Nonequilibrium processes of power and enviromental resistance of reinforced concrete structures to progressive collapse

V I Kolchunov\textsuperscript{1,3}, N B Androsova\textsuperscript{2,3}

\textsuperscript{1}Southwest State University, 50 Let Oktyabrya str., 305040 Kursk, 94, Russia
\textsuperscript{2}Orel State University named after I.S. Turgenev, Komsomolskaya str., 302026 Orel, 95, Russia
\textsuperscript{3}Scientific and research institute of construction physics of RAACS, Lokomotivny proezd, 21, Moscow, 127238, Russia

E-mail: ramia84@rambler.ru

Abstract. The problems of calculating the parameters of non-equilibrium power and environmental resistance of reinforced concrete elements of a structural system under special effects are considered. A static-dynamic diagram of the deformation of corrosion-damaged concrete during overlimit impact caused by the sudden removal of a supporting structure is constructed. The section of this diagram is described by the analytical dependence for change in the strength of loaded and corrosion-damaged concrete from time, which takes into account, on the one hand, the process of the increasing strength of “healthy” concrete in time (theory of concrete aging), and on the other, the process of the degradation of an aggressive environment on concrete. A section of the dynamic deformation diagram is described by the Kelvin-Voigt model in a version of the theory of plasticity of concrete G.A. Genius, which corresponds to the conditions of deformation of concrete as an elastic-viscous-plastic material. The dynamic tensile strength of corrosion-damaged concrete is taken into account by the coefficient of increase in the dynamic strength of the material based on the two-element model of its deformation.

1. Introduction
At present, the methodology for calculating reinforced concrete structures under special extreme conditions according to the current regulatory documents [1,2] applies to both new and operating reinforced concrete structures. However, these documents do not disclose the features of the calculation for such impacts of operated structures with a partially exhausted resource of their power resistance.

An analysis of scientific publications of the last decades shows that much attention is paid to the problem of corrosion wear and damage to reinforced concrete structures of operated buildings and structures. Currently, due to the need to calculate structural systems for special, including accidental
impacts, the class of tasks related to the protection of buildings from progressive collapse is expanding [3-4]. In solving such problems, research is needed not only for new, but also for exploited structures.

One of the important components in solving the problem of structural safety of buildings and structures is the most complete account of their operational wear and damage, and as a result, an assessment of the power and environmental resistance of such building structures. The development of such a conceptual and methodological approach for solving the problems of structural safety of structures is associated with the use of modern deformation models of power and environmental resistance of reinforced concrete in relation to such problems. In this direction, certain results of experimental and theoretical studies have been accumulated in the country and abroad, among them the studies of V.M. Bondarenko [5], G.A. Geniev [6], N.I. Karpenko [7], V.O. Almazov [8], Vl.I. Kolchunov [9], R.S. Sanzharovsky [10], B.S. Sokolov [11], G.A. Smolyago [12], A.I. Popesco [13], X. Lu [14], B.R. Ellingwood [15], N.V. Fedorova [16], V.I. Travush [17], A.G. Tamrazyan [18], V.S. Fedorov [19] and others. The results of these and other studies can be used to develop methods for the computational analysis of the deformation and fracture of structural elements under force and environmental influences in beyond design states.

2. Calculation model
Nonequilibrium processes of power and environmental resistance of reinforced concrete are determined by the level of loading and the type of stress state. With special influences on the structure caused by the sudden removal of one of the structures from the structural system, there is an instant redistribution of power flows and the statically loaded constructive system receives dynamic loading [8, 17, 18, 20].

Let us consider a diagram of the deformation of the reinforced concrete element’s cross section of a constructive system under such a loading mode for the case of operated structures when reinforced concrete degradation from corrosion is added to nonequilibrium processes of the power resistance of structures.

Differences in nonequilibrium processes based on the process of neutralizing concrete and corrosive medium, the aging process and corrosion of concrete at the same time, following [21], can be represented by the diagrams in Figure 1.

