Research Article

Diagnostics of Corrosion on a Real Bridge Structure

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Real bridge structures are affected by environmental conditions. The environmental loads in time cause the degradation of concrete and reinforcement. The diagnostics of real state of existing bridges are very important due to actual degradation and corrosion. In the frame of research activities of Department of Structures and Bridges, Civil Engineering Faculty, University of Žilina, the real bridge structure was observed for a few years. It is girder reinforced concrete bridge near town of Žilina in Slovakia. The results of diagnostics which focused on reinforcement corrosion are presented. The paper deals with reinforcement corrosion and its influence on the moment resistance of the existing concrete structures.

1. Introduction

Roadway bridges together with other roadway structures, such as tunnels, are the most critical components of road infrastructures not only in Slovakia but also in all European countries. Throughout their life, they require regular maintenance actions whose costs are generally supported by the operators and owners. Accordingly, it becomes important to define strategies to maximize the society benefits, derived from the investment made in these assets, within a limited budget. This investment should be planned, effectively managed, and technically supported by appropriate management systems [1]. To do this, the COST Action TU1406 entitled “Quality Specifications for Roadway Bridges, Standardization at a European Level (BridgeSpec)” was established [1]. The main objective of this COST Action is to develop a guideline for the establishment of Quality Control (QC) plans in roadway bridges, by integrating the most recent knowledge on performance assessment procedures with the adoption of specific goals. This guideline will focus on bridge maintenance and life-cycle performance at two levels: (i) performance indicators and (ii) performance goals. By developing new approaches to quantify and assess the bridge performance, as well as quality specifications to assure an expected performance level, bridge management strategies will be significantly improved, enhancing asset management of ageing structures in Europe.

To fulfill the main objective of the project, it is needed to collect data about codes, standards, and provisions concerning the inspections, evaluation, environment loads and conditions [2, 3], degradation processes [4–6], reliability [7–9], fatigue [10, 11], monitoring, maintenance, and diagnostic [12–14] of road bridges in all countries included in the project. The Department of Structures and Bridges, University of Žilina, was included into the project to represent Slovakia.

Knowledge of real state of existing bridges, their load-carrying capacity, and failures are very important parts of life-cycle performance [15–17]. In the decision-making procedure, they help decide what to do with the existing bridge structure: use only maintenance, repair, reconstruct, and strengthen the bridge, or replace with new one [18–20]. So, the diagnostic of bridges has significant influence on the bridge future.

2. Bridge Diagnostic Performed in 2005

In the frame of research activities of our department, numbers of bridges were diagnosed. In the paper, we focus on one bridge structure with denotation MO 244 in the village Kolárovice, part Škoruby, on the road I/10 (international road E442) between Bytča city and Makov village, over the Kolárovice river (Figure 1), which was for the first time diagnosed on 17 July 2005 in the frame of project APVT-20-012204 [21, 22]. Next diagnostics were performed on 13

FIGURE 1: The diagnosed bridge structure.

FIGURE 2: The bridge cross section.

November 2015 (after 10 years). The bridge was built and put into operation in 1937, so the age of the bridge is 79 years. It means that according to Eurocodes the remaining lifetime should be 21 years.

The bridge is the reinforced concrete single span beam bridge with theoretical span of 10.006 m (the length of the bridge superstructure is 10.824 m). The width of road is 7.51 m and the overall width of bridge is 9.51 m. The bridge skewness is 45.22°. The superstructure consists of bridge slab having thickness of 0.19 m and six main beams with dimensions of 0.325/0.84 m. End floor beams with dimensions of 0.58/0.84 m and three intermediate floor beams of dimensions of 0.20/0.74 m ensure the transverse load distribution (Figure 2). Denotation of beams from B1 to B6 is from the left-hand side to the right-hand side.

3. Results from Diagnostics Performed in 2005

From the results of the bridge diagnostic it follows that the type of the concrete is C30/37 using nondestructive method (Schmidt hammer) and the beams are reinforced by rebar of type A (10210) (smooth reinforcement without ribs) in two layers (5 ϕ A30 in the lower layer and 2 ϕ A30 in the upper layer); see Figure 3. The measured values of geometric and material properties, concerning all the girders and slab, are shown in Table 1.

