

ECF22 - Loading and Environmental effects on Structural Integrity

Decreasing bridge member's resistance due to reinforcement corrosion

Miroslav Strieška^{a,*}, Peter Koteš^a, Aleksandar Sedmak^b

^aUniversity of Žilina, Department of Structures and Bridges, Univerzitná 8215/1, 01026 Žilina, Slovakia

^bUniversity of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11,000 Belgrade, Serbia

Abstract

The traffic infrastructure is very important for the economy, people and progress of the country. The infrastructure consists of numerous structures and their structural members like bridges, abutments, piers, rails, guard-rails etc. This constructions are very loaded by surrounding environment. Aggressiveness of this environment is different in various areas in Slovak republic due to morphology of terrain, which causes the different corrosion depth in those areas. This corrosion depth can be calculated by standard ISO 9223, describing the calculation of the corrosion rate r_{corr} for the first-year and the standard ISO 9224 describe the estimation of the corrosion rate D for the following years. The input parameters for these calculation are sulphur dioxide SO_2 , chloride ions Cl^- , temperature T and relative humidity R_h measured by Slovak Hydrometeorological Institute (SHMÚ). The article is focused on the determining load-carrying capacity of reinforced concrete (RC) bridges changing in time due to corrosion of the reinforcement diameter. This information can be very useful not only for the design of the new bridge construction, but also for the estimation of the remaining lifetime of the existing structure.

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1. Introduction

All structures are subjected to the surrounding environment. Most of all, the structures like bridges, abutments, piers, vehicle parapets, expansion joints etc., which are built as a part of the traffic infrastructure, where the de-icing salts are applied (Krivy 2017, Göran 2001). Nowadays, the design of the new reinforced concrete (RC) structures is

* Corresponding author. Tel.: +421-41-513-5663; fax: +421-41-513-5690.
E-mail address: miroslav.strieska@fstav.uniza.sk

based on the assumption that the resistance of the structure is invariable in time. It means, that the resistance (the individual parameters like cross-section dimensions, yield strength, diameter of the reinforcement etc.) is still constant during the whole lifetime of the structure. To ensure this properties, the design principles must be satisfied, especially in the case of reinforcement corrosion, the minimum concrete cover due to environmental conditions $c_{\min, \text{dur}}$ calculated according to standard STN EN 1992-1-1+A1 (2015). Even though, it can be seen the degradation of the materials like corrosion of reinforcing steel in concrete or up to spalling of concrete cover on the existing structures. Degradations of structure or their members, under various environment, may leads to the decreasing of the resistance (Vican 2011, Vican 2017, Borko 2016). This leads to the conclusion that the resistance of construction can be changing during the lifetime.

2. Background

2.1. Moment resistance derived on base of corrosion rate of reinforcement according to actual approach

At first, it has to be mentioned that there is a lot of factors, which can affect the reliability margin G of constructions. The reliability margin in time $G(t)$ is the difference between the structural resistance $R(t)$ and the load effects $E(t)$ of the same element in time t and is given by following formula.

$$G(t) = R(t) - E(t) \geq 0 \quad (1)$$

This article is focused on the change of the structural resistance $R(t)$ in time, assumes that the reliability margin is equal to zero (structural resistance is equal to load effects) and passive stage (during which the corrosion is not run over) is neglected. The corrosion rate r_{corr} , as well as the corrosion model are considered according the actual standard approach and changing of the moment resistance in time $M_{Rd}(t)$ is observed – RC member subjected to bending.

Fig. 1 shows the factors affected the reliability of construction (reliability margin $G(t)$) influenced by corrosion and the assumptions applied in this parametric study (marked dashed line), as well. The moment resistance was calculated using the power-linear function model according to actual standard EN ISO 9224 (2012), see equation (2) for $t \leq 20$ years and equation (3) for $t > 20$ years. The input parameter for this calculation is first yearly corrosion rate r_{corr} calculated from dose-response function of carbon steel according to standard EN ISO 9223 (2012), equation (4)

$$D(t \leq 20) = r_{\text{corr}} \cdot t^b \quad (2)$$

$$D(t > 20) = r_{\text{corr}} \left[20^b + b(20^{b-1})(t-20) \right] \quad (3)$$

$$r_{\text{corr}} = 1.77 \cdot [SO_2]^{0.52} \cdot \exp(0.020 \cdot Rh + f(T)) + 0.102 \cdot [Cl^-]^{0.62} \cdot \exp(0.033 \cdot Rh + 0.040 \cdot T) \quad (4)$$

where t is the time, b is the metal-environment-specific time exponent for steel, r_{corr} is the corrosion rate ($\mu\text{m}/\text{year}$), $f(T) = 0.150 \cdot (T - 10)$ when $T \leq 10^\circ\text{C}$; otherwise $-0.054 \cdot (T - 10)$, SO_2 is the sulphur dioxide ($\mu\text{g}/\text{m}^3$ or $\text{mg}/(\text{m}^2 \cdot \text{day})$), where SO_2 in units $\text{mg}/(\text{m}^2 \cdot \text{day})$ is equal to $0.8 \cdot SO_2$ in unit $\mu\text{g}/\text{m}^3$, T is the temperature ($^\circ\text{C}$), Rh is the relative humidity (%), Cl^- is the chloride deposition rate ($\text{mg}/(\text{m}^2 \cdot \text{day})$).

