ASSESMENT OF BRIDGE STRUCTURE DURABILITY – ANALYSIS AND EXPERIMENTAL VERIFICATION

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Abstract
The paper is focused on the problem of durability of RC structure exposed to the typical ambient conditions for bridges. The causes and degradation processes of the structures, mechanisms of concrete carbonation and chloride penetration are described. Theoretical model which allows the prognosis of all changes affecting construction safety in time is presented. The findings of the theoretical analysis have been compared with the results of the experimental research of viaduct in its advanced degradation stage as well as the material samples taken from them.

Streszczenie
Artykuł jest poświęcony zagadnieniu trwałości na podstawie analizy obiektu mostowego. Opisano przyczyny i procesy degradacji obiektu, mechanizmy karbonatyzacji betonu i penetracji chlorkowej. Przedstawiono model teoretyczny pozwalający prognozować przebieg zmian bezpieczeństwa konstrukcji w czasie. Wyniki analizy teoretycznej porównano z rezultatami badań doświadczalnych obiektu mostowego w zaawansowanym stadium degradacji i pobranego materiału.

Keywords: **Carbonation; Corrosion; Maintenance; Service life.**

1. INTRODUCTION

Structural durability is referred to as the ability to fulfil during an expected time period the users' requirements, including safe transfer of all predictable loads as well as acceptable aesthetics of structural surface, considering ambient conditions, action of certain substances and without appearance of excessive costs of repairs. Knowledge of materials degradation mechanisms and their influence on the structure properties enables to predict their service period. Several processes lead to shortening of the structural durability assumed in design by provoking degradation of concrete and corrosion of reinforcement. In any environment, one should account for presence and diffusion of carbon dioxide, causing concrete carbonation and further corrosion of the non-protected reinforcement. Some structures are placed in aggressive atmospheres provoking accelerated degradation and corrosion process, as chemical production plants or bridges subjected to de-icing winter treatment. The issue of cyclic freezing-thawing effect is not addressed in this paper.

Awareness of the engineers on the importance of the design and construction decisions on durability is continuously increasing. Many structures built in the past show today damages resulting from corrosion. Today standard provisions require fulfilling several requirements and recommendations referring to cross-section layout and materials selection, which should result in improving the durability of a given member. But at the same time, need to predict the optimal time of repairs of existing structures remains important. Models of evaluation of theoretical degradation process of concrete members are helpful for such purposes. The aim of this work is to present an application of such model to a structure exposed to environmental and chlorides actions.

2. THEORETICAL MODEL OF DEGRADATION

Degradation process in concrete structures is generally divided into two main periods:

- incubation, when concrete passivates the embedded reinforcement and its deterioration is not yet started, but carbonation progress continuously enters inside the cross-section,
- propagation, when reinforcement corrosion is started and progressing decrease of reinforcing bars diameter provokes simultaneous decrease of load-bearing capacity.

Chloride ions presence in concrete at any time – propagation or incubation – will provoke pitting corrosion, several times faster than the standard uniform corrosion of depassivated steel. Composition of the model presented below follows this two-fold approach.

2.1. Period of incubation

The goal of calculation for this period is limited to the evaluation of the time needed for carbonation of the whole cover thickness. The incubation time t_i is obtained from the expression:

$$t_i = \left(\frac{x}{K}\right)^2 \qquad \text{[in years]} \tag{1}$$

where (details in [4]):

x – thickness of the concrete cover layer, mm;

K – carbonation rate factor depending on the set of parameters: the relative ambient humidity, the concrete compressive strength and the environment conditions, factor in [mm/years $^{0.5}$].

In concrete exposed to chlorides action, concentration of chlorides at the given depth from surface depending on time may be evaluated from the formula involving Gauss error function *erf* (…):

$$C_x(t) = C_0\left[1 - erf\ \frac{x}{2\cdot(D\cdot t)^{1/2}}\right] \tag{2}$$

where:

$C_0(t)$ – chlorides concentration in the surface layer of concrete at time t,

C_x – chlorides concentration at the distance x from the surface layer of concrete,

D – diffusion coefficient assuming for the overall chlorides concentration in concrete,

x – depth from the surface penetrated by chlorides.

