ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2024-22-4-5

World of Transport and Transportation, 2024, Vol. 22, Iss. 4 (113), pp. 158–166

Method for Determining Durability of a Bridge Superstructure


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ABSTRACT

The objective of the study is to develop a method for determining the durability of a reinforced concrete girder of a superstructure when exposed to aggressive environments.

The scientific substantiation of the method is based on the laws of establishing a uniform distribution of atmospheric gas concentrations among homogeneous parts of reinforced concrete and determining the depth of their diffusion. To describe the penetration rate, analytical equations are applied to determine the depth of diffusion of atmospheric gases into concrete. When the diffusion products reach the main reinforcement, corrosion processes start, which cause a decrease in the effective area, and, therefore, a loss of the bearing capacity of the girder of the superstructure during operation of the bridgework.

The proposed calculation method has allowed to build a regression model for assessing durability of reinforced concrete structures depending on the diffusion of aggressive environments and on a variable number of days per year with precipitation. Analysis of the obtained results has shown that when the diffusion products of atmospheric gases reach the main reinforcement, processes of irreversible changes (irreversible decrease) in the bearing capacity of the superstructure begin. It has been established that the service life before failure when exposed to halogens and hydrohalic acids may not exceed 30 years. The application of the method makes it possible to determine the residual service life of the superstructure based on assessment of the bearing capacity resource and to develop regulatory documents on timing of repair work.

Keywords: *transport construction, durability, service life, bearing capacity, superstructure, bridgework, reinforcement corrosion, aggressive environment.*

For citation: *Ogurtsov, G. L., Ermoshin, N. A. Method for Determining Durability of a Bridge Superstructure. World of Transport and Transportation, 2024, Vol. 22, Iss. 4 (113), pp. 158–166. DOI: https://doi.org/10.30932/1992-3252-2024-22-4-5.*

The original text of the article in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

BACKGROUND

Bridge structures are an integral part of highways, the condition of which influences road traffic safety. To prevent critical condition of highway bridges, it is necessary to determine the bearing capacity of their structural elements, considering defects caused by the impact of transport and aggressive environments.

The dependability of reinforced concrete superstructures is in many cases determined by their durability and failure-free operation. A decrease in the bearing capacity of the superstructure because of defects caused by the impact of aggressive environments reduces the service life and is one of the main reasons for premature destruction of bridge structures, causing harm to human life and health, property and the environment. To ensure the working condition of bridge structures, it is necessary to carry out premature repairs, restoration or replacement of failed structural elements [1].

Natural and climatic conditions and man-made factors influence the occurrence of defects in the superstructure that reduce the bearing capacity [2]. Natural and climatic conditions cause gradual aging of materials, a decrease in the modulus of elasticity and tensile and compressive strength of concrete, a decrease in the useful area of reinforcement and, consequently, a loss of bearing capacity and failure of the bridge structure. Man-made factors, first, include changes in the traffic intensity and composition of vehicles. Their impact causes accumulation and development of fatigue deformations and damage, as well as wear of materials of structural elements. At present, regulatory documentation[1,2], provides that the parameters of a reinforced concrete element (cross-sectional dimensions, reinforcement diameter, compressive strength, etc.) remain unchanged throughout its service life. However, due to the fact that concrete has a capillary-porous structure, the defects of the superstructure arise during operation of the bridge structure which are corrosion of reinforcement, change in the tensile and compressive strength of concrete, as well as a decrease in the area of main reinforcement under cyclic loading, which leads to a decrease in the bearing capacity of the superstructure girders.

Thus, the *objective* of the study is to develop and substantiate a method for determining durability of a reinforced concrete girder of a bridge superstructure under the influence of aggressive environments, the influence of which leads to degradation of the properties of materials and a decrease in the bearing capacity.

