Influence of Chloride Corrosion on Probabilistic Assessment of Bearing Capacity of Beamless Slabs Overlap

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Abstract. The impact of aggressive environment on reinforced concrete beamless slabs leads to corrosion in the structure. This significantly affects the safety, durability and usability of buildings and structures. The bearing capacity of the construction of the beamless slab decreases with time. The more corroded the section of reinforcement in concrete, the greater the likelihood that the destruction of the reinforced concrete slab will occur earlier than the maximum service life of the structure. Various states of the design of a beamless slab in time, affecting the reliability of the structure, are considered. The destruction of the protective layer of concrete and the reduction of the diameter of the working reinforcement significantly affect the bearing capacity and reliability of the beamless slab. Reducing the area of working reinforcement and increasing the volume of corrosion products is an important parameter. The model of steel reinforcement weight loss over time is analysed. The dependence of the increase in the weight of corrosion products over time is revealed, and it is calculated that after 35 years with a complete loss of the thickness of the protective layer of concrete in the structure, the weight of the corrosion products will be 15% of the total mass of steel reinforcement. According to the results of the calculation, it was obtained that during the operation of a reinforced concrete beamless slab in a slightly aggressive environment under chloride corrosion, destruction will occur after 38 years if measures are not taken to inspect and repair it. These values are used for a probabilistic assessment of the effect of corrosion on the bearing capacity of the structure data.

1. Introduction

The object of the study is a reinforced concrete beamless slab.

The relevance of research. Reliability is calculated in order to prevent the structure from exceeding its ultimate state. Under the limit state refers to any violation or termination of the normal operation of the structure. Causes of failure of the structure are damage, which consists in the violation of the quality of its individual elements. By their nature, such damages are gradual. The causes of such damage are the conditions of an aggressive environment.

The methods of calculation and design of reinforced concrete structures in aggressive media in their work considered E.A. Guzeev [1], A.G. Tamrazyan [2-6], Bondarenko V.M. [7], V.I. Rimshin [8], G.A. Smolyago [9], N.V. Fedorova [10], C.G. Nogueira [11], P.G. Malerba [12] and Shakouri, M. [13].

A significant amount of research was devoted to chloride corrosion of steel in concrete, and a number of models were developed for such corrosion [14].
During the operation of buildings and structures, such as the overlap of multi-storey car parks, buildings of enterprises for the production of mineral fertilizers, are exposed to chlorides. Chloride corrosion is the most dangerous type of corrosion, since at a certain chloride concentration, concrete immediately loses its protective properties with respect to reinforcement, corrosion develops locally and deep into the rod, leading to significant losses of its cross section, often without visible damage on the concrete surface. Analysis of the model for the development of chloride corrosion allows us to solve the problems associated with the destruction of structures, namely, the reliability of structures in aggressive environments [15].

According to research results, the process of chloride-induced corrosion can be divided into two separate phases: chloride penetration and steel corrosion. The first phase is the period of time when chloride ions begin to penetrate the protective layer of concrete before the onset of corrosion. This period is called the start time of corrosion. The second phase is between the time of onset of corrosion and the time when cracks and corrosion products reach a certain level of damage. The period between them is called the cracking time.

In the subsequent phase of corrosion of the reinforcement, the cross-section of the reinforcement is reduced and corrosion products are formed, thereby causing stresses in the concrete. After some time, cracks appear.

The aim of the study is a probabilistic assessment of the effect of chloride corrosion on the load-carrying capacity of a beamless slab.

Objectives of the study:
• the influence of aggressive environment on the bearing capacity of reinforced concrete floor slabs;
• a probabilistic assessment of the carrying capacity of a corrosion-damaged reinforced concrete beamless slab.

2. Method
From the practice of operating buildings and structures for various purposes there is a large number of damages to reinforced concrete structures caused by exposure to chloride salts on concrete. The reason for damage to structures is the penetration of chlorides into concrete, the loss of the protective layer of concrete in relation to steel and the development of corrosion of reinforcement.