2.2. Period of propagation

In the propagation period, corrosion of the steel bars progresses. Its important result for the structural safety is reduction of the bar diameter. Expression discussed in [11] has the following form derived from Faraday's law; it gives the thickness of corroded steel in the course of time

$$\delta(t) = \alpha\cdot\lambda\cdot i_{cor}\cdot(t - t_i) \tag{3}$$

where:

$\lambda = \dfrac{M}{\rho n F}$ – uniform penetration rate per current unit density, $\lambda = 0.01163$ for Fe; for iron: $M = 55.85$ g/mole (molar mass), $\rho = 7.85$ g/cm^3 (density), $n = 2$ (valency for Fe^{2+}), F = 96485 C/mole (Faraday's constant);

α – acceleration coefficient, equal to 1 for uniform corrosion, equal to 4 to 5 in the case of pitting corrosion provoked by chlorides;

t , t_i – time, incubation time, years;

i_{cor} - corrosion current density, μA/cm^2 :

$i_{cor,max}$ = 1.0 μA/cm^2 (aggressive atmosphere);

$i_{cor,med}$ = 0.5 μA/cm^2 (medium aggressive atmosphere);

$i_{cor,min}$ = 0.2 μA/cm^2 (low aggressive atmosphere).

3. PRESENTATION OF THE INVESTIGATED STRUCTURE

The above described expressions for depth of carbonation, chloride ion concentration, and for evaluation of the propagation periods will be adopted for the assessment of material degradations and structural serviceability life. The analysis is focused on a viaduct located in the south of Poland. The structure, which was built in the late 70s., is a 22-span bridge over river, 408.30 m in total length (Fig. 1). The bridge deck is composed of six prestressed concrete precast I-girders connected by a concrete slab cast in place (see Fig. 2 to 4). The superstructure is supported by RC column piers crowned with reinforced concrete beams.

The prestressed concrete precast girders have each a cross-section area of $A_{cp} = 0.32$ m^2, and cross-section depth of $h = 0.9$ m. Their standard lengths reach 16.0 m and 18.0 m, but their real lengths are larger: the distance between the support axes is between 16.72 m and 16.89 m for the girders "16.0 m" and 18.59 m to 18.93 m for girders "18.0 m". According to the design, the girders were cast of concrete with average compressive strength equal to 40 MPa. Pier cross-heads are symmetrical with an overall length of 8.40 m. Their cross-section is rectangular and varies between 600 mm × 700 mm and 1000 mm × 700 mm (depth x width). Piers and crossheads were cast of concrete with average compressive strength equal to 30 MPa. Reinforcement average yield strength of crossheads was measured at 410 MPa.

