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Strength resource calculation of the reinforced concrete elements according to the energy criterion

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Abstract

The article analyzes the main disadvantages of existing methods for calculating the residual life of building structure elements. A universal model and method for calculating the strength resource of reinforced concrete elements under conditions of long-term operation are proposed. The generalized deformation-force model of reinforced concrete elements resistance to force effects is developed up to the energy level due to the application of the hypothesis of invariability of the limiting potential deformation energy per unit volume and its independence from the loading mode. This hypothesis is recommended to be used as a universal energy criterion for the reinforced concrete elements bearing strength exhaustion, limiting their deflections and crack opening widths under the action of loads of any duration.

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1. Introduction

Establishing the building elements and structures actual stress-strain state with the determination of their residual resource will always remain one of the priority tasks that have to be solved during the reconstruction and modernization of building objects. This task is especially difficult for reinforced concrete elements, since it requires modeling their real stiffness characteristics during long-term operation. The overwhelming majority of the existing

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methods, the actual technical condition of the exploited reinforced concrete elements and structures is assessed according to the materials corresponding strength characteristics and the identified defects and damages totality. Under such circumstances, the reinforced concrete elements stiffness during their operation can be modeled only using the geometric parameters of their section. At the same time, it is known that a change in stiffness due to deformation parameters, in particular a decrease in the modulus of concrete deformations due to its creep, is more significant, since it can occur even without changing the geometric characteristics of the compressed cross-section of elements or structures. And in bending elements, it is the change in the mentioned deformation parameter that is also accompanied by a change in the geometric characteristics of the reinforced concrete elements section due to the deflections development and crack opening under conditions of long-term operation.

Therefore, the deformation model and calculation method, capable of reproducing the reinforced concrete elements and structures real technical state based on their cross-section stiffness characteristics, will make it possible to predict more reliably the residual life of reinforced concrete elements and structures not only by their bearing strength, but also by the permissible deflections and crack opening width. It is quite obvious that such models and techniques require the formulation of absolutely clear criteria for the onset of the reinforced concrete elements and structures limiting state under long-term operation conditions.

Nomenclature

M	bending moment
D	element section stiffness
f	element deflection
$1/r$	element curvature
E_c	concrete elasticity modulus
f_c	concrete strength
σ	stress
ε	strain
W	potential energy of deformation
s_r	cracking step
w	crack opening width
l	element length
t	time
φ	creep coefficient of concrete

2. Analysis of basic research and publications

Usually, the prediction of reinforced concrete elements and structures residual life is carried out on the basis of a force model of their resistance to external influences and loads. The calculation methods proposed within its framework differ in the severity of the formulation of the problem itself and its solution methods.

All currently known methods for calculating the residual life of building elements and structures according to the problem statement severity should be divided into deterministic and probabilistic.

Deterministic methods (Samolinov (2002), Shmatkov (2007) and Bigus (2015)) are used with insufficient or rather limited information about the investigated elements or structures (DBN B.1.2-14-2018 (2018)). Therefore, analytical dependences in the form of average degrees polynomials (Akulov et al. (2015)), involved in the description of their deformation basic laws, should be sufficiently convincing and properly substantiated. Indeed, in the case of a volitional choice of the behavior law of an individual element or structure during long-term operation, extrapolation of their stress-strain state according to certain specific parameters can lead to very serious miscalculations with extremely serious and undesirable consequences.

Probabilistic calculation methods (Sushchev (2009) and Bolotin (1982)) are based on a much larger volume of detailed information about actual external influences and loads. They need such information and about changes in

the strength properties of the structure under study. Undoubtedly, this makes it possible to significantly increase the reliability of both the calculations themselves and the conclusions regarding the reliability and durability of building structures. However, with this approach, special attention is paid only to the strength characteristics of materials, to the coefficients of their reserves or to individual technological indicators. The change in the deformation characteristics of materials during the long-term operation of reinforced concrete elements and structures is in no way taken into account.

All methods for calculating the residual life of reinforced concrete elements and structures proposed today can be conditionally divided into analytical and numerical.

Analytical simplified methods for calculating the residual life are implemented according to the criteria of the elements limiting states (Shmatkov (2007), Klimenko (2004) and Belyaev (2013)) while ensuring the necessary safety factors for their bearing capacity. A feature of these methods is that they need not only reliable information about the investigated elements and structures technical condition, but also the performance of mandatory verification calculations. In other words, these calculation methods are reduced to a fairly approximate extrapolation of the main parameters of the reinforced concrete elements and structures technical state, taking into account the existing defects, damages and actual properties.

