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CORROSION OF REINFORCEMENT VERSUS RELIABILITY OF RC GIRDERS

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Abstract: *Corrosion is the destructive attack on metal by chemical or electrochemical reaction with its environment. The quality and the durability of the concrete structures are affected a lot by the degradation processes. Reinforced concrete is considered as a versatile, economical and successful construction material. Usually it is durable and resistant material, performing well throughout its service life. The corrosion of reinforcing steel in concrete, due to invasive environment, is the phenomenon that highly affects the reliability and durability of reinforced concrete structures. The paper deals with reinforcement corrosion and its influence on reliability of the existing bridge concrete structures. In conclusion, changes of the failure probability and reliability index of the structure with time, influenced by reinforce corrosion, are shown.*

Keywords: Corrosion, Reinforcement, Concrete, Reliability, Existing structure.

1. Introduction

Deterioration by physical causes is not called corrosion, but is described as erosion, galling or wear. The term of corrosion is restricted to chemical attack on metals. There are three areas of concern when corrosion and its prevention are considered (Revie & Uhlig, 2008; Sastri et al., 2007). The three major factors are economics, safety and environmental damages. Metallic corrosion indeed affects many sectors of a nation's economy.

This paper deals with a problem of actual material degradation and its influence on reliability in time of existing bridge reinforced concrete structures. Two types of calculations are considered in this paper: during the passive stage and during the active stage of corrosion.

2. Corrosion of Reinforcement and Resistance - Theory

Analysis of corrosion influence on reinforced concrete (RC) members' reliability subjected to bending was performed using the engineering probability method. In that method, the reliability margin G(t) (Mrázik, 1987) is the basic parameter of structural reliability and it is described by formula

$$G(t) = R(t) - E(t) \qquad (1)$$

where R(t) is the generalized function of random variable structural resistance,
E(t) are random variable load effects of the same element.

From formula (1) follows, that the random variable resistance R(t), the random variable load effect E(t) and the reliability margin G(t) are variables dependent on time t. The resistance R(t) could change in time due to many factors. The different types of RC structure degradation are the best-known factors causing the resistance change with time. The most significant way of degradation of concrete structures is reinforcement corrosion as a consequence of diffusion of CO_2 to the concrete member called carbonatization or penetration of the chloride ions, Cl^-.

The process of CO_2 diffusion consists of two phases (Tuutti, 1982; Broomfield, 1997). The first phase is the passive stage, during the time period (0, t_0), when CO_2 penetrates through the concrete cover. During

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that time, the resistance of element is not changed since the material and geometric parameters do not change (slight increase and following decrease of concrete strength in compression is neglected). Length of the passive stage depends on the cover depth. The second phase – active stage during the time period (t_0, T), from the instance when CO_2 has penetrated through the concrete cover and reached reinforced bars until the end of the member's life, $T_d = 100$ years. During that time, the corrosion of reinforced bars occurs. The RC element subjected to bending was considered in this parametric study. The resistance R(t) of the bent concrete element is given by formula based on Eurocodes (STN EN 1992-1-1)

$$R(t) = M_{Rd,pl}(t) = A_s(t) \cdot f_y \cdot \left[\left(h - c - \frac{\phi(t)}{2} \right) - \frac{1}{2} \cdot \frac{A_s(t) \cdot f_y}{b \cdot f_c} \right] \quad (2)$$

where f_c is the concrete strength [$N.mm^{-2}$],
f_y is the reinforcement yield strength [$N.mm^{-2}$],
h is the cross-section height [m],
b is the cross-section width [m],
c is the concrete cover thickness [mm],
$\phi(t)$ is the reinforcement diameter, dependent on time [mm],
$A_s(t)$ is the reinforcement cross-section area, dependent on time [m^2]

$$A_s(t) = n \cdot \frac{\pi}{4} . \phi^2(t) \quad (3)$$

Input parameters b, c, h, f_c and f_y are considered as random variables and their notation is shown in Fig. 1.

