Testing to reassess – Corrosion activity assessment based on NDT using a prestressed concrete bridge as case-study

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Abstract. Corrosion of concrete reinforcement is one of the major damage mechanisms affecting both the load-bearing capacity and the serviceability of reinforced concrete structures significantly. The challenge of detecting corroding reinforcement is that the corrosion process is not immediately visible, especially in the corrosion initiation phase. When externally discernible damages are observed during visual inspections on the structure, the extent of the damage inside the concrete is often already significant. Corrosion caused by carbonation often leads to severe discoloration of the surface or even large-area spalling of the concrete cover. In contrast, chloride-induced corrosion is usually difficult to observe visually but can cause much more serious damage in less time. The effect occurs locally and can lead to weakening of the cross-section of the reinforcement. This, in turn, can cause sudden structural collapses without prior notice. Therefore, it is important to investigate whether there is protection against corrosion of the reinforcement in the concrete and to detect active corrosion in the structure at an early stage.

In the meanwhile, various non-destructive and minimally invasive testing methods are available to evaluate the resistance to penetration of corrosion-promoting pollutants and to detect active corrosion. In this paper, a bridge crossing the river Regen is used as a case-study to demonstrate how the information obtained applying different testing methods can be combined and evaluated in the context of structural reassessments. Both the results of the permeability testing and the electrical resistance measurement are considered, as well as active corrosion areas are localized using the half-cell potential mapping combined with the concrete cover measurement with the eddy current method and ground penetrating radar. The results are evaluated using drill cores and in addition laser-induced breakdown spectroscopy was applied to obtain information about possible chloride ion transport into the concrete.

Keywords: Corrosion, Existing Structures, Reassessment, Concrete Bridge, Non-destructive Testing, NDT.

1 Introduction

In summer 2018, an assessment according to the German reassessment guideline [1] revealed that the bridge across the Regen river near the Bavarian town of Roding no longer meets the requirements for the current traffic loads. The bridge was therefore dismantled and replaced by a new structure. The special conditions in the surrounding landscape with regard to nature conservation made a complex deconstruction measure necessary. A dismantling concept was developed, which provides for the cutting of the bridge into segments of different sizes. These segments were then removed using a mobile crane and subsequently dismantled in secured areas. During the structural assessment in preparation for the dismantling of the bridge, non-destructive testing methods were used on-site to obtain individually relevant information.

The geometric dimensions and the single cell hollow box cross-section of the longitudinally and transversely prestressed concrete bridge are typical for German road bridges (Fig. 1). The three-span bridge was built in 1965. The spans are 39 m + 55 m + 39 m and the total bridge length is about 133 m. The width of the bridge is approx. 12 m and the thickness of the web is about 78 cm. The height of the box girder varies between 1,20 m and 2,25 m. The prestressing of the bridge is ensured by 24 tendons in longitudinal direction per girder. These are post-tensioned with subsequent bond.

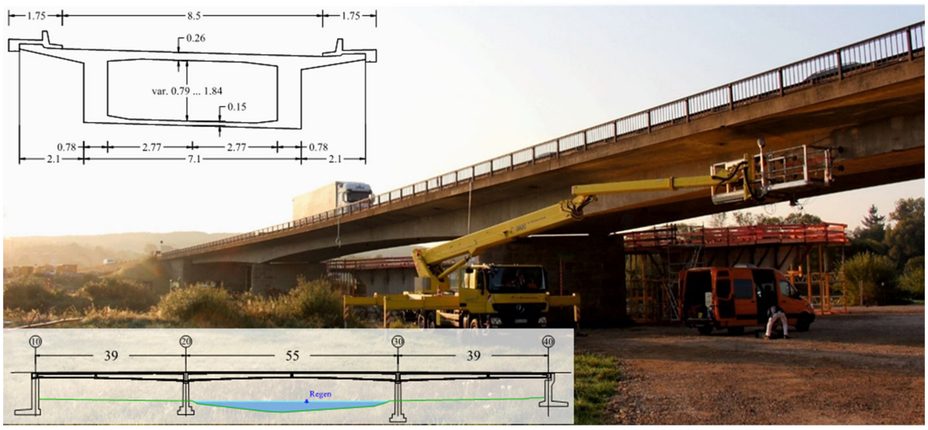

Fig. 1: Photo of the examined bridge with sketched cross-sections [2]

