On the issue of ensuring reliability of reinforced concrete structures of “northern execution”

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Abstract. The work is devoted to the design justification of the required resource of bearing capacity of bent reinforced concrete elements of “northern execution” based on ensuring the required reliability at the time of exhaustion of the frost resistance of concrete. The dynamic model of functioning of structure in severe climatic conditions is considered as a set of static tests at individual stages of cyclic temperature and humidity effects (FTC) formed on the basis of corresponding experimental samples of strength and deformability of concrete. For the criterion for reliability of structure, it is taken the value of strength and deformability of concrete, at which its bearing capacity over a normal section has a probability of at least 99.7%. Using graphic-analytical modeling, limit (failure) values were established and correction of the normative dependency by introducing a differentiating coefficient of reliability, accounting for the level of reinforcement and design negative air temperature, was proposed. The technical and economic unreasonableness of excessive, more than 80% of the boundary, reinforcement of normal sections of bent reinforced concrete elements of “northern execution” is established.

1. Introduction

Modern design methods allow us to consider reliability as a response of a building structure or a result of its interaction with the environment. In such a formulation, it can be identified with the probability of the occurrence of functional parametric failures in the form of undesirable limit states [1].

In the absence of statically representative data on structural failures in adverse operating conditions, the required design service life can be justified by the correction of calculated values of materials’ resistance, taking into account the physical and statistical laws governing their change. At the same time, adjustable and controlled parameters should have increased sensitivity to the probable failure, kinetics of change, and acceptable capabilities of ensuring information-statistical representation.

Taking into account the existing practice of design, operation, and control, it is advisable to select controlled parameters according to the criteria of the standard and recommendations [2-3] employing calculated dynamic models.

The fundamental difference between the latter from the corresponding normative functional dependences is the presence of time (time, cycles) and statistical distribution factors of significant response parameters of structures a priori accepted as random variables.

The experimental and analytical substantiation of such an approach to designing for reliability in the bearing capacity of bent reinforced concrete elements of “northern execution” is the goal of this work.

2. Materials and methods
A dynamic model of operation of structures in severe climatic conditions is considered as a set of static tests after a certain number of cycles \((N)\) of temperature-humidity \((T-W)\) impacts. Its acceptability follows from the Bailey principle [4], the adequacy of which for the conditions under consideration is confirmed experimentally [5-7]. The preferred test frequency is determined by physical laws of frost destruction of concrete, as a non-stationary process of an extreme form [8-10].

Taking into account the specifics of control and standardized indicators of quality as well as the possibility of summarizing numerous experimental data, the time factor is analyzed in the form of relative number of cycles of \(T-W\) impacts \((n = N/F)\) [11].

Controlled parameters of reliability are established by numerical modeling using criteria-based normative equations of bearing capacity and standardized indicators of their variability (tolerances). Comparative dynamics of FTC of strength and deformation properties was established experimentally [8, 14].

Prismatic strength of concrete \(R_0(n)\) and its ultimate deformability \(\varepsilon_{bu}(n)\), evaluated by the totality of random implementations at individual test stages were taken as experimental controlled indicators of reliability of bent elements according to the criteria of the standard [3]. Moreover, the durability of structures corresponds to the number of cycles, after which the probability of a decrease in \(R_0(n)\) is within the established tolerance (SP, SNiP, GOST) and is 99.7%.

The necessary correction of the calculated resistance of concrete based on ensuring reliability in the bearing capacity of a bent element for the duration of service life, corresponding to the frost resistance resource, is established by the graphic-analytical method in the following sequence.

The functional model of the strength of a bent element along the normal section in the parameters of random realizations is converted to:

\[
\tilde{R}_b = \frac{\bar{A}_s^2 \tilde{R}_0}{2b(\sigma_s \tilde{R}_0 - R_b)} \quad (1)
\]

\(\tilde{M}_0\) – a set of random values of the bearing capacity of an element under the assumption of a standardized variability of all parameters of the normative dependence.

Numerical modeling determines the failure value of concrete strength \(R_{bf}\), corresponding to the probability of a parametric failure of an element based on the bearing capacity of not more than 0.3%. Wherein, options for different levels of reinforcement (from minimum to maximum expected) and variability (from standard to predicted) are considered. Based on the numerical analysis, graphs of the dependence of the probability of parametric failure \((a = 0.3\%)\) on the adopted reinforcement and dispersion of concrete strength are constructed. At the same time, various options are considered for correcting the reduction in the estimated value when evaluating the design value of the bearing capacity MO.

Below, as an example, presented are the curves of changes in the failure value (under reliability condition) of concrete’s strength for two reinforcement options and various coefficient of variability \((C_v)\) of the concrete strength index (Figure 1). The significant influence of the level of reinforcement \((\mu = \mu_b)\) and statistical distribution indicators on the magnitude of failure value of concrete strength \(R_{bf}\), which indirectly characterizes the reliability of structure in bearing capacity, is clearly confirmed. The graphs of the risk of failure for the two most common options of correction of the calculated value \(\gamma_{bf}\) = 0.85 and 0.7 are also presented here. Ambiguity in the effect of corrective procedures on the relative (to the boundary) level of reinforcement and the density distribution of concrete strength is observed.

