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Survivability criteria for reinforced concrete frame at loss of stability

Критерии живучести железобетонной рамы при потере устойчивости

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Abstract. Analysis of scientific publications on the assessment of resistance of structures to progressive collapse, as well as existing and projects of design codes of different countries, in particular the project of Design Code "Protection of buildings and structures against progressive collapse. The design requirements. General conclusions", shows, that the main evaluating criteria are strength parameters. At the same time, structures, which are made of high– strength materials and have small sizes of cross-sections, as well as structures operating in aggressive conditions, when the cross-section decrease or the computational length suddenly increase, should be checked to the loss of stability of the bearing elements. The purpose of this study is to obtain the evaluating criteria of the survivability and residual life of reinforced concrete (RC) structural systems at sudden loss of stability of the element, caused by the evolutionary accumulation of a critical level of corrosion damage. The article presents analytical dependences to determine the critical value of the cross-section stiffness of the corrosively damaged element and the critical time, after which the structural system lose stability in conditions of simultaneous action of forces and aggressive environmental influences. Proposals are given to assign the survivability parameters of reinforced concrete structural systems, operating under exceeding limit states, that caused by the sudden loss of stability of the carrier element at the accumulation of critical value of corrosion damages.

Аннотация. Анализ научных публикаций, посвященных оценке сопротивляемости конструктивных систем зданий и сооружений прогрессирующему обрушению, а также существующих и разрабатываемых нормативных документов разных стран, в частности проекта СП «Защита зданий и сооружений от прогрессирующего обрушения. Правила проектирования. Основные положения», показывает, что в качестве критериев такой оценки, как правило, выступают прочностные показатели. В то же время для конструктивных систем из высокопрочных материалов при малых размерах поперечных сечений их элементов, а также для конструктивных систем, работающих в условиях воздействия агрессивных сред, когда уменьшается поперечное сечение или расчетной длины – в качестве критерия оценки сопротивляемости прогрессирующему обрушению необходимо рассматривать и потерю устойчивости несущего элемента конструктивной системы. Целью настоящего исследования являлось построение критериев для оценки живучести и остаточного ресурса конструктивных систем из железобетона при внезапной потере устойчивости одного из элементов, вызванной эволюционным накоплением критического уровня коррозионных повреждений. В статье приведены аналитические зависимости для определения критического значения жесткости поперечного сечения коррозионно повреждаемого элемента и критического времени, при котором конструктивная система потеряет устойчивость в условиях одновременного проявления силовых и средовых воздействий. Даны предложения по нормированию параметров живучести железобетонных конструктивных систем при запредельных состояниях, вызванных внезапной потерей устойчивости несущего элемента от накопления коррозионных повреждений.

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1. Introduction

A series of accidents and destruction of buildings and structures that occurred in the XX – early XXI century, such as the destruction of the WTC towers in New York, destructions of panel high-rise buildings caused by natural gas explosions, etc., gave a powerful impetus to the development of a new direction in building science – the calculation of buildings and structures against progressive collapse. The current regulatory documents of a number of countries, in particular the USA, Great Britain, EU, Ukraine, Russia [1–5] contain the basic provisions, allowing to carry out an assessment of risk of progressive collapse of buildings and structures. However, the number of new scientific publications on this subject suggests that there are many aspects, which still require further study. A significant number of recent publications are devoted to the study of the progressive collapse caused by explosive loads [6-11]. However, the start of avalanche destruction of the structural system may be caused by the accumulation of a critical level of damage of another nature [12–14], in particular of a corrosive damage [15–18]. At the same time, the loss of strength of bearing elements of the system is considered as a main criterion of such a process in an overwhelming number of scientific publications, devoted to the assessment of resistance of building and structures against progressive collapse. In our opinion it is expedient to consider the loss of stability of bearing elements as an additional criterion of resistance of designed and operating frameworks against progressive destruction. However, currently there are only a few papers in this direction [19–23], mainly presented in foreign publishing, the main number of which cover the assessment of resistance against progressive collapse of steel frames [20–26]. A number of authors in their publications combine the terms of stability and resistance against progressive collapse, implying in this case destruction due to the loss of strength of structural elements [27–28].