Due to this representative construction type for prestressed concrete bridges, which is typical for a number of bridges in Germany, various investigations were planned and conducted in order to evaluate non-destructive testing (NDT) methods on the real structure. For example, the positions of the longitudinal tendons were determined by ultrasound and radar measurements. After the bridge was dismantled, these NDT results were geodetically verified on the dismantled bridge segments. In addition, accurate geometric investigations of the bridge were performed using tacheometry and LIDAR. Based on the combination of the NDT results and the geometric measurements, it was determined that the incorporation of NDT results would provide a more realistic reliability assessment of the existing structure using probabilistic methods [3]. Another focus of the investigation was a load test with static and dynamic loading. In this loading test, natural frequencies as well as the geometrical deformations of the bridge were measured. The evaluation of these investigations is currently being undertaken. In addition to the testing methods used to determine the time-invariant condition of the bridge, further non-destructive measurement techniques were also used to assess time-variant processes such as chemical effects from the environment. In particular, the investigation of the progress of carbonation inside the concrete and the detection of active corrosion areas were performed.

2 Testing tasks, Methods and Measurements

Despite clear regulations in civil engineering, concrete infrastructures often demonstrate serious damage during their service life. A common cause of damage is corrosion of the reinforcement and the identifying and evaluating of corrosion processes is highly challenging. The major types of corrosion are due to carbonation and chloride-induced corrosion. For both types of corrosion, there are NDT methods that can be used to assess the progress and activity. The evaluation of the results is usually performed by minimally invasive destructive sampling. Table 1 lists a selection of test methods for evaluating corrosion probability on reinforced concrete.

Table 1. Methods for the evaluation of corrosion probability in reinforced concrete.

Testing task	Measurand	Testing method	References
Condition control	Air-Permeability	Torrent-Tester	[4,5]
Active corrosion	Electric	Half-Cell-Potential	[6,7,8,9]
Surface Moisture[1]	Electric resistance	Wenner-Probe	[8,9]
Concrete cover	Induced current	Eddy current	[8,9,10]
Concrete cover	Transit time	GPR[(1)]	[11,8,9]
Chemical analysis	Emission spectra	LIBS[(2)]	[12,13]

[(1)] Ground Penetrating Radar, [(2)] Laser-induced breakdown spectroscopy

Measurements were performed on the bridge at various stages of the demolition. Investigations were conducted directly on the structure with regard to active corrosion areas inside the box girder. In particular, an area was investigated where water containing deicing salts could penetrate the box girder through a damaged drainage pipe. Figure 2 shows the corroded and heavily damaged drainage pipe (crack) and the contaminated area of the floor slab in the box girder. Starting at the drainage pipe to the outlet, two-dimensional investigations were performed using the half cell-potential method, the eddy current method and GPR. In this case, the investigations with the GPR served to

[1] The surface moisture was also measured by the electrical impedance method ASTM F2659, showing values ranging between 2.2 and 4.2%, i.e. well below the upper limit of 5.5% prescribed in [5]; these data will be discussed in a future communication.

validate the measurement of the concrete cover with the eddy current method. Of particular interest was the detection of deeper reinforcement layers, such as those of the transverse tendons in the floor slab. Subsequently, drill cores were taken from critical areas with negative potentials and huge surrounding potential difference as well as from non-critical areas. Determination of chloride penetration and carbonation depth were subsequently performed in the laboratory using LIBS.

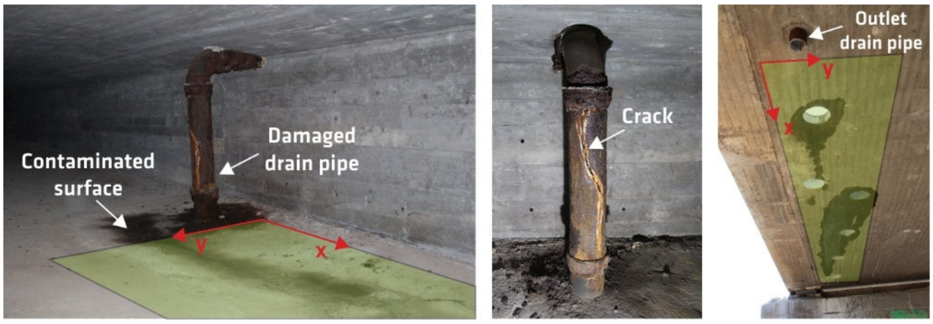

Fig. 2: View into the box girder with the damaged drainpipe. Measurement areas and positions of the drill cores taken are marked.