The moment resistance in time $M_{Rd}(t)$ can be derived from equations (5) – (7)

$$R(t) = M_{Rd}(t) = A_{s1}(t) \cdot f_{yd} \cdot \left[d - \frac{A_{s1}(t) \cdot f_{yd}}{2 \cdot b \cdot f_c} \right] \quad (5)$$

The diameter and the area of longitudinal tensioned reinforcement is expressed below

$$A_{s1}(t) = n \cdot \frac{\pi \cdot \phi(t)^2}{4} \quad (6)$$

$$\phi(t) = \phi - (t - t_0) \cdot 2 \cdot r_{\text{corr}} \quad (7)$$

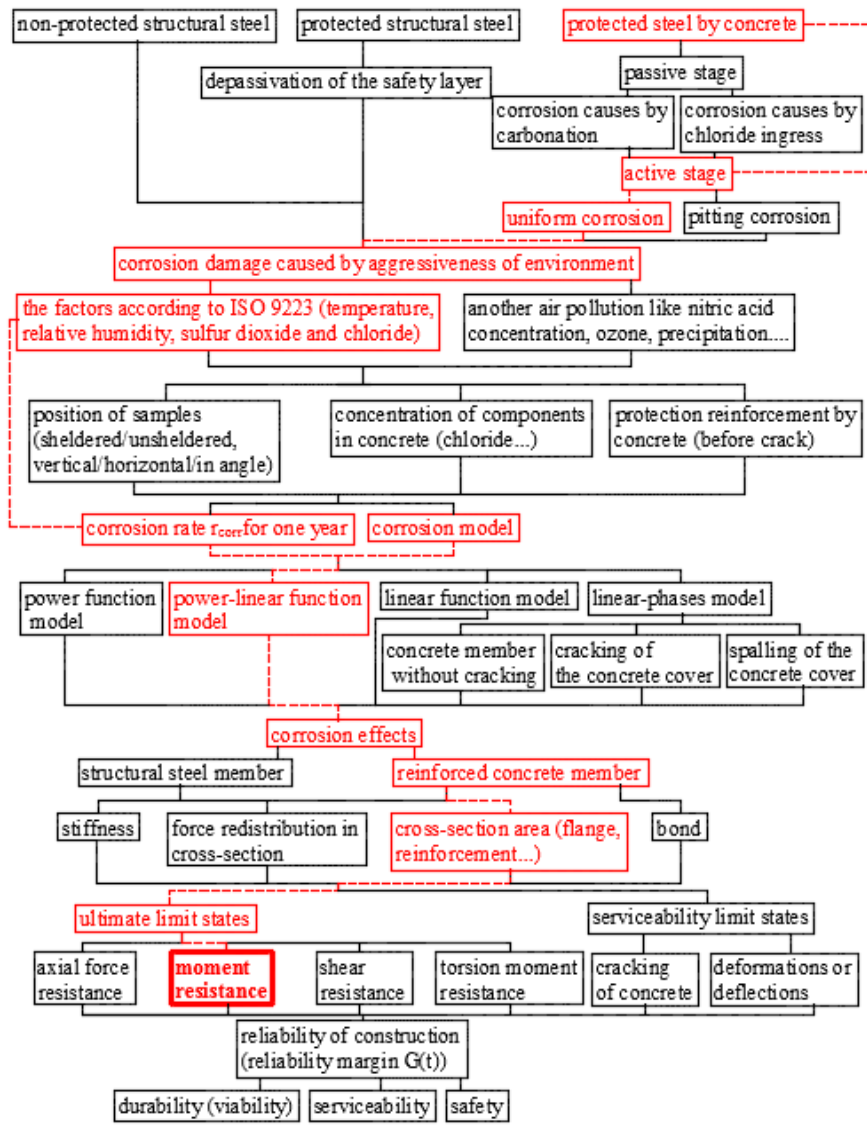


Fig. 1. Factors affected the reliability of construction influenced by corrosion.