Accordingly, the reinforcement corrosion was indicated. The corrosion caused the rebar diameter loss from the assumed initial value of 30 mm to actual average value of 29.37 mm (the minimal measured value is 28.7 mm). Change of bar diameter was measured on reinforcement R1 of spandrel beam B1 (Figure 3).

TABLE 1: Measured values of geometric and material characteristics.

Variables	The mean value	The standard deviation	Number of measurements
Strength of concrete, f_c [MPa]	49.780	4.8689	10
Beam height, h [m]	0.8370	0.00356	10
Beam width, b_w [m]	0.3222	0.00371	10
Concrete cover, c [mm]	29.6	1.14	5
Bar diameter of longitudinal reinforcement (B1-R1), $\phi(t)$ [mm]	29.37	0.6832	10
Slab height, h_f [m]	0.1864	0.00230	5

FIGURE 3: Bridge cross section: identified number of bars after the first diagnostics in 2005.

FIGURE 4: Bridge cross section: identified number of bars after the second diagnostics in 2015.

From visual inspection it can be seen that the insulation under asphalt is functional because the wet places and chloride drippstones between beams B2 and B5 were not found. The problem was on the edges between gadrone (cornices) and asphalt and behind edges of bridge, where wet places, chloride curtains, and corroded reinforcement were found, as well as the degraded concrete cover, which has dropped out at some places (Figure 1).

4. Results from Diagnostic Performed in 2015

The second diagnostics of the bridge were performed after 10.33 years (10 years and 4 months) on 13 November 2015 and were focused only on reinforcement corrosion. It means that only change of reinforcement diameter $\phi(t)$ due to corrosion was measured. At that time, reinforcement corrosion was measured on various bars of both spandrel beams (B1 and

B6). Moreover, on both beams, change of stirrups diameter $\phi_s(t)$ due to corrosion was also measured. The statistical characteristics of measures diameters are shown in Table 2.

Very important knowledge is that the bridge was in the worse state in comparison to the state in year 2005, reinforcement corrosion was larger, and the area of dropped out concrete cover was also bigger. Moreover, the concrete cover and the concrete layer between the reinforcements were expanding; thus it was possible to find another 3 bars inside the beam in the second layer. It means that the final number of reinforcement bars is 10, not only 7 (Figure 4).

5. Analysis of Results Obtained from Diagnostics

The histograms from measured values of bars' diameters are shown in Figures 5 and 6. For comparison, also histograms

TABLE 2: Measured values of reinforcement diameters.

Variables	Denotation	The mean value	The standard deviation	Number of measurements
<i>Beam B1</i>				
Beam B1, main longitudinal reinforcement R1, $\phi(t)$ [mm]	B1-R1	26.676	0.5615	10
Beam B1, main longitudinal reinforcement R2, $\phi(t)$ [mm]	B1-R2	29.363	0.3783	10
Beam B1, stirrup S1, $\phi_s(t)$ [mm]	B1-S1	5.976	0.5853	15
Beam B1, stirrup S2, $\phi_s(t)$ [mm]	B1-S2	4.834	0.8207	15
<i>Beam B6</i>				
Beam B6, main longitudinal reinforcement R1, $\phi(t)$ [mm]	B6-R1	29.763	0.1392	10
Beam B6, main longitudinal reinforcement R2, $\phi(t)$ [mm]	B6-R2	29.371	0.4016	10
Beam B6, main longitudinal reinforcement R6, $\phi(t)$ [mm]	B6-R6	29.741	0.2019	10
Beam B6, stirrup S1, $\phi_s(t)$ [mm]	B6-S1	7.139	0.6980	10
Beam B6, stirrup S2, $\phi_s(t)$ [mm]	B6-S2	6.571	0.5609	10
Beam B6, stirrup S3, $\phi_s(t)$ [mm]	B6-S3	7.203	0.5084	10
Beam B6, stirrup S4, $\phi_s(t)$ [mm]	B6-S4	7.261	0.6754	10

FIGURE 5: Histograms from measured values of bars' diameters: longitudinal reinforcements.

FIGURE 6: Histograms from measured values of bars' diameters: stirrups.

from the first measurement (diagnostics) of reinforcement B1-R1 are shown.

In the case of geometric parameters of members and cross sections, Eurocode EN 1990 [23] recommends using normal distribution of a random variable. The probability of occurrence and the density functions of normal distribution of a random variable of reinforcement diameter are also shown in Figures 7 and 8. The mean values and the standard deviations given in Tables 1 and 2 were used.