Numerical methods (Golodnov and Slyusar (2013)) are based on modeling the stress-strain state of reinforced concrete elements and structures using modern software systems. Here, defects and damage, including cracks, established based on the results of field surveys, are modeled using the finite element method. As a result, it all boils down to the fact that additional "reinforcement elements" are introduced into the design scheme of structures, the possible efforts in which are determined taking into account changes in the strength and geometric characteristics of the design section. There is no doubt that such methods are able to more accurately reproduce the real technical state of reinforced concrete elements and structures in conditions of long-term operation in comparison with simplified ones.

In modern deformation models (DSTU B V.2.6-156:2010 (2011), EN 1992-1-1 (2004)) the calculation of the reinforced concrete elements and structures residual life is implemented mainly using probabilistic numerical methods. However, here, too, the change in the defining deformation parameters of elements and structures during their operation is taken into account only mediocre or not taken into account at all.

Therefore, a generalized method for calculating the reinforced concrete elements and structures resource should be based on a certain complex deformation-force criterion, which makes it possible to reproduce from an energy standpoint the change in their stiffness characteristics during long-term operation.

3. Materials and research methods

The present research concerns the design and reconstruction of reinforced concrete elements and structures made of heavy concrete and periodic profile rebar during their operation under conditions of long-term loads. They are based on the general laws governing the reinforced concrete elements and structures deformation under the operational loads action and are reduced to modeling changes in the stiffness characteristics of these elements based on the energy criterion.

4. Research results

In mechanics of deformable solids (MDS), the reinforced concrete elements and structures stress-strain state at any stage of their deformation is described, as a rule, by the system of the following relations:

$$\left. \begin{array}{ll}
 \text{static} & M = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s), \quad N = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s); \\
 \text{geometric} & 1/r = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s); \\
 \text{physical (materials state)} & \sigma_c = f(\varepsilon_c), \sigma_{ct} = f(\varepsilon_{ct}), \sigma_s = f(\varepsilon_s).
 \end{array} \right\} (1)$$

For the force models, where the hypothesis of flat sections is not taken into account and idealized stress diagrams in materials are used, the solution of this system is reduced to using two traditional equilibrium equations. Therefore, in conditions of concrete creep, it is extremely difficult to determine the residual life of reinforced concrete elements and structures using an analytical method, and in most cases it is even impossible.

In the deformation models, relations (1) form a statically indefinite system, the solution of which, even without taking into account the concrete creep, is rather laborious and comes down to performing numerous iterations. Taking into account the concrete creep deformations, the number of iterative calculations increases markedly, and the solving of this system becomes even more complicated.

In the deformation-force model of the reinforced concrete elements and structures resistance to force effects, the most important force and deformation parameters of their deformation at all stages are interconnected by the stiffness function (Romashko and Romashko (2019)):

$$D = M / (1/r) = D_o - D_u \cdot \frac{1/r}{1/r_u} - (D_o - 2 \cdot D_u) \cdot \frac{M}{M_u} \quad (2)$$

from which the analytical dependence of the state universal diagram of the indicated elements "moment-curvature":

$$M = \frac{D_o \cdot 1/r - M_u \cdot ((1/r)/(1/r_u))^2}{1 + (D_o/M_u - 2/(1/r_u)) \cdot (1/r)}, \quad (3)$$

where D_o is the initial reduced stiffness of the reinforced concrete element section; D_u - the reinforced concrete element section stiffness when the bearing strength is exhausted $D_u = M_u / (1/r_u)$; M_u - bearing strength of a reinforced concrete bar (ultimate force in it); $1/r_u$ - the element curvature in the limiting state.

Since the state diagram (3) under certain boundary conditions is capable of transforming into the well-known fractional rational function of concrete deformation (4):

$$\sigma_c = f_{ck} \cdot \frac{E_{co} \cdot \varepsilon_c / (E_{cu} \cdot \varepsilon_{cu}) - (\varepsilon_c / \varepsilon_{cu})^2}{1 + (E_{co} / E_{cu} - 2) \cdot (\varepsilon_c / \varepsilon_{cu})}, \quad (4)$$

where f_{ck} is the characteristic value of the concrete compressive strength; E_{co} - the initial value of the concrete elasticity (deformation) modulus; E_{cu} - the limiting value of the concrete deformations secant modulus; ε_{cu} - the compressed concrete relative deformations limiting value, then the parameters of the limiting state, determined by the extreme Fermat criterion $dM/d(1/r) = 0$, make it possible to predict the ultimate deformations of not only tensile reinforcement, but also compressed concrete (Romashko and Romashko (2019)).