Consider a brief description of the influence of the gas environment on reinforced concrete structures. When HCl interacts with Ca(OH)$_2$ and CaCO$_3$ cement stone, CaCl$_2$ is formed, which due to diffusion penetrates into the concrete. At the same time, concrete loses its ability to passivate steel, which becomes active and begins to corrode, since the capillary-porous structure of concrete contains moisture and passes oxygen [16].

Since the corrosion product of steel has a larger volume than steel, the protective concrete layer gradually collapses, which in turn reduces the protective properties of concrete, the adhesion of reinforcement to concrete is broken, and the cross-sectional area of reinforcement decreases.

In this way:
- aggressive exposure to HCl and other chlorine compounds in the air is expressed in the neutralization of concrete, which leads to corrosion of reinforcement;
- delamination of concrete caused by an increase in the volume of products of corrosion of reinforcement;
- the destruction of the protective layer of concrete leads to even greater corrosion of the reinforcement.

During the corrosion process of steel reinforcement, the movement of ions between the anodes and cathodes forms an ion current with a density indicated by $i_{corr}$ in mA/cm$^2$. The rate of accumulation of corrosion products is proportional to the current density.

The corrosion rate is proportional to the current density according to [17]:
\[
r_{corr} = 0.0115i_{corr},
\]
where \( m_t \) - weight loss of steel reinforcement, \( r_{corr} \) - corrosion rate, mm/year, \( t \) - time, \( i_{corr} \) - current density, mA/cm\(^2\). Current density controls corrosion rate.

A formula for determining the corrosion current density \( i_{corr} \), mA/cm\(^2\), was obtained in [18, 19] in the first year after the initiation of corrosion under the action of chlorides at a relative humidity of more than 80%:

\[
i_{corr}(1) = \frac{27(1-W/C)^{-0.64}}{C},
\]

where \( W/C \) – water-cement ratio, is determined according to [20] (table E 1) depending on the concrete grade by water resistance (normal), \( C \) is the value of the protective layer of concrete, mm.

After the first year since the initiation, a decrease in the corrosion rate is observed, which is caused by the accumulation of corrosion products, which limit the access of aggressive media to the steel surface. The corrosion current density at time \( t \) is determined according to [18,19]:

\[
i_{corr}(t) = i_{corr}(1) \alpha(t-T)^\beta,
\]

where \( \alpha \) and \( \beta \) – charge transfer coefficients in the cathode and anode process.

In [17], the weight loss of steel reinforcement is estimated by reducing the diameter in the cross section of the rebar:

\[
d_s(t) = d_{s0} - mr_{corr}t,
\]

where \( d_s(t) \) - diameter reduction in time, \( d_{s0} \) - initial diameter of the rod, \( r_{corr} \) - corrosion rate mm/year, \( i_{corr} \) - current density in mA/cm\(^2\), \( m \) - constant depending on the type of corrosion, \( m = 2 \) for uniform corrosion and \( m = 4-8 \) for pitting corrosion, \( t \) – corrosion time (year).

1) The thickness of the corroded steel reinforcement is indicated \( d_s \). The mass of the corrosion product is proportional to the mass of the corresponding corroded steel:

\[
M_{steel} = \alpha M_{rust},
\]

where \( M_{steel} \) and \( M_{rust} \) represent the mass of steel reinforcement and corroded steel reinforcement, respectively, and \( \alpha \) is a factor depending on the type of corrosion products. \( \alpha \) - constant associated with the types of corrosion products and varying from 0.523 to 0.622, and it can be estimated from experiments. Then the area of corroded steel reinforcement:

\[
S_{steel}(14) = \alpha \frac{P_{rust}}{P_{steel}} S_{rust} = \alpha \frac{P_{rust}}{P_{steel}} (S_0 - S) = 0.622 \cdot \frac{3000}{7850} \cdot (0.0001539 - 0.0001521) = 0.0000004m^2,
\]

\[
S_{steel}(12) = 0.622 \cdot \frac{3000}{7850} \cdot (0.0001131 - 0.0001117) = 0.0000003m^2,
\]

where \( S_0 \) - initial bar area, \( S \) - rod area after corrosion, \( P_{rust} \) и \( P_{steel} \) - density of corrosion products and steel reinforcement, respectively.

