to the depth of corrosion $x_{corr,cr}$ (DuraCrete, 2000). The critical penetration depth of corroded steel $x_{corr,cr}$ is formulated as:

$$x_{corr,cr} = a_1 + a_2 \frac{C}{d_{ini}} + a_3 f_{t,ch} \qquad (5)$$

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

2.3. Spalling of concrete cover

The time of spalling of concrete cover $t_{p,sp}$, which again corresponds to the depth of penetration $x_{corr,sp}$. The critical penetration depth of corroded steel $x_{corr,sp}$ is calculated from (DuraCrete, 2000):

$$x_{corr,sp} = \frac{w^d - w_0}{b} + x_{corr,cr} \qquad (6)$$

where parameter b depends on the position of the bar (for top reinforcement 8.6 µm/µm and bottom 10.4 µm/ µm), w_d is critical crack width for spalling (characteristic value 1 mm), w_0 is width of initial crack (known from previous ATENA computation) and $x_{corr,cr}$ depth of corroded steel at the time of cracking [m].

3. Implementation of presented model in ATENA software

The model is used on a structure of a pre-stressed reinforced concrete bridge of Mr. Pavel Wonka over the river Elbe in Pardubice, Czech Republic. The bridge is modeled by 4500+ shell elements. The pre-stressed reinforcement is realized by special "external cable" elements. For more details see (J. Červenka et al., 2016).

The concrete of the girder box was classified as C35/45. Estimated composition yields CEM 42.5, C_p= 350 kg/m^3 and water, W= 175 kg/m^3. Concrete box girder was loaded on its surface by carbonation and chlorides load and used the following parameters for carbonation: CO_2 = 0.00036, RH = 0.60. K_{CO2} has no influence since there are no SCM, for chlorides: mean value D_{ref} = 7.72e-13·86400 = 6.67e-08 m^2/day (assumed 90% confidence which is 1.19e-7), t_{Dref} = 3650 days, m_{coeff} = 0.37, t_{mcoeff} = 10950 days, C_s = 0.103, Cl_{crit} = 0.0185. Progressive period for both loads: 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, d_{ini} = 0.001 m, pitting corrosion R_{corr} = 1, corrosion rate after spalling 30 µm/year.

The Figure 2 shows calculated reduction coefficient for reinforcement cross sectional area with concrete cover 20 mm. For the first 50 years the reinforcement does not corrode, but at the age of 100 years about 50% of the reinforcement has corroded and at 150 years there is only about 30% of the original reinforcement.

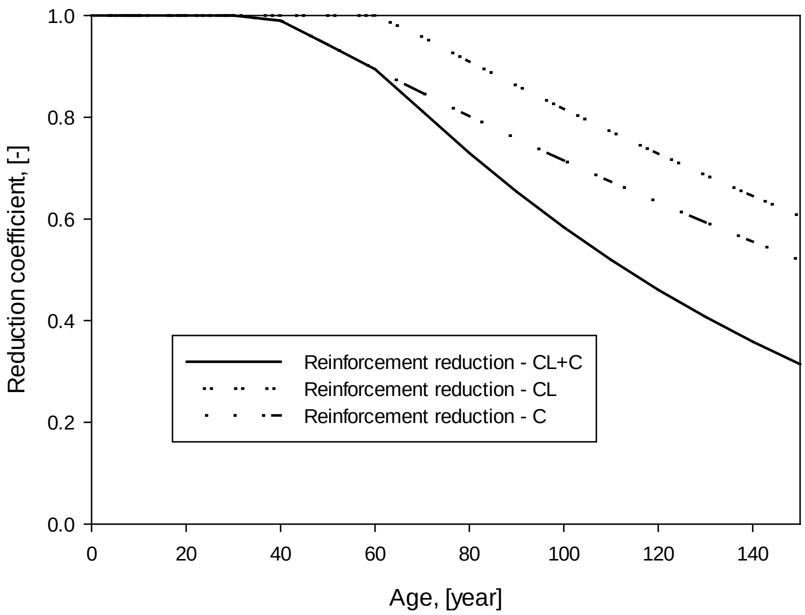

Fig. 2: The worst reinforcement reduction coefficient for bars with concrete cover 20 mm with the influence of cracks.

4. Conclusions

The presented model was implemented in ATENA software and allows us to model reinforcement mass loss during the propagation phase due to two main corrosion mechanisms, carbonation and chloride ingress. The results shows that durability analysis could be a part of design of structures. It allows simulate negative effects of external environmental conditions on the structure and to modify its design accordingly, increase depth of reinforcement cover, modify properties of concrete mixture, improve surface isolations, etc.

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