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PIOTR GWOŹDZIEWICZ, MARCIN MIDRO*

DURABILITY EVALUATION OF BRIDGE STRUCTURE: COMPARISON BETWEEN ANALITICAL APPROACH AND EXPERIMENTAL INVESTIGATIONS

OSZACOWANIE TRWAŁOŚCI KONSTRUKCJI MOSTU: PORÓWNANIE PODEJŚCIA ANALITYCZNEGO Z BADANIAMI NA OBIEKCIE

Abstract

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

Keywords: *carbonation*, *corrosion*, *maintenance*, *service life*

Streszczenie

Niniejszy artykuł poświęcony jest zagadnieniu trwałości konstrukcji. Opisano w nim 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.

Słowa kluczowe: *karbonatyzacja*, *korozja*, *konserwacja*, *czas użytkowania konstrukcji*

* Ph.D. Eng. Piotr Gwoździewicz, M.Sc. Eng. Marcin Midro, Cracow University of Technology, Faculty of Civil Engineering, Cracow, Poland.

1. Introduction

Knowledge of materials degradation mechanisms and their influence on structural properties enables predictions regarding the duration of a given RC member's 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 the presence and diffusion of carbon dioxide, causing concrete carbonation and further corrosion of non-protected steel. Some structures are placed in aggressive atmospheres provoking an accelerated degradation and corrosion process, as for instance in chemical production plants or bridges subjected to winter de-icing treatment. The issue of the cyclic freezing-thawing effect is not addressed in this paper.

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

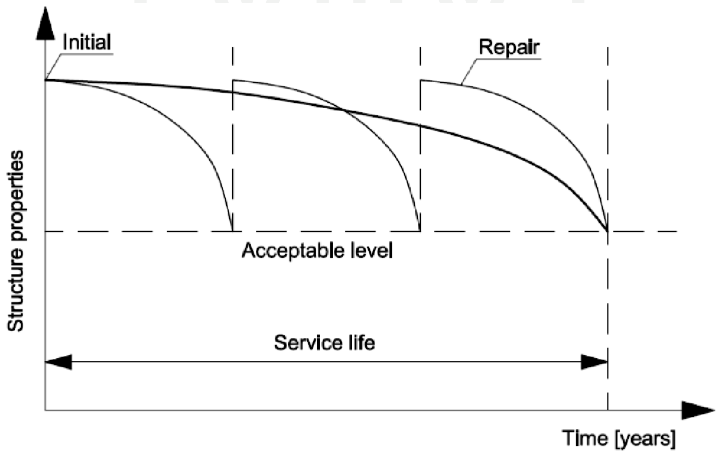

Fig. 1. Decrease of structure properties on service life

2. Theoretical model of degradation

The degradation process in concrete structures is generally divided into two main phases:

- incubation – when concrete passivates the embedded reinforcement and its deterioration is yet to start but the carbonation progress is continuously penetrating the cross-section,
- propagation – when reinforcement corrosion has started and the decreasing diameters of the reinforcing bars provokes a simultaneous decrease in the load-bearing capacity.

The presence of chloride ions in concrete during either phase, propagation or incubation, provokes pitting corrosion which is several times faster than the standard uniform corrosion of depassivated steel. The 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:

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

where (details in [5]):

- c – 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$^{0.5}$]:

$$K = \gamma \cdot k \cdot f_{(HR)} \tag{2}$$

where:

- $f_{(HR)}$ – coefficient related to the relative ambient humidity HR:

$$f_{(HR)} = -3.5833 \cdot HR^2 + 3.4833 \cdot HR + 0.2 \tag{3}$$

- k – transport coefficient, depending on concrete compressive strength:

$$k = \sqrt{365} \cdot \left(\frac{1}{2.1\sqrt{f_{ck}}} - 0.06\right) \tag{4}$$

- γ – exposition coefficient established on the base of experiments [5] depending on the environment conditions at a value equal to one from the following: 1.5, 1.2, 0.9.

