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Stability exposure of building structural systems under environmental damage

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Abstract. Environmental impacts on reinforced concrete structures may cause a decrease of in resource of their robustness under design and unforeseen actions. The research in this field mainly focusses on investigation of the behavior of bending elements as eccentrically compressed and damaged by corrosion reinforced concrete elements such as columns require more intensive investigation. Thus, the study has the purpose to assess the influence of the depth of corrosion on the bearing capacity of eccentrically compressed reinforced concrete columns of building frames, as well as to evaluate the time for exhaustion of load capacity. The phenomenological model, which was proposed by V.M. Bondarenko, has been adopted in order to account long-term processes of corrosion damage. The study established an increase in the depth of corrosion damage leads to a decrease in the bearing capacity of eccentrically compressed reinforced concrete columns since the effective cross-sectional depth decreases which makes column more flexible. The relative cross-sectional depth lost strength resistance resource due to corrosion varies depending on the current stress-strain state of the reinforced concrete column that is adaptation mechanism of the structure to long-term actions. The exposure of building structural systems under environmental damage depends significantly on the parameters of the action as well as the stress-strain state of the structural element. The paper established that it may differ by several times depending on avalanche or clogging damage scenario.

Keywords: reinforced concrete, column, corrosion, load capacity, exposure, slenderness ratio

Экспозиция устойчивости длительно нагруженных конструктивных систем зданий при средовом повреждении

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Аннотация. Ряд аварий, произошедших в последние годы с объектами капитального строительства, показывает, что средовые воздействия на железобетонные конструктивные системы приводят с течением времени к снижению ресурса их силового сопротивления при особых аварийных воз-

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действиях. При этом представленные в научной литературе результаты исследований по данному вопросу преимущественно относятся к изгибаемым элементам, в то время как применительно к внецентренно сжатым коррозионно повреждаемым железобетонным элементам рассмотрены либо частные аспекты силового сопротивления в условиях контакта конструкций с агрессивными средами, либо полученные расчетные зависимости достаточно сложные для их практического применения. В связи с этим цель исследования – оценить влияние глубины продвижения фронта коррозии на несущую способность внецентренно сжатых железобетонных элементов конструктивных систем зданий и сооружений, а также спрогнозировать время исчерпания несущей способности. Для учета длительных неравновесных процессов коррозионного повреждения использована феноменологическая модель В.М. Бондаренко. Установлено, что рост глубины коррозионного повреждения приводит к снижению несущей способности внецентренно сжатых железобетонных элементов вследствие уменьшения эффективной рабочей высоты сечения и увеличения их гибкости. При этом относительная глубина разрушенного слоя, не учитываемого в расчете, меняется в зависимости от текущего напряженно-деформированного состояния, реализуя механизм приспособления конструкции к меняющимся во времени параметрам воздействий. Время достижения критической глубины коррозионного повреждения существенно зависит от параметров средовых воздействий и напряженно-деформированного состояния элемента и может отличаться в несколько раз при реализации траекторий лавинного или кольматационного повреждения.

Ключевые слова: железобетон, колонна, коррозия, несущая способность, экспозиция, гибкость

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Introduction

Structural systems of buildings and structures during their service life are subject to the action of combinations of force and environmental factors. The latter one considers exposure to high or extremely low temperatures, aggressive media action. With regard to reinforced concrete structural systems, environmental impact factors can lead to degradation of the mechanical characteristics of cross sections, a decrease in the adhesion resistance between reinforcement and concrete. The result of this may be the exhaustion of the bearing capacity of individual load-bearing elements and, as a result, the complete or partial collapse of the building's load-bearing system, as happened in the case of a partial collapse of the building of a residential complex in Surfside [1] or the collapse of the pavement structure of the Basmanny market [2]. In this regard, an urgent problem is the prediction of changes in the parameters of the survivability of reinforced concrete structural systems of buildings during the evolutionary accumulation of environmental damage in them.