METHODOLOGY

The onset of corrosion of the reinforcement of the superstructure is caused by the process of diffusion of gas contained in the atmosphere into concrete and subsequent depassivation of the reinforcement bars. The depassivation process consists of formation and propagation of transcrystalline (transgranular) cracks deep into the metal with a decrease in the useful area of its cross-section because of simultaneous action of cyclic tensile loads and anodic dissolution of the metal. Diffusion is described by analytical equations of the Fick's first and second laws [3]. The impact of aggressive environments depends on operating conditions of the bridge structure and measures for its maintenance [4; 5]. The degree of influence of the diffusion process is determined by the different composition and concentration of atmospheric gases. The main atmospheric gases interacting with concrete and reinforcement were considered in the studies [6–8]. Carbon dioxide (CO_2), halogens (Cl_2) and hydrohalic acids (HCl) deserve special attention, since when the diffusion front reaches the reinforcement bars, the corrosion process starts [9], which leads to a change in the bearing capacity of the superstructure.

The articles [3; 10; 11] present the results of the studies that determined the rate of carbon dioxide diffusion into concrete samples. The diffusion rate depends on concentration of carbon dioxide on the surface of the samples, the water-cement ratio and the concrete filler used. The depth of carbon dioxide diffusion [3] is determined by formula (1):

$$X_c = \sqrt{2 \cdot D_{CO_2} \cdot a^{-1} \cdot (c_1 - c_2) \cdot \tau_{carb}}\ , \quad (1)$$

where τ_{carb} is carbon dioxide exposure time, s;

D_{CO_2} – the diffusion coefficient of CO_2 into concrete, m^2/s, which depends on the composition of the concrete, the degree of hydration and the moisture content;

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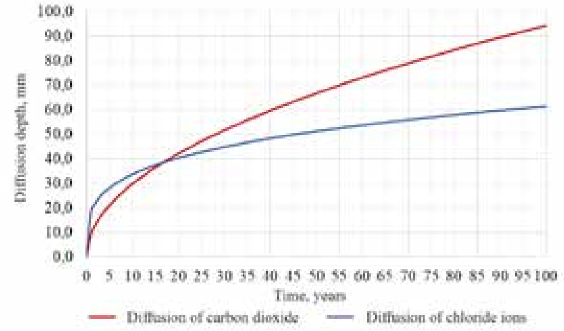
[1] SP [Construction rules] 63.13330.2018 Concrete and reinforced concrete structures. Main provisions. [Electronic resource]: https://ano-alpha.ru/upload/iblock/58c/mjvjzkirysdmzq31jd53bipez0mxsqd5/SP_63.13330.2018_-2.pdf. Last accessed 01.08.2024.

[2] SP [Construction rules] 35.13330.2011 Bridges and pipes. [Electronic resource]: https://www.mos.ru/upload/documents/files/4784/SP35133302011MostiitrybiAktyalizirovannayaredakciyaSNiP20503–84(sIzmeneniemN1)_Tekst.pdf?ysclid=m8sod9x4tj580224091. Last accessed 01.08.2024.



Pic. 1. Diffusion depth of carbon dioxide and chloride ions [developed by the authors].

c_1 and c_2 – respectively, the content of carbon dioxide on the outer surface of concrete and at the carbonation boundary (infinitesimal value), parts per million (ppm);

a – the amount of CO_2 required to convert all carbonisable cement hydration products [12], kg/m^3, determined by formula (2):

$$a = 0,4 \cdot f \cdot p \cdot C, \qquad (2)$$

where f is the degree of neutralisation of concrete, equal to the ratio of the amount of basic oxides that have reacted with carbon dioxide to their total amount in the cement, taken as 0,6;

p – the amount of basic oxides in cement in terms of CaO in relative values by weight according to chemical analysis data, taken as 0,6;

C – numerical equal content of cement in concrete, kg/m^3.