Under such circumstances, it is proposed to build a methodology for calculating the reinforced concrete elements and structures residual life based on those parameters that can be determined directly during field surveys using geodetic, photogrammetric or any other method. In addition to real defects, damages and mechanical characteristics of construction materials, deflection can serve as such a parameter f_l . Using it, it is quite easy to calculate the averaged values of the bending reinforced concrete element curvature in the operational stage (Fig. 1, a):

$$1/r_{fl} = f_l / (s \cdot l^2), \quad (5)$$

where s is the coefficient depending on the loading and fastening schemes of the element; l - calculated length of a reinforced concrete element.

At the same time, the bending reinforced concrete element initial curvature in the averaged design section under the action of operational loads can be determined from the generalized diagram of its state (3) by the expression:

$$\frac{1}{r_f} = \frac{1/r_u}{2M_u} \left[\left(1 - \frac{M_l}{M_u}\right) \frac{D_o}{r_u} + 2M_l - \sqrt{\left(\left(1 - \frac{M_l}{M_u}\right) \frac{D_o}{r_u} + 2M_l\right)^2 - 4M_l \cdot M_u} \right], \tag{6}$$

where M_l is the bending moment from the operating load action.

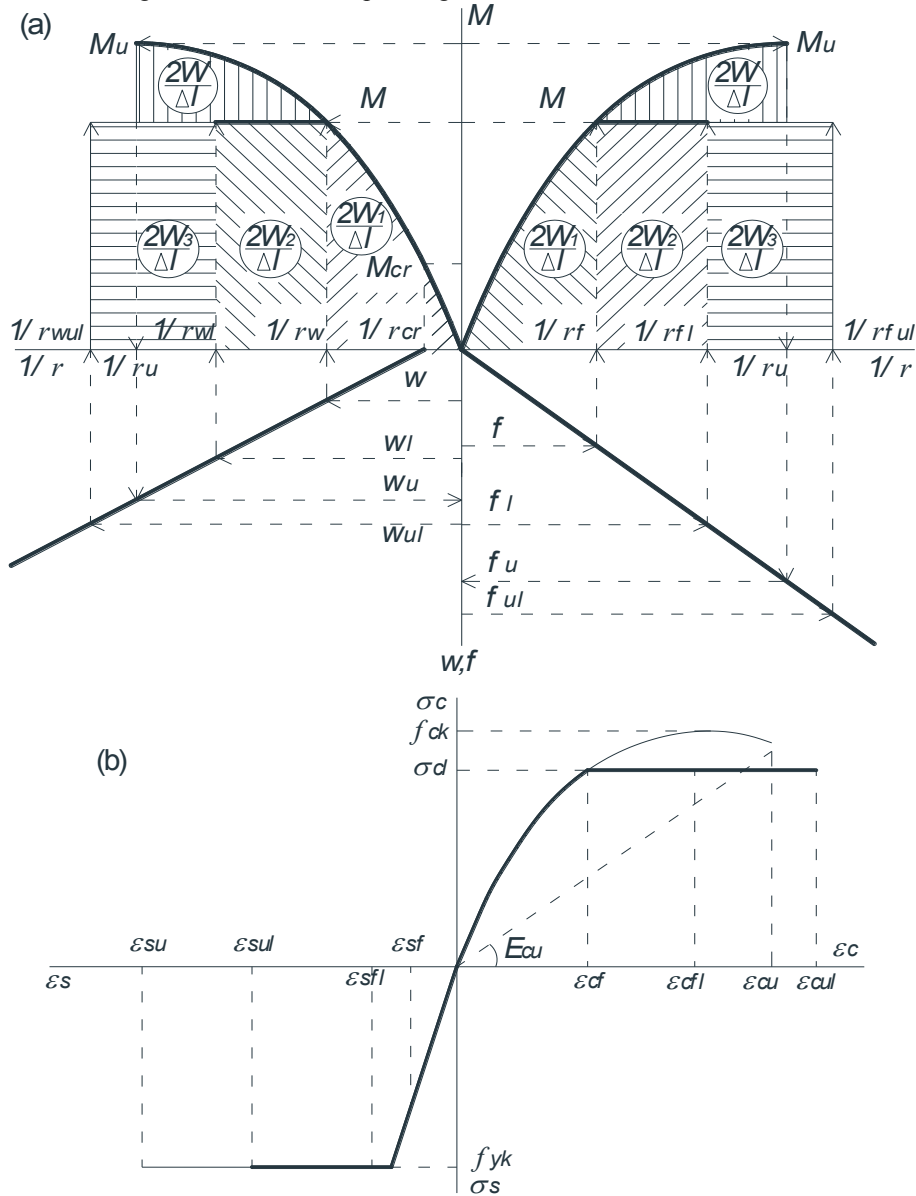


Fig. 1. To the calculation of reinforced concrete elements resource according to the energy criterion: the type of element state diagrams and the potential energy of its deformation (a); type of reinforcement and concrete deformation diagrams under different loading conditions (b).

The main difference of the deformation-force model in comparison with others is that with the help of the above-mentioned force and deformation characteristics (M and $1/r$) it is possible not only to control the change in the reinforced concrete elements stiffness characteristics, but also to estimate the potential energy of their deformation. For this, in the deformation-force model, a hypothesis of the invariability of the potential destruction energy of the

reinforced concrete element ($W = \text{const}$) per unit volume and its independence from the loading mode is put forward. At the same time, it serves as an energy criterion for calculating the residual life of a reinforced concrete element (Romashko and Romashko (2019)).

In particular, the potential energy of a bending reinforced concrete element limiting deformation in a certain destruction area for a short-term action of a full load (Fig. 1, a) can be calculated by the expression:

$$W = \frac{\Delta l}{2} \int_0^{1/r_u} Md(1/r) = \frac{\Delta l \cdot M_u \cdot (1/r_u)}{2 \cdot (K-2)} \left[-\frac{1}{2} + \frac{(K-1)^2}{(K-2)} - \left(\frac{K-1}{K-2} \right)^2 \ln(K-1) \right], \quad (7)$$

where Δl is the section length (computational block), within which the destruction of the element occurs, is taken under the condition $s_r \leq \Delta l \leq h$; s_r - the distance between normal cracks (their step); h - the height of the element cross-section in the destruction area; $K = D_o \cdot (1/r)_u / M_u$ - characteristic of the reinforced concrete element deformability.

The reinforced concrete element potential deformation energy in the same section from the short-term impact of the operating load (Fig. 1, a) should be calculated by the expression:

$$W_1 = \frac{\Delta l}{2} \int_0^{1/r_f} Md(1/r) = \frac{\Delta l \cdot M_u}{2 \cdot (K-2)} \left[-\frac{(1/r_f)^2}{2 \cdot (1/r_u)} + \frac{(1/r_f) \cdot (K-1)^2}{(K-2)} - (1/r_u) \cdot \left(\frac{K-1}{K-2} \right)^2 \ln \left(1 + (K-2) \frac{1/r_f}{1/r_u} \right) \right], \quad (8)$$

and from its long-term action (Fig. 1, a) - according to the formula (9):

$$W_2 = \Delta l \cdot M_l \cdot (1/r_{f_l} - 1/r_f) / 2. \quad (9)$$

Taking into account dependences (7) ... (9), the potential energy of a bent reinforced concrete element deformation, corresponding to its residual resource (Fig. 1, a), can be determined by the expression:

$$W_3 = W - W_1 - W_2 = \Delta l \cdot M_l \cdot (1/r_{f_{ul}} - 1/r_{f_l}) / 2, \quad (10)$$

where $1/r_{f_{ul}}$ is the limiting value of a reinforced concrete element (by deflection) curvature when the bearing strength is exhausted under prolonged exposure to loads.

At the same time, together with the limiting curvature of the element averaged section, it is possible to predict the ultimate concrete deformations under prolonged exposure to the operating load (Fig. 1, b). This can be done using the system of relations (1) by drawing the well-known flat sections hypothesis:

$$1/r_{ful} = (\varepsilon_{cul} + \varepsilon_{sul}) / d, \quad (11)$$

where ε_{cul} is the limit values of the concrete average deformations of the most compressed face in the area between normal cracks; ε_{sul} - limit values of the most stretched reinforcement averaged deformations on the same section of its active adhesion to concrete (Romashko and Romashko (2018)); d - working height of an element section.