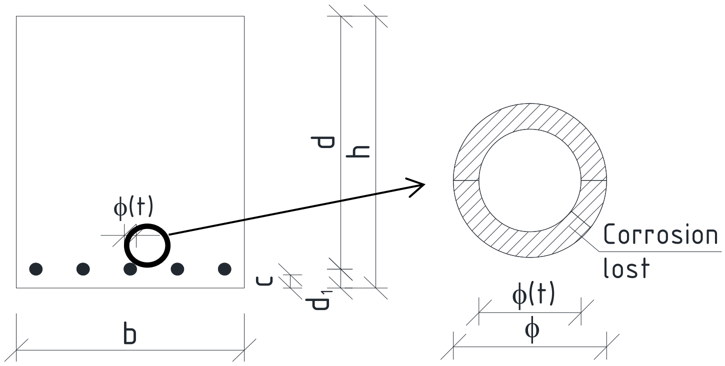

Fig. 1: Scheme of the profile parameters notation and loss of cross/section area due to corrosion.

The change of resistance R(t) with time depends on the loss of the reinforcement cross-section area. The corrosion model according to Andrade et al. (1996) (see Fig. 1) was considered in the parametric study. This model is one of the most used corrosion models. The diameter loss, $\phi(t)$, for the planar uniform corrosion is described by formula

$$\phi(t) = \phi - 0.0232 \cdot (t - t_0) \cdot i_{corr} \quad (4)$$

where i_{corr} is the corrosion current density [$\mu A/cm^2$] (1 $\mu A/cm^2$ is equal to 11.6 μm/year of corrosion),
t_0 is period of the passive stage.

The corrosion current density i_{corr} was measured on the real bridge structures (Andrade et al., 1996) and used values are shown in Tab. 1.

The beginning of the resistance changing with time depends on the length of the passive stage. The process of CO_2 diffusion is described by the second Fick's law (Matoušek & Drochytka, 1998). Many CO_2 diffusion models were derived for practical use. Those models depend on various factors. Only one model of passive stage calculation was used in this parametric study. In that model is assumed that the length of the passive stage depends on the concrete cover c and material constant D. This model is simple and it is cited in many references. Length of the passive stage is given by formula

$$t_0 = \frac{c^2}{2.D} \tag{5}$$

where D is a material constant presented in Tab. 1.

3. Influence of Corrosion of Reinforcement on Reliability in Time - Parametric Study

The parametric study was performed in order to find the influence of reinforcement corrosion on RC member's reliability subjected to bending. The values of h, b, c, ϕ, f_c, f_y and i_{corr} in relations (2-4) were considered as normally distributed random variables in the parametric study. The statistical characteristics of variables are given in Tab. 1.

Tab. 1: Statistical characteristics of RC cross-section.

Variables	**mean value**	**standard deviation**	**coefficient of variation**
Yield strength – f_y [N.mm^{-2}]	*400.81480*	*23.96686*	*0.06800*
Strength of concrete – f_c [N.mm^{-2}]	*24.64000*	*2.68000*	*0.10877*
Height – h [m]	*0.797800*	*0.01360*	*0.01705*
Width – b [m]	*0.49570*	*0.00740*	*0.01493*
Bar diameter – ϕ [mm]	*19.770*	*0.223*	*0.01128*
Number of bars – n [pieces]	*7*	*-*	*-*
Concrete cover – c [mm]	*24.00*	*1.30*	*0.05417*
Corrosion current density - i_{corr} [μA/cm^2]	*1.00*	*0.20*	*0.20*
	3.00	*0.60*	*0.20*
	5.00	*1.00*	*0.20*
Material constant – D [mm^2.s^{-1}]	*$4.82 \cdot 10^{-7}$*	*-*	*-*

Numerical calculation of the resistance R(t) time dependence was realized by simulation by the Monte-Carlo method. It is possible to use other methods for simulation, also, for example LHS, Important sampling (Kala, 2001) etc. The results of simulation are shown in Fig. 2 and Fig. 3.