The diffusion depth of chloride ions [3] is expressed by formula (3):

$$X_{Cl} = \sqrt{4 \cdot D_{Cl0} \left(\frac{t_0}{t}\right)^{\left(3 \cdot \frac{V}{C} - 0,6\right)} \cdot \left(erf^{-1}\left(\frac{C_s - C_{crit}}{C_s}\right)\right)^2 \cdot \tau_{Cl}}, \quad (3)$$

where τ_{Cl} – chloride ion exposure time, s;

C_s and C_{crit} – respectively, concentration of chlorides on the surface of the concrete protective layer and the critical concentration of chlorides on the surface of the reinforcement, % by weight of cement;

t_0 and t – age of concrete $t_0 = 28$ days and actual age t, respectively, days;

erf^{1} – Gaussian error function;

D_{Cl0} – diffusion coefficient of chlorides in concrete [3], m^2/s, determined by formula (4):

$$D_{Cl0} = 10^{(-12,06+2,4 V/C)}. \qquad (4)$$

Using expressions (1) and (3), graphs of the diffusion depth of carbon dioxide and chloride ions [14] as per years were constructed (Pic. 1) for constant values of formulas (1) and (3). The processes of carbon dioxide and chloride ions penetration occur from the surface of unaffected concrete into the element.

The articles [8; 10; 11; 14] present the results of experimental studies of the effects of carbonation products on the strength of concrete at different concentrations of carbon dioxide. Dependencies have been established indicating that with an increase in the time of accelerated carbonation and concentration of carbon dioxide, the ultimate compressive strength of concrete increases, while there is no information on changes in the ultimate tensile strength. In the process of carbonation [14–17] of concrete, complex polymer intergrowths are formed and there is a lack of visible needle-shaped crystals of calcium hydrosilicate cementing the structure of concrete, which leads to a decrease in cohesion and tensile strength of concrete but increases the compressive strength of concrete. As studies have shown [18], the diffusion of chloride ions leads to a decrease in the compressive and tensile strength of concrete.

When the diffusion products of carbon dioxide and chloride ions reach the reinforcement bars, as well when the acid-base balance of concrete decreases, the corrosion process begins, during which the effective area of the reinforcement bar decreases. Reinforcement corrosion is an electrochemical process that occurs when the alkalinity of the environment decreases to pH values equal to 11, as well as under the action of chloride ions [19; 20]. To describe this process [3], formula (5) is used:

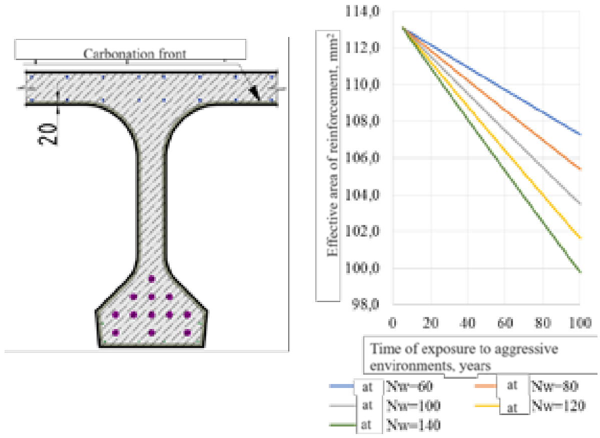
$$A_{cor} = \pi \cdot \left(\frac{d}{2} - 0,01 \cdot \frac{N_W}{365} \cdot t_{cor}\right)^2, \qquad (5)$$

where N_w – number of days per year with precipitation over 2,5 mm;

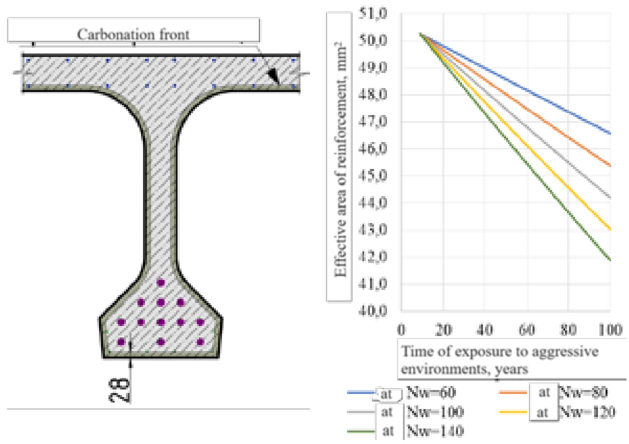
t_{cor} – corrosion time, years.