The studies presented in the scientific literature on the problem of the force resistance of reinforced concrete structural elements under conditions of their contact with aggressive media can be conditionally separated into two groups: a) studies of the effect of corrosion damage of longitudinal and transverse working reinforcement on the force resistance of elements [3–12]; b) studies of degradation processes in concrete under various types and concentrations of aggressive media, the shape and size of samples, stress-strain state, etc. [13–18]. However, it is appropriate to note that the degradation processes of concrete and reinforcing steel, as a rule, occur in load-bearing elements at the same time and should be taken into account jointly when assessing the exposure of the survivability of a structural system, following the terminology [3; 7; 19].

Given the large number of factors affecting the development of non-equilibrium processes in reinforced concrete elements exposed to aggressive media, as well as the largely random nature of the change in the parameters of impacts over time, for practical purposes, they often resort to the use of phenomenological degradation functions [6; 8; 12]. The studies presented in the scientific literature on this problem mainly cover the issues of resistance of bent reinforced concrete elements [6; 10; 12; 18; 20]. For eccentrically compressed elements, the evaluation of their load-bearing capacity is complicated by the influence of the phenomenon of buckling, changes in stiffness and eccentricities of the application of longitudinal force overtime due to the accumulation of corrosion damage. In this regard, the results of research in this area mainly cover particular aspects of force resistance under conditions of contact of structures with aggressive media [15; 17] or lead to calculated dependences that are quite complex for their practical application [3].

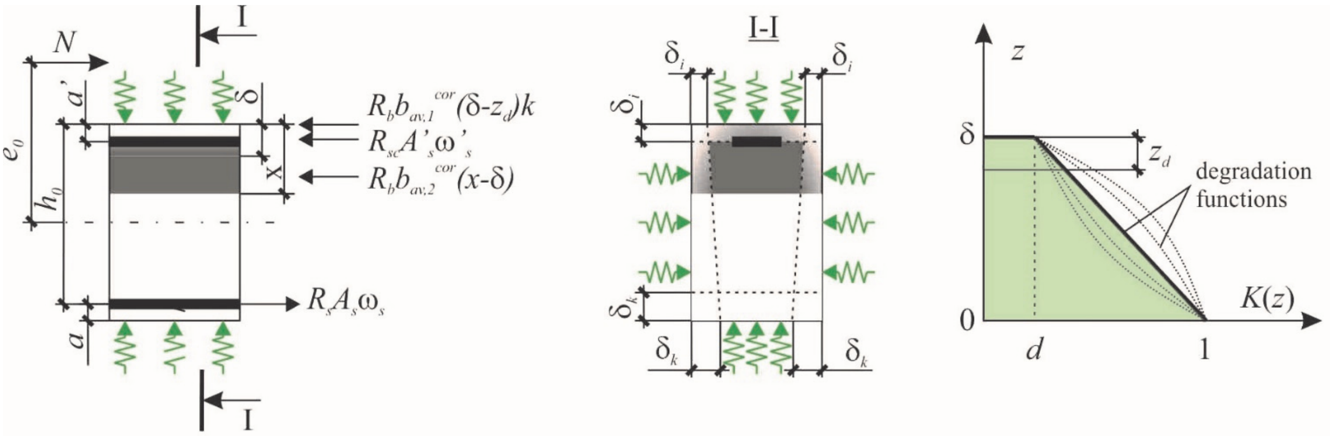
Therefore, the presented study was aimed to assess the effect of the depth of corrosion front advancement on the bearing capacity of the structural system of reinforced concrete frames of buildings in case of corrosion damage to eccentrically compressed columns, as well as to predict the exposure of stability which is the time of operation under conditions of force and environmental impact until the load bearing capacity is exhausted.

Methods

Let us use the hypothesis of the constant change in the parameters of the force resistance of corrosion-damaged concrete [6; 7] (Figure 1, *a*):

$$\frac{R_{b(bt)}^{\text{cor}}(t)}{R_{b(bt)}} = \frac{E_b^{\text{cor}}(t)}{E_b} = \frac{\varepsilon_{b2(bt2)}^{\text{cor}}(t)}{\varepsilon_{b2(bt2)}}, \tag{1}$$

where $R_{b(bt)}$, E_b, $\varepsilon_{b2(bt2)}$ is the design compressive (tensile) resistance, initial modulus of elasticity, ultimate compressive (tensile) strain of concrete without corrosion damage; $R_{b(bt)}^{\text{cor}}(t)$, $E_b^{\text{cor}}(t)$, $\varepsilon_{b2(bt2)}^{\text{cor}}(t)$ are the same for corrosion-damaged concrete with duration of exposure to an aggressive environment *t*.



