Influence of concrete damage on reinforcement corrosion

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Abstract. Concrete damage (cracks, voids and delamination) significantly influence initiation and propagation phase of reinforcement corrosion. The three methods are combined in the framework of this research: (i) on-site testing on concrete bridges, (ii) application of an advanced numerical model for service life prediction on existing structures and (iii) laboratory experiments on permeability of cracked concrete. The aim of this research is to determine the mutual interaction of material, structural, environmental and climate performance indicators under following degradation mechanisms: chloride induced corrosion of reinforcement in concrete and concrete cracking due to mechanical and non-mechanical loading. The broader aim is to predict bridge service life more precisely as a base for establishment of an optimal bridge quality control plan. The focus of the paper is application of on-site testing on existing bridges. Influence of cracks in concrete on reinforcement corrosion on existing structures can be determined by application of non-destructive testing, not only by measured values but also to define area of structure on which a crack has impact.

1. Introduction

In the framework of the CODEbridges project [1] researchers from the University of Zagreb collaborate with the University of Stuttgart and four road authorities responsible for management, construction and maintenance of approximately 3 300 bridges in total on different type of roads in Croatia: motorways, national, county and local roads as well as city bridges. The overwhelming majority of the road bridges are made of concrete.

The major cause of deterioration and service life reduction of reinforced concrete (RC) bridges is chloride-induced corrosion of steel reinforcement in concrete due to exposure to sea and/or de-icing salts. Concrete structure deterioration is more progressive in multi-hazard environment: high sea salinity and strong winds depositing sea spray on all structural elements; large amounts of de-icing salts in combination with damage and cracks caused by freezing-thawing cycles, high seismicity region, extreme traffic load during summer tourist season, etc. Moreover, damage and cracks in concrete, as a consequence of errors in design and construction or mechanical action (static, dynamic and cyclic loading) accelerate the penetration of aggressive agents in concrete structure reducing steel reinforcement depassivation time and cause higher corrosion rate.
2. Determination of influence of concrete damage on reinforcement corrosion

In order to determine influence of concrete damage (cracks, voids, delamination) on steel reinforcement corrosion in concrete three methods are combined in the framework of this research: (i) on-site non-destructive testing on concrete bridges, (ii) application of an advanced numerical model for service life prediction on existing structures and (iii) laboratory experiments on permeability of cracked concrete.

Application of the 3D chemo-hygro-thermo mechanical (3D CHTM) model for numerical simulation of reinforcement corrosion in concrete on existing bridges demonstrate significant influence of cracks and damage in concrete on precisely determination of the steel reinforcement depassivation [2-4].

Experimental tests in laboratory on water permeability were performed on un-cracked and cracked concrete specimens. Cracks in concrete specimens are generated by splitting test and concrete specimens with crack width ranging from 0.05 to 0.20 mm are than tested on water permeability. Obtained experimental results are in well agreement with available literature [5] and concrete permeability in cracked concrete is up to 1000 higher than in un-cracked concrete. Laboratory results provide useful data for development of the model of concrete permeability and water diffusivity as a function of crack width and its implementation in the 3D CHTM model.

Results of provided on-site testing on the bridges will be presented in more detail in next chapter.

3. Visual inspection and non-destructive testing on concrete bridges

Visual inspection is the most commonly used method to assess condition of bridges and to make decision on non-regular maintenance such as repair, strengthening and reconstruction. Investigation works including destructive and non-destructive testing used to be conducted once the decision on bridge intervention is made based on the results of visual inspection, in order to define required scope of the repair design project. Accuracy of visual inspection depends a lot on the skills of the individual inspector and spent time [6, 7]. In order to improve objectivity and accuracy of bridge condition assessment visual inspection are combined with non-destructive testing [8].

3.1. Selection of NDT methods

The non-destructive testing methods, used to evaluate material, structural and reinforcement corrosion related bridge performance indicators (PIs), are selected based on the following favorable characteristics (table 1) [8]:

- Simple for use, fast to perform and cost-effective testing;
- Complemented by visual inspection to assure more reliable bridge assessment
- NDT device availability among inspectors
- Measured PIs are included in the 3D CHTM model for service life prediction.

Preparation for bridge testing starts by obtaining and reviewing the available documentation on design and maintenance. During preliminary visual inspection locations for testing are defined. Measuring locations are distributed among the bridge portions that can be accessed without special platforms, but in such a manner to include different structural members i.e. abutments and girders.