Initial measurement of reinforcement diameter was not available due to irrelevant measurements at the start of the bridge lifetime. So, the measurements were done at places, where the minimal or no corrosion of bars was assumed. From this reason, the reinforcements' diameters R1 and R2 of the beam B2 (B2-R1 and B2-R2) and reinforcement R1 of

the beam B3 (B3-R1) were also measured. Due to previous measurements, it was assumed that the initial reinforcement diameter was about 30 mm. The results of measurements are shown in Table 3 and Figure 9.

The diagnostics indicate significant influence of environmental loads on material degradation in the form of reinforcement corrosion. In 2005, the corrosion of longitudinal reinforcement was indicated only on beam B1 due to dropped concrete cover. Only the surface corrosion of stirrups and dropping out of stirrups concrete cover were indicated on beam B6. Due to 10 years of environment influence on reinforcement corrosion of bar B1-R1, the mean value of diameter changed from $m_\phi = 29.37$ mm to $m_\phi = 26.68$ mm (Figure 10).

FIGURE 7: Probability of occurrence and density functions of bars' diameters: longitudinal reinforcements.

6. Influence of Corrosion on the Beam Resistance

It is very important to take into account the reinforcement corrosion influence on change of the moment resistance of the beam in time t (Ultimate Limit States). The reinforcement

diameter $\phi(t)$ change in time may be described according to Thoft-Christensen [24]:

$$\phi(t) = \phi \quad \text{for } t \leq t_0, \quad (1a)$$

$$\phi(t) = \phi - (t - t_0) \cdot r_{\text{corr}} \quad \text{for } t > t_0, \quad (1b)$$

FIGURE 8: Probability of occurrence and density functions of bars' diameters: stirrups.

where r_{corr} is the corrosion rate [$\mu\text{m}/\text{year}$] of steel, t_0 is the length of time of passive stage [years], and t is time [years].

By the reversed calculation, it is possible to determine the corrosion rate r_{corr} as

$$r_{\text{corr}} = \frac{\phi(t_1) - \phi(t_2)}{t_2 - t_1} = \frac{\phi(t_1) - \phi(t_2)}{\Delta t} \quad (2)$$

$$= 0.2604 \text{ mm/year} = 260.4 \mu\text{m/year},$$

where $\phi(t_1) = 29.37 \text{ mm}$ is the measured reinforcement diameter in time t_1 [mm], $\phi(t_2) = 26.68 \text{ mm}$ is the measured reinforcement diameter in time t_2 [mm], $t_1 = 07/2005$ is time of the first measurements [years], $t_2 = 11/2015$ is time of the second measurements [years], and $t = 10.33$ years.

The value of $r_{\text{corr}} = 260.4 \mu\text{m}/\text{year}$ is great, but it represents the corrosion of free reinforcement without any protection: reinforcement B1-R1 was cleaned from rust during the

FIGURE 9: Results from measurements of initial bars' diameters: B2-R1, B2-R2, and B3-R1.

TABLE 3: Measured values of reinforcements' diameters.

Variables	Denotation	The mean value	The standard deviation	Number of measurements
<i>Beam B2</i>				
Beam B2, main longitudinal reinforcement R1, $\phi(t)$ [mm]	B2-R1	29.777	0.1031	15
Main longitudinal reinforcement R2, $\phi(t)$ [mm]	B2-R2	30.055	0.1183	15
Beam B2, stirrup S1, $\phi_s(t)$ [mm]	B2-S1	8.572	0.1142	15
Beam B2, stirrup S2, $\phi_s(t)$ [mm]	B2-S2	8.655	0.0393	15
<i>Beam B3</i>				
Beam B3, main longitudinal reinforcement R1, $\phi(t)$ [mm]	B3-R1	29.978	0.3239	15
Beam B3, stirrup S1, $\phi_s(t)$ [mm]	B3-S1	8.691	0.2165	15

FIGURE 10: Comparison of diameter $\phi(t)$ change of B1-R1 in time t .

first diagnostic and it was not guaranteed against corrosion with the new concrete cover (using repair mortar). The corrosion is due to chloride ions from the defrosting salt. Corrosion rate r_{corr} of other reinforcements was not possible to calculate because we had only one measurement.