a *b*

Figure 1. Design scheme of an eccentrically compressed corrosion-damaged reinforced concrete element:
a – cross-sectional design scheme; *b* – a general view of the degradation function for the concrete layer damaged with corrosion

The change in the parameters of the force resistance along the depth of the corrosion-damaged layer of concrete, we accept an empirically established degradation function of the form (Figure 1, *b*) [6; 21]:

$$K(z) = \sum_{0}^{2} a_i z^i. \tag{2}$$

Taking into account the above assumptions, the bearing capacity of an eccentrically compressed corrosion-damaged element of a rectangular element is determined by the expressions:

– for $x \geq \delta$:

$$(Ne_0\eta)_{\text{ult}} = R_b\left[b_{av,1}^{\text{cor}}(\delta - z_d)k\left(h_0 - \delta + z_{\text{c.t.},1}\right) + b_{av,2}^{\text{cor}}(x-\delta)\left(h_0 - \frac{x+\delta}{2}\right)\right] + \left(R_{sc}A_s'\omega'_s - \frac{N}{2}\right)(h_0 - a'); \tag{3}$$

– for $x < \delta$:

$$(Ne_0\eta)_{\text{ult}} = R_b b_{av,1}^{\text{cor}}(x - z_d)k\left(h_0 - x + z_{\text{c.t.},1}\right) + \left(R_{sc}A_s'\omega'_s - \frac{N}{2}\right)(h_0 - a'). \tag{4}$$

In expressions (3), (4) $\eta = 1 / (1 - N / N_{\text{cr}})$ is the coefficient that takes into account the effect of buckling, which can be determined in accordance with the current regulatory documents[1]; N, N_{cr} are the calculated value of

[1] SP 63.13330.2018. *Concrete and reinforced concrete structures. General provisions.* (In Russ.) Available from: https://docs.cntd.ru/document/554403082 (accessed: 20.06.2022); BS EN 1992-1-1. *Eurocode 2. Design of concrete structures. Part 1–1. General rules and rules for buildings.* British Standards Institution; 2004. Available from: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf (accessed: 20.06.2022).

the longitudinal force, determined by the static calculation of the carrier system for the main combination of loads, and the value of the conditional critical force in the event of buckling; R_b, R_{sc}, R_s are design resistance of concrete to compression, reinforcing steel to compression and tension respectively; A_s, A'_s are the area of tensioned (least compressed) and compressed longitudinal reinforcement; h_0 is the working depth of the section; δ is the depth of corrosion damage of the element; ω_s, ω'_s are coefficients that take into account the reduction in the effective cross section of bars of longitudinal tension and compression reinforcement and (or) the reduction in adhesion resistance due to corrosion damage to reinforcement and concrete; $b^{\text{cor}}_{av,1}$, $b^{\text{cor}}_{av,2}$ are the average reduced width of the cross section within the depth of the corrosion-damaged layer δ and within the range from δ to $(x-\delta)$ respectively, determined from the expression:

$$b^{\text{cor}}_{av,1(2)} = b - 2\delta_{i(k)}\left(1 - \frac{1}{\delta_{i(k)}}\int_0^{\delta_{i(k)}} K(z)dz\right);$$

k is the reduction factor for the area of the corrosion-damaged part of the section, determined from the expression:

$$k = \frac{1}{\delta - z_d}\int_0^{\delta - z_d} K(z)dz\,;$$

x is the height of the compressed zone of the section, determined at $x \le x_R$ by the formula

$$x = \delta + \frac{N + R_s A_s \omega_s - R_{sc} A'_s \omega'_s - R_b b^{\text{cor}}_{av,1}(\delta - z_d)k}{R_b b^{\text{cor}}_{av,2}};$$

– for $x > x_R$ by formula

$$x = \delta + \frac{N + R_s A_s \omega_s \dfrac{1+\xi_R}{1-\xi_R} - R_{sc} A'_s \omega'_s - R_b b^{\text{cor}}_{av,1}(\delta - z_d)k}{R_b b^{\text{cor}}_{av,2} + \dfrac{2R_s A_s \omega_s}{h_0(1-\xi_R)}},$$

where z_d is the thickness of the corrosion-damaged layer, counted from the most compressed face, for which the condition $\varepsilon \le \varepsilon_{b2} \cdot K(z_d)$ is not satisfied, i.e., it lost resource of force resistance.