2) The void space in the concrete porous zone surrounding the reinforcement is shown as thick \( d_0 \). The volume of this layer depends on the properties of the porous zone, which, in turn, depends on such primary factors as the surface area of reinforcing bars, the water-cement ratio of concrete, the conditions of concrete hardening, the size of aggregates in concrete, etc.

3) The space generated by the bulk expansion of corrosion products until the start of cracking is shown in thickness \( d_{st} \).
A simplified model was proposed in [17], in which it is assumed that the concrete surrounding the reinforcement is a uniform and elastic cylinder with an internal radius \(a(14) = (d_{s0} + 2d_o)/2 = (14 + 2 \cdot 1)/2 = 8\) mm, \(a(12) = (d_{s0} + 2d_o)/2 = (12 + 2 \cdot 1)/2 = 7\) mm and outer radius \(b(14) = (c + a) = (23 + 8) = 31\) mm, \(b(12) = (c + a) = (25 + 7) = 32\) mm, where \(c\) - cover of concrete, and the pressure \(P_e:\)

\[
P_e(14) = \frac{E_{ef}d_s}{a[(b^2 + a^2)/(b^2 - a^2) + \nu_c]} = \frac{840 - 0.00005}{0.008 \left[\left(0.038^2 + 0.008^2\right)/\left(0.038^2 - 0.008^2\right) + 0.2\right]} = 4.06\text{MPa},
\]

\[
P_e(12) = \frac{840 - 0.00005}{0.007 \left[\left(0.037^2 + 0.007^2\right)/\left(0.037^2 - 0.007^2\right) + 0.2\right]} = 4.71\text{MPa},
\]

where \(E_{ef}\) - value of concrete deformation modulus,
\(E_{b,c} = E_b / (1 + \phi_{b,cr}) = 300 / (1 + 1.8) = 840\text{MPa},\)
\(E_b\) - initial modulus of elasticity of concrete,
\(\phi_{b,cr}\) - concrete creep factor,
\(\nu_c\) - coefficient of lateral deformation of concrete (Poisson’s ratio).

Assuming that the crack propagates vertically onto a concrete surface, which is observed in experiments, the minimum critical pressure \(P_{crit}\) that is required for the formation of cracks in concrete can be expressed as [21]:

\[
P_{crit}(14) = \frac{cR_{bc}}{a} = \frac{0.03 \cdot 1.05}{0.008} = 3.94\text{MPa},
\]

\[
P_{crit}(12) = \frac{0.03 \cdot 1.05}{0.007} = 4.5\text{MPa},
\]

where \(R_{bc} = 1.05\text{MPa}\) - design tensile strength of concrete,

\[
d_s(14) = \frac{cR_{bc} \left(a^2 + b^2\right) + \nu_c}{E_{ef} \left(b^2 - a^2\right)} = \frac{0.032 \cdot 1.05}{840} \left(0.008^2 + 0.03^2\right)/\left(0.03^2 - 0.008^2\right) + 0.2) = 0.00005m,
\]

\[
d_s(12) = \frac{0.035 \cdot 1.05}{840} \left(0.007^2 + 0.032\right)/\left(0.032^2 - 0.007^2\right) + 0.2) = 0.00006m,
\]

Consequently, the weight of corrosion products causing cracks in the protective layer of concrete can be calculated:

\[
W_{cr}(14) = p_{rust} [\pi (d_s + d_{rust}) d_o + S_{surt}] = 3000 \cdot [3.14 \cdot (0.001 + 0.00005) \cdot 0.014 + 0.0000004] = 0.139\text{kg/m},
\]

\[
W_{cr}(12) = 3000 \cdot [3.14 \cdot (0.001 + 0.00006) \cdot 0.012 + 0.0000003] = 0.121\text{kg/m}.
\]

As a result, for Ø14 fittings, the weight of corrosion products that cause cracks is 11%, and for Ø12 reinforcements it is 14% of the total mass of steel reinforcements.