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

$$C_x(t) = C_0 \left[1 - erf \frac{x}{2 \cdot (D \cdot t)^{1/2}}\right] \tag{5}$$

where:

$C_0(t)$ – chloride concentration in the surface layer of concrete at time t,
C_x – chloride concentration at distance x from the surface layer of concrete,
D – diffusion coefficient assumed for the overall chloride 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. An important structural safety consequence of this reduction is the reduction of the bar diameter. The expression discussed in [11] has the following form derived from Faraday's law; this gives the thickness of corroded steel over the course of time

$$\delta(t) = \alpha \cdot \lambda \cdot i_{cor} \cdot (t - t_i) \tag{6}$$

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+}), $F = 96{,}485$ 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),
$i_{cor,\text{med}} = 0.5$ 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 the 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. This analysis is focused on a viaduct located in the south of Poland. The structure, which was built in the late 70ies, is a 22-span bridge over a river, its total length equals 408.30 m (Fig. 2). The bridge deck is composed of six prestressed concrete precast I-girders connected by a concrete slab which was cast in situ (see Figs. 3 to 5). The superstructure is supported by RC column piers crowned with reinforced concrete beams.

The prestressed concrete precast girders each have a cross-section area of $A_{cp} = 0.32$ m^2, and a 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 "16.0 m" girders and 18.59 m to 18.93 m for the "18.0 m" girders. According to the design, the girders were cast of concrete with an 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 1,000 mm × 700 mm (depth × 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.