The limiting value of the height of the compressed zone x_R of the corrosion-damaged section with a two-line approximation of the state diagram of concrete is determined from the expression:

$$x_R = \frac{\alpha(h_0 - z_d)}{1 + \dfrac{\varepsilon_{s,el}}{\varepsilon_{b2} K(z_d)}},$$

where α is determined depending on the deformation at a depth δ of a corrosion-damaged element by the formula:

– for $\varepsilon(\delta) > \varepsilon_{b1,\text{red}}$:

$$\alpha = 1 - \frac{\varepsilon_{b1,\text{red}}}{2\varepsilon_{b2} K(z_d)};$$

– for $(\delta) \le \varepsilon_{b1,\text{red}}$ $\alpha = 0.5$.

When determining the conditional critical force, the stiffness of the reduced corrosion-damaged section in the first approximation will be determined by the formula

$$B_{\text{red,cor}} = k_b E_b \int_{-\frac{h}{2} - z_{\text{c.t.}}}^{\frac{h}{2} - z_{\text{c.t.}}} b(z)K(z)z^2 dz + k_s E_s \left(A_s \omega_s \left(\frac{h}{2} + z_{\text{c.t.}} - a\right)^2 + A'_s \omega'_s \left(\frac{h}{2} - z_{\text{c.t.}} - a'\right)^2\right),$$

where k_b, k_s are the coefficients according to SP 63.13330.2018, EN 1992-1-1, taking into account the physical non-linearity of concrete and reinforcement deformation; $z_{\text{c.t.}}$ is the displacement of the geometric center of gravity of a corrosion-damaged section relative to the center of gravity of the same section, which is not exposed to an aggressive environment.

The displacement of the geometric center of gravity $z_{\text{c.t.}}$ leads to an increase in the eccentricity of the application of the longitudinal force, so it should be added to the calculated eccentricity obtained for the element without corrosion damage.

To assess the exposure of the survivability of the structural system of reinforced concrete frames of buildings in case of corrosion damage to the columns, which is determined by the time of exhaustion of the bearing capacity, we used the phenomenological model of V.M. Bondarenko [7], according to which the depth of corrosion damage of a structural element for time t can be found from the expression

$$\delta(t,t_0)=\delta(\infty,t_0)\left\{1-\left[\alpha(1-m)(t-t_0)+\left(1-\frac{\delta(t_0,t_0)}{\delta(\infty,t_0)}\right)^{1-m}\right]^{\frac{1}{1-m}}\right\}, \tag{5}$$

where t, t_0 are the current time and the start time of the observation; $\delta(\infty, t_0)$ is the limiting depth of corrosion damage with the established parameters of the aggressive environment, the shape and material of the structural element, as well as the stress-strain state (Figure 2); $\delta(t_0, t_0)$ is the depth of corrosion damage at the time of the start of observation (if the start of observation coincides with the beginning of exposure to an aggressive environment, then $\delta(t_0, t_0) = 0$); α, m are empirically set parameters (Figure 2).

From (5) we find the time t_{cr} to reach the critical depth of corrosion damage and, accordingly, the exhaustion of the resource of the power resistance of the element of the reinforced concrete carrier system:

$$t_{\text{cr}}-t_0=\frac{1}{\alpha(1-m)}\left[\left(1-\frac{\delta_{\text{cr}}(t_{\text{cr}},t_0)}{\delta(\infty,t_0)}\right)^{1-m}-\left(1-\frac{\delta(t_0,t_0)}{\delta(\infty,t_0)}\right)^{1-m}\right]. \tag{6}$$

