Concept of design assurance for operational reliability of reinforced concrete structures in severe conditions

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Abstract. This work considers the concept of a systematic approach to the design assurance of equal reliability of structures under normal and severe operating conditions during their service life corresponding to the time of exhaustion of concrete frost resistance resource. It is proposed to analyze the reliability of structures in terms of the probability of a parametric failure, diagnosed as the achievement of the design and normative level by technical suitability indicators. The necessary (under conditions of equi-reliability!) correction of the initial values of concrete and reinforcement strength indicators is explained by dynamic models that take into account statistical patterns of their change during freezing-thawing cycles as well as the effect of reinforcement level. The time factor of the fatigue wear process is modeled by relative (to the design frost resistance) cycles, while the aggressiveness of external environment is modeled by an equi-consequential number of standard frost test cycles.

1. Introduction

Among the most important indicators regulated by the state quality standard for construction products [1], along with the indicators of "purpose" (strength, stiffness, crack resistance, fire resistance, frost resistance, etc.), "constructiveness" (shape, dimensions, geometry), "manufacturability" (labor intensity, maintainability) are the parameters of reliability (preservation, durability, recoverability). In this case, the defining characteristic of reliability of structures is the probability function \( p(t) \) of the stay of multidimensional vector of quality in the permissible range of values during the established service life [2]. The admissible area of space of quality in the most generalized form is given by a system of equations as follows:

\[
\Psi_i(t) = \bar{r}_i(t) - \bar{q}_i(t) \geq 0, \quad \text{(1)}
\]

\( i \) – regulated indicator of quality;
\( \bar{r}_i(t), \bar{q}_i(t) \) – random values of impact and corresponding resistance of the structure

In such a formulation, the failure (non-compliance) of the structure to meet the requirements is represented as an ejection of function \( \Psi(t) \) outside the range of admissible realizations.

Analytically closed solutions for the system of these inequations in terms of design consideration of the processes of interaction between buildings and structures with the environment is not possible. Engineering-acceptable solutions are possible on the basis of specialization of models of operability of structures, taking into account physical, mechanical and statistical patterns of degradation processes in the considered operating conditions, as well as the “responsibility of the structure” in ensuring the survivability (preservation) of the building.
Justification of a systematic approach to the design assurance of reliability of reinforced concrete structures of the "northern execution" is the key task of this analysis.

2. Methods of analysis
The specialization of the criterion model of reliability (1) is based on the refinement of the concept of failure for structures that are already operating or undergoing the design phase. The functional state of the former, as a rule, does not have an unambiguous assessment [3] predetermined by the failure parameters as an ejection outside the range of permissible changes. Therefore, “fuzzy failures” or levels of performance [4] may be considered. In this case, the conditions of technical suitability (1) are necessary but insufficient criteria for refusal to use the structure for its intended purpose. In making a decision, factors of economic and social responsibility (violation of technology, obsolescence, changes in working conditions, additional costs for repairs, etc.) are of no small importance.

At the stage of making design decisions, failure is associated with a probabilistic assessment of the fulfillment of the design conditions for operability of structures. Therefore, their functional state is assessed unambiguously as:

a) operable if criteria (1) are met;

b) inoperable if one or more criteria are not met.

In this formulation, the necessary and sufficient conditions for the functional suitability of the structure is fulfillment of the system of in equations (1), in which the impact and resistance correspond to their calculated (determined) values. In this case, failure is considered as the probability of an ejection of random functionality of strength, stiffness, crack resistance, etc. beyond the limits set a priori. In physical terms, its onset is identical to the achievement of the calculated limit state. It is fundamentally important that the probabilistic forecast of the initial reliability and durability is associated with an assessment of the risk of the onset of the calculated, and not the actual precondition. In essence, we evaluate the probability of a parametric failure, the occurrence of which is not identical in terms of consequences to “harmful” realizations [3-6].