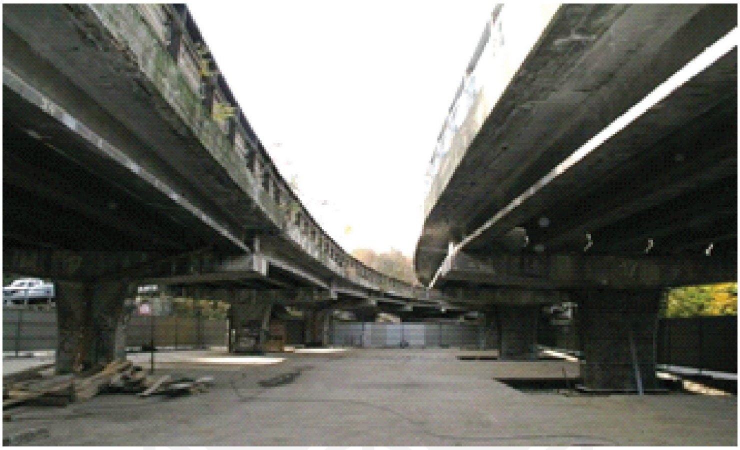

Fig. 2. View of viaduct before repair

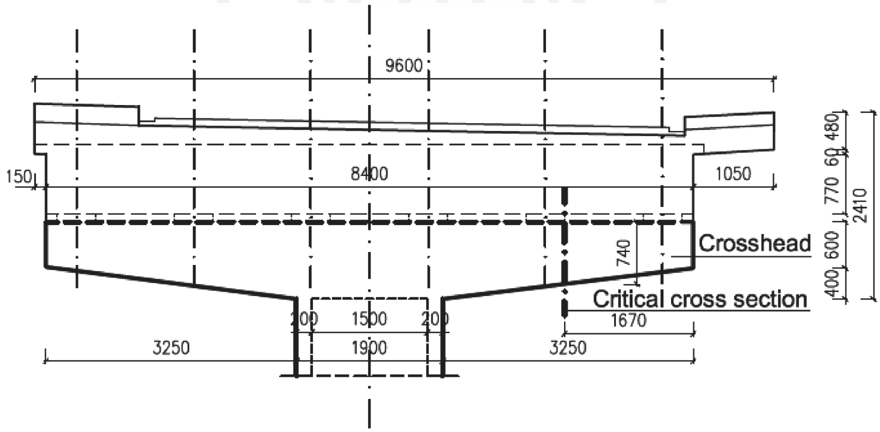

Fig. 3. Geometry of the crosshead on a RC pier

The bridge is built in an area of Poland that has the longest winter climatic conditions. Starting from the beginning of its work, the structure was subjected to the action of unfavorable ambient conditions, such as: air temperature variations (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 put on both concrete members: girders and crossheads. These were in a location particularly susceptible to chloride corrosion since water from the viaduct surface had been leaking for a prolonged period through expansion joint gaps and out of a non-tight collector (Fig. 6). After preliminary studies, prestressed concrete girders of the bridge load carrying structure were found to be in good condition. The crossheads are the most damaged parts of this viaduct and they serve as the research subject. The structural safety assessment is related to the bending moment born by a cantilever cross-section. Although from a static point of view, the most critical section may be that which is at the cross-beam connection to the column, the observed corrosion state influenced the selection of another cross-section, located at 1,670 mm from the free end of the cantilever (shown in Fig. 3).

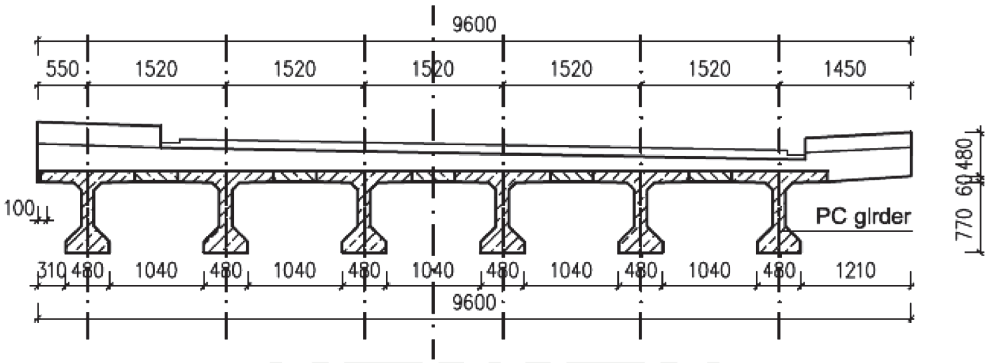

Fig. 4. Cross-section of bridge at one of the spans

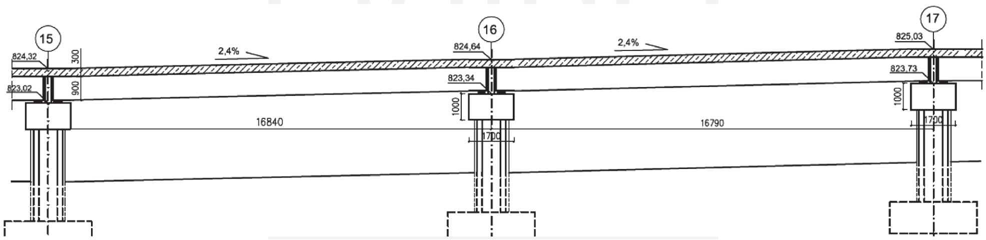

Fig. 5. Part of longitudinal section of the bridge

a) b)

Fig. 6. Bridge before repair: a) view of the investigated crosshead in the axis no. 15, b) non-tight collector above the pier cross-beam of bridge

Following the renovation project provisions which assumed 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 a protective layer.

4. Chemical analysis of concrete samples collected from structure

Results of laboratory tests on selected specimens collected from the viaduct are presented in this section. The aim is to determine the technical state of the structures, in particular, the advancement of the corrosion process. As already mentioned, concrete samples were taken from locations particularly exposed to corrosion, i.e. from crosshead numbers 15 and 16, including the zone situated directly below the expansion joint. The samples were obtained by crushing pieces of concrete cover or were 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 collected. Six drilling locations were located on the less corroded crosshead no. 16 and ten on the more corroded crosshead no. 15 (Fig. 7).

