Energy resource of reinforced concrete elements and structures for the deformation-force model of their deformation

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Abstract. This article provides a critical analysis of existing methods for calculating the residual life of reinforced concrete elements and structures by the rigor of the original problem statement and how it is solved. The most important provisions of the universal method of calculating the residual energy resource of reinforced concrete elements and structures under conditions of long operation are outlined. It is based on the deformation-force model of resistance of reinforced concrete in general and the hypothesis of invariance in unit volume and independence from the mode of loading of potential energy of deformation of reinforced concrete element. This hypothesis is reformulated to the energy criterion of exhaust bearing capacity of reinforced concrete elements under different load modes. The implementation of the proposed method for calculating the residual energy resource of the bearing strength capacity of reinforced concrete elements and structures is possible also in a temporary dimension. This can be done using the concrete creep parameters.

1. Introduction

Usually, the modernization and reconstruction of construction sites requires not only the establishment of a valid technical condition, but also the determination of the residual load-bearing capacity of structural structures. These tasks are particularly important, and even more difficult for reinforced concrete elements and structures, as they involve significant changes in their operational rigidity. However, most existing regulations [1, 2] completely ignore such changes, and therefore the technical condition of reinforced concrete elements and structures is assessed only on the aggregate of defects and damage detected without proper formalized calculations. The reason for such a primitive approach to establishing the true technical condition of building objects is the lack of an effective scientifically sound method of calculating the residual load-bearing capacity of structural structures. It is through such a technique that the process of reliable estimation of the technical condition of construction objects could be formalized as a result of the calculation of the residual load-bearing capacity of reinforced concrete elements and structures.

Obviously, the overall versatility and proper effectiveness of the above methodology could provide:

• substantiated model of deformation of reinforced concrete elements and structures in real conditions of long operation;
• the relevant assumptions, hypotheses and prerequisites necessary to implement the model;
• clear criteria for the limit state of reinforced concrete elements and structures under conditions of long-term operation.

2. Analysis of recent research and publications
The calculation of the residual life of buildings and structures is performed by different methods, which are different from each other, usually by the rigor of the original task and the way it is solved.

By the rigor of the problem statement, all known methods of estimating the residual life of building structures can be divided into two groups.

The first group includes deterministic methods [3-5], which are used with insufficient or limited design information. In such circumstances, depending on the description of the functional qualities of the structure, preferably in the form of polynomials of intermediate degrees [6], should be sufficiently substantiated. When a wilful choice of the law of the behaviour of a structure up to its limiting state, extrapolation by a certain parameter can lead not only to significant errors, but also to extremely grave consequences.

The second group consists of probabilistic calculation methods [7, 8], which require a much larger amount of detailed information not only about external loads and impacts, but also about the properties of the materials of the structure itself. Undoubtedly, due to the increased amount of necessary information, the reliability of the calculations and conclusions about the reliability and durability of buildings and structures is significantly increasing. With this approach, the external conditions of operation of the structure are considered random processes, and the calculation of the residual resource is carried out according to the determining parameters of the technical condition. Among the latter, particular attention is paid to changes in the mechanical characteristics of materials, to the coefficients of strength stocks and even to some technological indicators.

According to the method of solving the problem, the methods of calculating the residual life of building structures can also be divided into two groups.

The first group is formed by methods of calculating the residual resource according to the criteria of boundary states [4, 9, 10] while providing the coefficients of the reserve of structures. They are based on the tracking and extrapolation of the parameters of the technical state of the structures up to their limit values. The calculation method itself requires reliable information on the technical condition of the structure and the mandatory execution of the verification calculations, taking into account the existing defects, damages and the true properties of the materials.

The second group should include those methods based on the simulation of the stress-strain state of reinforced concrete structures by numerical methods [11, 12] using various software complexes. Defects and damages, including cracks, established on the basis of field surveys, are modelled by modifying the stiffness characteristics of the elements using the finite element method. Probable efforts in the “reinforcement elements” are determined by changing the stiffness characteristics or adding additional elements to the calculation scheme.

Thus, strength or deformation criteria are laid as the basis for all the above methods of calculating the residual life of reinforced concrete structures [2]. But the universal method of such calculations should be based on some complex deformation-force (energy) criterion.