In this way, the purpose of the paper is to obtain criteria for evaluate state of structures over the limit state, caused by loss of stability of a bearing reinforced concrete element at corrosion damage accumulation. The following tasks are solved to achieve this purpose: obtain analytical model to evaluate bending stiffness of reinforced concrete element cross section, destructured by corrosion; derive relationship to determine critical time tcr, when structural element loss stability because of corrosion damages.

2. Methods

This article explores the issues of survivability of reinforced concrete structural system at sudden buckling of the bearing structural element due to the accumulation of a critical level of corrosion damage. Stability problem are solved analytically by Euler's statement using deformation method. The phenomenological model proposed by V.M. Bondarenko [15] is used in this paper to account for long-term processes of corrosion damage of structural elements, contacting with aggressive environment.

According to this model the depth of corrosion damage of reinforced concrete structure $\delta(t,t_0)$ at colmatation can be described by the following mathematical relationship as it is shown in Figure 1 (a).

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

where δ_{cr} is ultimate depth of corrosion damage at colmatation; α and m are parameters, which characterize penetration speed of the corrosion damage front; t and t_0 are current time and initial time of observation the damaged structural element. It should be noted that $m < 0$ corresponds to the area of avalanche penetration of corrosion front in time; $m > 0$ corresponds to the area of colmatation (penetration of corrosion front damped in time); $m = 0$ corresponds to the boundary line of the filtration development of the damage process. The parameters δ_{cr}, α and m can be approximated by polynomials [16], as it is shown in Figure 1 (b):

$$\delta_{cr}=\sum_{i=0}^{3}q_{\delta_i}\cdot(\sigma/R_b)^i,$$

$$\alpha=\sum_{i=0}^{3}q_{\alpha_i}\cdot(\sigma/R_b)^i,$$

$$m = \sum_{i=0}^{3} q_{m_i} \cdot (\sigma / R_b)^i ,$$

where q_δ, q_α, q_m are parameters, which should be determined empirically for defined aggressive environment and initial mechanical characteristics of concrete.

Also it should be noted, that the function of corrosion damage depth $\delta(t, t_0)$ can take the trajectory of avalanche (1) or fading (2) development once more after an additional dynamic impact on the reinforced concrete element with depth of corrosion damage about δ_{cr} at time t_1 , as it is shown in Figure 1 (a).

