Probabilistic assessment of the shear resistance of reinforced concrete elements under low-temperature impacts

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Abstract. This study considers the issue of design support and required reliability of the strength of bent reinforced concrete elements along inclined sections for the period of operation corresponding to the time of exhaustion of the resource of frost resistance. A dynamic model of the change in the potential of internal resistance (coefficient of safety) is proposed, the time indicator of which is characterized by the relative (to the frost resistance grade) level of temperature and humidity impacts. Numerical experiments have established a significant difference in the kinetics of decreasing the strength indices of inclined sections and the likelihood of achieving their reliability. Employing probabilistic-statistical method with the use of experimental data, the necessary correction of the calculated parameters of concrete resistance for structures in severe operating conditions has been substantiated.

1. Introduction

According to modern scientific concepts [1-5], the destruction of reinforced concrete elements along inclined sections begins with the formation of normal cracks in the support areas. The nature and direction of its further development depends on the presence and anchoring of longitudinal, transverse and inclined reinforcement.

The method for calculating reinforced concrete elements for the strength of inclined sections is based on a separate consideration of acting in them forces received by concrete and reinforcement being crossed by a critical inclined crack. It also includes a system of design constraints that collectively eliminate a sudden brittle nature of failure. In this case, the forces in concrete above the inclined crack are considered [1, 6] as the resultant of normal and tangential stresses in a normal section at the end of the inclined crack. In this view, the ultimate resistance of concrete can be estimated by the criteria of its strength in a plane stress state, that is, the joint resistance to compression and tension.

Considering the significant statistical variability of the mechanical properties of concrete under low-temperature impacts, it seems reasonable to assess the probabilistic design correction of the initial parameters of concrete strength included in the normative functional models of the strength of inclined sections of "northern execution" elements.

2. Research methodology

Correction of normative models is made on the basis of conditions of achieving with the required probability the strength along inclined sections for a service life corresponding to the period of
exhaustion of the concrete frost resistance resource (F). The required design life of the structural resistance is justified by the fulfillment of criterion inequations as follows:

\[ \bar{\psi}_i(n) = \bar{r}_i(n) - \bar{r}_i(0) \geq 0 \] (1)

where, \( n = N/F \) – the relative level (operating time) of depletion of the resource of frost resistance after N cycles of standard temperature and humidity impacts (FTC);

\( \bar{r}_i(n) \) – instant random value of the i-th resistance indicator at the n-th stage;

\( \bar{r}_i(0) \) – its calculated (according to "Set of Rules (SR) in Construction") value with the established assurance.

The practical implementation of the proposed approach is carried out by numerical modeling using normative functional dependencies. In this case, the time nature of the process of changing the internal resistance is indirectly taken into account by using experimentally established [7, 8] dynamic models of the kinetics of depletion of the average value of the indestructibility resource \( \bar{\psi}(n) \) in terms of the resistance to the design shear force and the safety factor \( \gamma \) [9] are considered criterion parameters of reliability.

\[ \gamma = \frac{m_1^{1-1}}{\sqrt{\sum C_{vj}^2 m_j^2 + C_{vq}^2}} \] (3)

where, \( m_1 = \bar{r}(n)/r(0) \);

\( m_j \) – coefficients of "significance" of the j-th parameter of resistance;

\( C_{vj}, C_{vq} \) – coefficients of variability adopted according to the experimental (table 1) and normatively established limits for deviations of dimensions and strength.

Verification calculations were performed for normally reinforced (\( \mu = \mu_b / \mu_c = 0,398 \)) bending elements of rectangular section, with longitudinal reinforcement of class A400 and clamps A240 with linear resistance \( q_{SW} = 0,5R_{bt} \). The kinetics of depletion of the average value of the indestructibility resource \( \bar{\psi}(n) \) in terms of the resistance to the design shear force and the safety factor \( \gamma \) [9] are considered criterion parameters of reliability.

**Figure 1a.**
The kinetics of changes in FTC of the safety margin of resistance against shear forces: 1 – according to

**Figure 1b.**
Kinetics at FTC of the safety factor for the strength of an inclined section: 1 –
SR, 1’- with correction $\gamma_f = 0.85$. according to SR, 1’- with correction $\gamma_f = 0.85$.

The data obtained (Figure 1a) allows us to assume that the strength of structures along an inclined section based on (T-W) impacts corresponding to the frost resistance of concrete is sufficient to withstand shearing forces (curve 1a) and proportionally increases with a decrease in the design resistance by introducing the coefficient $\gamma_{bt} = 0.85$ (curve 1’a).