Results and discussion

Let us evaluate the change in the parameters of the force resistance of a column with a section of 400×400 mm of a reinforced concrete frame of a multistory building exposed to an aggressive environment along all four faces. Column construction materials: class B30 concrete (normative resistance of concrete to axial compression $R_{b,n}$ = 22 MPa, E_b = 32 500 MPa), longitudinal working reinforcement – 4Ø32 A500 ($R_{s,n} = R_{sc,n}$ = 500 MPa, E_s = 200000 MPa), $a = a'$ = 50 mm. By varying the parameters of the depth of corrosion damage $\delta(t,t_0)$; the thickness of the corrosion-damaged layer z_d, which has exhausted the resource of force resistance, and the flexibility of the element λ_h, we determine the boundaries of the areas of the bearing capacity of such elements in the coordinate axes $N – M$, corresponding to a special limiting state[2]. At the same time, when constructing diagrams $N – M$, in order to take into account the effect of flexibility of reinforced concrete corrosion-damaged elements on their bearing capacity, we divide the right and left parts of expressions (3) and (4) by the coefficient of influence of buckling η. Diagrams of the bearing capacity of eccentrically compressed corrosion-damaged reinforced concrete elements in the coordinate axes $N – M$ are shown in Figures 2–3.

Analysis of diagrams in Figure 2 indicates that with an increase in the depth of corrosion damage, a decrease in the bearing capacity occurs due to a decrease in the effective working height of the section and the flexibility of the element. Thus, with flexibility λ_h = 8 and an established relative depth of the destroyed layer z_d/δ = 0.8 for a relative depth of corrosion damage δ/h_0 = 0.2, the limiting value of the longitudinal force decreases by 11.4%, and the limiting bending moment by 21.0% compared to an element undamaged by corrosion. In this case, the limiting moment for bending elements (N = 0) decreases only when the longitudinal reinforcement bars are within the corrosion-damaged layer δ (Figure 2 at δ/h_0 = 0.15, 0.2) and their effective area decreases cross section, as well as reduced adhesion resistance. It should be noted that a decrease in the relative depth of the damaged layer introduced into the calculation leads to an increase in the limiting value of the longi-

[2] BS EN 1992-1-1. *Eurocode 2. Design of concrete structures. Part 1–1. General rules and rules for buildings*. British Standards Institution; 2004. Available from: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf (accessed: 20.06.2022).

tudinal force for a fixed relative depth of corrosion damage δ/h_0, which is associated with the redistribution of forces on the sections of the section not damaged by corrosion in elements with random and small eccentricities of the longitudinal force. At the same time, there is a downward shift of the limiting bending moment point in the diagram, which is due to a decrease in the limiting compressive strains $\varepsilon_{b2(bt2)}^{\text{cor}}(t)$. It is pertinent to note that the relative depth of the destroyed layer z_{raz}/δ, taken fixed when plotting the diagrams in Figure 2, in fact, will change during loading of a structural element, realizing the mechanism of adaptation of the structure, therefore, to fully take into account the reserves of the bearing capacity, one should use the envelope of the $N - M$ diagram constructed at a fixed value of the relative depth of corrosion damage δ/h_0 and a variable value of the relative depth of the destroyed layer z_{raz}/δ.