Figure 1.
View of viaduct before repair

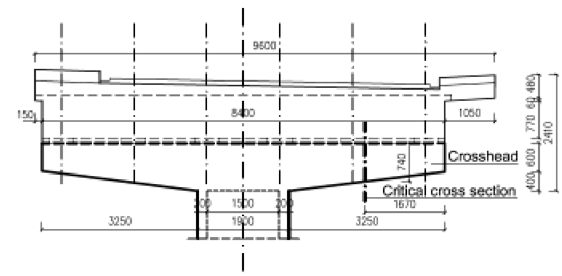

Figure 2.
Geometry of the crosshead on a RC pier

The bridge is built in an area, where winter conditions exist during the longest period for the whole country. Starting from the beginning of its exploitation, the structure was subjected to the action of unfavourable ambient conditions, as air temperature variations in yearly and daily cycles including freezing, variable humidity as well as the appearance of chloride ions as a result of winter road maintenance (planned de-icing of roads). The main attention is focused on both concrete members: girders and crossheads. They were in the place particularly susceptible to chloride corrosion, since water from the viaduct surface was leaking for a long time through expansion joint gaps and out of non-tight collector (Fig. 5). After preliminary studies, prestressed concrete girders of the bridge load carrying structure were found in a good condition. The crossheads are the most damaged parts of this viaduct and they serve as the research field. The structural safety assessment is related to the bending moment born by a cantilever cross-section. Although from the static point of view the most critical section may be the one at the cross-beam connection to the column, observed corrosion state influenced the choice of another cross-section, located at 1670 mm from the free end of the cantilever (shown in Fig. 2).

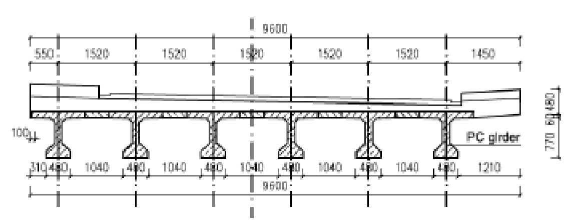

Figure 3.
Cross section of bridge in one of the spans

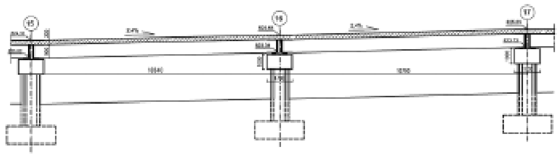

Figure 4.
Part of longitudinal section of the bridge

Following the renovation project provisions, assuming an increasing structure capacity to the highest load class, the present viaduct was subjected to an advanced reconstruction. Pillars and crossheads were cleaned and stiffened by an additional concrete layer (0.2 m). Girders were sandblasted and covered with protecting layer.

Figure 5.
Bridge before repair: a) view of the investigated crosshead in the axis no. 16, b) non-tight collector above the pier crossbeam of bridge

4. CHEMICAL ANALYSIS OF CONCRETE SAMPLES TAKEN FROM STRUCTURE

Results of laboratory tests on selected specimens collected from the viaduct are presented in the following section. The aim is to determine the technical state of the structures, in particular the state of corrosion process. As already mentioned, concrete samples were taken from locations particularly exposed to corrosion, i.e. from crossheads no. 15 and 16, including the zone situated directly below the expansion joint. The samples were obtained by crushing pieces of concrete cover or taken in the form of drillings from 0-50 mm deep holes, separately for every 10 mm. Seven core drilled specimens and drillings at 16 locations were separated. Six drilling locations were located on the less corroded crosshead no. 16 and ten on the more corroded one no. 15 (Fig. 6).

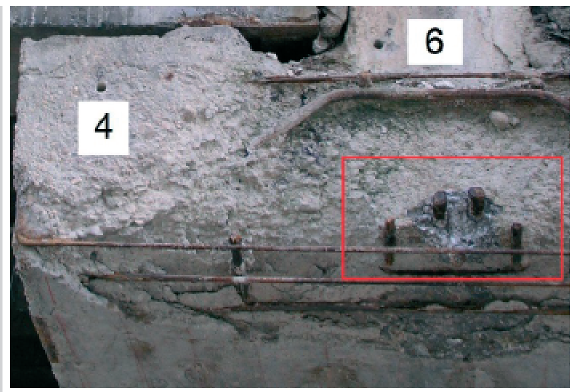

Figure 6.
Drilling locations on the more corroded crosshead no. 15

The samples were subjected to chemical analysis in accordance with test standards given in the codes [7-8]. The analysis included: determination of pH for water extract and percentage of chloride ions in the cement gel. For all drillings and core drillings, the results show similar pH factor values for all locations, but varied mean amount of chloride ions. The pH for all the drillings are in the range 9.55-11.73, below the threshold value at 11.80 [2], which represents safe conditions for reinforcement passive state. The pH variations with depth of drilling for both crossheads are similar. Selected results are shown in Table 1.