Once there is a crack with a width of 0.3 mm or more [17], or local damage, the process of reinforcement corrosion accelerates. This process [3] is described by formula (6):

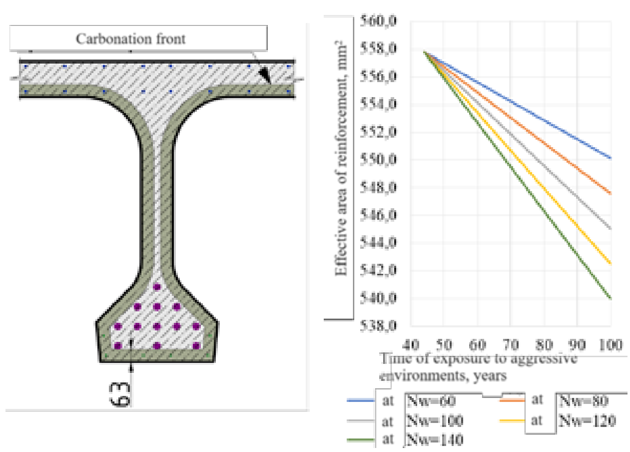
$$A_{cor} = \pi \cdot \left(\frac{d}{2} - 0,06 \cdot \frac{N_W}{365} \cdot t_{cor}\right)^2. \qquad (6)$$



Pic. 2. Distribution of the carbonation front of the cross section after five years [developed by the authors].



Pic. 3. Distribution of the carbonation front of the cross section after nine years [developed by the authors].

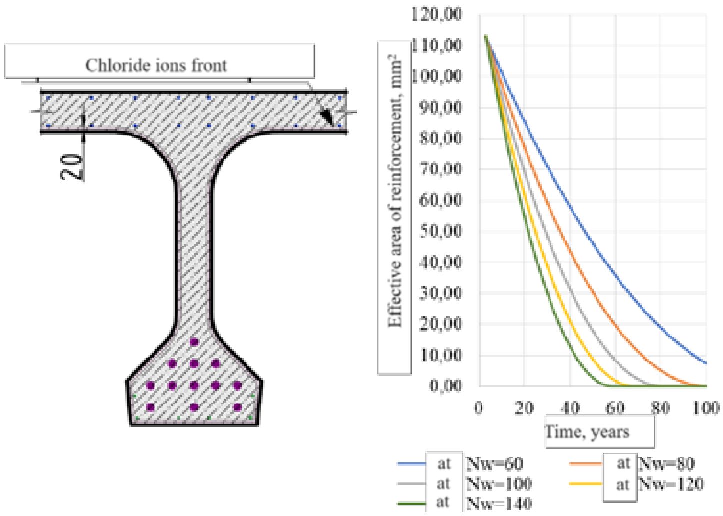


Pic. 4. Distribution of the carbonation front of the cross section after 44 years [developed by the authors].

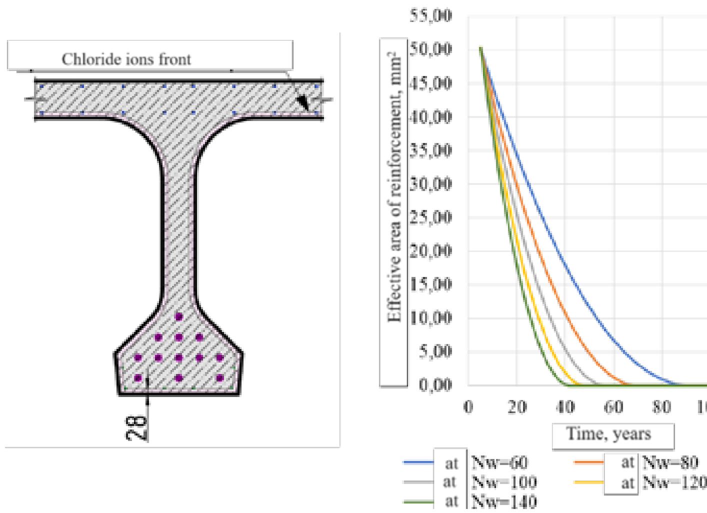
When chloride ions act on the reinforcement, the corrosion rate increases. The effective area in this case [3] is determined by formula (7):