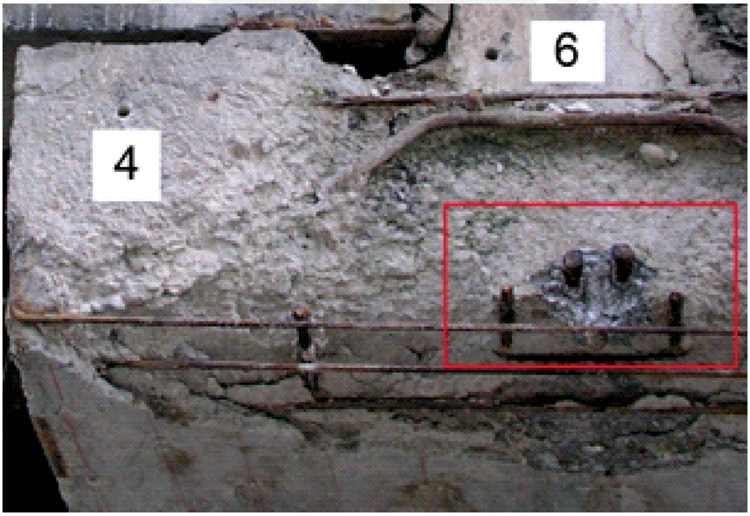

Fig. 7. Drilling locations on the more corroded crosshead no. 15

The samples were subjected to chemical analysis in accordance with test standards given in codes [7–8]. The analysis included the determination of pH for water extract from the specimens and the 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 quantities of chloride ions. The pH for all the drillings are in the range 9.55–11.73, below the threshold value of 11.80 [2] which represents safe conditions for the reinforcement passive state. The pH factor variation with depth of drilling for both crossheads is similar. Selected results are shown in Tab. 1.

Table 1

Chemical analysis results for the material obtained through the drilling of 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 displayed visibly more advanced corrosion development than other similar structures. Reinforcement corrosion was observed mainly at locations where water from the bridge surface leaked through the expansion joints and collectors – this is where splitting of the concrete cover was also observed. A higher amount of chloride ions was also observed in crosshead no. 15 compared to crosshead no. 16. This proves a popular opinion that the presence of chloride ions Cl^- in concrete provokes highly accelerated reinforcement corrosion progress compared to instances of carbonation alone [10]. Chemical analysis allowed the determination of the percentage of chloride ions in relation to concrete depth and also the determination of the depth of chloride ion penetration. A slightly higher concentration for crosshead no. 15 was observed. The average saturation of chloride ions for all the tested specimens to a 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 analyze the durability of the structure subjected to progressive degradation, in order to estimate its service life. Firstly, the incubation time t_i, is determined based on concrete carbonation and chloride ingress, taking into consideration the environmental conditions (relative ambient humidity, chloride concentration). Secondly, the propagation period is analyzed based on the corrosion rate derived from Faraday's law, when progressive reinforcement corrosion develops. For viaduct members, corrosion provokes a continuous reduction of load-bearing capacity in critical sections. Parameters of the corrosion process measured in the laboratory tests are used to build a relationship 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, 50%, 60% and 70%, are shown on greyed rows. For further analysis, the incubation time for reinforcement was assumed at 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 levels: crossheads (c = 40 mm)

RH	Incubation time [years] for c = 40 mm
40%	7.26
50%	6.91
60%	7.55
70%	9.70
80%	15.72

Evaluation of the carbonation depth for the 35-years old RC crossheads was carried out using the same analytical approach and accounting for an available boundary values. This revealed that for concrete at this age, for relative humidity assumed in the range 50% to 70%, the pH factor of concrete is lower than the threshold value of 11.80 at a concrete depth of 69–82 mm (see results in Tab. 3). It may be noticed that the carbonation depth evaluated is in agreement with results obtained in the chemical test program. Both theoretical and measured pH factor values at a depth of 50 mm from the concrete surface are lower than 11.80 (see Tab. 1).

Table 3

Depth of carbonized concrete layer for 35 years (crosshead)

RH	Depth of concrete layer [mm]
40%	79
50%	82
60%	78
70%	69
80%	54

As this structure was exposed to chloride action, another calculation based on Eq. (2) was performed in order to evaluate the penetration of chloride ions in the concrete depth. The average concentration of chloride ions at the 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 was 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 a depth of 74 mm. The comparison shows the convergence of the results obtained from analysis and measurements. An important observation is that the steel reinforcement state demonstrates advanced corrosion provoked by a high chloride concentration in spite of the alkalinity of the surrounding concrete, but below the 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. 4). Cracking and splitting of the concrete cover was observed as an effect of the increased volume of corrosion products – most of the surface cracks were located directly above and parallel to the reinforcing steel bars and the splitting of the concrete cover exposed steel for intensified corrosion. Along excessive cracks, reinforcement pitting corrosion was also found (below a leaking expansion joint). The corrosion of bars results in a decrease in their cross-sectional size. The nominal diameter of the main bar of #20 mm was found to have decreased locally to even to 17.6 mm. This decrease causes the simultaneous reduction of the load-bearing capacity – this is investigated in the next part of this paper.