Table 1.
Chemical analysis results for the material obtained by drilling from crossheads (average)

No.	Location of sample	Depth of concrete cover [cm]	pH value	Cl^- [% weight of cement]
1	Crosshead no. 15	0.0-1.0	9.55	1.46
		1.0-2.0	10.40	1.70
		2.0-3.0	11.24	2.06
		3.0-4.0	11.11	1.62
		4.0-5.0	11.49	1.20
2	Crosshead no. 16	0.0-1.0	9.77	0.63
		1.0-2.0	10.24	0.66
		2.0-3.0	11.34	1.30
		3.0-4.0	11.73	1.10
		4.0-5.0	11.63	0.80

The viaduct presented visibly more advanced corrosion development than other similar structures. Reinforcement corrosion was observed mainly at the locations, where water from the bridge surface leaked through the expansion joints and collectors, where splitting of concrete cover was also observed. Higher amount of chloride ions was observed also in crosshead no. 15 compared to the other one. This proves a popular opinion that the presence of chloride ions Cl^- in concrete provokes highly accelerated reinforcement corrosion progress compared to the case of pure carbonation [10]. Chemical analysis allowed to determine the percentage of chloride ions in relation to concrete depth and also to determine the depth of chloride ions penetration. Slightly higher concentration for the crosshead no. 15 was observed. The average saturation of chloride ions for all the tested specimens to the depth of 80 mm is above the limit value, which for concrete structures equals 0.4% of the cement weight [2]. Values obtained for the depths of 2.0-3.0 cm reach over 2-5 times more than the limit. This limit value is exceeded three times in surface layers of the concrete cover due to "washout" of chloride ions.

5. COMPARISON OF EXPERIMENTAL RESULTS WITH THEORETICAL CALCULATIONS

The model described in this paper is used to analyse the durability of the structure subjected to progressive degradation, in order to estimate its service life. Primarily, the incubation time t_i, is determined based on concrete carbonation and chloride ingress, taking into consideration the environmental conditions (relative ambient humidity, chlorides concentration). In the second step the propagation period is analysed based on corrosion rate derived from Faraday's law, when progressive reinforcement corrosion develops. For viaduct member types, corrosion provokes continuous reduction of the load bearing capacity in critical sections. Parameters of the corrosion process measured in the laboratory tests are used to build a relation between the analysis and the observed condition of the structures.

The incubation time is calculated according to Eq.(1). In Table 2, theoretical values of the incubation times in years are presented for the relevant concrete cover thickness for reinforcing bars and for various levels of the relative humidity of the ambient air. Results obtained for the most adequate values of the relative humidity of the ambient air – 60% and 70% – are shown on grey background. For the further analysis, incubation time for reinforcement was assumed for 8 years as a representative value for the usual relative humidity level of the ambient air.

Table 2.
Incubation time for the given thickness of concrete cover and various relative humidity: crossheads (c = 40 mm)

RH	Incubation time [years] for c = 40 mm
50%	6.91
60%	7.55
70%	9.30
80%	15.72

Using further the same analytical approach and basing on available boundary values, evaluation of the carbonation depth for the 35-years old RC crossheads is carried out. It brings the information that at this concrete age, for relative humidity assumed in the range of 60% to 70%, the pH factor of concrete is lower than the "threshold value" of 11.80 at concrete depth of 69-78 mm (see results in Table 3). It may be noticed that the carbonation depth evaluated is in an agreement with results obtained in the chemical test program. Both theoretical and measured pH factor values at the depth of 50 mm from the concrete surface are lower than 11.80 (see Table 1).