![Figure 1](image_url)

**Figure 1.** Diagram of the change of a concrete limit strength of $R_b$ at time: 1 - the process of increasing the concrete strength at time $t$ (aging of concrete); 2 - the process of neutralizing concrete with a corrosive medium at time $\tau$ (concrete corrosion); 3 - at the same time the process of “aging” and concrete corrosion.

If we take into account the modes of static loading and then dynamic loading of damaged concrete, then in the general case, the character of the “$\sigma_{b-e_b}$” diagram can be described by a non-linear section of static loading “O-A” with an initial module of deformation $E_0$ and a section of fast dynamic loading “A-$B_1(B_2)$” with the module of deformation $E_1(E_2)$ (Figure 2). In a first approximation, changes in the
strength of loaded and corrosion-damaged concrete over time, taking into account the process of increasing the strength of “healthy” concrete (theory of concrete aging), and the process of the influence of a corrosive medium on concrete, can be described using the G.A. Geniev deformation model [20, 21] as follows:

\[ R_b(t, \tau) = R_b^*(\tau) + R_b(t) - R_b(\tau_0). \]  

(1)

where \( R_b^*(\tau) \) - dependence of the corrosion-damaged concrete strength limit on time \( \tau \); \( R_b(t) \) – the dependence of the “healthy” concrete strength limit on time \( t \); \( R_b(\tau_0) \) – the concrete compressive strength limit before exposure to a corrosive medium.

The hypotheses are accepted for formation a dynamic deformation section of a static-dynamic deformation diagram of loaded and neutralized concrete by corrosion:

- the relationship between stresses and deformations in corrosion-damaged concrete during its short-term loading is affinely similar to the similar dependences of intact concrete;
- limit deformations of concrete under static and dynamic loading modes are equal to each other \( (\varepsilon_{b2} = \varepsilon_{b2}^d) \).

The static and dynamic deformation sections of loaded and corrosion-damaged concrete can be described by different deformation models, depending on the purposes of the solved problem [7,18].

For the considered task of static-dynamic loading, the two-element Kelvin–Voigt model was used in the version presented in [21–23], according to which the static deformation section of concrete “O-A” in general form can be described by the following equation (figure 2):

\[ \sigma_b = \frac{R_b(t, \tau)}{R_b(t, \tau)} \varepsilon \leq \varepsilon_0 \]

\[ \sigma_b = 2 \left[ 1 - \left( \frac{\varepsilon}{2\varepsilon_{b2}} \right) \right] \frac{\varepsilon}{\varepsilon_{b2}}. \]  

(2)

where \( \varepsilon_{b2} = \frac{R_b(t, \tau)}{E_0} \).

(3)

The dynamic deformation section can be described by the following dependence when loading from the stress level \( \sigma_0 \):
\[ \varepsilon_0 \leq \varepsilon \leq \varepsilon_{bz}^{d} \quad \frac{\sigma}{R(t, \tau)} = 2\varphi \left[ 1 - \left( \frac{\varepsilon}{2\varepsilon_{bz}^{d}} \right) \right] \frac{\varepsilon}{\varepsilon_{bz}^{d}}, \]

where \( R(t, \tau) = \varphi \cdot R_{b}(t, \tau) \).

The coefficient \( \varphi \) is determined from the equation, obtained when solving the Riccati equation [20] at loading from the stress level \( \sigma_{0} \), with the substitution of the given values of \( \gamma \) and \( \xi \):

\[ \frac{2}{\sqrt{\varphi-1}} \arctg \frac{\gamma-1}{\sqrt{\varphi-1}} = \xi + C, \]

\[ C = \frac{2}{\sqrt{\varphi-1}} \arctg \frac{\gamma_0-1}{\sqrt{\varphi-1}} - \text{integration constant.} \]

After some transformations, equation (6) takes the form:

\[ t \cdot \omega = \frac{2}{\sqrt{\varphi-1}} \left( \arctg \frac{\gamma-1}{\sqrt{\varphi-1}} - \arctg \frac{\gamma_0-1}{\sqrt{\varphi-1}} \right). \]

The determination of the coefficient of increase in the concrete dynamic strength (\( \varphi \)) is made in this sequence. The values are pre-calculated:

\[ \omega = \frac{G_0}{K}, \]

where \( G_0 \) – initial modulus of elasticity in shear; \( K \) – concrete’s dynamic coefficient of viscosity.