Since the amount of corrosion products depends on the time and rate of corrosion, with a known critical amount of corrosion products \(W_{crit}\), the time to start corrosion can be estimated.

According to [17], the corrosion rate decreases with time of the corrosion process:

\[
\frac{dW_{rust}}{dt} = \frac{k_p}{W_{rust}},
\]
where \( W_{\text{rust}} \) - the amount of corrosion products (mg/mm), \( t \) - corrosion time (year), \( k_p \) - corrosion development rate:

\[
k_p(14) = 0.098 \pi d_i \alpha / \alpha = 0.098 \cdot 3.14 \cdot 1.4 \cdot 5.3 / 0.622 = 3.67 \text{cm}^2 / \text{year} = 367 \text{mm}^2 / \text{year},
\]

\[
k_p(12) = 0.098 \cdot 3.14 \cdot 1.2 \cdot 4.8 / 0.622 = 2.84 \text{cm}^2 / \text{year} = 284 \text{mm}^2 / \text{year},
\]

where \( d_s \) - diameter of reinforcement (cm), \( i_{\text{cor}} \) - the initial value of the corrosion current density (mA/cm\(^2\)).

Taking into account that the corrosion rate is inversely proportional to the thickness of corrosion products, the quantity of corrosion products was modeled in [17]. Integrating equation (11), one can obtain the growth of corrosion products:

\[
W_{\text{rust}} = \sqrt{2 k_p \int_{0}^{t} dt},
\]

Assuming that \( k_p \) is constant, then we get time to initiate corrosion \( t_{\text{in}} \):

\[
t_{\text{in}}(14) = \frac{W_{\text{rust}}^2}{2k_p} = \frac{139^2}{2 \cdot 367} \approx 26 \text{years}
\]

\[
t_{\text{in}}(12) = \frac{121^2}{2 \cdot 284} \approx 26 \text{years}.
\]

It follows from this that the time of onset of corrosion in reinforcement mainly depends on the concrete cover, the strength of concrete in tension, the properties of steel and concrete, the types of corrosion products.

Table 1 shows the dependence in time of decreasing the diameter of the working reinforcement in a slightly aggressive chloride medium. The working reinforcement is A500C (Rs = 435 MPa), the diameter of the working bars of the reinforcement is \( d_s = 14 \text{ mm} \) and \( d_s = 12 \text{ mm} \) (\( A_s = 14.889 \text{ cm}^2 \)), the spaced of the bars is \( s = 200 \). Concrete B25 (Rb = 14.5 MPa), the protective concrete cover \( c = 30 \text{ mm} \).

Knowing from what point in time the development of corrosion in reinforcement and concrete will begin, we can calculate the period when the bearing capacity of the plate is less than the moment value from the external load, and thus the structure will be destroyed.

| Construction time, year | With bar diameter of 12 mm | With bar diameter of 14 mm | Total area of reinforcement, cm\(^2\) |
|-------------------------|--------------------------|--------------------------|-------------------------------------|
| 25                      | 12.00                    | 14.00                    | 14.889                              |
| 26                      | 11.93                    | 13.93                    | 14.847                              |
| 27                      | 11.87                    | 13.86                    | 14.723                              |
| 28                      | 11.80                    | 13.79                    | 14.516                              |
| 29                      | 11.73                    | 13.72                    | 14.229                              |
| 30                      | 11.67                    | 13.64                    | 13.861                              |
| 31                      | 11.60                    | 13.57                    | 13.413                              |
| 32                      | 11.54                    | 13.50                    | 12.887                              |
| 33                      | 11.47                    | 13.43                    | 12.284                              |
| 34                      | 11.41                    | 13.36                    | 11.603                              |
| 35                      | 11.34                    | 13.30                    | 10.846                              |
| 36                      | 11.28                    | 13.23                    | 10.013                              |
To summarize, for each rebar $i$, we have:

$$ A_i(t) = A_0 = \pi d_0^2 / 4 \quad \text{for} \quad t < t_{in} $$

$$ A_i(t) = A_0 - \pi ((d_0 - d_i) t_{corr})^2 / 4 \quad \text{for} \quad t > t_{in}, $$

where $A_0$ - the initial area of each of the reinforcing bars, which in this case have diameters of 12 and 14 mm.