Additionally, 56 drill cores were taken along the entire length of the bridge. The cores were drilled completely through the bridge girder and have an average length of 100 cm and a diameter of 12 cm. The cores were then cut in half in the laboratory and examined with the Torrent method for air-permeability, standardized in Switzerland since 2003 [5]. This procedure made it possible to obtain a statement about the air permeability from the inner and outer areas of the bridge at each drilling point. Parallel to the measurements with the Torrent -Tester, the moisture of the concrete was measured with the Wenner-Probe and the electrical impedance methods. After the completion of these measurements, 9 samples were selected which represent different concrete qualities in the spectrum. These range from “very good” quality to “poor” quality according to the classification by [14

3 Results of Testing and Assessment

3.1 Condition assessment – Active corrosion

The results of the investigations for the detection of corrosion-active areas are shown in Fig. 3 (upper part). The measurements with the half-cell potential measurement were carried out in accordance with Specification B03 of the *Deutsche Gesellschaft für zerstörungsfreie Prüfung e.V.* (DGZfP) (German Society for Non-destructive Testing) [16]. The distance between the measuring points is 25 cm in a uniform measuring grid. Areas with similar electrical potentials are represented by a uniform color of the assigned scale. The dashed lines indicate the area along which the chloride-containing water flowed (see Fig. 2). High potential differences correspond to a high probability of active corrosion and were described as so-called potential funnels [12]. The lowest potentials are present in the range from x = 0 cm to x = 150 cm around the damaged drain pipe. Furthermore, large potential differences can be seen in a range from x = 300 cm to x = 360 cm. Overall, it can be observed that the potentials decrease from x = 0 cm to x = 900 cm in the area of the pillar. Based on this information, sampling was carried out using drill cores (black circles). In addition to these measurements, the coverage of the reinforcement near the surface was determined using the eddy current method. With the GPR, the deeper reinforcement layers are imaged down to a depth of t = 9 cm. In the C-scan of the GPR measurements, the positions for the tendons are additionally highlighted by a green dashed line.

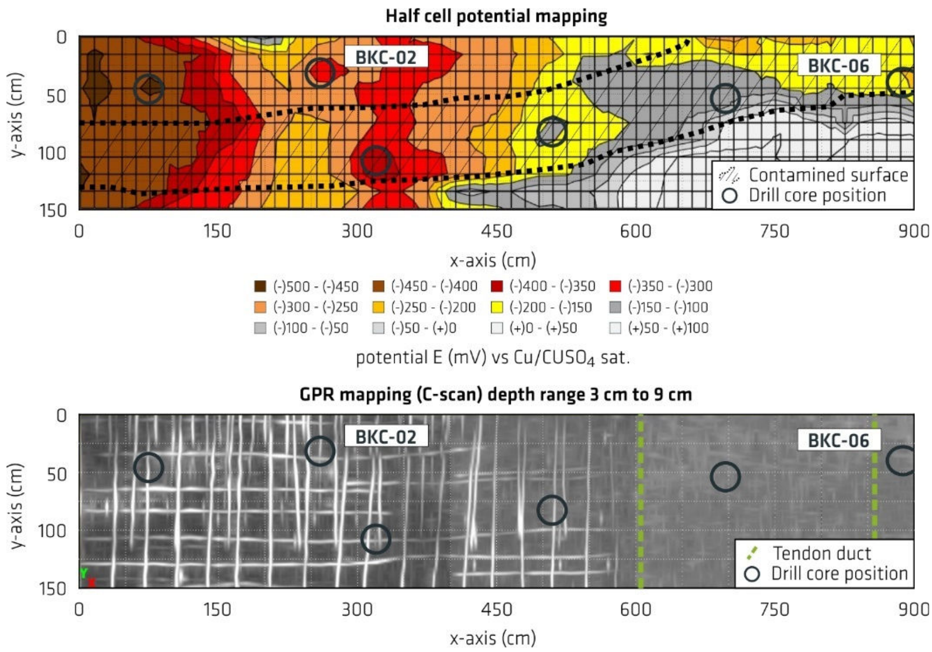

Fig. 3: Mapping of half-cell potential method (top) and GPR (bottom) results from the box girder with position marker of the drill core locations.