NDT starts with cleaning of concrete surface and identification of position and alignment of reinforcement, then concrete cover and rebar diameter are measured. Crack width is measured by ruler (crack width rod) and optical microscope, while crack depth and dynamic elastic modulus is estimated by ultrasonic pulse velocity device. Crack pattern and concrete cover delamination for the location with significantly damaged concrete due to reinforcement corrosion is recorded based on visual inspection and by sounding it (tapping it) with a hammer. Schmidt hammer is used to assess the uniformity of concrete strength, discover potential location of lower quality and determine concrete compressive strength. At the end of testing, half-cell potential and concrete resistivity are measured after wetting of the concrete surface.
### Table 1. Applied NDT methods and measured performance indicators (PIs) [8].

| NDT methods and techniques      | PI                          | Impact on structure load – bearing capacity | Impact on reinforcement corrosion |
|---------------------------------|-----------------------------|---------------------------------------------|----------------------------------|
| Schmidt hammer                  | Compressive strength       | ●                                           |                                  |
| Ultrasonic pulse velocity (UPV) | Modulus of elasticity      | ●                                           | ●                                |
|                                 | Crack depth                | ●                                           | ●                                |
| Optical microscope              | Crack width                | ●                                           | ●                                |
| Cover meter                     | Position and alignment of reinforcement | ●                                           | ●                                |
| Wenner probe                    | Electrical resistivity of concrete | ●                                           |                                  |
| Voltmeter                       | Half-cell potential        | ●                                           |                                  |

#### 3.2. Case study

Six concrete bridges exposed to chlorides are selected for visual inspection and NDT in the framework of this research project. The bridges are of different load-bearing type, age, material and traffic demands. Four of them are exposed to de-icing salts and continental climate, while two structures are located in maritime environment on the Adriatic Coast and attacked by sea salts and strong wind [9-11]. Due to paper constrains more details and results are shown only for one case study: Adriatic bridge across Sava River in Zagreb (figure 1, table 2).

Adriatic bridge across Sava River in Zagreb was built in 1981. With a length of 479 m, the bridge comprises: main bridge (central dilatation) with seven spans, single span north approach viaduct and south approach viaduct with four spans, respectively. Most of the superstructure comprises 39 m long prestressed concrete (PC) girders, RC cross girders and a RC deck. The largest span above the river was achieved by utilizing 12 m pier cantilevers comprising box cross sections between two PC girders [8, 12]. During the last visual inspection in 2017, investigative works were done to determine carbonatization depth according to the code HRN EN 1542, chloride content in concrete using rapid chloride penetration test, tensile and compressive strength according to the HRN EN 1542 and HRN EN 12504-1, respectively. Inspection determined that the damage to structural parts of the bridge are of such a scope that the bearing capacity of the bridge is reduced [13].

![Figure 1. Adriatic Bridge layout with specified measuring locations [8].](image-url)
Figure 2. Measuring locations on the Adriatic Bridge: AB2 – the U4 abutment wall, AB3 – the U4 abutment wing and AB5 – bottom of the girder N6.

3.3. Results

Summarized results of provided testing on the Adriatic Bridge are presented in table 2. Surface plots of measured half-cell potential and electrical resistivity on the south U4 abutment wall (AB2) are shown in figure 3. Correlation between half-cell potential and electrical resistivity is shown for all provided measurements in figure 4. Each measuring location includes at least one crack, mainly or partially caused or progressed by reinforcement corrosion [8].

Table 2. Summarized results of provided NDT measurements on Adriatic Bridge [8].

| Measuring location | AB2 | AB3 | AB5 |
|--------------------|-----|-----|-----|
| Structural element | Abutment U4 - wall | Abutment U4 - wing | Girder N6-bottom |
| Values             |     |     |     |
| Concrete cover [mm] | 34 | 56 | 43.21 |
| Diameter [mm]      | 18 | 27 | 23.75 |
| Concrete cover [mm] | 52 | 52 | 52 |
| Diameter [mm]      | 28 | 28 | 28 |
| Half-cell potential [mV] | -434 | -126 | -291.51 |
| El. resistivity [kΩcm] | 6.3 | 39.1 | 6.33 |
| Compressive strength [MPa] | Q | Q | Q |
| Schmidt hammer test | 39.2 | 3- 65.1 | 18-63 |
| Width [mm]         | 1.2 | 0.5 - 1.05 | 0.078 |
| Depth [mm]         | 52 (cc) | 30 ; 118 | 131 |
| Length [mm]        | 1000 | 420; 750 | 300 (flange width) |

*absence or delamination of concrete cover*
Figure 3. Surface plot of measured a) half-cell potential and b) electrical resistivity for the U4 abutment wall of the Adriatic Bridge (AB2).