Then, using the dependences [24], the limit time \( (t_d) \) of dynamic loading for the load-bearing elements of the building frame determined by:

- for structural of a column:

\[ t_d = \frac{\pi}{2} \sqrt{\frac{y_{st}}{g}}, \]

where \( g \) – acceleration of gravity; \( y_{st} \) – displacements near a static elastic line as systems with one degree of freedom.

- for a crossbeam loaded with a force \( N(t) \), the dependence for determining the time of dynamic action [24]:

\[ t_d = \frac{1}{\omega} \arccos \left( 1 - \frac{m \omega^2 N}{y_{st}} \right). \]

Here \( \omega \) – the oscillation frequency, determined by the formula:

\[ \omega = \frac{a^2}{l^2} \cdot \frac{B}{\sqrt{m}}, \]

where \( a \) – coefficient depending on the conditions for fixing the ends of the element; \( l \) – calculated span; \( m \) – linear mass of an element; \( B \) – reduced bending stiffness.

From equation (8), the coefficient \( \varphi \) is determined having set the level of the \( \gamma_0 \) stress-deformation state of a (n) -once statically indeterminate structural system and the level of the stress-deformation state of a (n-1) -once statically indeterminate structural system.

3. Analysis of the reinforced concrete continuous beam’s static-dynamic deformation

We construct a static-dynamic diagram of the deformation of one sections of a continuous three-span beam loaded with concentrated forces \( P \), taking into account the nonequilibrium processes of power and environmental resistance. For the calculation analysis of the beam, the following initial data were adopted: the length of each span \( l = 1200 \text{ mm} \); section \( b = 70 \text{ mm}, \ h = 120 \text{ mm} \); concrete B25; reinforcement of 8 mm diameter, grade A400. The calculated section A-A in the middle of the beam’s third span is considered.
We assume that the beyond design impact is caused by the brittle fracture of the moment bond over the second intermediate support (Figure 3, a). With the instantaneous application of beyond design impact, the efforts from the application of the reaction in the removed connection with the opposite sign are added to the existing efforts in the original primary system. These forces (bending moments) will exceed the forces determined by the static calculation of the system according to the primary calculation scheme (see Figure 3, a).

According to the results of the static calculation according to the primary calculation scheme (see Figure 3, a) for a given level of load application \( P = 3.75 \text{kN} \) and \( l = 1.2 \text{m} \), at which application of beyond design impact occurs, moments in \( n \)-system and \( (n-1) \)-system are equal:

\[
M_{n}^{st} = 1.06 \text{kN} \cdot \text{m} \text{ и } M_{n-1}^{st} = 1.69 \text{kN} \cdot \text{m}.
\]

![Figure 3](image)  

\[ M_n^d = 1.97 \text{kN} \cdot \text{m} \]  
\[ M_{n-1}^d = 1.83 \text{kN} \cdot \text{m} \]

As a result of a quasistatic calculation based on the energy method, using the equality of the areas of the figures “aeb” and “bcd” [20], we obtained: \( M_{n-1}^d = 2.11 \text{kN} \cdot \text{m} \).

Accordingly, the curvature is calculated by the formula of the current standards [25], is:

\[
\varphi_{n-1} = 5.74 \cdot 10^5 \text{mm}^{-1}.
\]

The limiting value of the moment, taking into account the increase in the dynamic strength of concrete after beyond design impact in the beam structure intact corrosion and the beam damaged by corrosion, respectively, was: \( M_{n-1}^d = 2.11 \text{kN} \cdot \text{m} \).