On the other hand, the ultimate concrete deformations under prolonged exposure to operational load can be predicted using the concrete creep characteristics of through the ultimate stiffness of the reinforced concrete element average cross section in general or the limit value of the intersecting concrete deformation modulus in particular:

$$E_{cul} = E_{cc} / (1 + \varphi(\infty, t_o)), \quad (12)$$

where E_{cc} is the sectioning concrete deformations modulus under short-term action of operational load (Romashko

and Romashko (2019)); $\varphi(\infty, t_o)$ - the limit value of the concrete creep coefficient under prolonged exposure to the operating load, take according to current regulations (DSTU B V.2.6-156:2010 (2011), EN 1992-1-1 (2004)).

Due to the flat sections hypothesis, the use of the above energy criterion in the calculations of the reinforced concrete elements and structures residual life becomes possible even when the initial parameter of field research is not deflection f , but the step s_r and normal cracks width w (Fig. 1, a). They are related to the curvature of the following dependence:

$$1/r = (\varepsilon_c + w/s_r + \varepsilon_{ctu})/d, \quad (13)$$

according to which the limiting value of the normal cracks opening width (Romashko and Romashko (2018)) under prolonged exposure to the operating load can be determined by the formula:

$$w_{ul} = (d/r_{wul} - \varepsilon_{clu} - \varepsilon_{ctu}) \cdot s_r, \quad (14)$$

where $1/r_{wul}$ is the limit value of the reinforced concrete element (cracks curvature of) when the load-bearing strength is exhausted by prolonged exposure to loads; ε_{ctu} - limit values of stretched concrete averaged deformations in the area between normal cracks.

According to the above method, theoretical prediction of normal cracks long-term opening was performed for one of the beams tested by Gilbert and Nejadi (2004). In this case, the compressed concrete average deformations from the initial $\varepsilon_c = \sigma_{cl}/E_{cc}$ to the final values $\varepsilon_{cfl} = \sigma_{cl}/E_{cfl}$ were determined according to expression (12) using the concrete creep coefficient $\varphi(t, t_o)$. The results of this prediction are graphically displayed in Fig. 2.

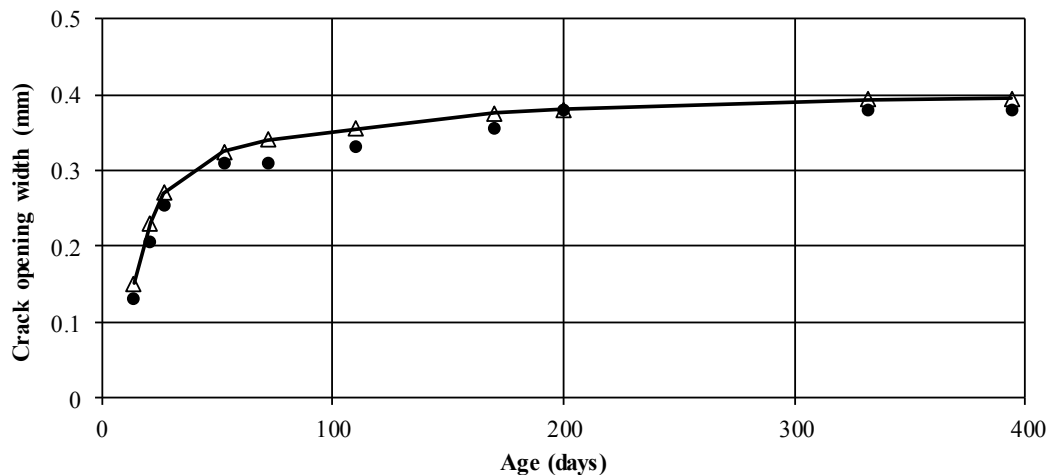


Fig. 2. Comparison of the experimental (●) and theoretical (Δ) values of the normal cracks opening width in a reinforced concrete beam (Gilbert and Nejadi (2004)) under prolonged exposure to a load.

5. Conclusion

Thus, based on the research results, the following conclusions can be drawn: the application of the energy criterion of the reinforced concrete elements and structures bearing strength exhaustion allowed to develop a generalized deformation-force model of their resistance to force to the energy level; the hypothesis of invariance in unit of volume and independence from a loading mode of potential energy of a reinforced concrete element deformation allows to carry out calculation of its total and residual resources from uniform methodological positions; the use of the energy criterion of the reinforced concrete elements and structures bearing strength exhaustion allows to calculate their total and residual resources directly from the measured deformation parameters of field studies (deflections, pitch and normal cracks width); forecasting the reinforced concrete elements and

structures residual life requires detailed studies of the concrete creep parameters.

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