$$A_{cor} = \pi \cdot \left(\frac{d}{2} - 0,28 \cdot \frac{N_W}{365} \cdot t_{cor} \right)^2 . \qquad (7)$$

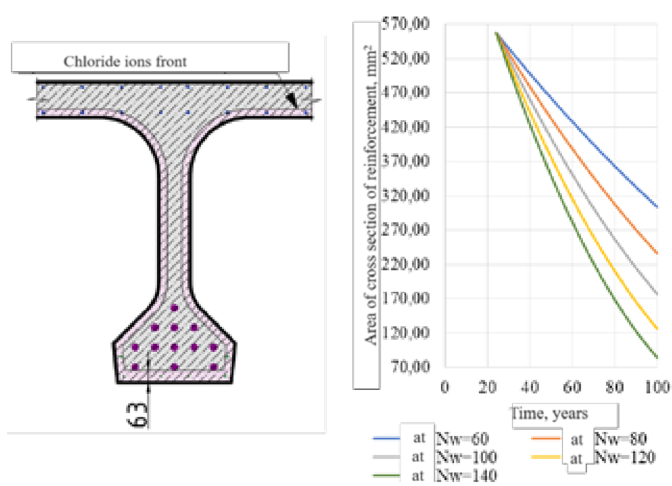
This study has considered the cross-section of beam B 3300.b.153-TV of the superstructure corresponding to the working drawings of Soyuzdorproekt. In accordance with dependence (1), it was determined that, when exposed to



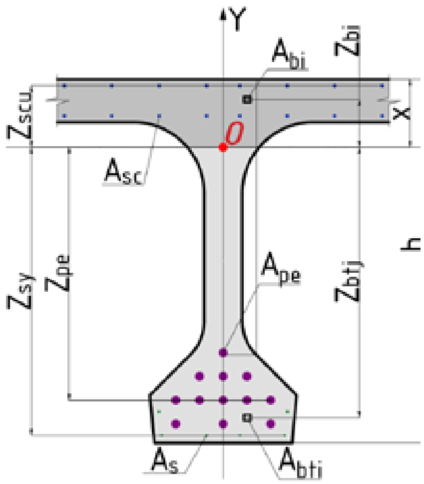
Pic. 5. Distribution of chloride ions in cross section after three years [developed by the authors].



Pic. 6. Distribution of chloride ions in cross section after five years [developed by the authors].



Pic. 7. Distribution of chloride ions in cross section after 24 years [developed by the authors].



Pic. 8. Design scheme of a normal section [developed by the authors].

carbon dioxide, the diffusion front reaches the upper non-stressed main reinforcement (AIII ∅12) of the superstructure within five years (Pic. 2) and the lower non-stressed reinforcement (AI ∅8) within nine years (Pic. 3). Corrosion of the prestressed reinforcement (K7 24∅5V) begins 44 years after the commissioning of the structure (Pic. 4). The change in the effective area during corrosion is described by a quadratic dependence, but due to the small change in the reinforcement diameter, it proceeds slowly, approaching a linear dependence (see Pics. 2–4).

During the service life of the superstructure, the diffusion of chloride ions results in beginning of corrosion of the upper and lower non-stressed reinforcement at the age of three and five years, respectively (Pics. 5 and 6), and of the prestressed reinforcement at the age of 24 years (Pic. 7) because of crack opening [3].

Substantiation of the patterns of change within the area of reinforcement bars because of the carbonation process allows us to proceed to determining the bearing capacity of reinforced concrete structures.