The relative loss of steel reinforcement in cross section $R_{AL}$ can be expressed as:

$$ R_{AL} = \{A_0 - A_i(t)\} / A_0. $$

One of the criteria for the reliability of structural elements is their initial reliability - the ability of elements or structures to maintain the required strength and stability at a given initial time interval, i.e. the work of the structure during its manufacture, construction, during the test and in the initial period of operation under the design load.

The variability of these values is described by the normal distribution law [22,23]. The initial reliability is written as:

$$ R = \frac{1}{2} + \frac{1}{2} \Phi[\beta], $$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-t^2} dt$ - Laplace function.

To assess the reliability of the beamless slab, we determine the safety characteristic:

$$ \beta = \frac{\bar{M}_{ult} - M_{cal}}{\hat{M}_{ult}}, $$

where $M_{cal} = 89.6kNm$ – the calculated value of the external bending moment in the beamless slab; $\bar{M}_{ult}$ - random value of the limiting bending moment perceived by the floor slab by the formula (22); $\hat{M}_{ult}$ - the standard of the limiting bending moment according to the formula (23).

The random value of the limiting bending moment perceived by the slab according to [24]:

$$ \bar{M}_{ult} = f(\bar{\sigma}_b, \bar{\sigma}_s) = \bar{\sigma}_s A_x (h_0 - 0.5\bar{x}), $$

where $\bar{\sigma}_b$ – random value of concrete resistance to compression for limit states of the first group;

$\bar{\sigma}_s$ – random tensile strength of bar reinforcement; $A_x$ – cross-sectional area of tensile bar reinforcement (5Ø12 and 6Ø14); $h_0$ – estimated section height; $\bar{x}$ – height of the compressed zone of concrete;

$$ \bar{x} = \frac{\bar{\sigma}_s A_x}{\bar{\sigma}_b b}, $$

where $b=1000mm$ – plate width.
Substitute the expression for \( x \) in the formula (20):

\[
\bar{M}_{ult} = \bar{\sigma}_s A_s h_0 - 0.5 \left( \frac{\bar{\sigma}_s A_s}{\bar{\sigma}_b} \right)^2 .
\]  

(22)

Given the general expression (20), we have for the mathematical expectation of the limiting moment:

\[
\bar{M}_{ult} = \bar{\sigma}_s A_s h_0 - 0.5 \left( \frac{\bar{\sigma}_s A_s}{\bar{\sigma}_b} \right)^2 ,
\]

(23)

where \( \bar{\sigma}_s, \bar{\sigma}_b \) – accordingly, the expectation of concrete resistance and reinforcement strength.

We will determine the coefficients for calculating the standard of the limiting moment, and taking into account that in case of corrosion in the section of a beamless slab, a variable parameter is the area of the reinforcement, we will also determine \( D_{A_s} \):

\[
D_s = \frac{\partial M_{ult}}{\partial \sigma_s} = A_s h_0 - \frac{\sigma_s A_s^2}{\sigma_s b} = \frac{A_s}{\sigma_s b} (\sigma_s h_b - \sigma_s A_s). \]

(24)

\[
D_s = \frac{\partial M_{ult}}{\partial \sigma_s} = \frac{0.5 \sigma_s^2 A_s}{\sigma_s^2 b} \left( \frac{\sigma_s A_s}{\sigma_s b} \right)^2 , \]

(25)

\[
D_{A_s} = \frac{\partial M_{ult}}{\partial A_s} = R_b h_0 - \frac{\sigma_s^2 A_s}{\sigma_s b} . \]

(26)