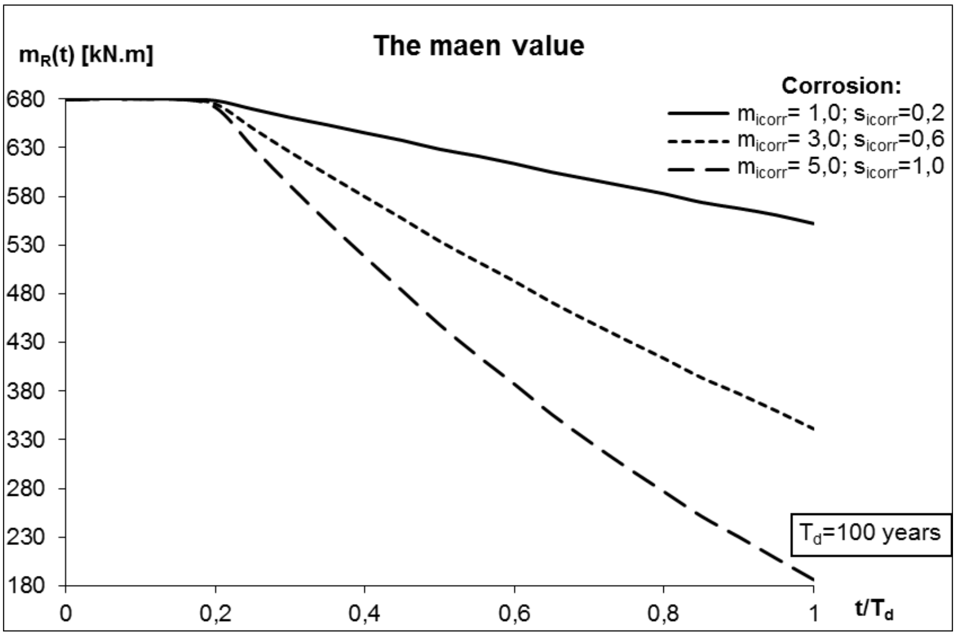

Fig. 2: Change with time of the resistance mean value $m_R(t)$.

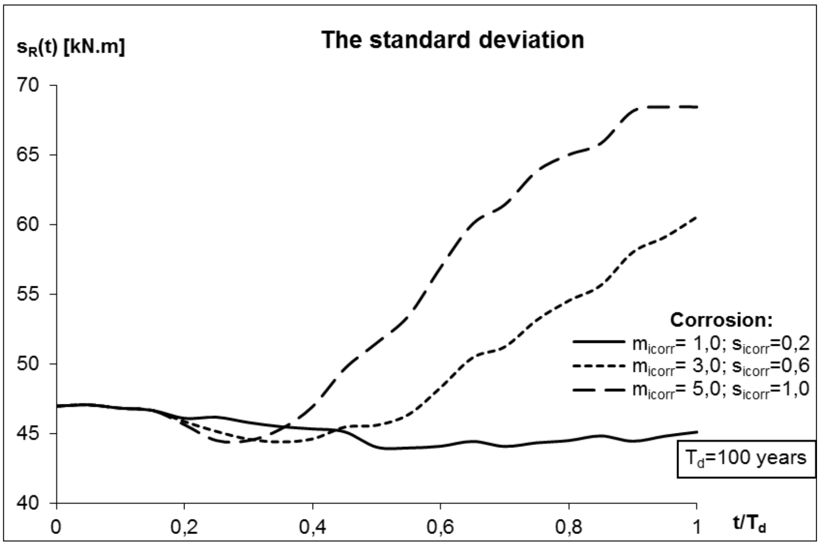

Fig. 3: Change with time of the resistance standard deviation $s_R(t)$.

If the designed lifetime of the bridge member, equals to T_d = 100 years, and the reliability level for the newly designed bridge members, equals to β_d = 3.652, are considered, the corresponding load effects are given by (normally distributed) parameters $m_E(t = t_0) = 464.752$ N.mm^{-2}; $s_E(t = t_0) = 35.237$ N.mm^{-2}.

4. Conclusions

In this paper is presented the influence of reinforcement corrosion on the resistance and reliability of the concrete bridge element, subjected to bending. The values of the corrosion current density i_{corr} significantly affect the mean value and standard deviation of resistance R(t). Higher value of i_{corr} corresponds to higher decrease of the resistance mean value. The highest value of i_{corr} should not be applied in our region (it corresponds to very aggressive conditions). The resistance standard deviation R(t) depends greatly on standard deviation of corrosion current density i_{corr}. The resistance standard deviation increases in time with higher standard deviation of i_{corr}. The failure probability $P_f(t)$ and reliability index $\beta(t)$ are changed significantly after the half of their lifetime.

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