Table 3.
Depth of carbonized concrete layer for 35 years (crosshead)

RH	Depth of concrete layer [mm]
50%	82
60%	78
70%	69
80%	54

As this structure was exposed to chloride action, another calculation based on Eq.(2) is performed in order to evaluate the penetration of chloride ions in the concrete depth. Average concentration of chloride ions at concrete surface for the material obtained from crosshead no. 15 was found at 1.46%. For the analysis, Byfors diffusion coefficient $D = 1.75 \times 10^{-12}$ m^2/s is estimated in relation to concrete properties according to [9, 11]. It is thus determined that the limit amount of chloride ions (0.4%) is exceeded to the depth of 74 mm. The comparison shows the convergence of the results obtained from analysis and measurements. An important observation is that steel reinforcement state demonstrates advanced corrosion provoked by high chloride concentration in spite of alkalinity of the surrounding concrete, but below safety limit of 11.80.

In situ observations of the structure had confirmed an advanced corrosion level of longitudinal reinforcement in crossheads, especially crosshead no. 15 (Fig. 6). Cracking and splitting of the concrete cover were observed as the effect of an increased volume of corrosion products: most of the surface cracks were located directly above and parallel to the reinforcing steel bars and splitting of concrete cover exposed steel for intensified corrosion. Along excessive cracks, reinforcement pitting corrosion was also found (below a leaking expansion joint). Corrosion of bars results in their cross-section decrease. The nominal diameter of the main bar of #20 mm was found to be decreased locally even to 17.6 mm. This decrease causes simultaneous reduction of the load bearing capacity, as this is investigated in next part of this paper.

6. PREDICTION OF THE DURABILITY FOR THE INVESTIGATED STRUCTURE

In a reinforced concrete member, whose initiation process of corrosion is theoretically finished, continuous decrease of the load bearing capacity should be considered. The model previously described gives a base for the prediction of the service life of a given member.

For theoretical evaluation, it is assumed that the service life ends at the time when the estimated load bearing capacity falls below the extreme value of generalized stress resulting from the predicted load combinations. This approach is used for the viaduct pier, which is subjected to safety assessment regarding the reinforced concrete crossheads for the time of the design and of the investigation as well as for the evaluation of its potential durability.

In order to evaluate the initial safety margin for crosshead no. 15, bending moment resulting from loads is compared to the evaluation of the load-bearing capacity at a critical cross-section located below a leaking expansion joint (Fig. 2 and 5). The geometry of the cross-section is as follows: $d = 0.69$ m, $A_s = 31.3$ cm^2. The initial safety margin (15%) results from the difference between the initial load-bearing capacity of $M_{Rd} = 773$ kNm and the maximal bending moment in the cross-section at $M_{Ed} = 672$ kNm (Fig. 7). This margin is constant until corrosion propagation period starts. To establish the relationship between bar corrosion process and decrease of structural load-bearing capacity, Eq. 3 based on Faraday's law is used. Thus, with the assumption of aggressive environment ($i_{cor} = 1.0$ μA/cm^2), the diameter decrease of a steel bar in the course of time writes:

$$\Delta\phi_i(t) = 0.0232\,(t - t_i) \qquad \text{[mm/year]} \tag{4}$$

For the age when renovation was started (2013), the residual load bearing capacity in bending was determined at $M_{Rd\,(35\text{years})} = 701.4$ kNm. Theoretically, decreasing load bearing capacity in the analysed cross-beam would be exceeded after ca. 42 years since the beginning of viaduct exploitation (i.e. 7 years from the repair undertaken).

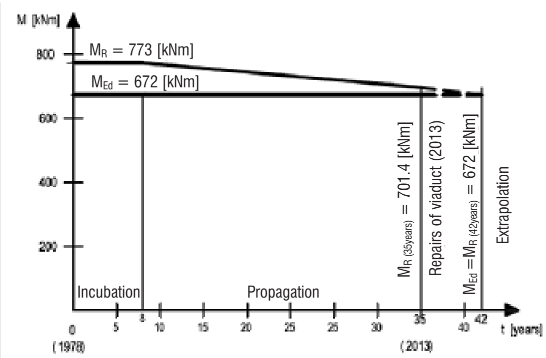

Figure 7.
Bending moment and load bearing capacity in bending for RC element in critical cross-section

Renovation works definitely will improve this lifetime: concrete cover is to be rebuilt and a protective layer will be sprayed on concrete surface. An important issue is that winter treatment of road surfaces may result in accelerating corrosion. For this reason it is important to ensure permanent tightness of the water escape system.