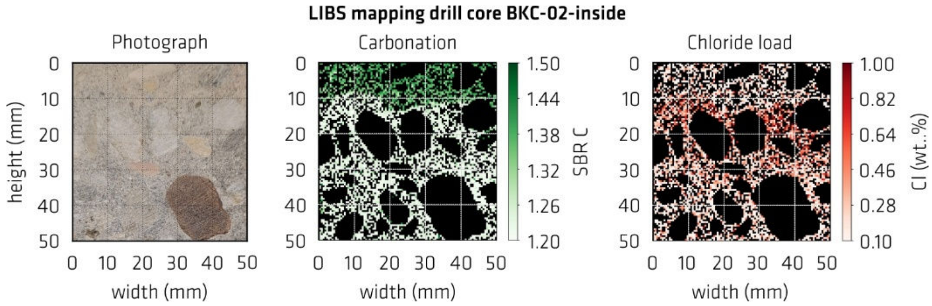

Fig. 4: Results of LIBS measurements on a drill core (BKC-02-inside) with spatial resolution of 0.5 mm x 0.5 mm. The carbon content is indicated in qualitative terms, and the chloride content is given as a percentage by weight related to the hardened cement paste.

Figure 4 demonstrates an example of the evaluation of the chemical analysis with LIBS on the BKC-02-inside drill core. Measurements were performed with a spatial resolution of 0.5mm x 0.5mm. Of all the cores measured, the maximum carbonation depth was determined at about 15 mm and the maximum chloride penetration at about 30 mm.

Using the half-cell potential method, areas of active corrosion could be determined and evaluated by taking drill cores. In this case, the active corrosion only affects the reinforcement near the surface. The deeper-lying tendons are not at risk from carbonation or chloride penetration. However, it cannot be ruled out that chlorides may have penetrated deeper into the concrete in local areas along cracks, potentially leading to chloride-induced corrosion on the tendons. Cracks could not be detected in the examined area during visual inspection.

3.2 Condition assessment – Air-Permeability

The 58 drill cores were sawn into 4 parts with different lengths. Thus, 2 samples (inner-outer area per core) each with a diameter of 120 mm and an average thickness of 80 mm were available for the measurements with the Torrent-Tester. Because of their very different surface properties, only 54 samples of the 58 cores were suitable for air-permeability measurements. The measurements were conducted under laboratory conditions at BAM.

The first step was to evaluate whether the permeability measurements directly at the bridge were consistent with the results of the laboratory measurements. No significant difference in the measured data could be observed. Prior to the permeability measurements, the moisture content of the concrete was determined using Wenner-Probe with values ranging between 120 and 1900 kΩ.cm. These high values indicated that the concrete was sufficiently dry to get meaningful air-permeability test results [17]. In the second step, selected samples were sawed and chemically analyzed using LIBS.

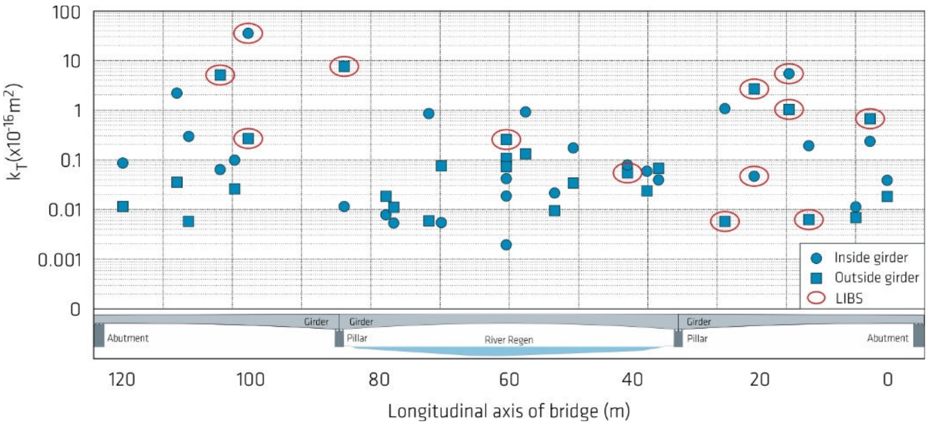

Fig. 5: Diagram of k_T--values (Torrent-tester) combined with schematically profile of bridge in longitudinal bridge axis.