The obtained databank of graphical dependences of failure values \(R_{bf}\) in the scattering fields \(\mu - C_v\) was adopted as the basis for an indirect assessment of reliability of reinforced concrete structures of “northern execution” according to the results of standard compression tests of prismatic samples after cyclic freezing and thawing of various intensities. About one hundred samples of normally hardened concrete (Cement : Sand : Gravel : Water = 1 : 1.75 : 2.9 : 0.45) were exposed to temperature-humidity impacts (minus 42°C and thawing of water 20 ± 2°C). Periodically, the samples were tested for compression with a constant deformation rate (0.05 mm/s) with automatic control of deformations (\(\sigma-\varepsilon\) diagram). The number of simultaneously tested prisms (12-18 items) made it possible to obtain
statistically reliable data on the main distribution indices [8-11] of concrete strength at the stages of exhaustion of the normalized resource of its frost resistance.

Using experimental values of statistics and the databank of failure strength values under the conditions of ensuring the required reliability of structures (not less than 0.997), average values of \( R_{ba} \) were established for bending elements with different relative levels of reinforcement \( \mu' \) (Table 1).

As it has been expected, the failure value of concrete strength, considered a criterion for ensuring the necessary reliability for bearing capacity of a normal section, depends on the level of reinforcement and is a sensitive indicator to the impact of external conditions. Its monotonic increase is observed with increasing reinforcement and practical stabilization at \( \mu' = 0.85 \mu_R \). Similar tendencies are preserved in the time aspect, up to the moment of exhaustion of the resource of normalized frost resistance of concrete \( F \).

A comparative assessment of the distribution statistics \( R_0(n) \) and \( R_0 \) allows us to state that at the initial stages of cyclic T-W impacts (\( n \leq 0.3 \)), the calculated functional model of norms \( (\gamma_F = 1.0) \) provides the required level of reliability in the strength of the normal section for the entire range of reinforcement under analysis. A simple interpolation of the presented data shows that in prospect \( (n > 0.3) \) the risk of parametric failure may exceed the permissible level \((0.3 \%)\) in elements with \( \mu' \geq (0.4-0.45) \mu_R \).

In our opinion, there is a fundamental difference in the basic premises of the normative (deterministic) method for calculating bearing capacity and the probability-statistical forecast of durability. The first assumes the presence of a boundary height of the compressed zone \( e_R \), which for a given reinforcement a priori excludes the possibility of a dual nature \([12, 13]\) of parametric failure. The second postulates the probability of a different type of destruction, due to the statistical laws of the joint distribution of significant indicators of the structural properties of reinforcement and concrete. That is, parametric failures due to the destruction of the compressed zone until the tensile yield of reinforcement is quite likely when reinforcement is significantly lower than the boundary \((\mu_R)\). As \( \mu \) increases, its probability increases, which is confirmed by the dynamics of the failure value of \( R_{ba} \). The need is confirmed for differentiated correction of the design resistance taking into account the established laws and assurance of the necessary level of the design reliability of structure for the period of operation in severe climatic conditions identical to its frost resistance.

The data presented in the table indicate the possibility of achieving parity of \( R_0(n) \) and \( R_{ba} \) by acceptable reduction of the calculated value by 15-30\% \((\gamma_F = 0.85-0.7)\). Wherein the level of reinforcement of bent elements should not exceed 0.8 \( \mu_R \). It is not difficult to verify that ensuring the reliability of more reinforced sections is associated with an economically problematic decrease in the design resistance and calls for an appropriate rationale.

### 3. Conclusions

Taking into account the physical and statistical laws of frost destruction of concrete and reinforced concrete \([5, 7, 14]\), the temperature of the operating environment \((T)\) and the structural features of elements \((\mu')\), the correction of the criterion equation of bearing capacity by introducing the coefficient of reliability of concrete is proposed in a first approximation.

\[
\gamma_{DF} = (1 - 0.0075T)(1.36 - 0.48 \mu') \leq 1 \tag{2}
\]

The value of \( \gamma_{DF} = 1-0.5 \) at a design temperature of up to minus 60\(^\circ\) C and \( \mu' \leq 1.2 \mu_R \).

**Table 1.** Changes of failure value \( R_{ba} \) in FTC.

| \( n \) | Distributions statistics of concrete strength | \( \gamma_{DF} \) | \( R_{ba} \) for bent elements with \( \mu' \) equal to |
|---|---|---|---|
| \( R_0(n) \), MPa | Average \( C_{riD} \), % | \( 0.181 \) | \( 0.398 \) | \( 0.833 \) | \( 1.087 \) | \( 1.449 \) |
| 0 | 24.0 | 12.5 | 7.5 | 11.9 | 15.4 | 15.6 | 16.0 |
| 0.29 | 24.5 | 14.2 | 1 | 8.1 | 12.8 | 16.6 | 16.8 | 17.1 |
|------|------|------|---|-----|------|------|------|------|
| 0.86 | 20.2 | 20.7 | 0.85 | - | - | 21.0 | 21.3 | 22.2 |
| 1.0  | 19.7 | 23.4 | 0.85 | - | - | 17.0 | 17.4 | 19.8 |
| 1.29 | 19.1 | 27.0 | 0.85 | - | - | 14.5 | 22.1 | 28.8 |

a) $\mu' = 0.398 \mu_R$

b) $\mu' = 1.087 \mu_R$

**Figure 1.** Change $R_{bc}$ in the field of dispersion of coefficient of variability of concrete strength with relative reinforcement a) $\mu' = 0.398 \mu_R$; b) $\mu' = 1.087 \mu_R$
Figure 2. Change in $R_{\text{b}}$ for bent elements of different levels of reinforcement with a coefficient of variability of concrete strength a) $C_{Rb} = 10\%$; b) $C_{Rb} = 30\%$

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