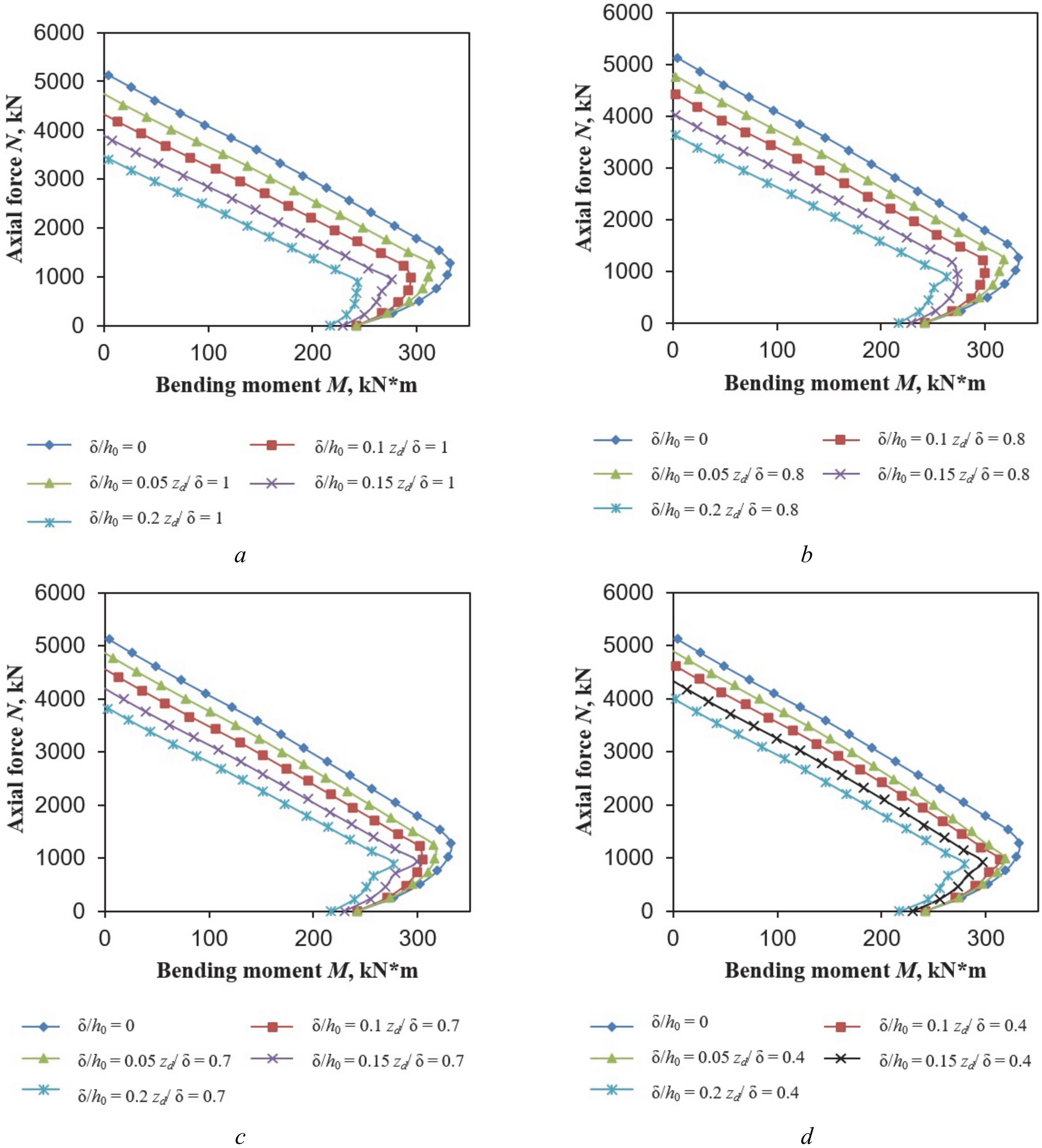


Figure 2. $M - N$ interaction diagrams for corrosion-damaged eccentrically compressed reinforced concrete elements with slenderness ratio $\lambda_h = 8$ depending on the relative depth of corrosion damage:
a – for $z_d/\delta = 1$; *b* – for $z_d/\delta = 0.8$; *c* – for $z_d/\delta = 0.6$; *d* – for $z_d/\delta = 0.4$