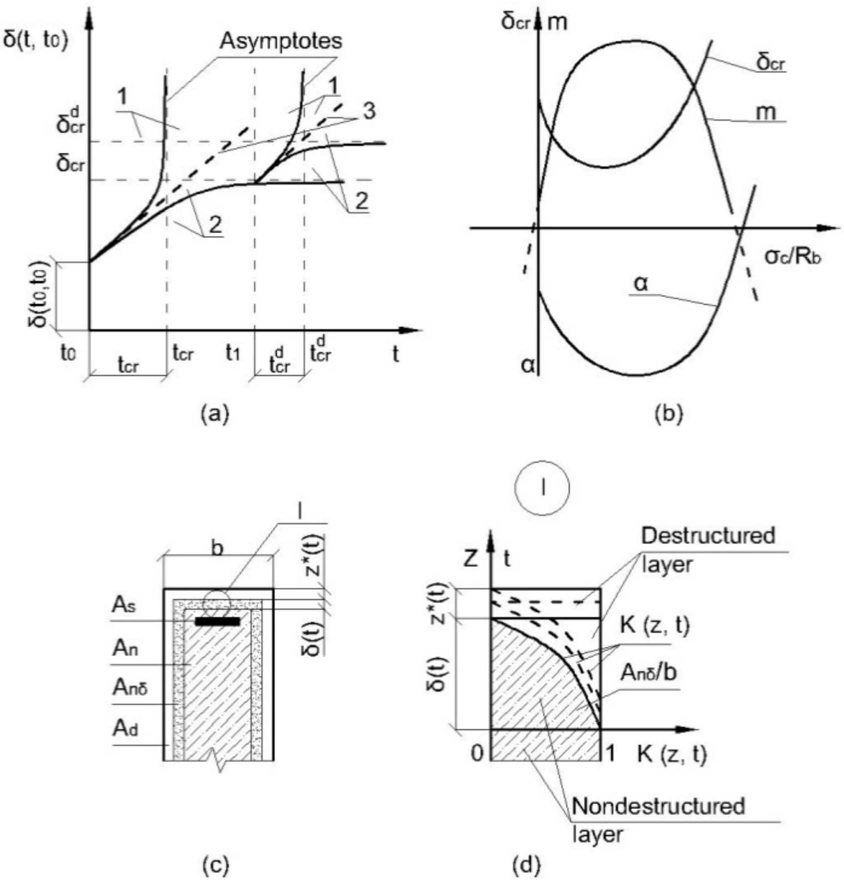

Figure 1. Scheme of the corrosion damage kinetics of compressed concrete
(a): scheme to determine parameters δcr, α, m;
(b): cross-section of the corrosion-damaged reinforced concrete element;
(c): general view of the corrosion damage function K(z, t);
(d): 1 corresponds to the area of avalanche corrosion penetration (m < 0);
2 corresponds to the area of colmatation (m > 0);
3 is the boundary line (m = 0)

3. Results and Discussion

In the present article we consider only colmatational process of corrosion damage development in accordance to which the stiffness of the cross section of corrosion damaged element can be determined from the following expression:

$$B_{red}(\delta(t)) = E_t \cdot I_{red}(\delta(t)) \tag{2}$$

where E_t is variable strain modulus of concrete, which depends on deformation, caused by loading and creep [21];

I_{red} *(δ(t))* is the reduced inertia moment of cross section, which can be calculated by the formula:

$$I_{red}\left(\delta(t)\right)=A_n r_{cn}^2+\sum_{i=1}^{l} A_{n\delta,i} r_{cn\delta,i}^2+I_n+\sum_{i=1}^{l} I_{n\delta,i}+\frac{\omega_s}{\psi_s}\cdot\alpha\cdot A_s\cdot r_{cs}^2 \tag{3}$$

where A_n is area of part of section without corrosion damage; $A_{n\delta,i}$ is area of i-th part of section exposed to corrosion, which is determined in accordance to function of corrosion damage *K(z, t)* as it is shown in Figure 1 (c); A_s is area of reinforcement cross section; r_{cn}, $r_{cn\delta,i}$ are distance from center of mass of not damaged section to center of mass of whole section and distance from center of mass of i-th part of section damaged by corrosion to center of mass of whole section, which is determined in accordance to function of corrosion damage *K(z, t)*, respectively; r_{cs} is distance from center of mass of reinforcement cross section to center of mass of whole section; In is inertia moment of not damaged section with respect to own center of mass; $I_{n\delta,i}$ is inertia moment of i-th part of damaged section with respect to own center of mass; ω_s is coefficient of corrosion damage of reinforcement; ψ is coefficient of influence of tensiled concrete; $\alpha = E_s / E_t$ is coefficient of reduction of reinforcement to concrete.

Assuming that the corrosion damage of the section can be modeled by the function *K (z, t),* as it is shown in Figure 1 (d), taking into account the scheme shown in figure 1 (c), we obtain:

$$\begin{gathered}I_{red}(t)=\left(b-2z^*(t)\right)\frac{4\delta(t)}{3}\left(\frac{h}{2}-z^*(t)-\frac{3}{5}\delta(t)\right)^2+\frac{\left(b-2z^*(t)\right)}{6}\left(\frac{2\delta(t)}{3}\right)^3+\\ +\left[h-2z^*(t)-2\delta(t)\right]^3\frac{\delta(t)}{9}+\frac{1}{12}\left[b-2z^*(t)-2\delta(t)\right]\cdot\left[h-2z^*(t)-2\delta(t)\right]^3+\\ +\frac{\omega_s}{\psi}\cdot\alpha\cdot A_s\cdot(h-2a)^2\end{gathered} \tag{4}$$