Measurement of diameter of reinforcement B2-R2 and B3-R1 shows that there is not corrosion or corrosion is very low and can be negligible: diameter is very close to assumed value of 30 mm. In the case of B2-R1, the small corrosion was found.

Using the reversed calculation, it is possible to calculate the length of the passive stage $t_0 = 65.6$ years provided that $r_{\text{corr}} = 260.4 \mu\text{m}/\text{year}$. Of course, the corrosion of free reinforcement (without concrete cover) and corrosion of protected reinforcement in concrete (under the concrete cover) are different, but the initial measurements were not known.

At the same time, using the obtained value of r_{corr} , it was possible to calculate the moment resistance of the beam and how it changed with time during the remaining lifetime: $t_r = 21$ years.

The resistance $R(t)$ of the bending concrete element is given by formula, derived in [25] and based on Eurocodes [26]:

$$R(t) = M_{\text{Rd,pl}}(t) = A_s(t) \cdot f_y \cdot \left[\left(h - c - \frac{\phi(t)}{2} \right) - \frac{1}{2} \cdot \frac{A_s(t) \cdot f_y}{b \cdot f_c} \right], \quad (3)$$

where f_c is the concrete compressive strength [$\text{N}\cdot\text{mm}^{-2}$], f_y is the reinforcement yield strength [$\text{N}\cdot\text{mm}^{-2}$], h is the cross section height [m], b is the cross section width [m], b_{eff} is the effective cross section width [m], c is the concrete cover [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], and n is number of bars:

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

FIGURE 11: Change of moment resistance $M_{\text{Rd}}(t)$ in time of RC bridge girder due to the reinforcement corrosion.

The influence of the corrosion on changing the moment resistance of the RC flanged bridge beam in time is shown in Figure 11.

The basic value of the moment resistance at time $t = 0$ year is equal to $M_{\text{Rd}}(t = 0) = 977.391 \text{ kNm}$. Hypothetically, the decrease of moment resistance during the remaining lifetime can be 49.9%.

7. Conclusions

The measurements of reinforcement corrosion on real reinforced concrete girder bridge are presented in this paper. Two diagnostics within the 10 years were performed. From the results it follows that the reinforcements in corners of the beams' cross sections are more incoherent due to degradation (corrosion) because the degradation factors enter into the beam not only from the bottom part but also from the side. Measurements indicate that the spandrel beams are mainly affected by chloride ions Cl^- penetration and cause large degradation of concrete cover, corrosion of reinforcement, and consecutive concrete cover dropping out. Internal beams

are affected by carbonization (ingress of CO_2 into concrete) if the insulation is functional. The importance of diagnostics shows the fact that not all the reinforcements may be found in cross section without using quality destructive or nondestructive diagnostic methods.

In addition, the influence of reinforcement corrosion on the moment resistance $M_{\text{Rd}}(t)$ in time of the concrete bridge element subjected to bending is presented. From the results it may be seen that the moment resistance may decrease about 49.9% during remaining lifetime. It is not a negligible value and it points to a huge influence of environmental loads on degradation of materials. However, it is necessary to mention that the value of the corrosion rate r_{corr} was calculated for the free reinforcement without the concrete cover.

Competing Interests

The authors declare that they have no competing interests.