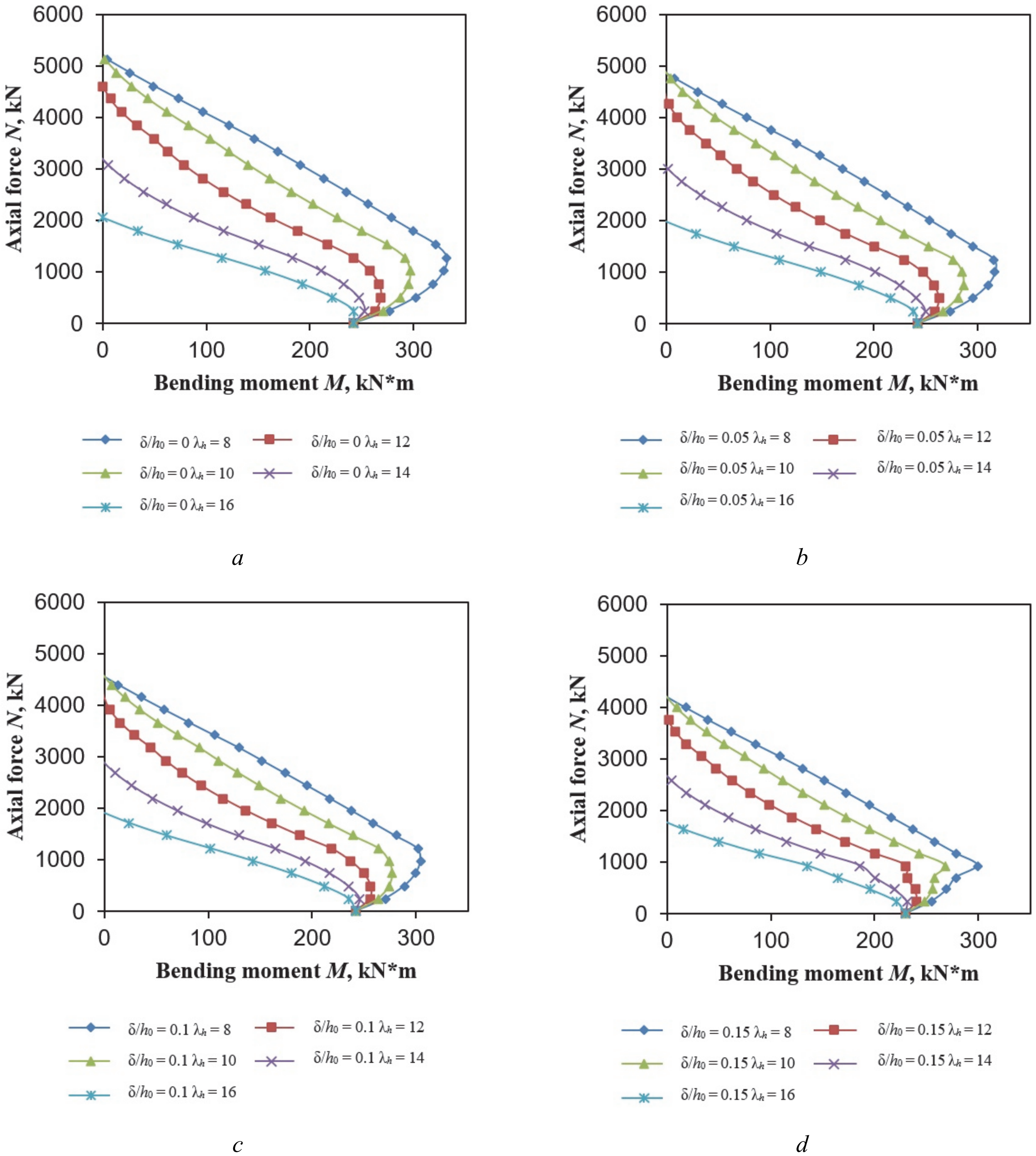


Figure 3. M – N interaction diagrams depending on the slenderness ratio λ_h of eccentrically compressed reinforced concrete elements for $z_d/\delta = 0.6$:
a – $\delta/h_0 = 0$; *b* – $\delta/h_0 = 0.05$; *c* – $\delta/h_0 = 0.1$; *d* – $\delta/h_0 = 0.15$

With an increase in the flexibility of the elements λ_h over 12 (Figure 3), there is a decrease in the value of the limiting longitudinal force perceived by eccentrically compressed elements with random and small eccentricities. With flexibility $\lambda_h = 16$, there is an almost twofold decrease in the limiting longitudinal force perceived by the section, and the limiting bending moment corresponds to the case of transverse bending ($N = 0$). At the same time, an increase in the relative depth of corrosion damage enhances this effect due to an increase in the effective flexibility of corrosion-damaged elements compared to elements without damage.