So, the ultimate resistance moment of cross-section in time $M_{Rd}(t)$, is given by following formulas.

$$M_{Rd} = M_{Rd}(0) = A \cdot \sigma^2 - B \cdot \sigma^4 \tag{8}$$

$$M_{Rd}(t \leq 20) = M_{Rd}(0) + k_1 \cdot (t - t_0)^b + k_2 \cdot (t - t_0)^{2 \cdot b} - k_3 \cdot (t - t_0)^{4 \cdot b} \tag{9}$$

$$M_{Rd}(t=20) = k_4 - k_5 \tag{10}$$

$$M_{Rd}(t > 20) = M_{Rd}(t=20) + k_6 \cdot (t^*) + k_7 \cdot (t^*)^2 + k_8 \cdot (t^*)^3 + k_9 \cdot (t^*)^4 \tag{11}$$

where (t^*) is equal to $(t - t_0 - 20)$, t_0 is time of the passive stage, $k_1 - k_9$ are parameters depending on materials' and geometrical characteristic and A, B are parameters constant in time

$$k_1 = -4 \cdot A \cdot \phi \cdot r_{corr} + 8 \cdot B \cdot \phi^3 \cdot r_{corr} \quad (12)$$

$$k_2 = 4 \cdot A \cdot r_{corr}^2 - 24 \cdot B \cdot \phi^2 \cdot r_{corr}^2 \quad (13)$$

$$k_3 = 16 \cdot B \cdot r_{corr}^4 \quad (14)$$

$$k_4 = A \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b)^2 \quad (15)$$

$$k_5 = B \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b)^4 \quad (16)$$

$$k_6 = 4 \cdot r_{corr} \cdot b \cdot 20^{b-1} \left[2 \cdot B \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b)^3 - A \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b) \right] \quad (17)$$

$$k_7 = A \cdot (2 \cdot r_{corr} \cdot b \cdot 20^{b-1})^2 + 6 \cdot B \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b)^2 \cdot (2 \cdot r_{corr} \cdot b \cdot 20^{b-1})^2 \quad (18)$$

$$k_8 = 4 \cdot B \cdot (2 \cdot r_{corr} \cdot b \cdot 20^{b-1})^3 \cdot (\phi - 2 \cdot r_{corr} \cdot 20^b) \quad (19)$$

$$k_9 = B \cdot (2 \cdot r_{corr} \cdot b \cdot 20^{b-1})^4 \quad (20)$$

$$A = \frac{\pi \cdot f_{yd} \cdot n \cdot d}{4} \quad (21)$$

$$B = \frac{\pi^2 \cdot f_{yd}^2 \cdot n^2}{32 \cdot b \cdot f_{cd}} \quad (22)$$

where $A_{s1}(t)$ is the area of longitudinal tensioned reinforcement changed in time (m^2), ϕ is the initial diameter of reinforcement bar (m), f_{yd} is the design value of reinforcement yield strength ($MN \cdot m^{-2}$), f_{cd} is the design value of compression strength of concrete ($MN \cdot m^{-2}$), d is the effective depth of cross-section (m), n is the number of bars, b is the width of cross-section (m).

2.2. First-year corrosion rate projected to corrosion maps

Subsequently, the programs like Microsoft Excel, Surfer, QGIS (previously known as Quantum GIS) and GIMP (GNU Image Manipulation Program) was used to create so called corrosion maps according to dose-response function (4), see Fig. 2. The corrosion map in 2005 represent the yearly corrosion rate in the year when the observation of the bridge in village Kolárovice was started, further information about the bridge is in Section 3. The map in 2016 was created for comparison of these two years.

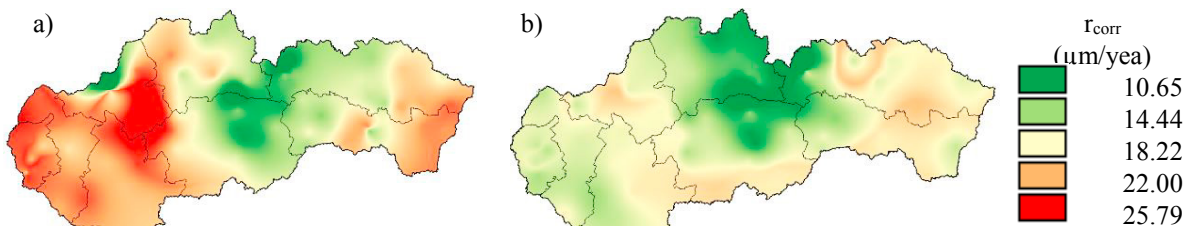


Fig. 2. Calculated first-year corrosion rate r_{corr} according to dose-response function (a) in 2005 (b) in 2016

3. Parametric study of moment resistance in time

For the parametric study, the real cross-section of the girder of the RC bridge in village Kolárovice near town Žilina in Slovakia was selected (Fig. 3). This bridge is observed by researches of the Department of Structures and Bridges, Civil Engineering Faculty, University of Žilina since 2005 (Koteš 2018). The bridge was build and put into operation in 1937 and by 68 years the corrosion of reinforcement and the spalling of concrete cover occurred, which was observed in 2005.