When calculating the ultimate moments, the operating time of the structure and the time of neutralizing concrete with corrosion \( t = 360 \text{days} \) were taken, and the limiting time of dynamic loading of the section calculated by the formula (11): \( t = 0.04 \text{seconds} (\varphi = 1.61) \).
It follows from this that taking into account the nonequilibrium processes of increasing the concrete strength over time and concrete corrosion significantly (in the considered example, 30%) affects the dynamic strength of concrete during its dynamic loading.

4. Conclusion
The proposed calculation model for studying the nonequilibrium processes of the power and environmental resistance of reinforced concrete structures when calculating for progressive collapse allows one to take into account the accumulation of degradation damage and the change in concrete strength over time during the operation of structures when determining the parameters of the dynamic section of the "moment-curvature" deformation diagram after application of beyond design impact.

References
[1] Russian Building Code SP 296.1325800.2017 Buildings and structures. Accidental actions
[2] Russian Building Code SP 385.1325800.2018 Protection of buildings and structures against progressive collapse. Design code. Basic statements
[3] Kodysh E N 2018 *Industrial and civ. Eng.* 10 95-101
[4] Bondarenko V M, Kolchunov V I 2013 *Industrial and civ. Eng.* 2 28-31
[5] Bondarenko V M 2015 *Struct. Mech. of Eng. Constr. and Build.* 5 34-38
[6] Geniev G A 2000 Issues of long-term and dynamic strength of anisotropic structural materials (Moscow: GUP CNIISK named after V.A. Kucherenko)
[7] Karpenko N I, Karpenko S N, Petrov A N, Paluvina S N 2013 The model of reinforced concrete deformation in increments and the calculation of beam walls and flexural plates with cracks (Petrozavodsk: Publishing PetrGU)
[8] Almazov V O, Khoi K Z 2013 The dynamics of the progressive destruction of monolithic multi-story frames (Moscow: MGSU)
[9] Bondarenko V M, Kolchunov V I 2004 Computational models of force resistance of reinforced concrete (Moscow: Publishing ASV)
[10] Sanzharovskiy R S, Manchenko M M 2015 *Struct. Mech. of Eng. Constr. and Build.* 2 33-40
[11] Sokolov B S 2011 The theory of force resistance of anisotropic materials to compression and its practical application (Moscow Publishing ASV)
[12] Smolyago G A, Dronov A V, Frolov N V 2017 *Izvestiya Yugo-Zapadnogo gosudarstvennogo universiteta* 1 43-49
[13] Popesco A I, Antsygin S I, Dailov A A 2009 *Beton i zhelezobeton* 2 17-20
[14] Ren P, Li Y, Lu X, Guan H, Zhou Y 2016 *Eng. Structures* 118 28-40
[15] Cha E J and Ellingwood B R 2013 *Structural Safety* 40(1) 11-19
[16] Kolchunov V I, Kolchunov VI I, Fedorova N V 2018 *Industrial and civ. Eng.* 8 54-60
[17] Travush V I, Fedorova N V 2018 *Mag. Civ. Eng.* 81 73-80 doi: 10.18720/MCE.81.8
[18] Tamrazyan A G, Popov D S 2019 *Industrial and civ. Eng.* 2 19-26
[19] Fedorov V S, Bashirov H Z 2017 *Academia. Arhitektura i stroitel'stvo* 1 109-11
[20] Genitv G A, Kolchunov V I, Klyueva N V 2004 Strength and deformability of reinforced concrete structures with beyond design impacts (Moscow: Publishing ASV)
[21] Klyueva N V, Kolchunov VI I, Gubanova M S 2016 *Zhislishchne stroitel'stvo* 5 4-12
[22] Emelyanov S G, Klyueva N V, Korenkov P A 2016 *Izvestiya VUZov. Tekhnologiya tekstil'noj promyshlennosti* 3 252-70
[23] Klyueva N V, Shuvalov K A 2011 *Vestnik MGSU* 2 145
[24] Fedorova N V, Korenkov P A 2016 *Build. Reconstr.* 6 90-100
[25] Russian Building Code SP 63.13330.2012 Concrete and won concrete construction. Design requirements