Let us evaluate the exposure of the bearing capacity of the column under consideration in continuous contact with a sulfate medium with pH = 3.5. To determine the parameters of equation (5), which determine the kinetics of the corrosion damage process, we used the experimental data presented in [10]. Taking $\delta(\infty, t_0) = 0.5$ h, corresponding to the corrosion of the entire section, we obtain the average value $\alpha = -0.00024$, which practically does not change when the parameter *m* changes. The results of determining the time to reach the depth of corrosion damage $\delta_{cr}(t_{cr}, t_0)$ depending on the value of the parameter m are shown in Figure 4.

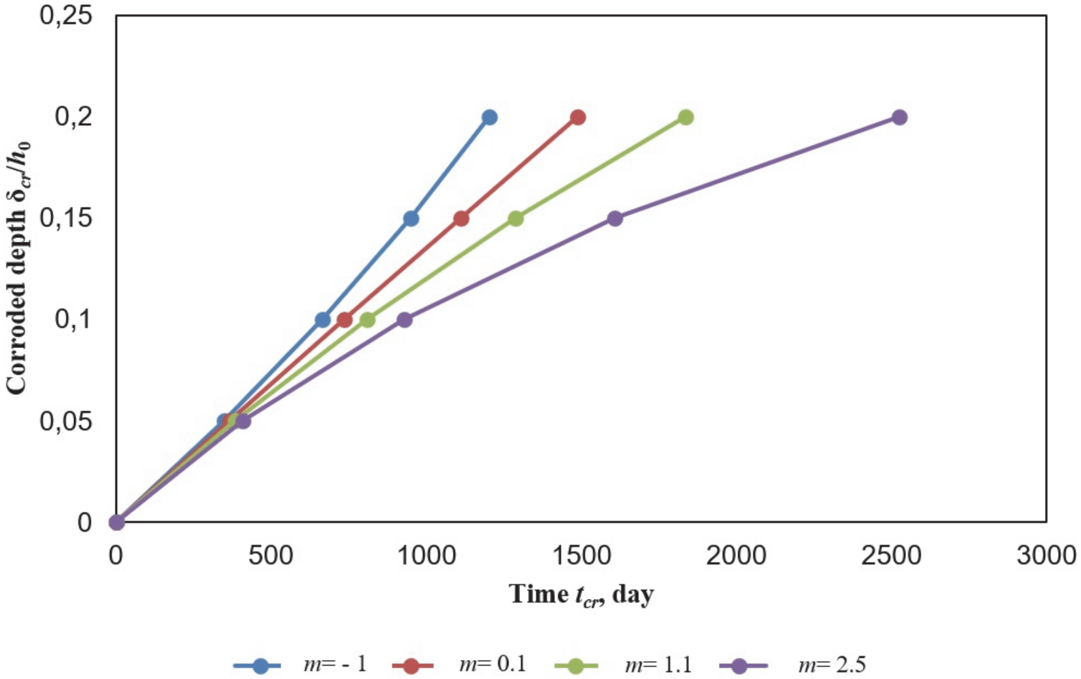


Figure 4. Time t_{cr} for reaching the critical depth of corrosion damage $\delta_{cr}(t_{cr}, t_0)$

The time to reach the relative depth of corrosion damage $\delta/h_0 = 0.2$ with the avalanche damage trajectory ($m = -1$, $t = 1203$ days, Figure 4) for the considered reinforced concrete element turned out to be almost two times less than the time to reach this depth with the avalanche damage trajectory clogging damage ($m = 2.5$, $t = 2523$ days). With the trajectory of filtration damage, reaching the same depth of corrosion damage will take $t = 1488$ days.

Conclusion

If the depth of corrosion damage increases then it leads to a decrease in the bearing capacity of eccentrically compressed reinforced concrete elements due to a decrease in the effective working height of the section and an increase in their flexibility. Then the relative depth of the damaged layer z_d/δ, which is not taken into account in the calculation, varies depending on the current stress-strain state.

An increase in the flexibility of elements λ_h leads to a decrease in the value of the limiting longitudinal force perceived by eccentrically compressed reinforced concrete elements. At the same time, an increase in the relative depth of corrosion damage enhances this effect due to an increase in the effective flexibility of such elements compared to elements without damage.

The duration of exposure under aggressive media until reaching the critical depth of corrosion damage depends significantly on the parameters of this media as well as the stress-strain state of the structural member and may vary in accordance with avalanche or clogging damage implementing.

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