where h and b are the height and width of the intact section respectively; a is the distance from the center of gravity of the reinforcement to the face of the reinforced concrete element as it is shown in Figure 1 (c); $\delta(t)$ is the thickness of the layer, is partially damaged by corrosion which can be determined from the expression

$$\delta(t)=\delta(t,t_0)-z^*(t) \tag{5}$$

In which $\delta(t,t_0)$ can be obtained by the formula (1); $z^*(t)=t\frac{d}{dt}\left(z^*\right)$ is the approximate relationships for the depth of the entirely destructured concrete; approximate model of corrosion destruction ω_s of steel reinforcement can be calculated from the equations:

$$\begin{cases}\omega_s=1 \quad at \quad \delta(t,t_0)<a-d/2;\\ \omega_s=\dfrac{\pi}{4A_s}\left[d-\dfrac{t-t_s}{8760}\dfrac{d}{dt}(\omega_s)\right]^2 \quad at \quad \delta(t,t_0)>a-d/2;\\ \omega_s=0 \quad at \quad z^*(t)\geq a-d/2.\end{cases} \tag{6}$$

Let us consider a fragment of a multi-storey frame (Figure 2) to develop an algorithm for analytical stability analysis of corrosion-damaged concrete structural system of the building. For this construction, we define the value of the parameter k_{cr} of special functions of the method of displacement, which characterize critical force and can be determined from the expression:

$$k_{cr}^2=\frac{P_{cr}l^2}{B_{red}} \tag{7}$$

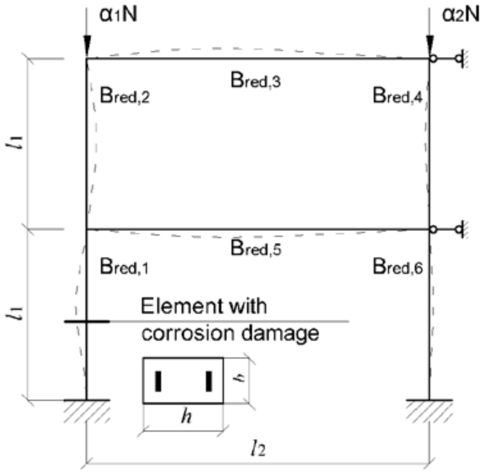

Figure 2. Computational model of the fragment of a multi-storey reinforced concrete frame

Let us assume that the elements of the structural system are compressed by longitudinal forces $N_i = \xi_i \cdot P_{cr}$, where ξ_i is the safety factor of stability of the i-th element of the system at the most unfavorable calculated combination of forces, P_{cr} – Euler's critical force for the structural system.

Taking into account that the k_{cr} parameter depends only on the boundary conditions at the end sections of the frame structural element, we carried out an expression for the critical value of the bending stiffness of the corrosion-damaged element, at which it will lose the stability:

$$B_{red,cr} = \frac{\xi_i P_{cr} l^2}{k_{cr}^2} \tag{8}$$

Equating expressions (8) and (2) and taking into account expressions (1), (5), (6), we obtain an equation, in which all parameters can be expressed through a critical time t_{cr}, corresponding to the moment of loss of the stability due to reaching a critical level of corrosion damage:

$$\begin{aligned} \frac{\xi_i P_{cr} E_t l^2}{k_{cr}^2} &= \left(b - 2z^*(t_{cr})\right)\frac{4\delta(t_{cr})}{3}\left(\frac{h}{2} - z^*(t_{cr}) - \frac{3}{5}\delta(t_{cr})\right)^2 + \frac{\left(b-2z^*(t_{cr})\right)}{6}\left(\frac{2\delta(t_{cr})}{3}\right)^3 + \\ &+ \left[h - 2z^*(t_{cr}) - 2\delta(t_{cr})\right]^3 \frac{\delta(t_{cr})}{9} + \frac{1}{12}\left[b - 2z^*(t_{cr}) - 2\delta(t_{cr})\right]\cdot\left[h - 2z^*(t_{cr}) - 2\delta(t_{cr})\right]^3 + \\ &+ \frac{\omega_s}{\psi}\cdot\alpha\cdot A_s\cdot(h-2a)^2 \end{aligned} \tag{9}$$