Calculation of the ultimate bending moment is performed based on the strength of the normal section of the reinforced concrete superstructure. In this model, ultimate forces are taken for compressed concrete, equal to the compressive resistance R_b; for tensioned concrete, equal to the tensile resistance R_{bt}; for tensioned longitudinal non-stressed reinforcement, equal to the tensile resistance R_s; for compressed longitudinal non-stressed reinforcement, equal to R_{sc}, for prestressed longitudinal reinforcement, equal to the tensile resistance R_p. The compressive and tensile resistances of concrete are assumed to be uniformly distributed over the compressed and tensioned zones.

The normal section (Pic. 8) is divided into a set of elements of area with a step S.

The ultimate forces created on the elements of area are applied to the centre. The solution to the problem is reduced to finding the position of point «O», which is located on the boundary of the compressed and stretched zones. Since the problem is axisymmetric, point «O» is located on the vertical axis of the normal section.

The ultimate bending moment of a normal section is determined by formula (8), which is obtained by solving the equation of equilibrium of moments relative to point «O»:

$$\sum_{i=1}^{n} R_b \cdot A_{bi} + \sum_{u=1}^{p} R_{sc} \cdot A_{scu} - \sum_{j=1}^{m} R_{bt} \cdot A_{btj} - \\ -\sum_{y=1}^{k} R_s \cdot A_{sy} - \sum_{e=1}^{l} R_p \cdot A_{pe} = 0 \quad , \qquad (8)$$

where Z_{bi} is the arm of action of the force for the *i*-th element of area of compressed concrete, mm;

Z_{scu} – arm of action of force for the *u*-th compressed reinforcement, mm;

Z_{btj}– arm of action of the force for the *j*-th element of area of stretched concrete, mm;

Z_{sy} – arm of action of force for the *y*-th tensile reinforcement, mm;

Z_{pe}– arm of action of force for the *p*-th prestressed reinforcement, mm;

A_{bi}, A_{scu}, A_{btj}, A_{sj}, A_{pe} – areas of elements of area of compressed concrete, compressed reinforcement, tensioned concrete, tensioned reinforcement and prestressed reinforcement, respectively, mm².

The arms of action of forces are deterministic quantities that are determined by the formulas (9–13):

$Z_{bi} = x - 10 \cdot a_i,$ (9)

$Z_{btj} = 1530 - x - 10 \cdot b_j,$ (10)

$Z_{scu} = x - Z_u,$ (11)

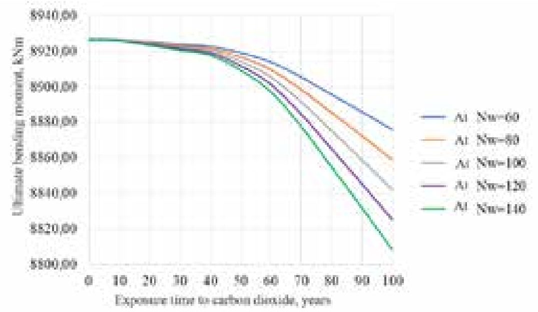
$Z_{sy} = 1530 - x - Z_y,$ (12)

$Z_{pe} = 1530 - x - Z_e,$ (13)

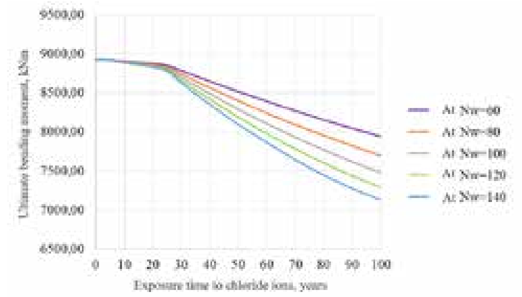
where *x* – actual height of compressed zone, mm;

a_i, b_j – ordinal number of the horizontal row of compressed and stretched elements of area, respectively;

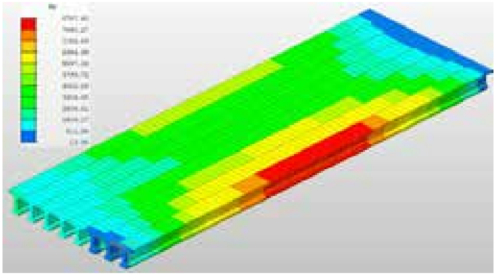
Z_u, Z_y, Z_e – distances from the centres of compressed, stretched and prestressed reinforcement to the nearest edge of the element, mm.