7. CONCLUSIONS

The model applied to the structure considered shows a good agreement for the specific case of chlorides ingress: the theoretical penetration of chlorides is confirmed by laboratory tests.

Reinforcement corrosion is accelerated by the concentration of chloride ions. In non-carbonated concrete, corrosion of reinforcement is progressing steadily. Higher concentration of chloride accelerates the corrosion process.

Corrosion influence on the decrease of reinforcement diameter is in a good agreement with site observations.

The concentration of chloride ions in one of the investigated members exceeded 5 times the limit amount of 0.4% weight of cement, which shows the importance of protecting concrete structures from attack of chlorides used for de-icing road infrastructure.

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REFERENCES

[1] EN 1992-1-1: 2004 + AC:2010, Eurocode 2: Design of concrete structures, General rules and rules for buildings

[2] *Wieczorek G.*; Korozja zbrojenia inicjowana przez chlorki lub karbonatyzację otuliny (Corrosion of reinforcement initiated by chlorides of carbonation of the cover). Dolnośląskie Wydawnictwo Edukacyjne, Wrocław, 2002 (in Polish)

[3] *Ajdukiewicz A.*; Konstrukcje betonowe projektowane na okres użytkowania – badania a nowe ujęcie normatywne: Problemy naukowo-badawcze budownictwa (Concrete structures designed for lifespan – tests vs. new standard approach: Scientific and research problems of civil engineering). Wydawnictwo Politechniki Białostockiej, Białystok, Vol.II, 2007; p.15-38 (in Polish)

[4] *Alonso C., Andrade C., Rodriguez J., Diez J. M.*; Factors Controlling Cracking of Concrete Affected by Reinforcement Corrosion. Materials and Structures, No.31, 1998; p.435-441

[5] Association Française de Génie Civil; Conception des bétons pour une durée de vie donnée des ouvrages. Maîtrise de la durabilité vis-à-vis de la corrosion des armatures et de l'alcali reaction (Design of concrete for a given lifetime of structures. Duravility vs. corrosion of reinforcement and alkali reaction). Documents scientifiques et techniques, 2004 (in French)

[6] *Ahmad S.*; Reinforcement corrosion in concrete structures, its monitoring and service life prediction-a review. Cement & Concrete Composites, Vol.25, 2003; p.459-471

[7] BS 1881: Part 124. Methods for analysis of hardened concrete

[8] PN-EN 196-2: 2006. Metody badania cementu: Analiza chemiczna cementu

[9] *Neville A.M.*; Właściwości betonu (Properties of concrete). Polski Cement, Ed. 4, Kraków, 2000 (in Polish)

[10] *Ściślewski Z.*; Trwałość konstrukcji żelbetowych (Durability of reinforced concrete structures). Wydawnictwa Instytutu Techniki Budowlanej, Warszawa, 1995 (in Polish)

[11] *Destrebecq JF., Gwoździewicz P., Midro M.*; Durability estimation of a reinforced concrete structure with regard to corrosion processes. 6th International Conference AMCM, Łódź, 2008

[12] *Poulsen E., Mejlbro L.*; Diffusion of chloride in concrete: Theory and application. Taylor & Francis, 2006

[13] *Zybura A., Jaśniok M., Jaśniok T.*; Diagnostyka konstrukcji żelbetowych. Tom 2: Badania korozji zbrojenia i właściwości ochronnych betonu (Diagnostics of reinforced concrete structures. Vol.2: Tests of corrosion of reinforcement and protective properties of concrete). Wydawnictwo Naukowe PWN, Warszawa, 2011 (in Polish)