Let us analyze the stability of a fragment of a reinforced concrete frame (figure 2), one of the bearing elements of which (the lower left rack) is subject to the action of an aggressive environment. Initial parameters of the frame: l_1 = 3 m, l_2 = 6 m, initial section width b = 0.2 m, initial section height h = 0.35 m, the distance from the most compressed face to the center of gravity of the reinforcement a = 40 mm as it is shown in Figure 1 (a). Concrete B25 class, reinforcement A_s = A'_s – 4 rod A400 class with a diameter of 16 mm. The level of aggressiveness of the environment is medium ($z'(t)$ = 1 mm/year). Values of parameters δ_{cr}, α, m are taken by paper V.M. Bondarenko [15]. At the moment t_0 = 0 the safety factor of the stability of the corrosion-damaged rack ξ_i = 0.8, and the value of the critical force P_{cr} = 2860 kN, the ratio of the load parameters $\alpha_2/\alpha_1 = 4$.

Solving equation (9) in accordance with expressions (1), (5), (6), we obtain the graph B_{red} - t, which is shown in Figure 3 (b). The intersection point of this graph with the line of the ultimate value of stiffness $B_{red,cr}$ corresponds to the value of the critical time of the aggressive environment impact on the loaded structure t_{cr}, after which the frame will lose the stability.

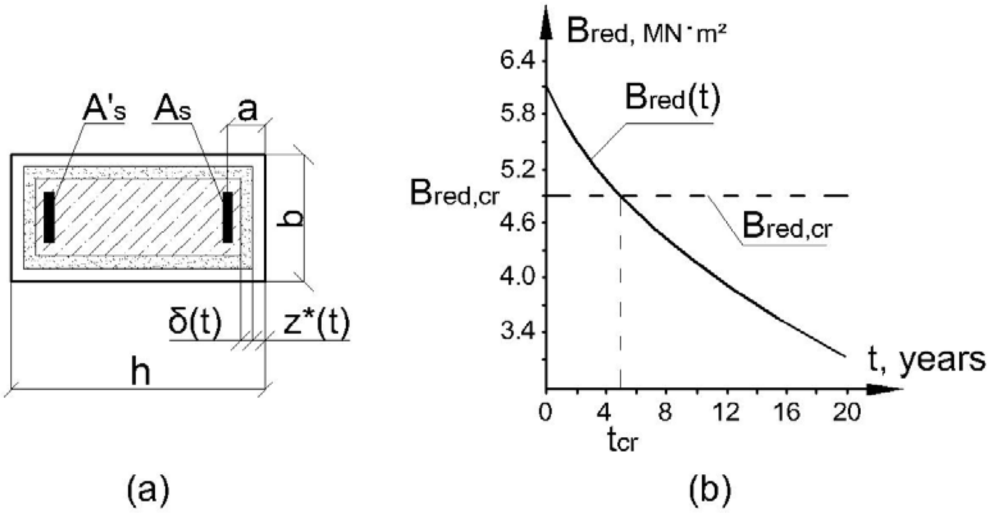

Figure 3. Scheme of the rack cross section (a) and graph B_{red} – t (b) for corrosion-damaged structural element

The ultimate value of the cross-section stiffness of the damaged structural element $B_{red,cr}$ or critical time t_{cr}, after which the structural system will lose stability, can be used as criteria to assess the survivability of reinforced concrete structural system at exceeding of the limit states, caused by a sudden loss of stability of the bearing element at acting of the loading and corrosion.

4. Conclusions

1. Analytical relationships for the critical stiffness value of the cross-section $B_{red,cr}$ of the corrosion-damaged element of the reinforced concrete frame are obtained.
2. "Exposure time of survivability" (by the terminology of V.M. Bondarenko, V.I. Kolchunov [29]) t_{cr} is determined on the basis of the stability criteria of a structural system, subjected acting of load and aggressive environment impact.
3. It is proposed criteria to assess the survivability of reinforced concrete structural system at exceeding of the limit states, caused by a sudden loss of stability of the bearing element at acting of the loading and corrosion.

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