Pic. 9. Change in ultimate bending moment under the influence of carbon dioxide and for different number of days with precipitation per year [developed by the authors].



Pic. 10. Change in ultimate bending moment under the influence of chloride ions and for different number of days with precipitation per year [developed by the authors].



Pic. 11. Bending moment diagram My, kN·m [developed by the authors].

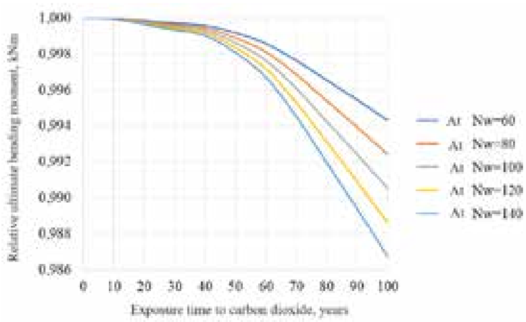
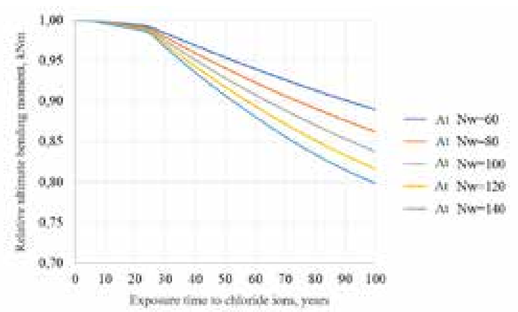


Рис. 12. Изменение относительного предельного изгибающего момента при воздействии углекислого газа и разном количестве дней с осадками в год [разработано авторами].



Pic. 13. Change in relative ultimate bending moment under the influence of chloride ions and different number of days with precipitation per year [developed by the authors].

The areas of elements of area of a normal section are constant values for a certain moment in time.

When determining the ultimate bending moment, condition (14) must be satisfied, which is obtained by solving the equation of equilibrium of forces on the longitudinal axis (orthogonal to the plane of the normal section) of the element:

$$\sum_{i=1}^{n} R_b \cdot A_{bi} + \sum_{u=1}^{p} R_{sc} \cdot A_{scu} - \sum_{j=1}^{m} R_{bt} \cdot A_{btj} - \\ - \sum_{y=1}^{k} R_s \cdot A_{sy} - \sum_{e=1}^{l} R_p \cdot A_{pe} = 0, \quad (14)$$

The calculation of the normal cross-section over time is performed in accordance with formulas (8) and (14). The values of the effective area of the main reinforcement are determined in accordance with Pics. 2–7 for a specific moment in time. The results of the calculations are shown in Pic. 9 for different amounts of precipitation during the year under the influence of carbon dioxide, and in Pic. 10 under the influence of chloride ions.

RESULTS

To determine the forces that arise, a modelling of a sectional superstructure made using 3300.b.153-TV girders was performed. When a moving load is located above the girder in the centre of the suoerstructure, a bending moment M_y = 8787,90 kN·m is created (Pic. 11).

The analysis of the obtained results (see Pics. 9, 10) showed that when the main reinforcement is reached, the processes of irreversible changes (irreversible decrease) in the bearing capacity of the superstructure begin. In the process of carbon dioxide diffusion, the reinforcement bars corrode, which leads to a decrease in the bearing capacity of the superstructure girders. Before the onset of corrosion of the prestressed reinforcement (45 years), a loss of 0,03 % of the initial bearing capacity of the superstructure girder is observed, and after 45 years the loss is 0,52 %.

The rationale of the forecasting formula for the current ultimate bending moment is based on the graphs shown in Pics. 12, 13.