3. The purpose and objectives of research
Therefore, the research data are aimed at developing a methodology for calculating the residual life of reinforced concrete elements and structures by the energy criterion of deformation. It is based on:
• generalized deformation-force model of resistance of reinforced concrete elements and structures by force influences [13];
• universally recognized system of equations of deformed solid body mechanics (MDS);
• defining hypotheses of nonlinearity of rigidity and boundary equilibrium;
• energy criterion for deformation of reinforced concrete elements and structures.
4. Results and discussion
The most important strength and deformation parameters of the deformation of reinforced concrete elements at all stages are interconnected by the stiffness function. Therefore, it is advisable that the method of calculating their residual resource should be based on the use of those parameters of field studies (surveys), which would allow directly or indirectly to evaluate the rigidity of the elements. In addition to real defects, damages and mechanical characteristics of materials, such a deflection can serve as a deflection of an element or structure, the value of which can be determined by survey geodetic, photogrammetric, stereophotogrammetric or otherwise. By the magnitude of the deflection, it is quite easy to determine the central curvature of the bending element in the operational stage (Figure 1):

\[ 1/r_{f1} = f_1/(s \cdot l^2) \]  

(1)

where \( s \) is the coefficient depending on the schemes of loading and fixing of the element, \( l \) is the estimated length of reinforced concrete element.

![Figure 1. To determine the potential energy of deformation of the bending reinforced concrete element under the action of loads of different duration.](image_url)

The initial value of the average curvature in the design section of the bending reinforced concrete element in the operational stage can be determined based on a generalized diagram of its state [14, 15]:

\[ M = \frac{D_0 \cdot 1/r - M_u \cdot ((1/r)/(1/r_u))^2}{1 + (D_0/M_u - 2/(1/r_u)) \cdot (1/r)} \]  

(2)
by the expression:

\[
\frac{1}{r_f} = \frac{1}{2M_u} \left[ (1 - \frac{M_I}{M_u}) \frac{D_0}{r_u} + 2M_I - \sqrt{(1 - \frac{M_I}{M_u}) \frac{D_0}{r_u} + 2M_I}^2 - 4M_I \cdot M_u \right]
\]

(3)

where \(1/r_u\) is the limit value of the curvature of the element when they exhaust their bearing capacity, \(M_u\) is the bearing capacity of the same element (maximum effort in it when the limit state), \(M_I\) is the bending moment from the operational load, \(D_0\) is the value of the total initial rigidity of the reinforced concrete element.

The parameters of the limit state and are determined according to the deformation-force model of resistance of reinforced concrete elements and structures to the forces and main provisions of the MDS by the following system of equations:

\[
\begin{align*}
\text{static} & : M = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s) \\
\text{geometric} & : 1/r = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s) \\
\text{physical (state of materials)} & : \sigma_c = f(\varepsilon_c), \sigma_{ct} = f(\varepsilon_{ct}), \sigma_s = f(\varepsilon_s)
\end{align*}
\]

(4)

with the addition of its analytical dependence of the state diagram of the element \(M - 1/r\) and the function of boundary deformation of compressed concrete \(\varepsilon_{ct} = f(\varepsilon_{ct}, \rho_1, x_{ct}, m_h, m_h)\) [13].

Then the potential energy of the boundary deformation of the bending reinforced concrete element with short-term full load action (Figure 1) can be calculated by the following expression:

\[
W = \frac{1}{r_f} \int_0^{1/r_u} \left[ D_o \cdot (1/r) - \frac{M_u}{(1/r_u)^2} \cdot (1/r)^2 \right] \left[ 1 + (K - 2) \frac{(1/r)}{(1/r_u)} \right] d(1/r) = \frac{M_u \cdot (1/r_u)^2}{(K - 2)} \left[ -\frac{1}{2} + \frac{(K - 1)^2}{(K - 2)} \right] - \frac{(K - 1)^2}{(K - 2)} \ln(K - 1)
\]

(5)

where \(K = D_0 \cdot (1/r_u)/M_u\) is the deformability characteristic of the reinforced concrete element.