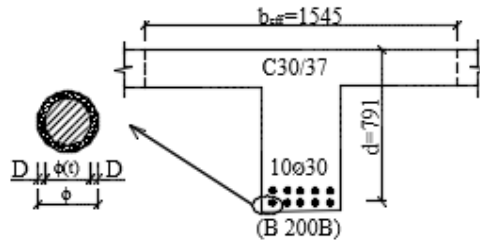


Fig. 3. T-beam cross-section of bridge in village Kolárovice.

Fig. 4 represents the bending moment resistance changed in time $M_{Rd}(t)$ created from the above described data (cross-section parameters, derived formulas and yearly corrosion rate). Fig. 4a shows the parametric study created according to information from the corrosion map, where the yearly corrosion rate was chosen in the range of these maps and that $r_{corr} = 10.65, 12.44, 18.22, 22.00$ and $25.79 \mu\text{m}/\text{year}$. Fig. 4b (continuous lines) describes the decreasing of the moment resistance based on the corrosion rate measured on the bridge in Kolárovice, $r_{corr} = 206.76, 338.79$ and $408.51 \mu\text{m}/\text{year}$ (Koteš 2018).

The great different can be seen when it is compare these two approach. The corrosion maps show only five percentage decreasing of the moment resistance in the most aggressive environment in the Slovak republic after one hundred years ($r_{corr} = 25.79 \mu\text{m}/\text{year}$) whilst the real bridge structure up to 63 percentage ($r_{corr} = 408.51 \mu\text{m}/\text{year}$). On these results can be seen a great difference between structures which are, or are not, subjected to the direct contact of chloride ions, when the drain of the bridge is damaged and the chloride ions from de-icing salts directly attack the reinforcement. In this case the deposition rate of chloride can be approximately $8000 \text{ mg}/\text{m}^2/\text{day}$, (Göran 2001). The standard EN ISO 9223 (2012) describe the maximum value of the chloride ions Cl^- which can be used as an input parameter to the dose-response equation (4). In the case, when maximum chloride ions ($700 \text{ mg}/\text{m}^2/\text{day}$) was substituted to the equation, the first-year corrosion rate increases from 10.65 to $121.08 \mu\text{m}/\text{year}$ or from 25.79 to $148.15 \mu\text{m}/\text{year}$, seen dashed line in Fig. 4b.

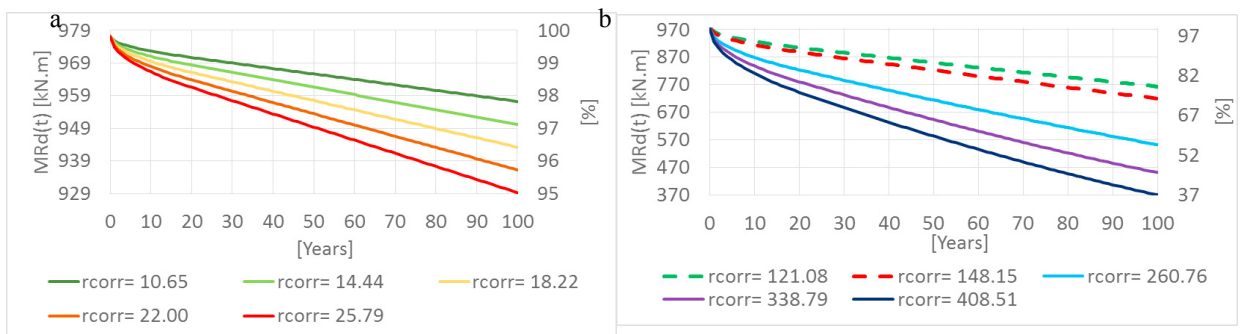


Fig. 4. Bending moment resistance of the bridge

4. Conclusions

The article is focused on the decreasing of the bending moment resistance in time $M_{Rd}(t)$ covered the actual standard approach for the corrosion losses in time (linear-power function model). Three methods of calculation of moment resistance $M_{Rd}(t)$ was compared. The first method is based on the calculated dose-response function and measured corrosion rate on the outdoor specimens, next method take into account the corrosion rate measured on the bridge in village Kolárovice and the last hypothetic method take into account the maximum value of Cl^- which can be used to the calculation of dose-response function ($700 \text{ mg/m}^2/\text{day}$).

The result shows that the direct contact of chloride ions, from de-icing salt, significantly influence the moment resistance of the RC member cross-section. The calculated corrosion rate from dose-response function do not reach this values even though the maximum Cl^- value is used.

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