A different dynamics is most likely for the safety factor of resistance (Figure 1b). Its nominal design-assumed level [7, 9] $\gamma \geq 2.75$ is maintained until 30–50% exhaustion of the frost resistance resource. Moreover, the latter (Figure 1b) corresponds to the normative correction $\gamma_{bt} = 0.85$ mentioned above. The effect, noted repeatedly [2, 7, 10, 11], is the increased sensitivity of reliability to an accelerated decrease in the density of the distribution of the shear strength of concrete in the process of its frost destruction.

The necessary correction of the computational model is achieved by the graphic-analytical method in the following sequence.

Statistical modeling methods are used to determine the areas of 0.3% failure risk in terms of strength of the inclined section of the element, identified with the achievement of the failure value of concrete tensile strength $[R_{bt}]\alpha$. At the same time, the range of expected distribution density indicators and various options for correcting the initial resistance value $\gamma_F$ are considered (Figure 2).

Figure 2. Areas of 0.3% risk of failure in the strength of an inclined section upon changes in the distribution density.

Based on experimental data using the maximum likelihood method [12, 13], the type of approximating distribution and its determining statistics are established (Table 1). For the obtained values of the coefficient of variability according to the calibration curves (Figure 2), failure indices of concrete strength $[R_{bt}]\alpha$ are established at different levels of the initial design correction $r(0)$ (Table 2).

Table 1. Parameters of the statistical distribution of the tensile strength of concrete.

| Level of impact | Approximating distribution | Pearson criteria | Statistics of distribution |
|-----------------|---------------------------|------------------|---------------------------|
|                 |                           |                  | Average, $R_b$, MPa | Dispersion, $D$, MPa | variability, $C_r$, % |
| 0               | normal                    | 0.116            | 3.52                     | 0.514                     | 20.3                     |
| 0.29            | normal                    | 0.606            | 3.17                     | 0.354                     | 18.8                     |
| 0.57            | equiprobable              | 0.416            | 2.68                     | 0.389                     | 22.0                     |
| 0.86            | equiprobable              | 0.532            | 1.94                     | 0.238                     | 24.8                     |
| 1.14            | composition of normal     | 0.232            | 1.01                     | 0.108                     | 36.8                     |
| 1.14            | equiprobable              |                  |                          |                           |                          |
Table 2. Change of failure value of strength at FTC with 99.7% assurance.

| $h$   | Calculated value, $R_{bt}$, MPa | $[R_{bt}]$ upon correction $\gamma_F$ equal | Note                                      |
|-------|---------------------------------|----------------------------------------------|-------------------------------------------|
|       |                                 | 1                             | 0.85 | 0.7  | 0.35 |                      |
| 0     | 2.24                            | 1.83                          | 1.48 | 1.12 | -    |                      |
| 0.29  | 2.02                            | 1.75                          | 1.45 | 1.23 | -    | A dash indicates values that are not of fundamental importance |
| 0.57  | 1.81                            | 1.87                          | 1.53 | 1.31 | -    |                      |
| 0.86  | 1.23                            | 1.95                          | 1.60 | 1.25 | -    |                      |
| 1.14  | 0.64                            | 2.37                          | 2.21 | 2.01 | 0.63 |                      |

From a comparison of the calculated and rejected values for the established assurance, it follows that it has been achieved with an acceptable correction ($\gamma_F \geq 0.7$) until the exhaustion of $60 \div 80\%$ of the frost resistance resource. The identity of changes in strength and reliability upon using the full potential of frost resistance is possible only with a 3-fold decrease in the initial design tensile strength of concrete. The expediency of such an adjustment should be justified by a comparative analysis of the reduced costs in comparison with the compensatory reinforcement of inclined sections with transverse reinforcement. Verification calculations allow for the assumption that the correction of the bearing capacity along the normal section [7, 8, 14] will be quite acceptable to ensure the strength of inclined sections reinforced with transverse reinforcement within 10–15% above the accepted design requirements.

3. Conclusions

1. The existing method for calculating bending reinforced concrete structural elements provides the necessary resource of internal resistance in terms of strength of inclined sections for a service life in severe climatic conditions identically to the period of exhaustion of the normalized frost resistance of concrete.

2. To ensure the required reliability in avoiding possible parametric failures in the strength of inclined sections, it is necessary to adjust the design approach in the direction of an economically acceptable reduction in the design parameters of resistance and tightening the design requirements for the transverse reinforcement of the supporting sections of structures.

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