Figure 4. Correlation between measured half-cell potential and electrical resistivity for all measuring location.

The measured values of electrical resistivity and half-cell potential show moderate risk of corrosion on all three location among which the south abutment wall (AB2) is the most vulnerable, with the lowest electrical resistivity and half-cell potential and the highest half-cell potential gradients. On this location determined chloride content in concrete at the reinforcement level (depth of 4 mm) is above threshold value of 0.05% of concrete mass [13]. Moreover, concrete has non-uniform quality and contains wide and deep cracks. The lowest measured tensile strength is 1.6 MPa. The cause of the abutment wall decay is with de-icing salts contaminated water leakage through the deteriorated expansion joints.
The wing of the south abutment (AB3) is less exposed to de-icing salts but executed concrete cover does not exist or it is very thin and delaminated (0-5 mm) enabling faster penetration of aggressive substances and depassivation of reinforcement corrosion.

Typical pitting corrosion is detected on the bottom of the girder (AB5), where the measured electrical resistivity is very low in cracked region with reinforcement corrosion, while the resistivity of sound (un-cracked) concrete only 80 cm away is more than 20 times higher [8, 11].

3.4. Discussion

Visual inspection combined by non-destructive testing provides current bridge condition assessment. However, to achieve sustainable bridge management system with effective and efficient bridge maintenance, it is necessary to predict future degradation processes on the structure. For this purpose, numerical models have been developed and subsequently improved in last four decades.

However, quantifying the material, mechanical and corrosion related parameters and their interactions are still challenging tasks and main objective of the current research project.

To assure more realistic simulation of degradation processes in future, more comprehensive and accurate input data for a numerical model are required, which can be obtained by visual inspection and NDT, e.g. concrete cover thickness, rebar alignment, crack position and geometry, electrical resistivity [11].

One of the most important PI related to reinforcement corrosion is concrete cover with sufficient quality and thickness. Executed concrete cover used to be lower than designed value [11].

Damage and cracks in concrete caused during construction and/or service life significantly accelerate reinforcement corrosion. Namely, crack with width from 0.2 to 0.4 mm can increase chloride diffusivity from 10 to 10³ times comparing to un-cracked concrete of the same quality [14].

Another time-varying PI important for durability is electrical resistivity of concrete, inversely proportional to corrosion rate - current density. Electrical resistivity depends on many parameters, e.g. porosity, water to cement ratio, aggregate, concrete curing, water and ions content in concrete, etc. Although several researches have been focused on determining influence of various parameters on electrical resistivity [15, 16], development of numerical models of resistivity as a function of the most influencing parameters is still challenging tasks. On the other side, electrical resistivity measurement technique is becoming popular non-destructive method in last two decades, due to its simplicity, rapidness, and cost during test conduction. Hence, measured electrical resistivity presents an important input parameter for service life prediction of concrete structure [15, 16].

Although measured half-cell potential cannot be directly compared with calculated values of electric potential in numerical model, great gradients and very negative potential values measured on real structures, provide useful information for anode and cathode configuration in model, whose surface and position should be assumed in advance due to computation issue [11].

4. Conclusion

Although, each NDT has limitations in terms of measurement accuracy, such as the determination of the depth of the crack in concrete by the ultrasonic method, and experiments in laboratory demonstrate more precisely the impact of cracks on each particular parameter related to transport processes and reinforcement corrosion, on-site destructive and non-destructive testing on existing bridges have many benefits for application since there is quite a difference between accelerated reinforcement corrosion on concrete specimen and a reinforcement corrosion on an existing structure in natural environment.

Reinforcement corrosion in concrete cannot be timely detected only by visual inspection. Namely, during the initiation phase of reinforcement corrosion, there are no visible damages on concrete surface, while at the beginning of the propagation phase damage are hardly detected. Only damages in advanced stage of reinforcement corrosion, manifested in the form of cracking and spalling of concrete cover, can be detected during visual inspection. Combining on-site testing with visual inspection of bridges, reinforcement corrosion on structural elements can be detected earlier and more precisely than in case when only visual inspection is performed, since invisible defects can be also detected and that was
confirmed by additional destructive testing on the case study bridge. Moreover, the speed of structure
degradation can be determined by comparing the periodic results of the provided NDTs.

Results obtained by visual inspection and NDTs presents valuable input data for numerical model
for service life prediction of structure, especially for inclusion of time and space variation of parameters
depending on a non-uniformity of concrete quality (local cracks, damage). Influence of cracks in
concrete on reinforcement corrosion on existing structures can be determined by application of NDTs,
not only by measured values but also to define area of structure on which a crack has impact.

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