6. Prediction of the durability of the investigated structure

In a reinforced concrete member in which the initiation process of corrosion is theoretically finished the continuous decrease of its load bearing capacity should be considered. The previously described model provides a basis 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 safety assessment of a viaduct pier. The reinforced concrete crosshead of the pier is subjected to the analysis regarding both the time of the design and of the investigation. In conclusion, evaluation of its potential durability is carried out.

In order to evaluate the initial safety margin for crosshead no. 15, the 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 (Figs. 3 and 6). 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. 8). This margin is constant until the corrosion propagation period begins. To establish the relationship between the bar corrosion process and the decrease of structural load-bearing capacity, Eq. (6) based on Faraday’s law is used. Thus, with the assumption of an aggressive environment ($i_{cor} = 1.0$ μA/cm^2), the diameter decrease of a steel bar over the course of time can be expressed as:

$$\Delta\phi_i(t) = 0.0232\left(t - t_i\right) \text{ [mm/year]} \quad (7)$$

In result of the theoretical analysis diameter of the corroded bar in the critical section of the crosshead no. 15 was estimated at 17.49 mm. The diameter is determined for the following data: i_{cor} = 1.0 μA/cm^2; α = 4.0; main bar #20 mm; analysis for 27 years of propagation, analysis for 8 years of incubation. The comparison shows the convergence of the results obtained from the analysis (17.49 mm) and measurements (17.6 mm).

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

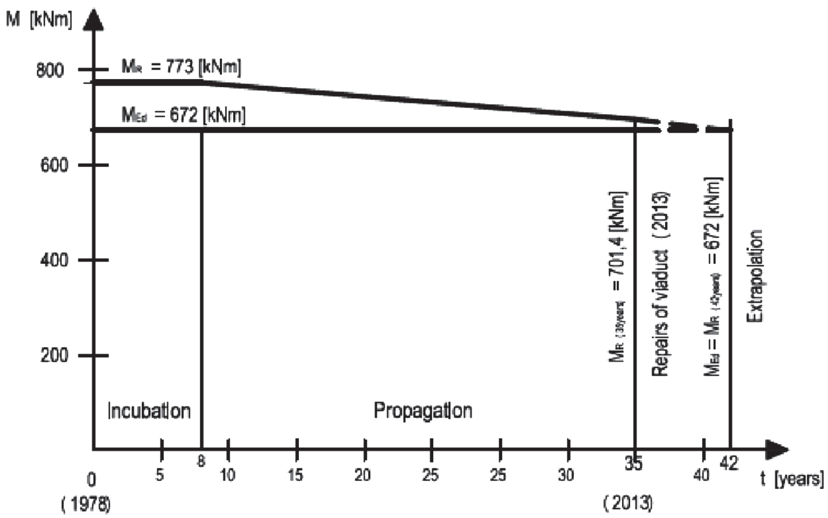

Fig. 8. Bending moment and load-bearing capacity in bending for RC element in critical cross-section

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

7. Conclusions

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

Reinforcement corrosion is accelerated by the concentration of chloride ions. In non--carbonated concrete, corrosion of reinforcement is progresses steadily. Higher concentrations of chlorides accelerate the corrosion process.

The influence of corrosion on the decrease of the reinforcement diameter is in good agreement with site observations.

The concentration of chloride ions in one of the investigated members is five times higher than the limit amount which is assumed equal to 0.4% of the weight of cement. Such high value shows the importance of protecting concrete structures from the attack of chlorides used for de-icing road infrastructure.

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