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References

- [1] <http://www.tul406.eu/>.
- [2] M. Cabrini, S. Lorenzi, and T. Pastore, "Corrosion behavior of carbon steels in CCTS environment," *International Journal of Corrosion*, vol. 2016, Article ID 3121247, 7 pages, 2016.
- [3] Y. Zhou, H. Tian, H. Cui, F. Xing, and L. Sui, "Model for sulfate diffusion depth in concrete under complex aggressive environments and its experimental verification," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 693834, 11 pages, 2015.
- [4] A. Zyburka, M. Jaśniok, and T. Jaśniok, *Diagnostyka Konstrukcji żelbetowych tom 2. Badania Korozji Zbrojenia i Właściwości Ochronnych Betonu*, Wydawnictwo Naukowe PWN, Warszawa, Poland, 2011.
- [5] T. Krykowski, *Modelowanie uszkodzenia otuliny wywołanego korozją zbrojenia w żelbecie. Studia z zakresu inżynierii*, Nr. 78, Komitet Inżynierii Lądowej i Wodnej, Polska Akademia Nauk, Warszawa, Poland, 2012.
- [6] J. Bilčík and I. Holý, "Effect of reinforcement corrosion on reliability," *Journal Beton TKS*, vol. 3, pp. 16–20, 2012.
- [7] Z. Kala, "Reliability analysis of the lateral torsional buckling resistance and the ultimate limit state of steel beams with random imperfections," *Journal of Civil Engineering and Management*, vol. 21, no. 7, pp. 902–911, 2015.
- [8] J. Antucheviciene, Z. Kala, M. Marzouk, and E. R. Vaidogas, "Decision making methods and applications in civil engineering," *Mathematical Problems in Engineering*, vol. 2015, Article ID 160569, 3 pages, 2015.
- [9] V. Benko, *Reliability of Structures (According to Eurocodes)*, SKSI, 2010.
- [10] J. Vičan, J. Gocál, and J. Jošt, "Fatigue resistance of typical fatigue prone riveted steel railway bridge structural detail," *Communications—Scientific Letters of University of Zilina*, vol. 13, no. 3, pp. 5–8, 2011.
- [11] M. Krejsa, "Probabilistic reliability assessment of steel structures exposed to fatigue," in *Safety, Reliability and Risk Analysis: Beyond the Horizon*, R. D. J. M. Steenbergen, P. H. A. J. M. van Gelder, S. Miraglia, and A. C. W. M. T. Vrouwenvelder, Eds., pp. 2671–2679, CRC Press, New York, NY, USA, 2013.
- [12] J. Bujňák, R. Hlinka, J. Odrobiňák, and J. Vičan, "Diagnostics and evaluation of footbridges," *Procedia Engineering*, vol. 40, pp. 56–61, 2012.
- [13] M. Moravčík and P. Bujňáková, "New precast bridge girder with combined prestressing," *Communications—Scientific Letters of University of Zilina*, vol. 13, no. 3, pp. 19–23, 2011.
- [14] S. Caprili, J. Moersch, and W. Salvatore, "Mechanical performance versus corrosion damage indicators for corroded steel reinforcing bars," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 739625, 19 pages, 2015.
- [15] K. Tuutti, "Corrosion of steel in concrete," in *CBI Forskning/Research*, vol. 4, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 1982.
- [16] H. Böhni, *Corrosion in Reinforced Concrete Structures*, Woodhead, Sawston, UK, 2005.
- [17] D. V. Val and R. E. Melchers, "Reliability of deteriorating RC slab bridges," *Journal of Structural Engineering*, vol. 123, no. 12, pp. 1638–1644, 1997.
- [18] P. Koteš, *Contribution to the determining reliability levels of existing bridge structures [Ph.D. thesis]*, University of Žilina, 2005.
- [19] P. Thoft-Christensen and I. H. Hansen, "Optimal strategy for maintenance of concrete bridges using expert systems," in *Structural Safety and Reliability*, I. Schueller, H. Shinozouka, and J. T. P. Yao, Eds., pp. 939–946, Balheme, Rotterdam, The Netherlands, 1994.
- [20] M. K. Alkam and M. Alqam, "Prediction of the service life of a reinforced concrete column under chloride environment," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 156298, 8 pages, 2015.
- [21] I. Drevený, P. Koteš, P. Kotula, and V. Piták, "Remaining service life and increasing of concrete structures reliability," in *Proceedings of the 15th Russian-Slovak-Poland Seminar "Theoretical Basis of Civil Engineering"*, pp. 329–334, Druk i Oprawa-Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw, Poland, 2006.
- [22] P. Koteš and I. Drevený, "Diagnostic and evaluation of existing bridges in village Kolárovice," in *Proceedings of the 4th Proceeding of International Scientific Conference on Quality and Reliability in Building Industry*, pp. 209–214, Levoča, Slovakia, 2006.
- [23] EN 1990 Basis of structural design, SUTN, 2009.
- [24] P. Thoft-Christensen, "Reliability based expert system for bridge maintenance," in *Proceedings of the Tekno Vision Conference*, Copenhagen, Denmark, May 1992.
- [25] P. Koteš, J. Vičan, and J. Slavík, "Influence of reinforcement corrosion on reliability of existing concrete structures," *Komunikácie—Vedecké Listy Žilinskej Univerzity*, vol. 4, pp. 41–49, 2001.
- [26] STN EN 1992-1-1, "Eurocode 2: Design of Concrete Structures, Part 1-1: General rules for buildings," SUTN, 2006.