The limit bending moment standard is defined as:

\[
\hat{M}_{ult} = \sqrt{(D_s \hat{\sigma}_s)^2 + (D_s \hat{\sigma}_b)^2 + (D_{A_s} \hat{\sigma}_{A_s})^2} .
\]

(27)

According to the calculated characteristics of the materials we determine their statistical characteristics:

- concrete B25 – \( \bar{\sigma}_b = 1.282 \) \( R_b = 1.282 \cdot 14.5 = 18.59 \) MPa = 1.86 kN/cm²;
  - \( \hat{\sigma}_b = 0.135 \bar{\sigma}_b = 0.135 \cdot 18.59 = 2.51 \) MPa = 0.25 kN/cm².
- reinforcement A500C \( \bar{\sigma}_s = 435 \) MPa = 43.5 kN/cm², the coefficient of variation \( V_s = 0.0436 \)
  \( [\text{Chyba! Nenašiel sa žiaden zdroj odkazov.}] \), \( \hat{\sigma}_s = 0.0436 \cdot 435 = 18.97 \) MPa = 1.90 kN/cm².
- coefficient of variation for reinforcement area \( V_{A_s} = 0.040 \).

3. Results and Discussion

Table 2 presents the results of the calculation of the carrying capacity and the index of reliability of a reinforced concrete beamless slab over time in a slightly aggressive environment.
Table 2. Probabilistic values of carrying capacity and reliability index of corrosion-damaged reinforced concrete beamless slab

| Operating time, year | Mathematical expectation of bearing capacity, $\overline{M}_{ult}$, kN m | Reliability Index | Reliability |
|---------------------|---------------------------------------------------------------------|-----------------|-------------|
| 25                  | 129.56                                                              | 3.60            | 0.9999205   |
| 26                  | 128.57                                                              | 3.56            | 0.9999070   |
| 27                  | 128.17                                                              | 3.55            | 0.9999000   |
| 28                  | 126.45                                                              | 3.48            | 0.998745    |
| 29                  | 124.06                                                              | 3.39            | 0.998315    |
| 30                  | 120.98                                                              | 3.25            | 0.997215    |
| 31                  | 117.23                                                              | 3.06            | 0.994465    |
| 32                  | 112.81                                                              | 2.78            | 0.9986400   |
| 33                  | 107.72                                                              | 2.39            | 0.9959000   |
| 34                  | 101.96                                                              | 1.82            | 0.9828100   |
| 35                  | 95.52                                                               | 1.00            | 0.9230700   |
| 36                  | 88.41                                                               | -               | -           |

The study of the mechanisms of destruction and models of the processes of destruction of reinforced concrete structures is important for assessing the carrying capacity of reinforced concrete structures. In this example, the reliability of the structure after 35 years was 0.92307. Comparing it with the conditional reliability equal to 0.99865, we determine the percentage of the reliability of the structure during destruction, which is 97.7%.

In figure 1, the graph shows the dependence of the reduction in the carrying capacity of a beamless slab over time in a slightly aggressive environment.

![Graph of bearing capacity of corrosion-damaged slab versus operation time](image)

**Figure 1.** Graph of bearing capacity of corrosion-damaged slab versus operation time

**4. Conclusions**

The estimation of the bearing capacity of the beamless slabs in a weakly aggressive environment was made by the probabilistic method. It was determined that for Ø14 fittings the weight of corrosion products causing cracks is 11%, and for Ø12 reinforcements it is 14% of the total mass of steel reinforcement. The dependence of the loss of steel reinforcement in the cross section $R_{ult}$ is revealed.
According to the results of the calculation, it was obtained that during the operation of a reinforced concrete beamless plate in a slightly aggressive environment under chloride corrosion, destruction will occur after 36 years of operation. In this example, the reliability of the structure after 35 years was 0.92307. Comparing it with the conventional reliability equal to 0.99865, the reliability of the structure at destruction was 97.7%. Consequently, with the help of the proposed method it is possible to make a probabilistic assessment of the bearing capacity of a structure and determine its service life.

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