Numerous studies and technical monitoring of reinforced concrete structures under extreme operating conditions [7-11] suggest that the most probable form of their failure is parametric. It is due to the development of cumulative fatigue processes with various physical and statistical patterns of structural degradation, leading to a gradual decrease in the significant parameters of technical suitability. In the absence of regulated functional time models of the kinetics of their change in severe climatic conditions, it seems appropriate to use engineering-acceptable system procedures that allow achieving the design equi-reliability of reinforced concrete structures under generally accepted and extreme operating conditions. Within the framework of the existing calculation method, the target task of such procedures is to provide a probabilistic and statistical substantiation of the correction of the normalized parameters of the internal resistance of concrete (reinforced concrete) for structures of "northern execution".

3. Conceptual approaches to design
The proposed concept is based on the following scientifically and experimentally substantiated and partially regulated premises.

1. Reinforced concrete is considered as a structurally unstable material, the wear of which, independently of the factors causing it, occurs in accordance with the principles of the kinetic concept of the strength of solids - the destruction rates from all unfavorable external factors are summed up and the principle of linear damage accumulation is valid. Its acceptability for concrete and reinforced concrete subjected to cyclic T-W impact has been repeatedly confirmed experimentally [7, 10, 12, 13].

2. The technical resistance potential of a structure is determined by the service life corresponding to the period of use of the concrete frost resistance resource (F). The continuous process of its depletion is modeled by mutually independent cycles of discrete temperature-humidity (FTC) impacts (N). In this case, the dynamic aspect of the model is represented by the level of impact, assessed by the ratio of the
The number of cycles to the frost resistance grade \((n = \frac{N}{F})\). The expediency of this approach is explainable by:

- an acceptable identity of the kinetics of curves of changes in FTC of the standardized indicators of strength and deformative properties of concretes of various resources (grades) for frost resistance [8, 10];
- the possibility of statistical generalization of numerous experimental data;
- the need for analytical and experimental verification of adequacy conditions of standard control for concrete frost resistance to the control of the required quality indicators of reinforced concrete structures.

Within the framework of this specialization, the system of criterion equations (1) is transformed to the form

\[ \bar{Q}_i(n) = \bar{r}_i(n) - \bar{q}_i(n) \geq 0 \quad (1') \quad n = [0,1]. \]

3. Only the probability of parametric failures in terms of technical parameters of the quality of reinforced concrete elements is considered, the criteria for the occurrence of which are inequalities.

\[ \bar{Q}_i(n) = \bar{r}_i(n) - r_i(0) \geq 0, \]  

\( r_i(0) \) - calculated (according to Set of Rules (SR) in Construction) value of the \( i \)-th performance indicator, considered the statistical equivalent of external influence.

The introduced error associated with the objective difference between the statistical distribution of impacts and the calculated resistance parameter does not exceed \(3 \pm 8.2\%\), provided that the coefficient of variability of the parameter is in the range of \(10\%\) - \(30\%\) [2, 10].

4. The statistical regularities of the distribution of performance indicators \( \bar{r}_i(n) \) are established indirectly by processing the experimental data of the controlled parameters (CP) of concrete, reinforcement, and the structure as a whole, which are most sensitive to thermal and humidity effects.

Their selection is carried out using normative functional models of structures performance according to standardized [14, 15] criteria of “informativity” (3), “sensitivity” (4) and “failure sensitivity” (5).

\[ \langle \hat{x}_j \left( \frac{dr_i}{dx_j} \right) \rangle = \min \langle \hat{x}_j \left( \frac{dr_i}{dx_j} \right) \rangle, \quad (3) \]

\[ \frac{dr_i}{dx_j} = \min \frac{dr_i}{dx_j}, \quad (4) \]

\[ \frac{dr_i}{dx_j} \approx \frac{[\Delta x_j]}{T}, \quad (5) \]

where \( \langle \ldots \rangle \) – means the mathematical expectation of the expression enclosed in it;

\( [\Delta x_j] \) – permissible threshold of change of the controlled parameter \( x_j \) from the condition of parametric failure or exhaustion of the regulated resource of frost resistance;

\( T \) and \( t \) – current and average operating time of a structure until parametric failure;