Similarly, determine the potential energy of deformation of the bending reinforced concrete element during short-term action of operational load (Figure 1):

\[
W_1 = \frac{1}{r_f} \int_0^{1/r_u} \left[ D_o \cdot (1/r) - \frac{M_u}{(1/r_u)^2} \cdot (1/r)^2 \right] \left[ 1 + (K - 2) \frac{(1/r)}{(1/r_u)} \right] d(1/r) = \frac{M_u}{(K - 2)} \left[ -\frac{(1/r)^2}{2} \frac{(1/r_u)}{(1/r_u)} - \frac{(K - 1)^2}{(K - 2)} \ln \left[ 1 + (K - 2) \frac{1/r_f}{1/r_u} \right] \right]
\]

(6)

and with long-term operating load (Figure 1):

\[
W_2 = M_I \cdot (1/r_f1 - 1/r_f)
\]

(7)

where \(1/r_f1\) and \(1/r_f\) is the curvature of the reinforced concrete element from the long and short-term action of the operational load, respectively.

Taking into account the expressions (5)… (7), the potential energy of deformation of the bending reinforced concrete element corresponding to its residual resource can be determined by the expression (Figure 1):
where \(1/\tau_{\text{f,ul}}\) is the limit value of the curvature of the element when it is exhausted by the bearing capacity for long-term loading.

Thus, it is proposed to perform the calculation of residual life of reinforced concrete elements and structures by deformation-force model with the use of another determining hypothesis - invariance in unit volume and independence from the mode of loading of potential energy of deformation of reinforced concrete element spent on its destruction. This hypothesis also serves as an energy criterion for calculating the residual resource in the proposed methodology and allows it to be implemented in a time dimension.

The calculation of the residual life of the reinforced concrete element in the temporal dimension is associated with the change in the time of stiffness of its cross-section in general and the modulus of deformation of concrete in particular:

\[
E_{cl} = E_{cc} / (1 + \varphi(t, t_0))
\]

where \(E_{cc}\) is the secant modulus deformation of concrete steps for short-term external load, \(\varphi(t, t_0)\) is the coefficient of creep of concrete for long-term action of external load, the limit value of which is accepted according to the current norms [2, 16].

The use of the proposed energy criterion in the calculations of the residual life of reinforced concrete elements and structures becomes possible even when the initial parameter of the field studies will serve not as a deflection but as a step and width for the opening of normal cracks (Figure 1). It should be noted that the proposed method allows to predict the operational values of the specified crack parameters for their level formation [17], taking into account the adhesion of reinforcement with concrete [18]. And this is made possible by the fact that the planar cross section hypothesis allows in the central design cross section to associate deformations of materials with the stiffness of an element due to its curvature:

\[
1/r = (\varepsilon_{c2} + \varepsilon_{c1})/d \quad \text{or} \quad 1/r = (\varepsilon_{c2} + \varepsilon_{c0})/h
\]

where \(\varepsilon_{c2}\) is the current values of relative deformations of concrete of the most compressed face, \(\varepsilon_{c0}\) is the current values of the relative deformations of the least compressed concrete face (in the absence of tensile), \(\varepsilon_{c1}\) is the current values of relative deformations of the most extended reinforcement, \(h\) and \(d\) are, respectively, the total and the working height of the section of the element.

However, it should be noted that the accuracy of calculating the residual energy resource of reinforced concrete elements step by step and the width of the opening of normal cracks is slightly lower than the deflection.

The energy criterion proposed by the authors allows not only to determine the life (stock) of the bearing strength capacity of a reinforced concrete element or the duration of its resistance to the action of a certain force, but also to solve the inverse problem - to predict the width of crack opening in the conditions of long-term operation of elements and structures. This can be confirmed by a comparison of experimental and theoretical values of the crack opening width of reinforced concrete beam B2-a [19] under the action of long loads (Figure 2).
Figure 2. Experimental and theoretical values comparison of crack opening width of reinforced concrete beams B2-a [19].

5. Conclusions
The proposed method of calculating the residual life of reinforced concrete elements and structures differs from all other in that it is based on:
• deformation-force model of resistance of reinforced concrete elements and structures by force influences;
• the hypothesis of invariance in unit volume and independence from the mode of loading of the potential energy of deformation of a reinforced concrete element;
• direct use of such initial parameters of field studies (measurements) as the deflection of the element, the step and width of the opening of normal cracks;
• possibility of its realization in time dimension by means of parameters of creep of concrete.

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