Figure 5 shows the results of all air-permeability measurements along the bridge girder, distinguishing between inner and outer areas of the structure (square – outside, circle - inside). For orientation, the bridge is shown schematically below the diagram. The results of the measurements can be divided according to the classification of [14. Of the total of 54 samples, 10 samples have a "very good" quality, 25 samples have a "good" quality, 11 samples have a "medium" quality, 7 samples have a "poor" quality and one specimen has a "very poor" quality. This scatter of values is typical of old concrete structures after decades of exposure to service and environmental loads [18].

3.3 Condition assessment – Carbonation

Finally, to evaluate the structure in terms of carbonation, a model according to [15] is used. This model is based on the evaluation of measurement data from various concrete structures. Therefore, the first step is to check whether the collected measurement data satisfy this evaluation. For this purpose, the carbonation progress was measured on 13 specimens of different concrete qualities using LIBS, with a result shown in Fig. 4. Figure 6 (diagram on the left) compares the measurement points and the resulting linear regression analysis with the results from [15]. One measurement point was removed due to the high variance in repeat measurements. The regression analysis shows that the carbonation rate deviates from the analytical model by less than 0.5 mm/y$^{1/2}$. Thus, the results are within the specified confidence interval according to [15] and the proposed model is applied for the evaluation of the bridge.

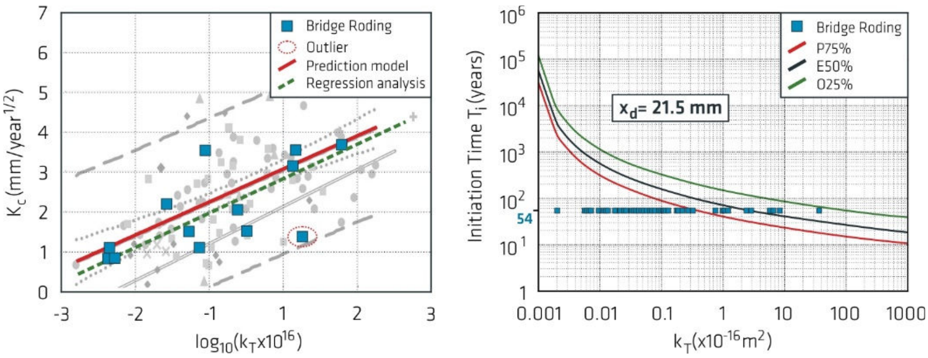

Fig. 6: Evaluation of the measured values of the bridge (Roding) for the method used according to [15] (diagram on the left). Calculation of the probability of occurrence of carboantization according to [15] (diagram on the right).

Based on the model according to [15], different scenarios were calculated for a concrete cover of x_d = 21.5 mm (x_d - from as-built drawings) with different probabilities of the occurrence of carbonation. These are shown in Figure 6 (Diagram right side) together with the results of the air-permeability measurement. For the pessimistic scenario (P75%), 11 measured values are above the value of k_T = 0.4 (x10^{-16}m^2). The measured average carbonation depth above this value is d = 19.1 mm. Thus, a timely rehabilitation would be recommended at this bridge and shows that the calculation method by R. Neves [15] provides good results.

4 Conclusion

Before and during the dismantling of the bridge built in 1964, a wide variety of investigations were conducted using non-destructive testing methods on-site. The objective of this investigation was to evaluate testing techniques, two of which are presented in this contribution. One the one hand, the progress of carbonation was determined by measuring the air permeability of the concrete. On the other hand, areas exposed to active corrosion were detected and subsequently evaluated.

The air permeability of concrete was measured using the Torrent tester on numerous samples drilled along the bridge girder. The utilization of the measurement results shows that the model developed by [15] leads to a very good estimation of the carbonation progress. Furthermore, it was possible to visually identify an area inside the box girder where increased chloride levels were expected. By means of half-cell potential mapping, parts of this active corrosion area could be localized non-destructively. Chemical analyses based on LIBS on additionally drill cores taken provided evidence that the chlorides did not damage the tendons in this area.

Acknowledgements

To Sadam Aljayyas and Guilherme Scheeren (BAM) and Dr. Verónica Bueno (MAS), for their cooperation in measuring air-permeability, surface moisture and resistivity of the cores.

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