The value of the ultimate bending moment for a beam exposed to carbon dioxide for a time t and for the number of days per year with precipitation greater than 2,5 mm N_w is determined by the formula (15):

$$M_t = M_{y,0} \cdot (1 - 0{,}13 \cdot N_w \cdot t^2 \cdot 10^{-7} + 0{,}04 \cdot N_w \cdot t \cdot 10^{-5}), \quad (15)$$

where t – actual time of exposure of the span structure to carbon dioxide;

N_w – number of days per year with precipitation over 2,5 mm;

$M_{y,0}$ – initial value of ultimate bending moment, kNm.

A decrease in the bearing capacity indicates a negative impact of carbon dioxide diffusion. During operation, measures should be taken to prevent the diffusion of atmospheric gases through painting the concrete surface and using additives that compact the structure. Also, it is necessary to control and replace the affected concrete before the front reaches the prestressed reinforcement. After the onset of corrosion of the prestressed reinforcement, an irreversible process of reducing the operational properties occurs, while the bending moment from the action of the moving load does not exceed the limit value during the service life. Failures of the superstructure girders occur at the age of 105; 117; 126; 139 and 158 years.

During operation of the superstructure, chloride ions reach the prestressed reinforcement because of the opening of cracks formed during corrosion of the non-prestressed lower reinforcement and a decrease in the strength of the concrete. Corrosion of the upper and lower non-prestressed reinforcement begins at the age of three and five years, respectively, and of prestressed reinforcement at 24 years. The rate of corrosion under the influence of chloride ions is 28 times higher than under the influence of carbon dioxide, but the penetrating ability is lower. Before the onset of corrosion of the prestressed reinforcement (24 years), a loss of 0,72 % of the initial bearing capacity of the superstructure girder is observed, after 24 years the loss is 9,84 %.

The value of the ultimate bending moment for a girder exposed to chloride ions for a time t and the number of days per year with precipitation greater than 2,5 mm N_w is determined by formula (16):

$$M_t = M_{y,0} \cdot (1 - 0{,}82 \cdot N_w \cdot t^2 \cdot 10^{-7} - 0{,}12 \cdot N_w \cdot t \cdot 10^{-4}), \quad (16)$$

where t is actual time of exposure of the superstructure to carbon dioxide;

N_w – number of days per year with precipitation over 2,5 mm;

$M_{y,0}$ – initial value of ultimate bending moment, kNm.

During operation of a bridge structure with a predominant effect of chloride ions, it is necessary to prevent the occurrence of cracks that will result in corrosion of the prestressed reinforcement. Failures of the superstructure girders occur at the age of 25; 26; 27; 28 and 30 years.

CONCLUSIONS

This study has proposed a method for determining the service life of a reinforced concrete girder of a bridge superstructure under the influence of aggressive environments. The proposed method consists of six stages:

1. Revealing the prevailing effect of an aggressive environment.
2. Determining the diffusion rate of atmospheric gases.
3. Determining the change in the effective cross-sectional area of reinforcement.
4. Evaluating of the bearing capacity of the superstructure girder at the beginning of operation.
5. Calculating of the current ultimate bending moment of the girder.
6. Determining residual service life.

The analytical dependences of the diffusion of atmospheric gases (carbon dioxide (CO_2), halogens (Cl_2) and hydrohalic acids) constituted a basis to determine the dependences of the ultimate bending moments of the superstructure's girder for various operating conditions. The number of days with precipitation during the year has been chosen as the main influencing condition.

The proposed method has been used to calculate the bearing capacity of the B 3300.b.153-TV reinforced concrete girder of the superstructure. It has been established that its service life before failure when exposed to carbon dioxide is 158 years, and when exposed to halogens and hydrohalic acids – 27 years.

Thus, the use of this method allows determining the remaining service life of the superstructure, as well as the resource for bearing capacity and predicting the required repair and restoration work.

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Article received 24.01.2024, approved 10.09.2024, accepted 12.09.2024.