\( \hat{x}_j \) – dispersion of CP distribution

It should be noted that significant differences in the kinetics of FTC significant parameters of criterion models of operability determine the need for differentiation of CP at different stages of useful operating time (cycles). In this case, as the initial dynamic models of the normalized indicators of concrete properties, functional dependences of their change during FTC, obtained by statistical processing and generalization of numerous experimental studies [7, 10, 13, 14, 15-20], can be used:

\[
\begin{align*}
\bar{R}_b(n) &= \bar{R}_b(1 + 0.167n - 0.335n^2), \\
\bar{R}_bt(n) &= R_{bt}(1 - 0.25n - 0.305n^2), \\
\bar{E}_b(n) &= E_b(1 + 0.073n - 0.55n^2 + 0.135n^3), \\
v(n) &= v_0 (1 - 0.91n + 0.28n^2),
\end{align*}
\]

(6)
5. The parametric reliability of structures for each pre-state is diagnosed when the installed "CP" reaches the failure value \( x_{j\alpha} \) with the required level of security (\( \alpha = p/n = 0.9973 \) for the "USL" of the first group, and 0.95 for the second). For this, criterion normative models of the USL are transformed into a form that characterizes the inverse dependence of the CP on the calculated value of the considered indicator of the performance of a reinforced concrete element. For example, the failure value of concrete strength from the condition of ensuring the bearing capacity of a one-sided reinforced bending element is estimated by the following relationship

\[
[\bar{R}_b]_\alpha = \frac{\bar{\sigma}_s \bar{A}_s}{\bar{z}_b(\bar{\sigma}_s \bar{A}_o - r(0))},
\]

where \( r(0) \) – strength of an element along a normal section, determined by SR.

6. Numerical modeling using functions of the controlled parameter (7) establishes the risk areas of parametric failure for the considered "USL" with a probability equal to \( 1 - \alpha \). The behavior of elements with different reinforcement levels at different distribution densities (\( C_\nu \)) of the index of the controlled parameter is analyzed. The graphic-analytical results of the numerical experiment (approximate) are shown in Figure 1. Also presented here is the possible correction of the failure values \([\bar{R}_b]_\alpha\) caused by reducing the calculated value of the bearing capacity at the stage of making design decisions by introducing the coefficient \( \gamma_F \), taking into account the calculated temperature of external environment and level of relative reinforcement \( \mu' = \frac{\mu}{\mu_R} \) [10].

![Figure 1](image_url)

**Figure 1.** Influence of structural statistical factors on failure values of controlled parameters with different correction of design resistance a) normally reinforced; b) excessively reinforced.

7. Climatic operating conditions in terms of temperature and humidity are modeled by statistically justified equivalent cycles (\( N_3 \)), identical in consequences to a certain number of standard (base) ones. Harmonization is carried out using "weight" functions, taking into account standard test methods of testing.
\[ k(T) = aT^2 + bT + c, \quad (8) \]

under the following boundary conditions:
\[ k(T) = 0 \quad \text{with} \quad T \geq -3^\circ \text{C} \quad \text{(the temperature of the probable cooling of the pores moisture to freezing)}; \]
\[ k(T) = 1 \quad \text{in standard tests with} \quad T = -18^\circ \text{C}; \]
\[ k(T) = \kappa_c \quad \text{in accelerated tests with} \quad T = -50^\circ \text{C}. \]

The approach used makes it possible to differentiate "weight" functions for concretes with different frost resistance potential. If necessary (in high level of moisture content), the effect of daily drops in negative temperatures is taken into account with a corresponding correction of the "weight" functions [10, 12].

4. Conclusions
Based on the analytical generalization of numerous experimental studies and results of technical monitoring of buildings and structures, the structure of a systematic approach to the design of the required operational reliability of reinforced concrete structures in severe climatic conditions has been developed.

A model is proposed for the probabilistic forecast of parametric failures of reinforced concrete structures, as well as a correction of the calculated indicators of internal resistance, taking into account design features, kinetics of fatigue wear during the service life corresponding to the period of exhaustion of the standard resource of frost resistance, and the "aggressiveness" of the external environment, assessed by conditional (equivalent to the standard) cycles of impact.

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